International Journal of Plant & Soil Science

22(1): 1-13, 2018; Article no.IJPSS.38388
ISSN: 2320-7035

Nutrient Dynamics in Eucalyptus Plantations of Different Ages before and during Intercropping

Stanley W. Nadir[1*], Caleb O. Othieno[2] and Syphiline J. Kebeney[2]

[1]Kenya Forestry Research Institute (KEFRI), P.O.Box 20412-00200, Nairobi, Kenya.
[2]Department of Soil Science, University of Eldoret, P.O.Box 1125-30100, Eldoret, Kenya.

Authors' contributions

This work was carried out in collaboration between all authors. Author SWN designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJPSS/2018/38388
Editor(s):
(1) Muhammad Shehzad, Department of Agronomy, Faculty of Agriculture, The University of Poonch Rawalakot, Pakistan.
Reviewers:
(1) Kabi Prasad Pokhrel, Tribhuvan University, Nepal.
(2) Nazmul Haque, Sher-e-Bangla Agricultural University, Bangladesh.
(3) Melodie Claire W. Juico, Davao Doctors College, Philippines.
Complete Peer review History: http://www.sciencedomain.org/review-history/23841

Original Research Article

Received 2nd November 2017
Accepted 9th January 2018
Published 27th March 2018

ABSTRACT

The study characterized and monitored changes in soil nutrients under different ages (1.5, 3, 6, 12, 20 and 40 years) of *Eucalyptus grandis* tree plantations and its tissues (litter and fresh leaves) before and during intercropping. Soil sampling for characterizing tree plantations was at; 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm depths while for monitoring nutrient changes during cropping was at 0-20 cm, 20-40 cm depths in crop plots. The planted crops under the trees were Irish potatoes where no fertilizer was applied. Radial cluster sampling in RCBD was used in plantations. Litter and fresh leaves were sampled from trees of ages 1.5, 3, 6, 12, 20 and 40 years. From the results; Eucalyptus tree age significantly affected nutrient concentrations in the understory soils i.e. available phosphorus, pH, calcium, potassium, magnesium and iron. In addition, the age of Eucalyptus influenced the concentrations of nutrients in canopy litter and its leaves i.e. total nitrogen, total phosphorus, total calcium, total potassium, total manganese and total iron. Potassium, magnesium, manganese and organic carbon levels were high in soil, litter and leaves. Crop cultivation under Eucalyptus trees reduced total nitrogen, potassium and calcium in the soil while available phosphorus, pH, magnesium and manganese increased. Soil carbon was unchanged. From this study, soil nutrient dynamics under Eucalyptus trees permits successful crop

**Corresponding author: E-mail: stanleynadir@yahoo.com;*

growing especially with the correct species of crop and tree spacing. However, phosphorus deficiency and possibility of manganese toxicity were the possible limitations to successful crop production under the trees.

Keywords: Agroforestry; Eucalyptus grandis; soil properties; soil depth; tree age.

1. INTRODUCTION

Successful Eucalyptus tree-crop intercropping is hindered by the soil nutrient dynamics and allelochemical accumulation in the soil under the trees [1,2]. Due to competition for scarce land resources between food crops and trees, there is a need for a balance to accommodate both, either in rotation programs or in agroforestry systems so as to fully maximize the arable lands under the tree plantations. In Kenya, the Eucalyptus tree has enormous benefits; including the provision of power transmission poles, cheap source of energy and high-quality fibre for pulp industry [3]. There is little information about the status of the nutrient dynamics in Eucalyptus plantation systems especially for the soil during intercropping with Eucalyptus trees with most of the past studies focusing mainly on comparing mono-cropping and Eucalyptus plantation systems separately. For instance, having long-term plantations of Eucalyptus trees on the land without intercropping has been reported to improve the soil fertility i.e. within a period of 8 to 10 years [4] and with no significant differences in fertility when compared to soils under grass. Furthermore, soils under Eucalyptus trees have been associated with crop yield reduction due to nutrient depletion and production of toxic exudates or allelopathy [5]. Studies on the effect of distance gradients from the Eucalyptus tree stand on soil fertility by Alemie [1], reported a significant change in available phosphorus, exchangeable calcium, total nitrogen with no change in potassium concentration in the soil. In addition, soil fertility depletion in soils previously under Eucalyptus plantations has been linked to nutrient mining and biomass export through harvesting of the trees [6]. The soil nutrient dynamics under Eucalyptus trees is influenced by the age factor and the rate of litterfall which is a key function influencing the mineralization rates in the soil. For successful intercropping, the fertility status (physical and chemical) of the soil under Eucalyptus trees needs to be understood adequately especially for the different ages of the tree plantations before introducing the crops or even its management. Therefore, this study was set up with the following objectives; first, characterizing the soil nutrient status under Eucalyptus trees of different ages (1.5, 3, 6, 12, 20 and above 40 years) and its tissues (litter and fresh leaves) with the aim of establishing crops under the trees. Secondly, the study monitored the soil nutrient changes under the trees after crops have been introduced inside the plantations. Thus, the results from this study were to provide information about the nutrient cycling in the Eucalyptus plantations and a guideline on what aspects of soil that needs amendments to enable successful and sustainable cropping under the Eucalyptus trees.

2. MATERIALS AND METHODS

2.1 Study Area

The experiments were conducted inside the *Eucalyptus grandis* plantations during the wet and dry periods of the years 2015 and 2016 at Kenya Forestry Research institute (KEFRI) Muguga, Kenya (latitude 1°15’ 0"S and longitude 36°40’ 0"E). The area averages rainfall of 900 – 1200 mm p.a. at an elevation of 2040 m above sea level and located in the agro-ecological zone of Lower Highlands - (LH_3) [7]. In addition, the area experiences both long and short rains. The area is characterized by heavy well drained, extremely deep, dusky red to dark reddish brown, friable clays of volcanic origin developed on tertiary basic igneous rocks [7]. The soils have moderate to high fertility with a pH of 5.8 and are classified as Eutric Nitisols [8].

