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Productivity, site evaluation and state of nutrition of *Gmelina arborea* plantations in Oluwa and Omo forest reserves, Nigeria

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Abstract

The high productivity associated with many tropical forest plantation species has contributed to their importance in meeting the world's growing demand for wood products. However, there is concern that their high growth rate and intensive management system might lead to site nutrients depletion. A total of 20 stands (10–28 years) of *Gmelina arborea* plantations in Oluwa and Omo forest reserves, Nigeria, was used to investigate the effect of *Gmelina* plantation development on site nutrients, aboveground productivity and nutrient accumulation. Standing biomass ranged from 81.5 to 392.1 t ha^{-1} in the youngest and oldest stands. Regardless of stand age, biomass partitioning was about 83.0, 13.5 and 3.5% to stem, branches and foliage, respectively. The size and age of trees did not significantly affect nutrient concentration in tree components. Nitrogen, Ca and Mg contents in tree tissue increased in the order of foliage > stem > branches while that of K and P increased in the order of foliage > branches > stem. Tree tissue nutrients concentration exhibited little change with stand development. Stand nutrient accumulation followed the same trend as standing biomass, with about 80% of each nutrient stored in the stem and 20% in branches and foliage. The accumulation of nutrients in stem, branches and foliage followed the order: Mg > N > Ca > P > K > Na. Though soil nutrients were slightly depleted between 10 and 19 years and re-built up afterwards, the overall effect of stand development on soil nutrients was not statistically significant, implying that the development of *Gmelina* plantations did not adversely affect the soil nutrient status. Consequently, productivity during the next rotation will most likely be affected by harvesting methods of current stands and management practices of the next rotation. The 20% accumulation of aboveground nutrients in branches and foliage implies that apart from the already replenished site nutrients, there will be an additional 20% nutrient input into the soil if the branches and foliage are left on the site after harvest. For long-term site quality and sustainability of production, successive plantations should be managed on 25 years rotation as lower rotation will most likely lead to steady depletion of site nutrients.

Keywords: Forest plantation; *Gmelina arborea*; Site quality; Nutrient accumulation; Soil management; Nutrient cycling; Biomass; Sustainability of production; Nigeria

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1. Introduction

Globally, the area of forest plantations has witnessed a phenomenal growth since the middle of the 20th century, especially within the past three decades (Pandey, 1987; Evans, 1998; Carnus et al., 2003; Evans and Turnbull, 2004). For example, the global forest plantation estate increased from 17.8 million ha in 1980 to 43.6 million ha in 1990 and from 124 million ha in 1995 to 187 million ha in 2000 (FAO, 1992; Pandey, 1995; Evans, 1998; FRA, 2000). This represents an increase of about 950% within 20 years (1980 and 2000). The increasing trend of plantations has resulted in a significant increase its share of global forest area. Forest plantation share of the global forest area increased from about 3% in 1995 to 5% in 2000 (FRA, 2000; FAO, 2001a; Carnus et al., 2003). Also on the increase is the rate of plantation establishment and re-establishment. Before 1970, the rate stood at about 0.25 million ha year^{-1}, but increased to 1.1 million ha year^{-1} by 1985, 3 million ha year^{-1} by 1995 and by the year 2000 it stood at 4.5 million ha year^{-1} (Pandey, 1987; Evans, 1998; FRA, 2000).

Among the factors responsible for the increasing trend of global forest plantation estate, their ability to produce high

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amount of biomass within a relatively short period of time and their fast growth rate are the most notable. Forest plantations possess the capacity of producing between 3 and 10 times greater commercial biomass (timber) per ha than natural forests (Pandey, 1995; Evans, 1999a; Evans and Turnbull, 2004). For example, while the maximum mean annual volume increment (MAI_v) in a natural tropical forest in Nigeria is 5 m^3 ha^{-1} $year^{-1}$, that of an adjacent *Nauclea diderrichii* (indigenous species) and *Gmelina arborea* (exotic species) plantations are 16 and 51 m^3 ha^{-1} $year^{-1}$, respectively (Lowe, 1997; Onyekwelu, 2001). Some plantation species (e.g. *Eucalyptus* spp., *Acacia mangium*, *G. arborea*, *Pinus caribaea* and *Pinus oocarpa*) have MAI between 30 and 55 m^3 ha^{-1} $year^{-1}$ (FAO, 2001b; Onyekwelu, 2001; Evans and Turnbull, 2004). It has been demonstrated that given proper planning, good management and application of tree breeding, much higher yield is possible. The maximum MAI of genetically improved *Eucalyptus grandis* plantations in Brazil and Cameroon was reported to range between 70 and 89.5 m^3 ha^{-1} $year^{-1}$ (Betancourt 1987 cited in FAO, 2001b; Pandey, 1995). This high productivity of tropical forest plantation species has contributed to making them very important in meeting the world's growing demand for wood products, especially industrial wood (FAO, 2001a). Recent estimates reveal that 34% of global industrial wood is sourced from forest plantations. Countries like New Zealand and South Africa are reported to obtain almost 100% of their industrial wood from plantations while Chile, Spain, Brazil, Japan and Zambia derive 50–95% of their industrial wood from plantations (FAO, 1999). The contribution of forest plantations to global wood supply is expected to increase in the next decades due to increasing rate of plantation establishment and re-establishment.

Understandably, this high growth rate and productivity of forest plantation species imply high demand on the nutrient base of the site, since actual stand productivity is determined by how well trees capture site resources. This is the anchor of the concern of biological sustainability or otherwise of forest plantations, which has been an issue of wide interest and a subject of much debate. For example, report of 30% yield decline in second rotation *P. radiata* plantations in Australia emerged in the early 1960s (Keeves, 1966 cited in Evans, 1999a) and Khanna (1998) noted that repeated loss of nutrients from site during site preparation and in harvested Eucalyptus and Acacia wood adversely affected soil fertility and long-term productivity. Contrary to the above observations, Stewart et al. (1985) noted no loss of productivity in Eucalyptus stands while Evans (1998) concluded that plantation forests are likely to be sustainable in terms of wood yield provided that good practices are maintained. In some quarters, improvement in productivity in second rotation was reported.

However, much of the concern about sustainability of production in forest plantations focuses on the question of depletion or improvement of the nutrient status of the site, especially during the second and subsequent rotations. Kimmins (2004) showed that the nutrient capital of a forest ecosystem can be restored to its original status, provided that whole tree harvesting is not practiced and the forest ecosystem is managed on a long rotation. Sustainability of forest ecosystem is defined to imply that long-term use of the ecosystem is maximised to the intensity where the resource base, structure or function of the ecosystem is not degraded or adversely changed (Sverdrup and Rosen, 1998). Thus, for plantation to be sustainable it will mean no significant depletion of adsorbed stores of base cations, depletion phosphorus and that the C/N ratio stays constant. In other words, no noticeable negative changes in the soil physical, chemical and biological conditions. Evans (1999b) identified two approaches usually adopted in assessing these changes: (1) observational—which compare sites in carefully matched pairs or observe changes over time on the same site (chronosequences) and (2) deductive—by modelling ecosystem dynamics such as the nutrient budgets, followed by testing theory with field experimentation. The former is more widely used and will be adopted in this investigation, which aims to assess soil physical and chemical conditions of *G. arborea* monoculture plantations in Oluwa and Omo forest reserves, Nigeria, as well as stand productivity and nutrient storage in different tree components in *Gmelina* plantations of different ages.

2. Methodology

2.1. The study areas

Oluwa and Omo forest reserves in south western Nigeria are the two largest industrial plantation sites in Nigeria. Oluwa covers an area of 87,816 ha while Omo occupies 139,006 ha (FORMECU, 1999). Oluwa lies between latitude 6°55′ and 7°20′N and longitude 3°45′ and 4°32′E while Omo is situated between latitude 6°35′ and 7°05′N and longitude 4°05′ and 4°40′E. The climate of both sites is tropical, comprising of distinct rainy and dry seasons and characterised by high mean annual temperature (about 26 °C) and well distributed high annual rainfall (1700–2200 mm). Rainy season covers a period of 9 months (March–November) annually, but intensive rainfall starts from April to October and peaks in June/July and/or September. Dry season lasts 3 months (December–February), but there could be little rains during the dry months. Annual average daily relative humidity is about 80% in both forest reserves (Onyekwelu, 2001). Average elevation in Oluwa is 100 m while that of Omo is 123 m. With reference to USDA soil taxonomy, the soils of Oluwa and Omo is Alfisols. They are typical of the variety normally found in the intensively weathered areas of basement complex formations in the tropical rainforest zone of south western Nigeria. The majority of the soils are representative of soils in the Ondo Association, which comprises of well-drained, mature, red, stony and gravely soils in the upper parts of the sequence, grading into the hill wash overlying original parent material or hard-pan layers in the valley bottom (Smyth and Montgomerry, 1962). The texture of the topsoil in both reserves is sandy loam, which gradually becomes heavier as ones digs deeper into the soil. The sub-soil consists of clay with gravel occurring at 30–60 cm depths.