2.2 Description of *Eucalyptus grandis* (Rose Gum) Plantations

The *Eucalyptus grandis* plantations were pure stands established in blocks of more than 0.5 ha and were not fertilized. For plantation ages of 1.5, 3, 6, 12, 20 years the spacing was 4 m by 3 m with very little undergrowth mainly grasses but for the 40 years of age, the plantation had scattered trees as some of them had died or fallen by strong winds over time. The plantations had been established on lands previously cropped with beans, maize or potatoes after they had been left fallow for at least a year.

2.3 Design and Methodology for Soil Sampling

Soil profile pits and auger samples under tree canopies were used for this study. The experiment adopted RCBD design with age of plantation being the treatment. Blocks were generated depending on the homogeneity of the land. Radial cluster method was used for sampling of soils i.e. one profile pit was surrounded by three soil auger samples. Three (3) soil profile pits were used for each age of *E. grandis* hence 18 auger points per age of plantation. Soil sampling for characterizing tree plantations of different ages was done at the following depths; 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm after which samples were pretreated and analyzed in the laboratory. For monitoring nutrient changes, soil samples were taken from the crop plots (Irish potatoes) after harvesting of the crops for every growing season at 0-20 cm, 20-40 cm depths.The crops were not fertilized.

2.4 Sampling of Plant Tissue Materials (Litter and Fresh Leaves)

In this study, litter referred to dead un-decomposed leaves and branches collected on the ground below the Eucalyptus tree canopy while the leaf samples referred to the fresh leaves plucked from the base and at the middle of the tree canopy. Radial cluster sampling was used whereby the trees near the auger points were sampled from which the surface litter in quadrats was collected for laboratory analysis. The litter from quadrats measuring 1 m by 1 m was heaped together and about 200 g of the material sampled and air dried for 7 days prior to laboratory analysis. The same amount was taken for fresh leaves after air drying for more than 7 days before laboratory analysis.

2.5 Elemental Analysis of Soil and Eucalyptus Tree Tissues (Litter and Fresh Leaves)

The following soil chemical analyses were done; organic matter (loss on ignition method), organic carbon, (Walkley & Black method), total nitrogen, (Kjeldahl method), total phosphorus (Kjeldahl digestion and colorimetric determination), available phosphorus (Olsen method), exchangeable cations (calcium, potassium, magnesium), extractable iron and manganese, pH and electrical conductivity (e.C) (Potentiometric method). For the plant tissues, the analyses were similar to the soil i.e. organic matter, organic carbon, (Walkley & Black method), total nitrogen (Kjeldahl method), total phosphorus, total cations (potassium, calcium, magnesium), total micronutrients (iron and manganese). The contents of total nitrogen and total phosphorus in soil and plant tissues were measured in a digest obtained by treating the plant sample with hydrogen peroxide, sulphuric acid, selenium powder and salicylic acid followed by colorimetric determinations using the UV spectrophotometer. For soil available (Olsen) phosphorus, the soil was extracted with 0.5 M solution of sodium bicarbonate at pH 8.5 followed by colorimetric determination using the UV spectrophotometer. To determine exchangeable bases (potassium, calcium and magnesium) in the soils; a soil sample was extracted with an excess of 1 M NH_4OAc (ammonium acetate) then amounts of each cation in the extract determined by atomic absorption spectrophotometry at specific metal wavelengths. For determination of extractable micronutrients (manganese and iron); the soils were extracted with 1% EDTA, and then the filtrate was aspirated into an air-acetylene flame of an atomic absorption spectrophotometer and absorbance read at specific metal wavelength. Total cation concentration of potassium, calcium and magnesium in plant tissues plus micronutrients (manganese and iron) were determined by first digesting samples detected through atomic absorption spectrophotometer at specific wavelengths. The organic carbon in the soil was determined by titration method by subjecting the soil to complete oxidation [9]. Organic matter in the soil and plant tissues was determined through the loss of ignition method at temperature of 550°C. Detailed information for these protocols is as outlined in [10].

2.6 Data Analysis

Data analysis involved Multivariate analysis of variance (MANOVA) to ascertain the effects of tree age and soil depth on the nutrient concentrations in the soils and the Eucalyptus tree tissues. In addition, Pearson's Correlations with two tailed T-test on soil nutrients was done. Multiple comparisons and Mean separation were done using Tukey's HSD tests. The statistical software packages used were GenStat Edition 16 [11] and the IBM SPSS Statistics version 23 formerly SPSS [12].

3. RESULTS AND DISCUSSION

3.1 Effect of Tree Age and Soil Depth on the Nutrient Concentration in Soils under *Eucalyptus grandis* Trees and Its Tissues (Litter and Fresh Leaves)

The age of the Eucalyptus tree and the soil depth significantly influenced the nutrient concentrations in Eucalyptus tree plantation systems (P<0.001). The differences in the age of Eucalyptus tree significantly affected the content of available phosphorus, pH, calcium, potassium, magnesium and iron contents in the soil (P < .001). In addition, variation in the soil depth under the tree canopy significantly affected the nutrient concentrations in the soil i.e. organic carbon (OC), total nitrogen (TN) and calcium (P < .05). The effect of Eucalyptus tree age on the concentrations of nutrients in the canopy surface litter and the fresh leaf influenced total nitrogen, total phosphorus, total calcium, total potassium, total manganese and total iron but not organic matter content. These changes could perhaps be attributed to the different rates of litter fall under different ages of Eucalyptus canopy which influenced the mineralization rates. Calcium and iron levels in the soil were low to medium despite their higher concentrations in the Eucalyptus litter and leaves. The concentration of exchangeable calcium in the soils under different Eucalyptus trees of different ages was positively correlated to pH, electrical conductivity, total nitrogen, phosphorus, copper and manganese (Table 1). The concentration of iron in the soil seemed to reduce with depth but not significantly with most of other soil nutrients. The amount of total nitrogen in the soil increased significantly with the increase in organic carbon, phosphorus, calcium and manganese. The concentration of exchangeable potassium in the soil profile was significantly reduced with the increase in exchangeable calcium and iron. Manganese had a positive and statistically significant correlation with calcium, copper, total nitrogen and pH (Table 1).

The age of the tree had a statistically significant effect on soil pH but not electrical conductivity. The two parameters had a similar trend peaking at the 12 year old canopy (7.07, 0.05) respectively (Fig. 1). The soil pH was constant and acidic (5.9 - 5.7) for ages 1.5, 3 and 6 years before it rose to reach neutral levels (7.07) at age 12 years and reduced but remained above (6.0). The trend was the same for electrical conductivity which was also high at 12 years of age. Soil depth had no significant effect on soil pH and electrical conductivity. Soil pH seemed to increase with soil depth up to 40 cm (pH = 6.57) after which it reduced and remained constant for remaining depths (Fig. 1). The 20-40 cm soil depth was significantly less acidic (increased pH) compared to top or underlying horizons across all the ages of Eucalyptus tree plantations studied. The soil electrical conductivity was highest at 20-40 cm depth (0.064) coinciding with the highest soil pH (6.57) and then reduced down the soil profile across all the ages of Eucalyptus tree plantations studied (Fig. 1).

Soil depth had a significant effect on available phosphorus and by the soil standards for crop growing [13,10,14], the amount of available phosphorus was very low (deficient to critically deficient) and it was constant for all the depths with top horizon 0-20 cm having marginally higher content (4.28 mg/ kg) as shown in Fig. 2. The leaf total P and litter total P were negatively correlated whereby the high levels of total P in the leaf was contrasted by low levels in the litter of the same canopy with both being equal in the 6 year old canopy. The maximum total P content occurred at age 12 (474 mg/ kg) and 20 (438 mg/ kg) for litter and leaf respectively (Fig. 2). The low availability of phosphorus in the soil could be attributed to high concentrations of manganese which lead to increased fixation. From literature,

Table 1. Pearson correlation coefficients for soil nutrients

Parameter	E.C (mS/cm)	OC (%)	N (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Mn (ppm)	Fe (ppm)
pH (1:2.5)	.19	-0.02	0.14	0.22	.44*	.50**	.20	.51**	-.21
E.C (mS/cm)		.34	.13	.25	-.05	.48**	-.18	.11	.16
OC (%)			.64**	.29	.06	.59**	.02	.30	-.03
N (%)				.39*	.22	.44*	.17	.38*	-.20
P (ppm)					.23	.46**	.41*	.05	-.35
K (ppm)						-.01	.42*	.01	-.23
Ca (ppm)							.02	.60**	-.15
Mg (ppm)								-.17	-.30
Mn (ppm)									.01

***. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)*

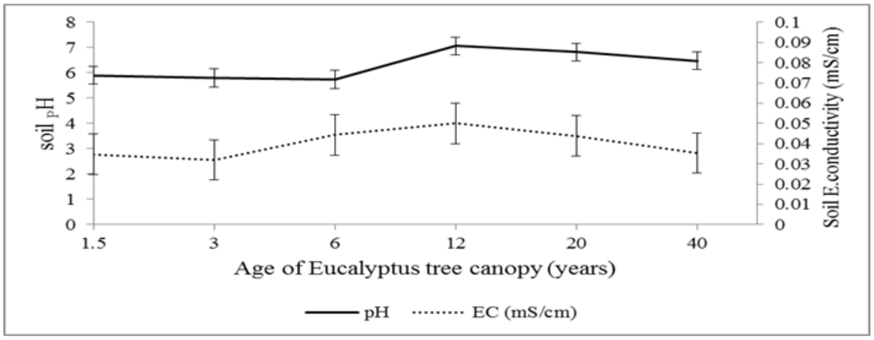

Fig. 1. Soil pH and electrical conductivity of the soils under *Eucalyptus grandis* trees of different ages

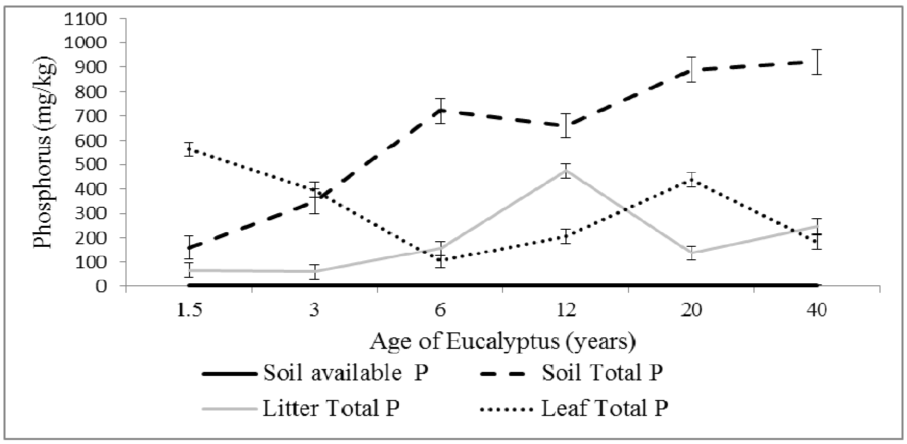

Fig. 2. Phosphorus content in the soil, litter and fresh leaf of *Eucalyptus grandis*

the forms of phosphorus variability and availability in the soil have been linked with the amount of extractable manganese in the soil [15]. Such results agree with the findings in this study as manganese, magnesium and potassium levels in the soil were very high and even in the Eucalyptus tissues and this could even affect the growth of very sensitive crops under the canopy especially from manganese toxicity. The findings in this study are also in agreement with those of [1], who studied on the effect of distance gradients from the Eucalyptus stand on soil fertility where a significant effect was found on soil available phosphorus, exchangeable calcium, total nitrogen (TN) with no change in potassium (K) concentrations.