Table 1
Soil physical properties of *Gmelina arborea* plantations in Oluwa and Omo forest reserves

	Plantation age (years)										Remark
	10	11	12	14	16	19	21	23	25	28	
Oluwa forest reserve											
Sand content (%)											
0–15	63.9 ± 13.2	67.5 ± 2.8	68.1 ± 6.5	71.7 ± 4.3	70.5 ± 1.0	64.8 ± 0.7	70.7 ± 2.1	67.9 ± 5.9	65.9 ± 6.2	66.1 ± 2.8	ns
15–30	58.1 ± 12.1	61.5 ± 2.8	64.2 ± 2.2	65.5 ± 7.5	67.9 ± 3.7	61.9 ± 0.5	60.7 ± 2.1	68.5 ± 5.1	63.5 ± 4.2	61.9 ± 3.0	ns
30–45	55.8 ± 7.4	58.0 ± 7.8	56.7 ± 19.6	63.2 ± 6.5	61.9 ± 6.6	62.1 ± 1.1	57.2 ± 12.6	63.1 ± 4.2	54.5 ± 1.3	58.1 ± 5.7	ns
45–60	52.1 ± 2.2	53.9 ± 9.3	53.8 ± 7.1	58.8 ± 10.6	60.9 ± 6.6	51.1 ± 1.2	53.3 ± 7.1	55.2 ± 1.2	47.1 ± 10.5	52.3 ± 2.5	ns
Clay content (%)											
0–15	25.0 ± 6.3	21.6 ± 1.4	22.0 ± 6.6	19.3 ± 5.6	19.3 ± 2.9	25.2 ± 0.5	19.7 ± 3.7	20.7 ± 0.9	24.4 ± 7.1	24.7 ± 0.9	ns
15–30	29.0 ± 6.1	25.4 ± 4.6	25.0 ± 8.0	23.3 ± 5.5	21.3 ± 2.8	27.0 ± 3.4	29.2 ± 2.6	22.3 ± 1.5	26.9 ± 3.5	28.5 ± 1.2	ns
30–45	31.1 ± 3.2	28.4 ± 3.1	30.4 ± 10.7	25.4 ± 5.7	23.6 ± 2.5	26.3 ± 4.3	32.4 ± 7.1	26.4 ± 1.4	30.5 ± 7.3	29.0 ± 0.5	ns
45–60	33.4 ± 5.8	31.6 ± 9.8	31.9 ± 6.4	27.3 ± 5.6	24.4 ± 1.4	33.4 ± 4.5	34.2 ± 3.1	30.1 ± 6.0	38.3 ± 8.6	33.4 ± 3.0	ns
Silt content (%)											
0–15	11.2 ± 7.0	10.8 ± 1.4	9.9 ± 0.1	9.0 ± 1.3	10.1 ± 2.9	10.0 ± 0.6	9.5 ± 3.8	11.3 ± 6.8	9.8 ± 0.9	9.1 ± 3.6	ns
15–30	12.9 ± 6.0	13.1 ± 1.8	10.8 ± 4.2	11.3 ± 2.0	10.8 ± 6.5	11.1 ± 3.8	10.1 ± 0.5	9.2 ± 6.6	9.6 ± 7.8	9.6 ± 4.2	ns
30–45	13.1 ± 4.2	13.5 ± 4.7	13.0 ± 6.9	11.5 ± 0.9	14.6 ± 4.0	11.5 ± 4.4	10.5 ± 5.5	10.6 ± 2.8	15.0 ± 8.6	12.9 ± 6.2	ns
45–60	14.5 ± 8.0	14.5 ± 0.6	14.3 ± 0.7	13.9 ± 5.0	14.8 ± 5.1	15.6 ± 3.3	12.6 ± 4.0	14.7 ± 7.3	14.6 ± 4.9	14.3 ± 5.4	ns
Bulk density (Mg m^{-3})											
0–15	1.56 ± 0.15	1.42 ± 0.23	1.46 ± 0.22	1.42 ± 0.31	1.47 ± 0.19	1.44 ± 0.20	1.51 ± 0.13	1.41 ± 0.28	1.42 ± 0.05	1.41 ± 0.16	ns

	Plantation age (years)										Remark
	11	13	15	16	19	20	21	24	25	26	
Omo forest reserve											
Sand content (%)											
0–15	72.1 ± 1.4	70.2 ± 6.4	76.0 ± 4.9	60.5 ± 24.0	69.6 ± 7.1	70.4 ± 1.4	70.6 ± 12.7	67.5 ± 8.5	70.2 ± 2.8	76.5 ± 5.4	ns
15–30	62.5 ± 7.1	61.5 ± 2.8	67.2 ± 5.7	56.0 ± 12.0	65.5 ± 11.3	65.8 ± 8.5	60.5 ± 15.6	58.6 ± 7.1	62.8 ± 8.5	60.5 ± 9.9	ns
30–45	57.3 ± 5.7	60.0 ± 0.7	54.5 ± 4.2	53.6 ± 2.8	60.0 ± 10.6	58.5 ± 9.9	60.4 ± 15.6	51.1 ± 0.7	58.5 ± 4.2	58.5 ± 9.9	ns
45–60	55.9 ± 2.8	53.2 ± 3.1	56.3 ± 7.1	46.9 ± 7.1	54.5 ± 18.4	56.5 ± 14.7	54.3 ± 4.2	49.5 ± 4.2	48.1 ± 6.4	49.4 ± 7.1	ns
Clay content (%)											
0–15	18.9 ± 8.5	18.6 ± 4.0	15.1 ± 3.5	27.6 ± 18.4	19.5 ± 11.3	16.7 ± 2.8	22.8 ± 14.1	21.6 ± 9.9	19.7 ± 5.7	14.6 ± 2.8	ns
15–30	29.6 ± 1.4	20.6 ± 8.5	18.9 ± 5.7	28.6 ± 19.8	21.6 ± 9.9	23.5 ± 9.9	24.6 ± 11.3	29.4 ± 7.1	25.5 ± 2.8	27.1 ± 4.9	ns
30–45	34.9 ± 0.7	20.6 ± 1.4	24.6 ± 9.3	31.8 ± 1.4	24.8 ± 7.1	26.6 ± 11.3	25.7 ± 7.1	34.6 ± 2.8	29.6 ± 7.1	28.1 ± 6.2	ns
45–60	35.5 ± 4.2	27.0 ± 3.1	21.7 ± 7.1	34.4 ± 8.5	27.6 ± 18.4	27.6 ± 13.0	29.8 ± 7.1	33.6 ± 1.4	35.6 ± 9.9	32.7 ± 1.4	ns
Silt content (%)											
0–15	8.9 ± 7.1	11.2 ± 3.1	8.8 ± 1.4	11.8 ± 5.7	10.9 ± 4.2	12.9 ± 4.2	6.6 ± 1.4	10.9 ± 1.4	10.1 ± 2.8	8.8 ± 1.4	ns
15–30	7.8 ± 5.7	17.8 ± 5.7	13.9 ± 0.7	15.3 ± 7.8	12.8 ± 1.4	10.7 ± 1.4	14.8 ± 4.2	12.0 ± 0.7	11.7 ± 5.7	12.3 ± 4.9	ns
30–45	7.8 ± 4.9	19.3 ± 2.1	20.8 ± 7.1	14.6 ± 4.2	15.3 ± 8.4	14.8 ± 3.1	13.9 ± 8.5	14.3 ± 3.5	11.8 ± 3.1	13.3 ± 4.9	ns
45–60	8.6 ± 1.4	19.8 ± 2.0	21.9 ± 0.7	18.7 ± 1.4	17.8 ± 0.7	15.8 ± 3.6	15.9 ± 2.8	16.8 ± 2.8	16.3 ± 3.5	17.9 ± 5.7	*
Bulk density (Mg m^{-3})											
0–15	1.44 ± 0.09	1.45 ± 0.15	1.47 ± 0.13	1.44 ± 0.31	1.43 ± 0.15	1.50 ± 0.29	1.55 ± 0.07	1.49 ± 0.03	1.45 ± 0.17	1.44 ± 0.19	ns

Values are means on three replicates ± standard deviation of the mean; ns: not significant at $p > 0.05$.
* Significant at $p < 0.05$.

2.2. Plantation development in the study areas

Plantation trials in Oluwa and Omo forest reserves began in the early 20th century but large-scale plantation establishment started during the 1960s. The plantations were established on sites that once carried degraded natural tropical rain forests described as "low value logged-over forests" (Onyekwelu, 2001). Plantations between 1960s and 1979 were established through the Taungya system (manual land preparation), while those from 1980 to date were established through mechanised land preparation. Indigenous species such as *N. diderrichii*, *Entandrophragma* spp., *Guarea* spp., *Terminalia* spp., *Khaya* spp., *Lophira alata*, etc., were mainly used at the early stage of plantation development in the study areas but exotic species (especially *G. arborea* and *Tectona grandis*) dominated from the 1960s till date. For example, out of the total of 224,524.00 ha of plantations established in Nigeria by 1996, over 80% are exotics (Onyekwelu, 2001). Over the years, *Gmelina* has emerged as the dominant plantation species in Oluwa and Omo forest reserves. By 1996, about 18,385.0 ha (89% of total plantations) and 24,486.0 (91% of total plantations) of *Gmelina* have been established in Oluwa and Omo, respectively. *Gmelina* plantations in the study areas were established through mechanised land preparation. Weeding operations were conducted during the early stage of the stands (between 1 and 3 years). The plantations were protected against annual fire attack, especially at their early stages. The plantations were established to provide pulpwood at rotation of 8–10 years. Consequently, thinning and pruning operations were not intended and till date the bulk of the plantations in both forest reserves have not been thinned. However, due to the inability of the paper mills to function properly, the objective of management has changed from pulpwood to timber production because over 80% of the plantations have outgrown the rotation age for pulpwood. Even with this shift in management objective, only few portions of the old stands have been lightly thinned.

2.3. Field data collection

A to total of 20 age series of Gmelina stands were selected for this study (i.e. 10 from each forest reserve). As much as possible, it was ensured that the chosen plantations spanned from the youngest to the oldest and depending on accessibility, selected stands were evenly distributed within this age bracket. This was to ensure that all stages of plantation development were captured. The chosen plantations were divided into 20 m × 20 m temporary sample plots, from which three were randomly selected, making a total of 30 plots per study site and 60 for this study. Within each plot, measurements of dbh of all trees were made as well as the total height, diameter at the base, middle and top of two mean trees and four dominant trees. A 6 m × 6 m sub-plot was laid at the centre of each sample plot for soil sample collection. Each sub-plot was divided into 2 m gridlines and soil samples collected from any three of the four meeting points of the gridlines. With reference to Smyth and Montgomerry (1962), soils samples were collected at four fixed depth of 0–15, 15–30, 30–45 and 45–60 cm, using a soil auger of 7.5 cm in diameter. The first depth (0–15 cm) consisted of the thin O horizon and part of A horizon with the second depth (15–30 cm) accounting for the remaining part of the A horizon, while the third and fourth depths (30–45 and 45–60 cm) corresponded to B and C horizons, respectively. Soils from similar depths within each plot were thoroughly mixed, from which composite samples were collected and labelled. Samples for bulk density determination were only collected from 0 to 15 cm depth, using a sharp-edged steel cylinder (4.8 cm high and 5.6 cm diameter), which was forced manually into the soil. Due to the absence of pre-planting soil data, it was decided to collect soil samples from adjoining natural forests, which have remained relatively undisturbed since the commencement of plantation establishment in Oluwa and Omo forest reserves. These served as control and were used for the purpose of evaluating the possible changes undergone by soil of the study sites due to plantation establishment. As much as possible, soil samples (in both study sites) were only collected from sites that are free of rock outcrops, with relatively flat ground (elevation $\leq$ 100 m), and with good drainage.

In Omo forest reserve, trees from a sample plot in each age class (plantation) were categorised into four diameter classes of <20, 20–30, 30–40 and >40 cm. A tree, whose dbh was closest to the mean dbh of each class, was felled, resulting to a total of 40 trees (i.e. 4 from each age class). Samples from the stem were taken at 0, 50 and 100% of stem total length. Branch samples, which include small and large branches, were collected at the 0% (base), 50% (middle) and 100% (top) of the crown length. Foliage samples were collected from outer and inner parts of the crown at the base (0%), middle (50%) and top (100%) and included young and old leaves and twigs.

2.4. Laboratory analyses of soil and tree component samples

Prior to analyses, soil samples were air-dried, ground in a Wiley mill to pass through a 2 mm sieve. Particle size analysis was performed using the hydrometer method, with sodium hexameta-phosphate (Calgon) as dispersing agent (Black et al., 1965). The USDA particle size classes classification viz. sand (2.0–0.05 mm), silt (0.05–0.002 mm) and clay (<0.002 mm) were followed in expressing the particle size fractions of soils. Soils were assigned into textural classes with the aid of textural triangle. After drying the core cylinder samples at 105 °C for two days, soil bulk density was calculated as the ratio of oven-dry weight of soil (Mg) to the cylinder volume (m^3). Soil pH was determined with a digital pH meter using 1:2 soil/water solution. Organic carbon content was estimated using Walkley and Black method (Walkley and Black, 1934). Organic matter was obtained by multiplying organic carbon content by a conversion factor of 1.724. Samples for total N determination were digested using micro Kjeldahl method with selenium catalyst (Bremner, 1965). The digested samples were distilled after addition of sodium hydroxide and the ammonia thus released was determined by simple acid–base titration. Due to the suitability of the molybdenum-blue method for samples of low P content, the method was used for available P determination. Extracts for available P were prepared using ammonium fluoride and the blue colour was developed using ascorbic acid and Murphy and Riley solution (Murphy and Riley, 1962). For exchangeable cations determination (Ca, Mg, K and Na), soil samples were first leached with 1N ammonium acetate solution (pH 7.0). Available Ca and Mg were determined by atomic absorption spectrophotometer (AAS), while available Na and K were determined by digital flame photometry.

The bole, branch and leaf samples were oven dried to a constant weight at 80 °C and ground to pass through 2 mm sieve. After sieving, the three stem samples were bulked together before nutrient analyses. Total N concentration was determined by the micro Kjeldahl method on a Technicon Auto-analyser II. Following nitric acid digestion, the concentrations of Ca and Mg in the digest were determined by AAS while K and Na were determined by digital flame photometry (Black et al., 1965; Lemenih et al., 2005). Phosphorus content was determined using ammonium molybdate blue method. Nutrient accumulations in tree components (stem, branch and foliage) were obtained as the product of each tree component biomass and the average nutrient concentrations in that component. Nutrient accumulation was then extrapolated to per ha basis by multiplying with the standing biomass per ha of each component.

2.5. Data analysis

Volume of individual trees was estimated using the dbh-volume equation for *Gmelina* plantations by Onyekwelu (2001). Volume per plot was calculated and then extrapolated to per ha basis. Biomasses of different tree components were derived with the aid of dbh-biomass equations for *Gmelina* tree component (Onyekwelu, 2004). Plot biomasses for the components were obtained and also extrapolated to per ha basis. One way analysis of variance (ANOVA) was used to test for significance difference in each soil nutrient across stands of various ages. A model for a three-factorial combination was used to analyse the changes in aboveground nutrient concentration. The main effects (factors) were: dbh classes, age series and tree components. In addition, interactions between the main effects were considered. The analyses were performed using SPSS for Windows 12.0. Means found to differ significantly were separated using Duncan's multiple range test.

3. Results

3.1. Soil physical and chemical properties

Sand content of *Gmelina* plantation sites at Oluwa and Omo forest reserves decreased with increase in soil depth, while clay and silt contents indicated a reversed trend (Table 1). At similar depth, sand, clay and silt contents of the soils in the two plantation sites were comparable. For example, at 0–15 cm depth, sand, clay and silt contents ranged between 63.9–71.7, 19.3–25 and 9.0–11.3%, respectively, across the different plantations in Oluwa while they varied between 60.5–76.5% (sand), 14.6–27.6% (clay) and 6.6–12.9% (silt) in the stands at Omo. These comparable results at 0–15 cm soil depth were also found to exist in other soil depths in both sites (Table 1). Except 45–60 cm depth at Omo, where a significant difference was found to exist between the silt contents of different age series, particle sizes (sand, clay and silt contents) at similar depth were not significantly different between the different stands in both Oluwa and Omo (Table 1). The sand and clay contents of the soils of both sites indicated that soil texture is sandy loam to sandy clay loam, especially to the depth of 30 cm, beyond which texture tended towards sandy clay (results not shown). Soil bulk density was found to vary from 1.41 to 1.56 Mg m^{-3} in Oluwa and from 1.43 to 1.59 Mg m^{-3} in Omo and showed no significant difference ($p > 0.05$) across the various ages in both plantation sites (Table 1).

The soils of both reserves could be described as neutral to slightly acidic (pH range of 7.2 and 6.0 in Oluwa and 7.1 and 5.7 in Omo), with the soil becoming increasingly acidic as one digs deeper (Table 2), implying that sub-soil is more acidic than topsoil. The pH of similar soil depths were not statistically significant ($p > 0.05$) between the different plantations in both sites (Table 2). Except exchangeable Na, which increased with increasing soil depth, all other exchangeable cations (K, Mg and Ca), available P, total N as well as organic matter contents generally decreased with increasing soil depth (Figs. 1 and 2, Table 2). Figs. 1 and 2 reveal that concentration of P, K, Mg, Ca, N as well as organic matter had similar developmental trends in *Gmelina* stands at Oluwa and Omo.

A similarity was observed to exist between the soil nutrient concentrations of natural forest sites and old age plantations (about 25 years and above), while the nutrient concentrations of the soils under young and middle-age plantations were observed to be slightly lower than that of natural forest site (Table 3; Figs. 1 and 2). Consequently, it appears that the concentration of all the nutrients and organic matter were initially depleted slightly in young and middle-age stands (between 10 and 19 years in Oluwa and 11 and 20 years in Omo) but tended to build up again in older plantations (Figs. 1 and 2). Exchangeable Potassium concentration is the only exception to this trend as it seems to be slightly higher in younger and middle-age stands than in older plantations, which is particularly noticeable in the plantations at Omo (Fig. 2e). The concentration of the nutrients in similar soil depths in each site were found not to differ significantly between the various plantations ($p > 0.05$), except for few depths where significant differences were observed as a result of low concentration in only one or two stands (e.g. exchangeable Na in 15–30 cm depth in Oluwa). Organic matter content of topsoil (0–30 cm) in Oluwa is generally lower than that of Omo, especially in young and middle-age stands (Figs.1a and 2a). Beyond this depth, organic matter content tended to be similar in both sites. Also, Mg, P and Na concentrations in Oluwa soil are slightly lower than those of Omo soil but the concentrations of K, Ca and N in both forest reserves are similar (Figs. 1 and 2).