The trends of total nitrogen in both leaf and litter were similar across the different ages of Eucalyptus with the maximum being 20 year old canopy (Fig. 3). The content of total nitrogen in litter was significantly different across different ages of Eucalyptus canopies but not the leaf content (Fig. 3). Total nitrogen content in litter and leaves have been reported not to change with time or age in soils under Eucalyptus trees [16], a fact attributed to sustainable N cycling rates. If considering crop production then nitrogen was adequate and considered high in the soil [13,10,14]. Soil depth significantly affected the content of total nitrogen and organic carbon (OC). Both total nitrogen and % OC reduced down the soil profile with top horizons of 0-20 cm having marginally higher content compared to lower soil depths. The high contents of both nutrients was in top horizons probably due to high litter fall on the soil surface which mineralizes to form % OC and then contributes to nitrogen pools. There was no significant difference in the quantity of OM % present in the leaf and litter of Eucalyptus tree of different ages (Fig. 4). Lack of significant changes in soil organic carbon levels under different ages of Eucalyptus tree canopies could also be attributed to presence of complex phenolic compounds which are responsible for low decomposition rates of soil organic matter a fact reported by [17-19].

Soil depth also significantly affected the content of exchangeable calcium in the soil but not potassium. Potassium content in the soil was very high with 20 year old tree canopy having the highest (705 mg/ kg) and 6 year old tree canopy the lowest (387 mg/ kg) (Fig. 5). Both leaf and litter total potassium contents were statistically significant across the different plantation ages with leaf content being more than litter. In addition, the contents for both were equal at the tree age of 12 years (8488 mg/ kg) which was a maximum for litter content (Fig. 5). The trend for leaf calcium content was similar to the soil calcium content. Calcium content reduced down the soil profile 0-20 cm (2363 mg/ kg), 80-100 cm (1150 mg/ kg), while potassium and magnesium increased a fact attributed to leaching and mobility of the elements compared to calcium which in most cases is bound to anions like phosphates hence less mobile in the soil. The content of calcium in both leaf and litter followed the trend of total phosphorus whereby increase in the leaf led to reduction in the litter for the same tree age with the maximum for litter occurring at 3 year old (6800 mg/ kg) and 40 year old (7900 mg/ kg) plantations while lowest in 6 year old (Fig. 6). For fresh leaf, calcium content was lowest in the 3 year old trees which surprisingly coincided with the highest litter content.

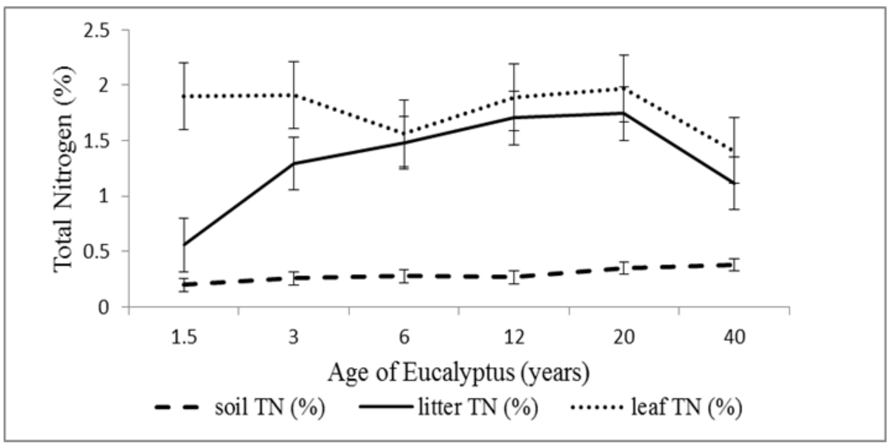

Fig. 3. Total nitrogen content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

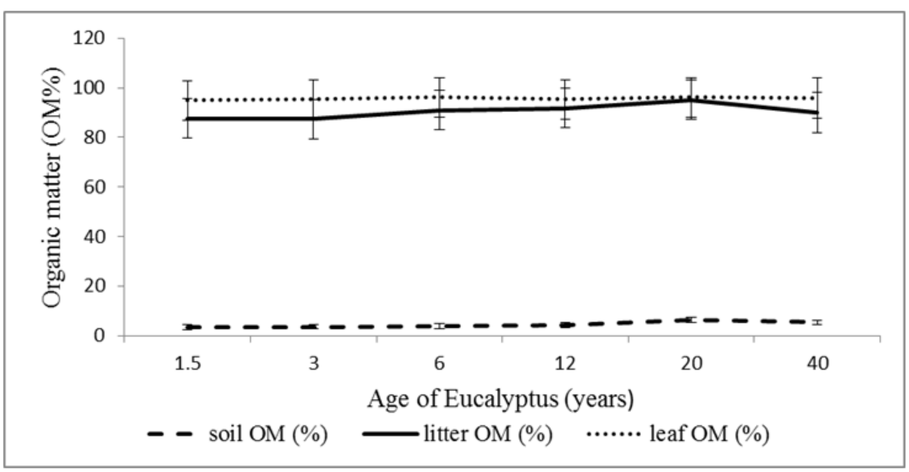

Fig. 4. Organic matter content in the soil, litter and fresh leaf from *Eucalyptus grandis* trees of different ages