3.2. Growth characteristics and biomass production

Mean dbh of *Gmelina* stands varied from 20.3 to 42.4 cm between 10 and 28 years in Oluwa and increased from 22.9 to 41.3 cm between 11 and 26 years in Omo. Mean basal area and volume production was 45.6 $m^2\ ha^{-1}$ and 422.8 $m^3\ ha^{-1}$ (10 years) and 80.7 $m^2\ ha^{-1}$ and 1023.4 $m^3\ ha^{-1}$ (25 years) in the stands at Oluwa and 44.4 $m^2\ ha^{-1}$ and 445.8 $m^3\ ha^{-1}$ (11 years) and 77.8 $m^2\ ha^{-1}$ and 978.3 $m^3\ ha^{-1}$ (25 years) at Omo. The slightly higher basal area and volume production in similar ages in Oluwa than in Omo is probably due to the higher number of trees in the stands at Oluwa (Tables 4a and 4b). The lower density, basal area and volume of 28 and 26 years old stands in Oluwa and Omo, respectively (Tables 4a and 4b) is attributed to the moderate thinning to which the stands (28 and 26 years) have been subjected. Stem, branch, foliage and total aboveground biomass (TAGB) accumulation in *Gmelina* plantations in the study sites increased with age. TAGB varied from 181.5 t ha^{-1} (10 years) to 392.1 t ha^{-1} (25 years) in Oluwa and from 184.4 t ha^{-1} (11 years) to 382.3 t ha^{-1} (25 years) in Omo (Tables 4a and 4b). The lower TAGB accumulation in 28 and 26 years plantations in Oluwa and Omo, respectively, than in some previous ages (Tables 4a and 4b) is attributed to the same reason given above. Maximum MAI of TAGB is 18.2 and 16.8 t ha^{-1} $year^{-1}$ in Oluwa and Omo, respectively, and was recorded at the ages of 10 and 11 years (Tables 4a and 4b). Since these were the youngest stands assessed in the two sites in this investigation, it was not possible to ascertain whether these

Table 2
pH and sodium concentration of *Gmelina arborea* plantation sites in Oluwa and Omo forest reserves

	Plantation age (years)										Remark
	10	11	12	14	16	19	21	23	25	28	
Oluwa forest reserve											
pH											
0–15	7.2 ± 0.07	7.3 ± 0.53	6.9 ± 0.90	7.3 ± 1.63	7.2 ± 0.53	6.8 ± 0.15	6.9 ± 0.81	7.1 ± 0.70	7.4 ± 0.74	6.8 ± 0.75	ns
15–30	7.0 ± 0.93	7.1 ± 0.68	6.8 ± 0.58	6.3 ± 0.35	6.9 ± 0.95	6.5 ± 0.35	6.5 ± 0.70	6.7 ± 0.46	7.3 ± 0.42	6.4 ± 0.50	ns
30–45	6.9 ± 0.57	6.9 ± 0.43	6.8 ± 0.54	6.2 ± 0.45	7.0 ± 0.54	6.1 ± 0.33	6.5 ± 0.97	6.7 ± 0.89	7.0 ± 0.23	6.4 ± 0.39	ns
45–60	6.8 ± 0.78	6.9 ± 0.50	6.6 ± 0.67	6.2 ± 0.56	6.8 ± 0.12	6.0 ± 0.34	6.3 ± 0.80	6.7 ± 0.53	6.3 ± 0.05	6.3 ± 0.45	ns
Exchangeable sodium (cmol kg^{-1})											
0–15	0.24 ± 0.04	0.23 ± 0.02	0.26 ± 0.02	0.24 ± 0.04	0.21 ± 0.07	0.27 ± 0.05	0.25 ± 0.04	0.25 ± 0.06	0.21 ± 0.01	0.27 ± 0.03	ns
15–30	0.21 ± 0.03b	0.24 ± 0.04ab	0.28 ± 0.01a	0.26 ± 0.06ab	0.25 ± 0.02ab	0.28 ± 0.01ab	0.27 ± 0.04ab	0.23 ± 0.01b	0.25 ± 0.01ab	0.30 ± 0.03a	*
30–45	0.25 ± 0.08	0.27 ± 0.10	0.28 ± 0.02	0.26 ± 0.01	0.27 ± 0.02	0.28 ± 0.12	0.28 ± 0.04	0.27 ± 0.01	0.27 ± 0.07	0.30 ± 0.02	ns
45–60	0.28 ± 0.01	0.27 ± 0.02	0.29 ± 0.04	0.30 ± 0.05	0.28 ± 0.04	0.31 ± 0.08	0.30 ± 0.07	0.29 ± 0.04	0.28 ± 0.02	0.32 ± 0.01	ns

	Plantation age (years)										Remark
	11	13	15	16	19	20	21	24	25	26	
Omo forest reserve											
pH											
0–15	6.61 ± 0.29	6.73 ± 0.20	7.13 ± 0.36	6.68 ± 0.21	7.06 ± 0.18	7.10 ± 0.21	6.87 ± 0.11	6.68 ± 0.38	6.58 ± 0.04	6.65 ± 0.35	ns
15–30	6.57 ± 0.04	6.34 ± 0.18	6.66 ± 0.16	6.30 ± 0.91	7.00 ± 0.32	6.62 ± 0.76	6.49 ± 0.26	6.70 ± 0.51	6.02 ± 0.38	6.33 ± 0.26	ns
30–45	6.43 ± 0.21	6.41 ± 0.21	6.04 ± 1.53	6.24 ± 0.35	6.82 ± 0.40	6.72 ± 0.26	6.42 ± 0.01	5.81 ± 1.05	6.06 ± 0.22	6.21 ± 0.18	ns
45–60	6.17 ± 0.66	6.25 ± 0.73	6.17 ± 0.09	6.20 ± 0.21	6.59 ± 0.45	6.14 ± 0.54	6.16 ± 0.06	5.66 ± 0.45	5.91 ± 0.30	6.28 ± 0.49	ns
Exchangeable sodium (cmol kg^{-1})											
0–15	0.35 ± 0.04	0.38 ± 0.04	0.40 ± 0.01	0.41 ± 0.01	0.42 ± 0.01	0.40 ± 0.11	0.38 ± 0.01	0.38 ± 0.04	0.40 ± 0.01	0.41 ± 0.03	ns
15–30	0.40 ± 0.08	0.39 ± 0.03	0.37 ± 0.02	0.43 ± 0.03	0.45 ± 0.05	0.43 ± 0.10	0.41 ± 0.01	0.40 ± 0.05	0.41 ± 0.09	0.42 ± 0.01	ns
30–45	0.41 ± 0.04	0.39 ± 0.01	0.43 ± 0.01	0.44 ± 0.01	0.43 ± 0.06	0.44 ± 0.10	0.42 ± 0.02	0.40 ± 0.04	0.44 ± 0.06	0.42 ± 0.04	ns
45–60	0.41 ± 0.07	0.42 ± 0.03	0.43 ± 0.01	0.48 ± 0.17	0.46 ± 0.04	0.47 ± 0.05	0.43 ± 0.06	0.43 ± 0.06	0.45 ± 0.07	0.44 ± 0.01	ns

Each value is the mean of three replicates ± standard deviation of the mean; ns: not significant at $p > 0.05$. Values followed by similar letters (a and b) are not significantly different ($p \leq 0.05$).

[*] Significant at $p < 0.05$.

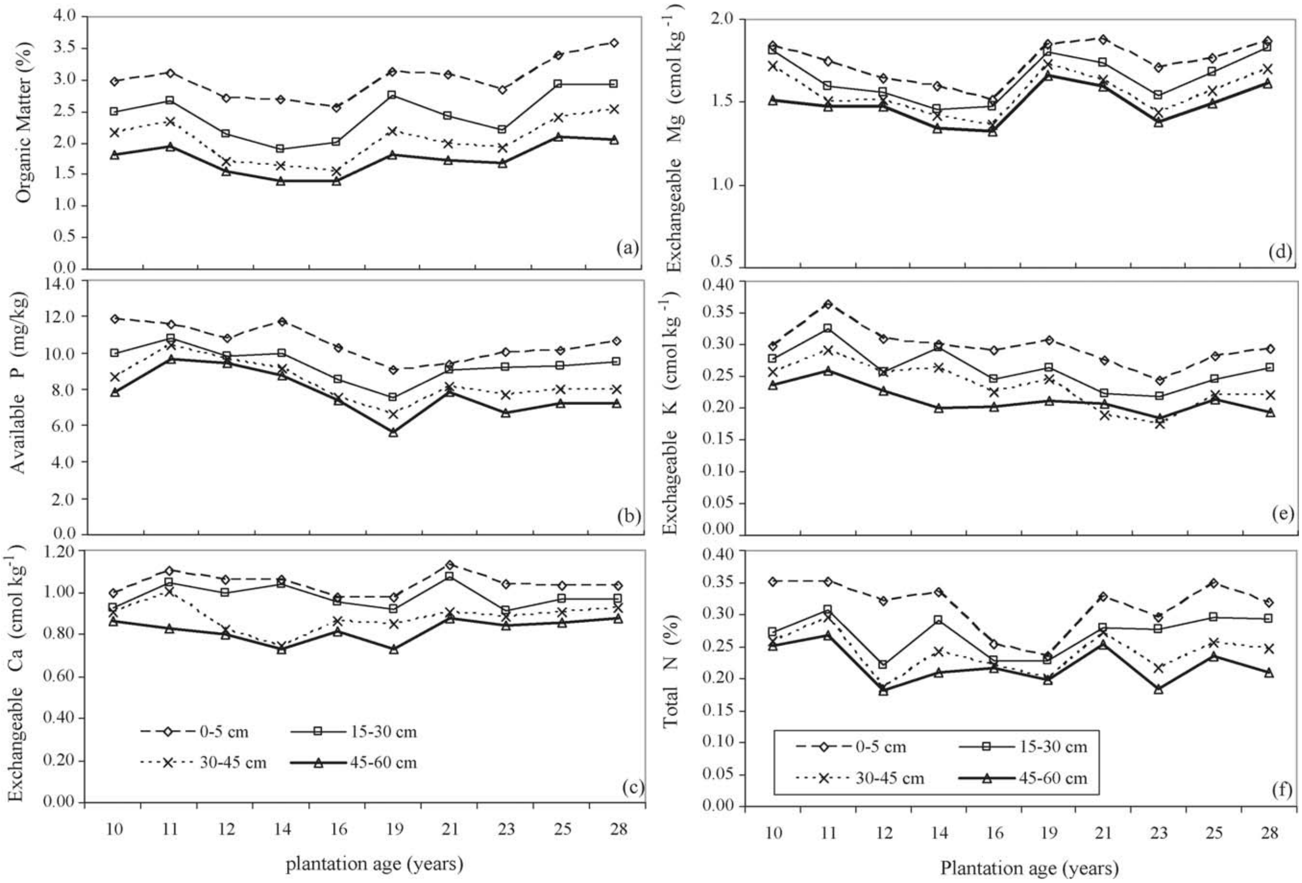

Fig. 1. Chemical properties of the soils of *Gmelina arborea* plantations at Oluwa: (a) organic matter, (b) available phosphorus, (c) exchangeable calcium, (d) exchangeable magnesium, (e) exchangeable potassium and (f) total nitrogen.

maximum were actually obtained at these ages (10 and 11 years) or at earlier ages. Stem biomass accounted for an average of 82.8% (range 81.9–84.0%) of TAGB, while branch and foliage biomasses accounted for 13.7 (range 12.5–14.5%) and 3.5% (range 3.1–3.7%), respectively, in the stands at Oluwa, which is similar to the biomass partitioning among tree components at Omo (stem: 83.0% (82.0–83.2%); branch: 13.5% (13.4–14.4%) and foliage 3.5% (3.3–3.6%)). The proportion of TAGB accounted for by branches and foliage slightly increased with dbh and plantation age.

3.3. Nutrient concentration and accumulation in aboveground tree components

Among the different tree components, tree tissue concentration of N, Ca and Mg increased in the order of foliage > stem > branches while the concentration of K and P increased in the order of foliage > branches > stem (Fig. 3). Interaction between the main effects (i.e. nutrient concentrations in dbh classes, age series and trees components) were found not to differ significantly ($p > 0.05$). Also the concentration of tissue nutrients was not significantly different ($p > 0.05$) between the four dbh classes as well as between the various age series. With the exception of Mg, the concentration of other nutrients in the different tree components varied significantly ($p < 0.05$), with the foliage having the highest concentration of all nutrients (Fig. 3). The results of mean separation show that the concentration of K, P, and N in the foliage differed significantly from that stored in the stem and branches, which did not differ significantly from each other (Fig. 3i, iii and v). For Ca, stem and foliage concentrations were not significantly different but both were significantly higher than Ca concentration in branches (Fig. 3ii).

Unlike nutrient concentration, their accumulation varied significantly ($p < 0.05$) among different tree components and age series. Stem, which accounted for a large proportion of TAGB (Table 4) was the largest contributor to stand nutrient pool while the second largest and least amounts of nutrients were accumulated in the branches and foliage, respectively (Table 5). Since tissue nutrient concentrations exhibited relatively little change with stand development (Fig. 3), total nutrient accumulation in the stands followed the same trend as biomass production. Thus, the older the stand, the higher the nutrients accumulated (Table 5). The accumulation of nutrients in the stem, branches and foliage followed the order: Mg > N > Ca > P > K > Na. Magnesium accumulation ranged from 201.4 to 461.1 kg ha^{-1} (82.9%), 31.8 to 77.1 kg ha^{-1} (13.5%) and 8.6 to 20.0 (3.6%) kg ha^{-1} in the stem, branches and foliage, respectively, while the storage of N in the respective components is 192.3–384.8 kg ha^{-1} (82.3%), 28.7–64.1 kg ha^{-1} (13.1%) and 9.8–22.7 kg ha^{-1} (4.6%) (Table 5). Storage of P and K in foliage and branches were higher than

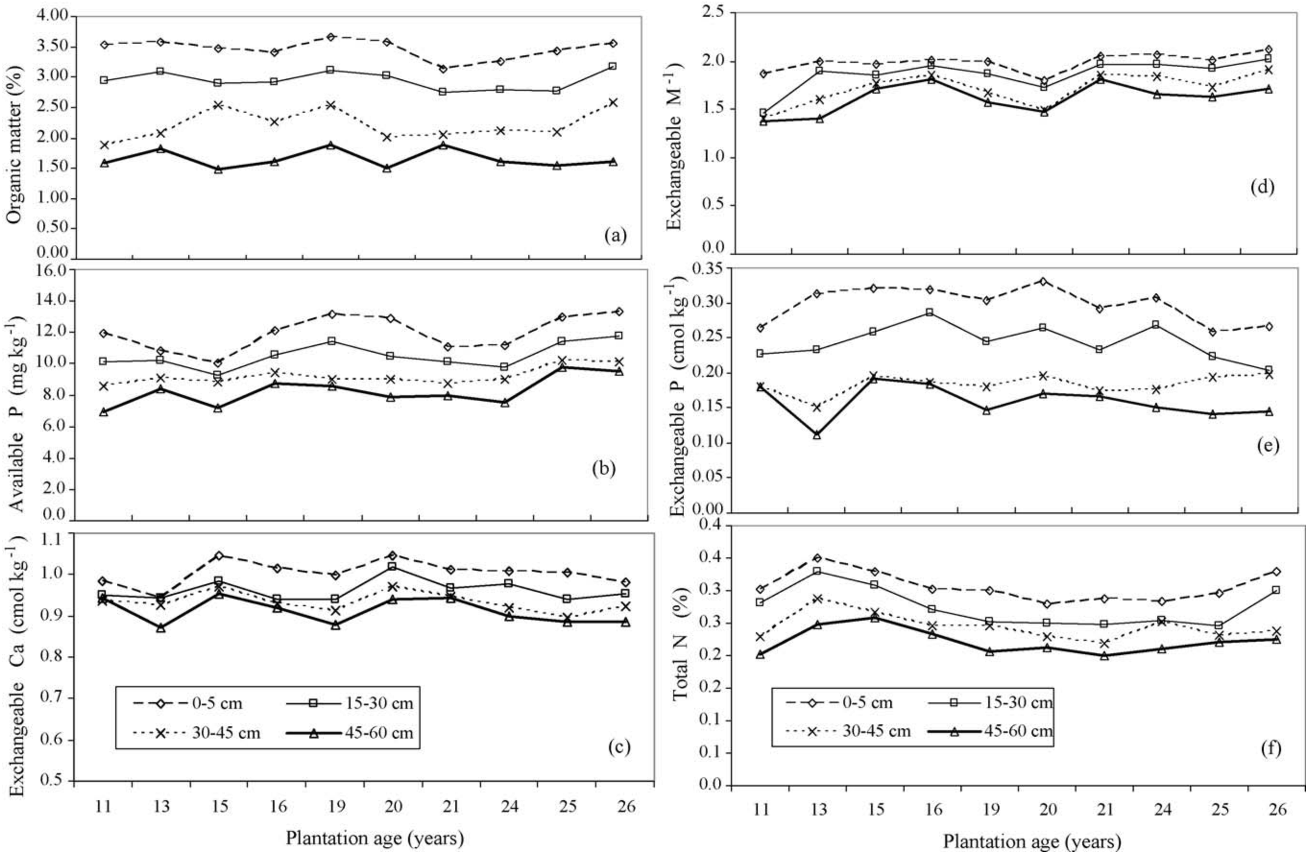

Fig. 2. Chemical properties of the soils of *Gmelina arborea* plantations at Omo: (a) organic matter, (b) phosphorus, (c) calcium, (d) magnesium, (e) potassium and (f) nitrogen.

those of Mg and N. Branches and foliage accounted for an average of 15.1% (6.3–14.4 kg ha^{-1}) and 4.8% (1.8–4.4 kg ha^{-1}), respectively, of the total P accumulation while stem accounted for 80.1% (34.7–71.9 kg ha^{-1}). Branches and foliage accumulation of K was even higher, accounting for 15.8% (2.9–8.4 kg ha^{-1}) and 5.9% (1.0–2.9 kg ha^{-1}), respectively, of total K while stem accounted for 78.3% (14.6–36.8 kg ha^{-1}). The share of stem, branches and foliage of total Ca accumulation was 83.8, 12.4 and 3.8%, respectively.