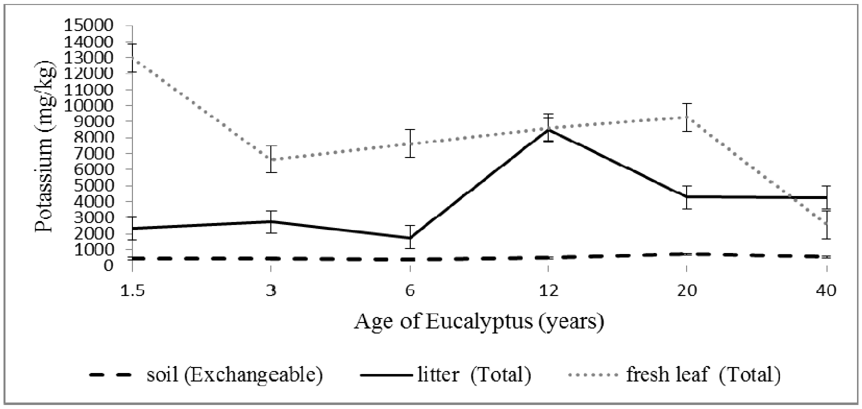

Fig. 5. Potassium content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

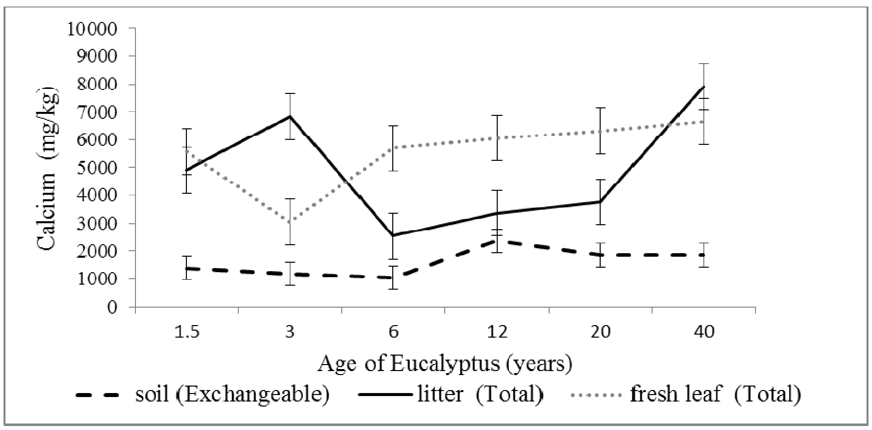

Fig. 6. Calcium content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

The 3 year old canopy was thick and closed with more leaves compared to 6 year old which was open with mostly less young leaves therefore the former was actively growing absorbing more calcium to its leaves and therefore its litter would have high content as the element is less mobile hence deficiency is seen in young leaves as supported by results from this study and by the fact that calcium has been found to be retained in the aging plant tissues [20]. Studies by Leite et al. [16] reported decrease below adequate levels in the concentration of phosphorus and calcium in *E. grandis* leaf of ages 2.5 to 6.75 years. In the same study, magnesium, zinc, and boron were below the critical levels with no significant changes with age of Eucalyptus tree.

For manganese in this study, the soil content correlated negatively to both litter and leaf contents whereby an increase in the soil content corresponded with a decrease in both leaf and litter with a maximum occurring in the tree plantation aged 20 years (1237 mg/ kg) which corresponded to lowest leaf and litter contents (Fig. 7). Manganese in both litter and leaf content had similar trends with peak values occurring in plantation aged 3 years (1458 mg/ kg) and (904 mg/ kg) with lowest in plantation aged 20 years (835 mg/ kg) and (633 mg/ kg) respectively (Fig. 7). Moreover, soil depth had no significant effect on the content of iron and manganese as both had a similar trend reducing down the soil profile with iron 0-20 cm (745 mg/ kg), 80-100 cm (710 mg/ kg) while manganese 0-20 cm (1212 mg/ kg) and 80-100 cm (1009 mg/ kg). For the content of iron in Eucalyptus tissues, the leaf content had a perfect but opposite trends with the soil whereby both reduced between tree age 1.5 and 3 years then took opposite directions with an increase in the soil content leading to a reduction in the leaf with a maximum of soil coming in 6 year old plantation (847 mg/ kg) corresponding to lowest content in leaf (260 mg/ kg) (Fig. 8). For iron content in the litter, the trend was different from both leaf and soil, producing double maxima at tree ages of 3 and 40 years (2550 mg/ kg) and double minima at ages 1.5 and 20 years (633 mg/ kg) (Fig. 8).

Manganese, iron and aluminium have been linked to phosphorus fixation [15], especially in acidic soils whereby they form insoluble complexes rendering them less mobile a fact supported by high content of soil total phosphorus in this study. Since the organic matter was very high in the soils then formation of complex compounds or chelation with humus could be another explanation of their immobility in the soil. It has been documented that soils high in organic matter (> 6.0%) and pH above 6.5 may exhibit manganese deficiency whereby increase in organic matter in the soil leads to reduction in exchangeable manganese as a result of formation of manganese complexes [21]. From literature [21], there is a balance between manganese and iron in the soil and even in the plant tissues especially the leaves whereby manganese toxicity leads to iron deficiency. This may be as a result of manganese ion being similar in size to magnesium and iron ions and can therefore substitute any of these elements in silicate minerals or iron oxides in the soil [21]. In this study, the soil was very high in manganese while low in iron content when the soil type was factored in [13,10,14]. Furthermore, manganese in the soil occurs as exchangeable manganese either as organic matter bound or as an oxide, and its content varies widely with some soils having up to 3000 ppm [21], 20-10000 mg/kg [22] and 15-17 mg/kg in acid soils [23,24]. Manganese contents of plant leaves differ greatly between species with levels of 30-500 mg/kg being reported as normal [25]. [21], reported manganese levels of between 300-400 ppm in plant tissues being labeled excessive, especially in crops and therefore basing on these findings, the contents of manganese in *Eucalyptus grandis* was very high. Studies on nutrient relations in *Eucalyptus grandis* (0.25, 2.5, 4.5, and 6.75 years) revealed nutrient concentrations in the tree tissues was significantly affected by population density [16]. Furthermore, the concentration of phosphorus, potassium, calcium and magnesium in litter and aboveground tissues reduced with increase in Eucalyptus age [16]. These differences in age have been attributed to the tree physiology as it grows whereby there is a reduction in leaves and branches and an increase in woody component of the stem [16]. Nutrient use efficiency in forest canopies has been reported to increase with age due to an increased wood mass which has low nutrient concentration [26,27]. According to [26] and [20], nutrient concentration in the forest canopies depends on the stage of growth or age whereby the nutrient concentrations are high in leaves and branches when the trees are very young where high amounts of nutrients are mined from the soil. This stage is followed by crown closing stage whereby in this study it occurred when trees were between 1.5 and 3 years old characterized by dense canopy. At this stage leaf biomass is believed to be stable with heartwood forming which in itself has low nutrient concentration with the last stage being described as the one where the produced biomass is being maintained by the tree [20].