4. Discussion

4.1. Productivity in forest plantations

The high productivity of *G. arborea* plantations in Oluwa and Omo forest reserves, which is in consonance with reports in literature (e.g. Kawahara et al., 1981; Nwoboshi, 1985, 1994; FAO, 2001b; Onyekwelu, 2004; Swamy et al., 2004), indicates that the species is one of the tropical forest plantation species

Table 3
Summary of soil physical and chemical properties of natural forest sites in the study area

	Soil depth (cm)							
	Oluwa forest reserve				Omo forest reserve			
	0–15	15–30	30–45	45–60	0–15	15–30	30–45	45–60
Sand content (%)	70.6	68.5	66.0	56.3	76.6	69.6	67.2	60.6
Clay content (%)	21.9	22.9	24.6	30.4	15.6	18.0	21.0	23.3
Silk content (%)	7.5	8.6	9.3	13.3	7.8	12.5	11.8	16.1
Bulk density (Mg m^{-3})	1.36	–	–	–	1.32	–	–	–
pH	6.7	6.5	6.3	6.1	6.4	6.1	5.9	5.7
Organic matter (%)	3.42	2.80	2.25	1.76	3.72	2.96	2.30	1.83
Total N	0.36	0.32	0.31	0.27	0.37	0.23	0.28	0.23
Available P	10.77	10.23	9.23	8.79	20.27	18.00	16.83	15.58
Exchangeable K	0.40	0.35	0.32	0.28	0.32	0.26	0.20	0.18
Exchangeable Mg	1.91	1.66	1.63	1.60	2.08	1.81	1.69	1.60
Exchangeable Ca	1.05	0.94	0.86	0.82	1.09	0.95	0.90	0.81
Exchangeable Na	0.25	0.27	0.29	0.31	0.35	0.36	0.37	0.42

Table 4a
Summary of growth characteristics and biomass production of *Gmelina arborea* plantations in Oluwa

Age (years)	Trees (ha^{-1})	Mht[a] (m)	dbh (cm)			BA[b] ($m^2\ ha^{-1}$)	Volume ($m^3\ ha^{-1}$)	Biomass ($t\ ha^{-1}$)				MAI ($t\ ha^{-1}\ year^{-1}$)
			Mean	Minimum	Maximum			Stem	Branch	Foliage	Total	
10	1175	18.4	20.3	6.0	42.6	45.6	422.8	152.4	23.4	5.7	181.5	18.2
11	1012	19.2	22.5	6.0	40.5	46.4	467.1	164.0	26.3	6.6	196.9	17.9
12	1000	19.2	23.1	7.1	52.4	50.7	492.0	179.7	29.0	7.7	216.4	18.0
14	933	20.4	25.3	6.5	48.5	52.5	572.0	197.9	32.3	8.0	238.3	17.0
16	950	21.1	26.9	8.9	50.8	60.5	675.6	231.9	38.1	9.5	279.5	17.5
19	800	23.1	31.9	13.5	51.7	67.8	859.5	267.2	44.2	11.0	322.4	17.0
21	800	22.8	32.2	9.6	54.0	72.9	899.2	302.2	49.8	12.7	364.8	17.4
23	742	23.5	34.5	10.8	65.5	77.9	963.6	308.7	54.0	13.5	376.1	16.4
25	683	24.2	36.6	15.5	67.8	80.7	1023.4	321.5	56.5	14.1	392.1	15.7
28	492	25.3	42.4	16.1	75.2	74.7	973.3	301.9	53.4	13.5	368.8	13.2

[a] Mht: mean total height.
[b] BA: basal area.

with high productivity. For example, Nwoboshi (1985, 1994) recorded biomass accumulation of 56 and 272 $t\ ha^{-1}$ in 3 and 10 years *Gmelina* plantations, respectively, in Ghana and Nigeria while Onyekwelu (2004) found biomass accumulation of *Gmelina* stands in tropical rainforest zone of Nigeria to vary from 83.2 to 394.9 $t\ ha^{-1}$ between 5 and 21 years. Kawahara et al. (1981) reported biomass yield of 127 $t\ ha^{-1}$ for 7 years *Gmelina* stands in the Philippines. The trend of MAI biomass indicates that annual stand biomass productivity is generally higher in younger plantations than in older ones. The high MAI biomass (13.2–18.2) further attests to the high productivity of the species. Some tropical plantation species with high annual biomass productivity include *Acacia auriculiformis*, *Paraserianthes falcataria* (Kumar et al., 1998) and *Eucalyptus* species. The pattern of biomass partitioning among tree components in this study appears to be characteristics of the species as evidenced by the similar results from other research workers (Singh, 1995; Fuwape and Akindele, 1997; Onyekwelu, 2004), though some authors (e.g. Swamy et al., 2004) have published slightly different biomass partitioning patterns among *Gmelina* tree components. The accumulation of a high proportion of aboveground biomass in the stem shows a high merchantability of *Gmelina* tree as well as the suitability of the species for timber. Furthermore, it is also an indication of the commercial viability of the wood of the species since the stem yields most of the commercially useable timber. The high maximum mean annual volume increment of 30–60 $m^3\ ha^{-1}\ year^{-1}$ between 8 and 15 years (Pandey, 1987; FAO, 2001b; Onyekwelu, 2001; Piotto et al., 2003) reported for the species further attests to its high productivity. The high productivity of the species in the study areas has been attributed to its fast growth rate on the one hand and the high stand density on the other (Onyekwelu, 2004). Furthermore, optimal site conditions for *Gmelina*, which include extremes of temperatures of 18 and 35 °C, annual rainfall of 1778–2286 mm and distinct dry season in which atmospheric humidity is not below 40% (Lamb, 1968 cited in Onyekwelu, 2001) as well as sandy loam soils, is available in the study sites. In addition, plant growth in Oluwa and Omo is continuous because their soils never dry out as precipitation always exceeds potential evapotranspiration and there is no prolonged period of drought.

4.2. Effect of plantation development on soil properties

Although the entire Oluwa and Omo forest reserves were designated for forest plantation establishment, a considerable portion has remained under natural forest condition till date. Some sections of these natural forests have remained relatively undisturbed, with no case of encroachment, timber exploitation activities or deforestation reported (Onyekwelu et al., 2005). Consequently, we assumed that if *Gmelina* plantations had not

Table 4b
Summary of Growth characteristics and biomass production of *Gmelina* plantations in Omo

Age (years)	Trees (ha^{-1})	Mht[a] (m)	Dbh			BA[b] ($m^2\ ha^{-1}$)	Volume ($m^3\ ha^{-1}$)	Biomass ($t\ ha^{-1}$)				MAI ($t\ ha^{-1}\ year^{-1}$)
			Mean	Minimum	Maximum			Stem	Branch	Foliage	Total	
11	967	19.6	22.9	8.0	45.6	44.4	445.8	153.5	24.8	6.1	184.4	16.8
13	900	19.5	24.1	6.0	51.2	47.4	490.6	180.7	29.6	7.4	217.7	16.7
15	825	20.9	26.2	9.4	57.5	50.5	550.5	193.9	31.9	7.9	233.7	15.6
16	817	21.0	26.6	11.0	52.0	52.0	565.5	201	33.1	8.2	242.3	15.2
19	742	22.1	30.0	12.0	59.0	60.1	687.1	240.3	40	10	290.3	15.3
20	800	22.7	31.1	13.5	54.2	67.0	808.3	266.2	44.2	11	321.4	16.1
21	800	23.3	33.0	14.0	55.5	74.7	933.0	286	50.1	12.5	348.6	16.6
24	717	23.8	34.9	12.5	58.9	75.6	957.5	298.5	52.1	13	363.6	15.1
25	675	24.0	36.1	13.5	65.7	77.8	978.3	313.4	55.1	13.8	382.3	15.3
26	450	25.4	41.3	18.0	70.7	65.9	903.2	283.9	48.3	12.1	344.3	13.2

[a] Mht: mean total height.
[b] BA: basal area.

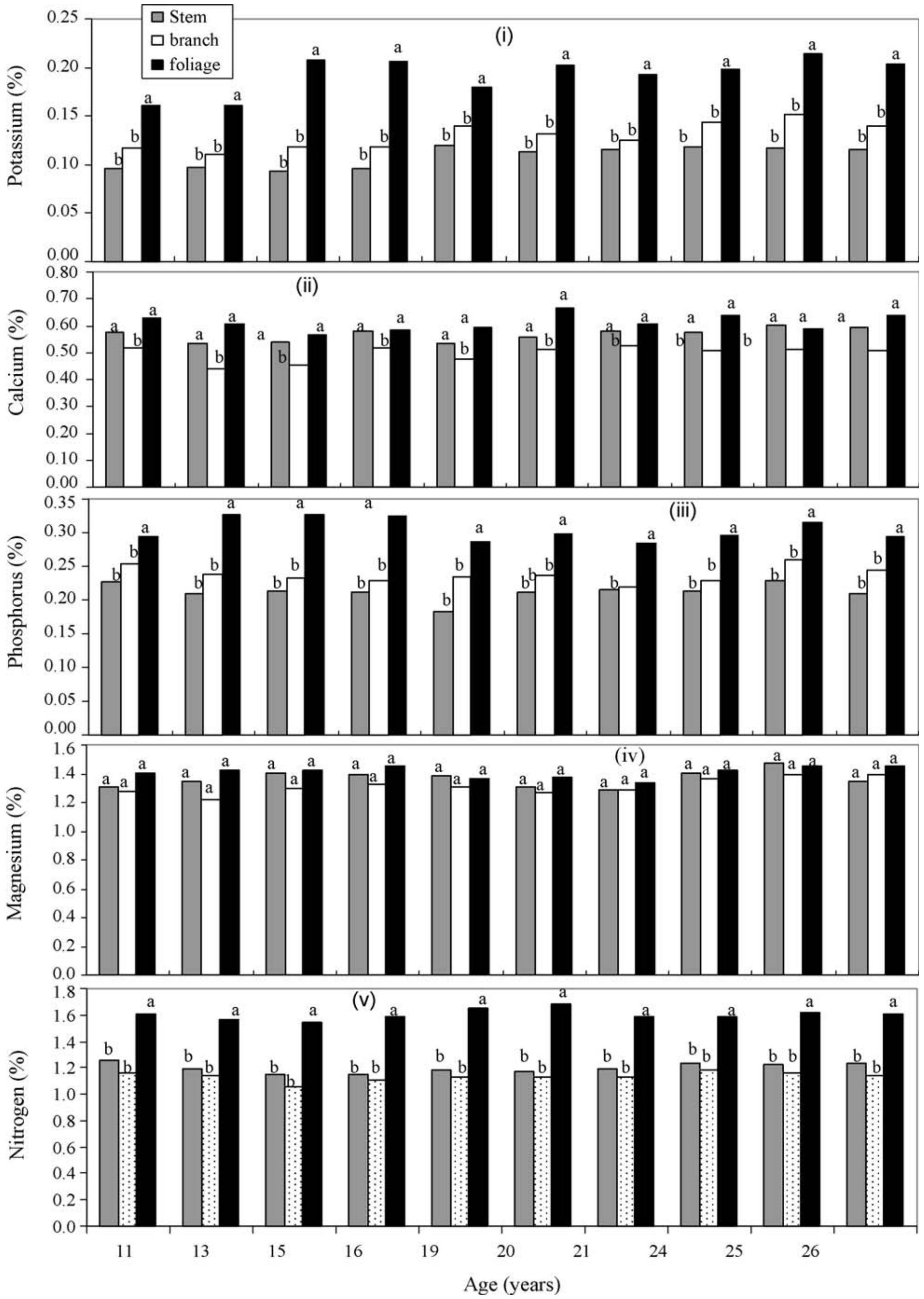

Fig. 3. Nutrient concentration in different components of *Gmelina arborea* trees at Omo. Values followed by similar letters at not significantly different ($p \leq 0.05$).

been established, its site conditions will most probably be the same as that of the natural forest. This assumption was necessary as pre-planting soil data for both study sites was not available. The absence of pre-planting soil data necessitated the use of natural forest soil data as baseline soil data/control for the purpose of evaluating the effect of plantation development on site nutrients.

Tropical rainforest soils are typically nutrient-poor, as a result most of the nutrients in the soils are held in the living organisms, especially in the above aground components. Because nutrients are swiftly leached by heavy precipitation, tropical rainforests have developed very efficient nutrient cycling system, aided by the warm and moist conditions in the forest, which are ideal for breaking down organic materials. This rapid decomposition of organic materials (Nwoboshi, 2000) result to very thin or totally absent O horizon (litter and humus layer) as was the case in the plantation sites in this study. Following decomposition, carbon and oxygen in the decomposing material are returned to the atmosphere, while N, P, K, Ca, and other nutrients are returned to the soil. The decreasing trend of nutrients concentrations and organic matter content as one digs deeper into the soil of the study sites is an indication of nutrient richer upper soil horizons (A and E) than lower ones (B and C). This is to be expected since the upper horizons (especially the A horizon) is the place of accumulation and decomposition of mineral and organic matter as well as

Table 5
Nutrient accumulation (kg ha^{-1}) in different tree components in *Gmelina arborea* plantations of different ages in Omo

Nutrients	Tree component	Plantation age (years)									
		11	13	15	16	19	20	21	24	25	26
Phosphorus (kg ha^{-1})	Stem	34.7	37.9	41.5	42.7	44.0	56.1	61.7	63.8	71.9	59.6
	Branch	6.3	7.1	7.4	7.6	9.4	10.4	11.0	12.0	14.4	11.8
	Foliage	1.8	2.4	2.6	2.7	2.9	3.3	3.6	3.8	4.4	3.6
	Total	42.8	47.4	51.5	53.0	56.3	69.8	76.3	79.6	90.6	74.9
Calcium (kg ha^{-1})	Stem	88.1	97.0	104.8	116.2	128.6	147.9	165.6	171.3	189.0	168.4
	Branch	12.8	13.1	14.4	17.1	19.0	22.6	26.4	26.5	28.2	24.6
	Foliage	3.8	4.5	4.5	4.8	5.9	7.3	7.6	8.3	8.1	7.7
	Total	104.7	114.5	123.7	138.1	153.5	177.8	199.6	206.2	225.4	200.7
Potassium (kg ha^{-1})	Stem	14.6	17.5	18.0	19.3	28.7	30.1	33.2	35.5	36.8	32.7
	Branch	2.9	3.3	3.8	3.9	5.6	5.8	6.3	7.5	8.4	6.7
	Foliage	1.0	1.2	1.6	1.7	1.8	2.2	2.4	2.6	2.9	2.5
	Total	18.5	22.0	23.4	24.9	36.1	38.2	41.9	45.5	48.1	41.9
Sodium (kg ha^{-1})	Stem	10.8	12.3	17.5	21.0	24.2	25.3	29.2	29.5	33.6	28.3
	Branch	1.8	1.9	2.1	2.3	3.5	3.8	4.0	4.5	4.2	3.9
	Foliage	0.7	0.8	1.0	1.0	1.4	1.3	1.5	1.6	1.8	1.5
	Total	13.4	15.1	20.6	24.3	29.1	30.5	34.6	35.7	39.6	33.6
Nitrogen (kg ha^{-1})	Stem	192.3	215.5	223.1	231.3	285.4	312.8	339.8	369.8	384.8	351.8
	Branch	28.7	33.8	33.7	36.8	45.0	49.7	56.6	61.5	64.1	55.2
	Foliage	9.8	11.6	12.2	13.0	16.5	18.5	19.8	20.7	22.4	19.5
	Total	230.8	260.9	269.1	281.2	346.9	380.9	416.2	451.9	471.3	426.5
Magnesium (kg ha^{-1})	Stem	201.4	243.4	272.1	280.1	332.4	348.1	368.0	420.5	461.1	383.4
	Branch	31.8	39.0	41.3	44.0	52.3	55.9	64.3	72.4	77.1	67.2
	Foliage	8.6	10.5	11.2	11.9	13.6	15.1	16.8	18.5	20.0	17.6
	Total	241.7	292.9	324.6	336.0	398.3	419.1	449.1	511.4	558.2	468.1

incorporation of decomposed organic and mineral matter into the soil (FAO, 1998). The rapid decomposition and concentration of organic and mineral matters in the upper soil horizons is explained by the active presence and activities of decomposers (e.g. earthworms) in this zone as well as the warm and moist conditions under tropical rainforests.The slightly lower soil nutrient concentrations in young and middle-age forest plantations than natural forest site is an indicating of slight depletion of nutrients in these plantations while the similarity of soil nutrients of natural forest sites and that of old-aged plantations reveal the ability of *Gmelina* plantations to replenish its site nutrients at old age. This slight decrease of nutrients in young and middle-age plantations and subsequent build up in older ones indicated by Figs. 1 and 2 is consistent with reports in literature. It has been pointed out that the years preceding canopy closure in forest plantations are characterised by major shift of nutrients from soil to tree biomass but subsequent to this, efficient internal re-use of nutrients means that there can be a rapid recharge of soil exchangeable nutrients (Attiwill, 1979; Miller, 1995, both cited in Evans, 1999b), which describes the observed trend in the study sites. The implication of the results is that if the plantations had been harvested for pulpwood after 10–12 years as previously planned, depletion of site nutrient resources would have resulted. This ‘‘failure’’ has therefore translated to a ‘‘win situation’’ for the site. This result is in consonance with the view of Kimmins (2004), who observed that stands managed on long rotations have the ability of restoring site nutrients to their original levels. The period of slight depletion in soil nutrient concentrations coincides with the period of active growth (i.e. higher MAI) while the period of build-up coincides with that of growth recession in *Gmelina* plantations in both sites (see Onyekwelu et al., 2003).