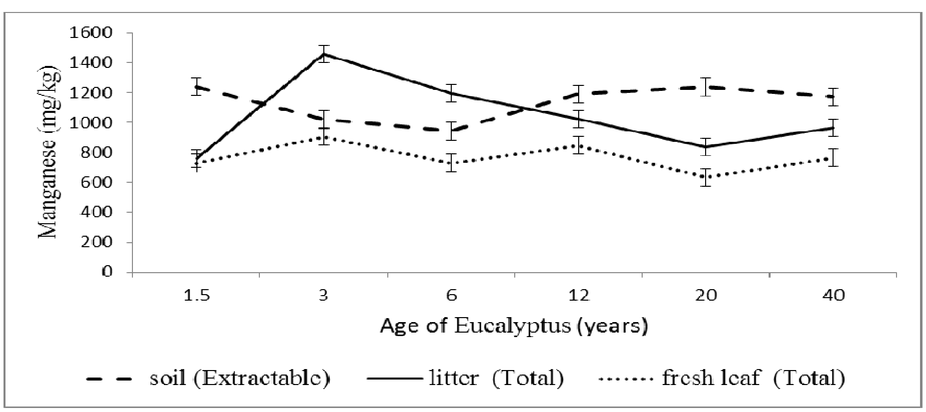

Fig. 7. Manganese content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

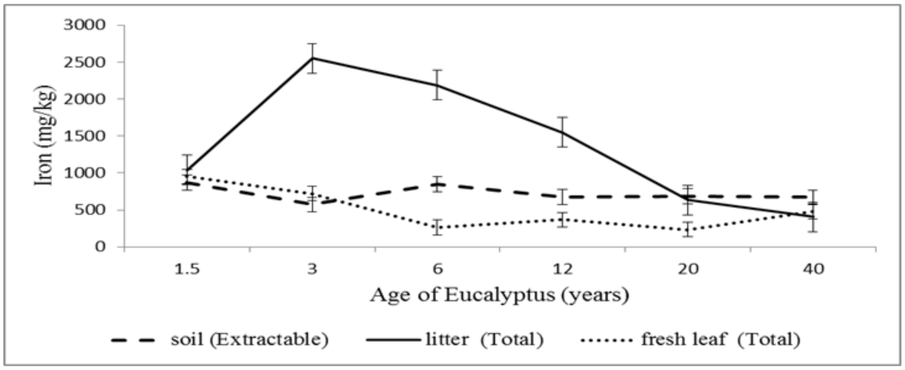

Fig. 8. Iron content in the soil, litter and fresh leaf of *Eucalyptus grandis* trees of different ages

3.2 Effect of Crop Cultivation on Soil Nutrient Dynamics under Eucalyptus Trees

Seasonal variations during cropping period under the Eucalyptus trees significantly affected soil pH (P < .001), available phosphorus (P < .001), Table 2; total nitrogen (P < .001), Table 3; exchangeable potassium (P = .029), exchangeable magnesium (P < .001) Table 4; extractable manganese (P = .036) Table 5; in the top soil depths (0-20 cm, 20-40 cm. Organic carbon (P = .063) Table 3; exchangeable calcium (P = .65) Table 4; extractable iron (P = .90), Table 3; were not affected by crop cultivation. The interaction of season and depth was statistically significant for available phosphorus (P =.036), total nitrogen (P < .001) exchangeable magnesium (P = .003) and % OC (P =.011). The soil pH increased significantly after the first season and reduced drastically after the second season although the 20-40 cm soil depth had higher pH for the differently aged plantations. The available phosphorus was significantly higher in 0-20 cm compared to 20-40 cm soil depth, Table 2. Cropping in Eucalyptus plantations did not alter the soil organic carbon which was high (> 4.0) for both crop and forest systems and this is very key for sustainable intercropping as the soil fertility will be maintained. This might imply that the rates of litter fall and mineralization were balanced during intercropping. Continuous cropping led to increased organic carbon in the underneath horizons i.e. 20-40 cm for the differently aged plantations but the nitrogen depletion down the soil was high and by the end of second successive season of cropping it may require additions especially for crops with high nitrogen requirements. The high rates of nitrogen depletion might have been contributed by the short time interval between the seasons with little soil moisture which meant little mineralization took place in between the cropping seasons. In addition, the type of crop intercropped (Irish potatoes) has high nitrogen requirements and therefore another possible factor. With continuous cropping, the levels of calcium, potassium, and iron seemed to reduce in the plough layer (0-20 cm) and accumulate in the sub-surface horizon (20-40 cm). However, the contents of magnesium and manganese increased in the soil with continuous cropping with magnesium levels increasing more than twice (Table 4).

The availability of soil phosphorus for crop use was the most pronounced problem in this study which could limit successful plant growth especially crop production under the tree averaging critical to very low levels (2 to 5 mg/kg). In addition, availability of soil phosphorus in the soil increased with the cropping seasons moving from critical to very low then low after two cropping seasons (2 to 11 mg/kg), Table 2. Such cases have been reported elsewhere including studies on soil phosphorus in the forested Alfisols inhabited by Oak trees [15] which recorded total phosphorus concentrations of 15.6 to 410 mg/kg and available phosphorus concentration of 0.29 to 30.6 mg/kg. The forms of phosphorus variability and availability in the soil have been linked to the amount of extractable manganese in the soil [15]. The soil organic carbon content under the tree was high when crop production is considered [13,10,14] and seemed not to fluctuate much per cropping season leading to the availability of nitrogen for crop use but the level of depletion was very high for nitrogen per season which may not sustain good yields and hence additional fertilization required. Among many factors such as high litter fall rates which maintain organic carbon levels under the tree canopy, the presence of complex phenolic compounds in Eucalyptus soils have been labeled responsible for low decomposition rates of soil organic matter [17,19]. In this study, the levels of exchangeable calcium, potassium and iron seemed to reduce in the plough layer (0-20 cm) and accumulate in the sub-surface horizons. These results are partly in agreement with studies by Couto et al. [4], which revealed that growing of Eucalyptus with crops in short rotation depleted soil nutrients rapidly but soils under same trees for longer periods without cropping contained higher levels of micronutrients. In sub-tropical forests in China [28], soils under old monsoon evergreen forests have been reported to contain more available phosphorus but less total phosphorus when compared to young pine and coniferous forests. In the same study, soil total nitrogen correlated significantly to soil available phosphorus which agrees with findings in this study whereby, total nitrogen in the soil positively and significantly correlated with organic carbon, phosphorus, calcium and manganese. The results of this study would be valuable and could form a basis of agroforestry programmes in Eucalyptus-crop mixtures especially when soil amendments is needed because the status of fertility are known, whether toxicity or deficiency. In addition, the results would be used in rehabilitating or amending the soils after Eucalyptus trees or plantation have been harvested for cropping purposes. The results are specific to a particular soil type i.e. Nitisols and other related soils like Acrisols but it would serve as a benchmark.

Table 2. Changes in soil pH and available phosphorus in the soil during cropping period under *Eucalyptus grandis* trees of different ages

	Season	**Age**					
		3 years			**6 years**		
		0-20 cm	**20-40 cm**	**mean**	**0-20 cm**	**20-40 cm**	**mean**
soil pH (H_2O)	Initial	5.99	6.12	6.05	5.35	6.06	5.70
	Season 1	6.06	6.45	6.25	5.85	6.11	5.98
	Season 2	5.55	5.66	5.60	5.57	5.75	5.66
	mean	5.86	6.07	5.97	5.59	5.97	5.78
		Season	**Depth**	**Age**	**season*depth**		
	LSD	0.12	0.10	0.11	0.17		
	CV%	12.00					
Available phosphorus (mg/kg)	Initial	3.87	3.09	3.48	3.99	3.45	3.72
	Season 1	7.75	4.75	6.25	6.95	5.11	6.03
	Season 2	9.00	6.60	7.80	11.0	7.80	9.40
	mean	6.87	4.81	5.84	7.31	5.45	6.38
		Season	**Depth**	**Age**	**season*depth**		
	LSD	0.84	0.68	0.61	1.18		
	CV%	12.60					

Table 3. Changes in %OC and total nitrogen in the soil during cropping period under *Eucalyptus grandis* trees of different ages

	Season	**Age**					
		3 years			**6 years**		
		0-20 cm	**20-40 cm**	**mean**	**0-20 cm**	**20-40 cm**	**mean**
%OC	Initial	4.00	2.00	3.00	3.87	1.41	2.64
	Season 1	4.27	3.00	3.63	3.72	2.77	3.24
	Season 2	3.90	3.55	3.72	3.20	2.85	3.02
	mean	4.05	2.85	3.45	3.59	2.34	2.97
		Season	**Depth**	**Age**	**season*depth**		
	LSD	0.56	0.48	0.41	0.79		
	CV%	16.00					
N%	Initial	0.23	0.38	0.31	0.32	0.34	0.33
	Season 1	0.39	0.09	0.24	0.33	0.14	0.23
	Season 2	0.04	0.03	0.03	0.04	0.02	0.03
	mean	0.22	0.16	0.19	0.23	0.16	0.19
		Season	**Depth**	**Age**	**season*depth**		
	LSD	0.053	0.043	0.04	0.074		
	CV%	24.90					

Table 4. Changes in calcium, potassium and magnesium in the soil during cropping period under *Eucalyptus grandis* trees of different ages

	Season	**Age**					
		3 years			**6 years**		
		0-20 cm	**20-40 cm**	**mean**	**0-20 cm**	**20-40 cm**	**mean**
Calcium (mg/kg)	Initial	2479.91	1226.76	1853.33	1775.11	1431.16	1603.13
	Season 1	1934.53	1555.87	1745.20	1714.86	1370.86	1542.86
	Season 2	1582.80	1690.06	1636.43	1491.62	1513.22	1502.42
	mean	1999.08	1490.89	1744.98	1660.53	1438.41	1549.47
		Season	**Depth**	**Age**	**season*depth**		
	LSD	368.97	300.96	311.10	520.96		
	CV%	20.50					
Potassium (mg/kg)	Initial	471.30	455.43	463.36	370.77	284.94	327.85
	Season 1	238.88	356.78	297.83	218.85	328.98	273.91
	Season 2	228.85	282.72	255.785	243.26	390.57	316.91
	mean	313.01	364.97	338.99	277.62	334.83	306.22
		Season	**Depth**	**Age**	**season*depth**		
	LSD	80.10	66.20	60.40	115.56		
	CV%	25.20					
Magnesium (mg/kg)	Initial	409.84	398.04	403.94	306.74	445.91	376.32
	Season 1	664.82	976.93	820.875	422.22	840.44	631.33
	Season 2	588.81	912.94	750.875	372.55	1108.17	740.36
	mean	554.49	762.63	658.56	367.17	798.17	582.67
		Season	**Depth**	**Age**	**season*depth**		
	LSD	118.48	96.74	90.40	167.55		
	CV%	17.50					

Table 5. Changes in Iron and manganese in the soil during cropping period under *Eucalyptus grandis* trees of different ages

		Age					
		3 years			**6 years**		
Iron	**Season**	**0-20 cm**	**20-40 cm**	**mean**	**0-20 cm**	**20-40 cm**	**mean**
(mg/kg)	Initial	695.74	550.24	622.99	513.98	819.65	666.81
	Season 1	589.28	641.76	615.52	717.09	787.4	752.24
	Season 2	527.05	578.22	552.63	718.61	862.19	790.40
	mean	604.02	590.07	597.04	649.89	823.08	736.48
		Season	**Depth**	**Age**	**season*depth**		
	LSD	193.90	158.40	144.10	274.20		
	CV%	26.70					
Manganese (mg/kg)	Initial	1148.58	1188.19	1168.38	777.88	1236.53	1007.20
	Season 1	1252.63	1378.95	1315.79	1271.48	1405.37	1338.42
	Season 2	1331.22	1351.29	1341.25	1344.33	1388.94	1366.63
	mean	1244.14	1306.14	1275.14	1131.23	1343.61	1237.42
		Season	**Depth**	**Age**	**season*depth**		
	LSD	214.73	175.30	175.00	303.68		
	CV%	15.70					

Finally, the choice of crops to be planted under Eucalyptus trees should be able to withstand low levels of available phosphorus and high levels of potassium, magnesium and the nearly toxic levels of manganese. For example; crops like beans, lettuce, oat, and soybean have high manganese requirements while forage legumes, mint, and potatoes are susceptible to manganese toxicity [21].