It has been demonstrated that the overall long-term response of soils to deforestation and subsequent conversion to agricultural lands in the tropics is decline in soil quality with increase in age (Islam and Weil, 2000; Lemenih et al., 2005). However, this does not appear to be the case with forest plantation establishment as demonstrated by our results. Though, the nutrients of the soils of young and middle-age plantations were generally slightly lower than those of older plantations and that of natural forest sites, no significant difference existed in soil nutrient concentrations of plantations of different ages, thus implying that plantation development in the study areas has no significant adverse effect on their soils. The nutrient status of the site has not been depleted to the extent that decrease in productivity during the next rotation would be anticipated. These findings agree with a host of others, with some reporting improvement in soil properties as the plantations advanced in age (Chijioke, 1980; Trouve et al., 1994; Mishra et al., 2003; Swamy et al., 2004). Trouve et al. (1994) found a progressive increase in organic matter under

Eucalyptus spp. plantations in Congo DR while Chijioke (1980) and Swamy et al. (2004) reported a significant improvement in soil nutrients status under *Gmelina* plantations in Nigeria and India, respectively. Even without additional nutrient input during a single rotation, *Gmelina* does not appear to exhaust the nutrient base of its site. Nwoboshi (1987 cited in Nwoboshi, 2000) revealed that out of the total site nutrient stock of 2771, 412, 5782 and 2124 kg ha^{-1} of N, P, K and Ca, respectively, average nutrient requirement for Gmelina in one rotation is 960, 371, 2425 and 615 kg ha^{-1} of N, P, K and Ca, respectively.

4.3. Nutrient concentration and accumulation in aboveground tree components

Foliage is the main repository of aboveground nutrients in *Gmelina* trees as revealed by this investigation. For example, N, Ca and Mg concentration in tree components increased in the order of foliage > stem > branches, while K and P increased in the order of foliage > branches > stem. Since the leaves of Gmelina are almost completely shed every year (Onyekwelu and Stimm, 2002), the high concentration of tree nutrients in the foliage of the species means that these nutrients will be available for recycling every year. This, coupled with the fast rate of decomposition of *Gmelina* leaves shows that the foliage plays a critical role in nutrient cycling. The trends for K and P concentrations in this study are similar to that reported by Swamy et al. (2004) and Lodhiyal and Lodiyal (1997) for *Gmelina* and *Populus deltoides* stands, however both authors found a higher concentration of N in branches than in stem against higher concentration of N in stem than in branches in this study. Chijioke (1980) and Swamy et al. (2004) reported higher K concentration (in all components), higher N (in foliage only) and lower P (in all components) in *Gmelina* stands than in this study. While the Ca concentration in all tree components in this study compares favourably with that of Chijioke (1980), Mg content in all components in the present study is higher than that of Chijioke (1980). The lack of significant effect of tree dbh and stand age on nutrient concentration in tree components implies that the amount of nutrient uptake by *Gmelina* trees is neither dependent on the size of the tree nor on its age.

Stand nutrients accumulation increased with plantation age, following the same trend as stand biomass accumulation. *Gmelina* is known to have a high aboveground nutrient storage, due probably to its high growth rate and high nutrient requirements (Chijioke, 1980). As much as 600 kg ha^{-1} of N and 1039 kg ha^{-1} of K and 553 kg ha^{-1} of Ca have been reported for 6 years *Gmelina* stand in Nigeria and Indonesia (Chijioke, 1980; Agus et al., 2004). Nitrogen and K accumulation in *Gmelina* stands in Omo is generally lower than that of *Gmelina* stands of similar ages in other parts of the world (Agus et al., 2004; Swamy et al., 2004). This could be explained by the lower concentration of the two nutrients in tree tissues in the present study. However, the total aboveground accumulation of Mg and P in *Gmelina* plantations in our study is higher than what was reported by the authors above.

The partitioning of nutrient distribution into stem, branch and foliage has improved our knowledge on the role played by each component in aboveground nutrient accumulation of *Gmelina* and consequently, the role each will play with respect to nutrient export from the site and nutrient recycling. The high proportion (over 80%) of aboveground nutrient accumulation in the stem appears to be characteristics of the species. Swamy et al. (2004) reported that a major fraction of the nutrients in *Gmelina* stands in India was locked in the stem. Since nutrient removal at harvest from a site depends on both nutrient concentration of different tissue fractions and biomass yield (Kumar et al., 1998), the stem of *Gmelina* will play a prominent role in nutrient export from sites bearing in mind its high biomass accumulation, its high stand nutrient storage and the fact that the stem is usually removed from the site following harvest. The harvest of *Gmelina* stands for timber at 25 years, for example, will drain 558.2 kg ha^{-1} Mg, 471.3 kg ha^{-1} N, 48.1 kg ha^{-1} K, 225.4 kg ha^{-1} Ca, 90.6 kg ha^{-1} P and 39.6 kg ha^{-1} Na from the site (Table 5), if whole tree harvesting is practiced. If on the other hand, branches and foliage are left on the site, the nutrients that will be exported from the site will then be about 461.1 kg ha^{-1} Mg, 384.8 kg ha^{-1} N, 36.8 kg ha^{-1} K, 189.0 kg ha^{-1} Ca, 71.9 kg ha^{-1} P and 33.6 kg ha^{-1} Na. The remaining 20% of the nutrient locked in the branches and foliage will be returned to the site for recycling.

4.4. Management implications

Nutrient accumulation and export from fast growing plantation sites has become an important consideration for long-term site quality and sustainability of production in short rotation, high-yield forest plantation ecosystems. While some researchers hold that the fast growth rate of the species deplete the nutrient base of the site and thus portends danger for long-term sustainability of production, others opine that the decrease in productivity in successive rotations, where it exists, is due to inappropriate management practices such as soil compaction during site clearing and preparation, topsoil and litter repositioning, burning of logging debris, harvesting methods and management of harvest residues (Will, 1992 cited in Evans, 1999a; Khanna, 1998; Kumar et al., 1998; Mathers and Xu, 2003; Chen et al., 2004). Our results indicate that the first rotation of *Gmelina* in Oluwa and Omo do not have adverse effect on the nutrient status of their sites. Consequently, if only the effect of current stands on the nutrient base of the site is considered, a decrease in productivity during the next rotation is not anticipated. It therefore implies that sustainability of production in the next rotation is more likely to be determined by harvesting methods of current stands and management practices of the next rotation. If well managed, increase in productivity might result as was reported for second rotation stands of some species (Long, 1997; Evans, 1999b). Kimmins (2004) demonstrated that if current stands are not harvested by whole tree harvesting method and if successive stands are managed on long rotations, site nutrient capitals in successive rotations are likely to be maintained at the original level. This will ensure long-term site quality and sustainability of production. In addition, management of soil organic matter is of particular importance as it contains the bulk of the nutrients (Evans, 1999a; Mathers and Xu, 2003). Thus, maintaining the current organic matter status and retaining harvest residues (foliage and branches) on-site following harvest would play a critical role in maintaining long-term soil fertility and productivity in the second rotation *Gmelina* stands in the study areas. Our results reveal that about 20% of all nutrients are stored in the branches and foliage of *Gmelina*. Thus, since it has been demonstrated that the nutrient status of the stands are almost replenished to their original status about 25 years after the initiation of plantation, it implies that the nutrient base of the sites will further be improved by this percentage (i.e. about 20% of the aboveground nutrient accumulation) if the foliage and branches are retained on the site following the harvest of current stands. Coupled with the already replenished organic matter content of current sites, nutrient that will be released from the foliage and branches will further enrich the site for the next rotation. To harness this entails that mechanical method should not be used for site clearing and land preparation at the initiation of the next rotation, since this method will among other things inevitably lead to soil compaction and disturbance of soil organic and mineral matter. The current practice in Nigeria is to leave foliage and branches on the site after harvesting. Since the bark contains a reasonable portion of the nutrients in the stem, the fertility of the site during the second rotation can further be improved by debarking the stem on the site. In view of the recommendation of long rotation length for site nutrient build-up in successive rotations (Kimmins, 2004) and our results, which suggests that a minimum of 25 years is required for sufficient build-up of nutrient pool in *Gmelina* stands, the rotation age of 15–20 years for *Gmelina* timber plantations in the study areas (FORMECU, 1999; Onyekwelu et al., 2003) must be reconsidered. This is because at the current rotation age (15–20 years), the nutrient status of the site is just beginning to build-up again (Figs. 1 and 2). The shift of management objective from pulpwood to timber production due to the out-growing of pulpwood rotation age of 8–10 years by a bulk of current plantations further justifies an extension of rotation to 25 years. At this age (25 years), a measure of nutrient build up (recharge) is expected. This should also apply to subsequent rotations. The need to shift rotation is further buttressed by the fact that nutrients removed through frequent harvests may exceed the natural rates of nutrient inputs (Kumar et al., 1998).

5. Conclusion

Gmelina plantations in Oluwa and Omo forest reserves have high productivity, a high percentage of which is stored in the stem. The continued growth of *Gmelina* plantations in both sites for about three decades has not adversely affected soil properties. Though an initial depletion of soil nutrient pool was observed, there was a build up (recharge) in older stands. Since the plantations did not adversely affect soil nutrient status, productivity during the next rotation will most likely be affected by harvesting methods of current stands and management practices of the next rotation. However, for site nutrient pool in the next rotation to be maintained at the original level, whole tree method should not be used in harvesting current stands. Apart from the nutrient built-up in older stands, an additional 20% of aboveground nutrient accumulation will be available for next rotation if the branches and foliage are left on the site after harvesting, which could be improved upon by debarking the harvested stems on the site. To ensure long-term site quality and sustainability of production, successive plantations should be managed on longer rotation 25 years. If the rotation age is not extended to 25 years, successive plantations will most likely lead to steady depletion of site nutrients, which will make intensive and expensive site fertilisation unavoidable if the high productivity of the species is to be maintained.

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