4. CONCLUSION

Nutrient dynamics in Eucalyptus plantation systems would permit successful intercropping especially with correct tree spacing and crop species. The age of the *Eucalyptus grandis* tree and the soil depth significantly affects the nutrient concentrations in the understory soils i.e. available phosphorus, pH, calcium, potassium, magnesium and iron. In addition, the age of the tree influences the concentrations of nutrients in its fresh leaves and litter i.e. total nitrogen, total phosphorus, total calcium, total potassium, total manganese and total iron. Crop cultivation under Eucalyptus trees reduces total nitrogen, potassium and calcium in the soil while available phosphorus, pH, magnesium and manganese increased. Soil carbon remains unchanged. The availability of soil phosphorus for crop use was the most limiting nutrient and the possibility of manganese toxicity, a minor limitation for successful crop production under Eucalyptus trees. More research is needed on how to improve phosphorus availability to crops and to reduce the possibility of manganese toxicity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Alemie TC. The effect of Eucalyptus on crop productivity, and soil properties in the Koga watershed, Western Amhara region, Ethiopia; 2009.
2. Sasikumar K, Vijayalakshmi C, Parthiban KT. Allelopathic effects of Eucalyptus on blackgram (*Phaseolus mungo* L.). Allelopathy J. 2002;9:205-214.
3. Oballa PO, Konuche PKA, Muchiri MN, Kigomo BN. Facts on growing and use of Eucalyptus in Kenya. Nairobi. Kenya Forestry Research Institute (KEFRI) Publication; 2010.
4. Couto L, Betters DR. Short-rotation Eucalypt plantations in Brazil: Social and environmental issues. Biofuels Feedstock Development Program. Oak Ridge National Laboratory, USA; 1995.
5. EI-Amin EA, Diab IE, Ibrahim SI. Influence of Eucalyptus on some physical and chemical properties of a soil in Sudan. Commun Soil Sci Plant Anal. 2001;32: 2267-2278.
6. Zerfu H. Ecological impact evaluation of *Eucalyptus* plantations in comparison with agricultural and grazing land-use types in the highlands of Ethiopia; 2002.
7. Jaetzold R, Schmidt H, Hornetz B, Shisanya C. Farm management handbook of Kenya, natural conditions and farm management information. Ministry of Agriculture, Nairobi. 2009;IIB.
8. IUSS Working Group. World reference base for soil resources 2006. A Framework for International Classification, Correlation and Communication. World Soil Resources Report No 103. FAO, Rome; WRB; 2006.
9. Nelson DW, Sommers LE. A rapid and accurate method for estimating organic carbon in soil. Proceedings of the Indiana Academy of Science. 1975;84:456-462.
10. Okalebo JR, Gathua KW, Woomer PL. Laboratory methods of soil and plant analysis: A working manual. TSBF-CIAT and SACRED Africa, Nairobi; 2002.
11. VSN International. Genstat for Windows, 16th Edition. VSN International, Hemel Hempstead, UK; 2013.
Available:www.Gensat.co.uk
12. IBM Corp. IBM SPSS Statistics for Windows, Version 23.0. Armonk, New York: Released; 2016.
13. Agricultural Bureaus of SA. Interpretation guides for the comprehensive acid and alkaline soil tests; 2010.
Available:www.naturalresources.sa.gov.au/southeast
14. Hughes B, Jacka J, Lewis D, Prance T. Standard soil test methods & guidelines for interpretation of soil results. Government of South Australia; 1996.
15. Singh G, Goyne K, Kabrick J. Determinants of total and available phosphorus in forested alfisols and ultisols of the Ozark Highlands, USA. Geoderma; 2015.
(Accessed March, 2017)
Available:www.elsevier.com/locate/geodrs
16. Leite PF, Silva RI, Novais FR, Barros FN, Neves LJ, Villani AE. Nutrient relations during Eucalyptus cycle at different population densities. R. Bras. Ci. Solo. 2011;35:949-959
17. Northup RR, Dahlgren RA, McColl JG. Polyphenols as regulators of plant-litter-soil interactions in northern California's pygmy forest: A positive feedback?" Biogeochemistry. 1998;42(1-2):189–220.
18. Bernhard-Reversat F. Changes in relationships between initial litter quality and CO2 release during early laboratory decomposition of tropical leaf litters. Eur J Soil Biol. 1998;34(3):117–122.
19. Min K, Freeman C, Kang H, Choi S. The regulation by phenolic compounds of soil organic matter dynamics under a changing environment. Biomed Res Int. 2015;11.
(Accessed March, 2017)
Available:www.hindawi.com/journals/bmri/2015/825098

20. Grove TS, Thomson BD, Malajczuk N. Nutritional physiology of Eucalypts: Uptake, distribution and utilization. In: Attiwill, P.M. & Adams, M.A., (eds). Nutrition of Eucalypts. Collingwood. CSIRO Publishing. 1996;77-108.
21. Schulte EE, Kelling KA. Soil and applied manganese. Understanding Plant Nutrients Cooperative Extension Publications, University of Wisconsin-Extension; 1999. (Accessed April, 2017) Available:www.cecommerce.uwex.edu
22. Sparks D. Environmental soil chemistry. San Diego, Academic Press. 1995;352.
23. Hue N, Mai Y. Manganese toxicity in watermelon as affected by lime and compost amended to a Hawaiian acid Oxisol. HortScience. 2002;37:656-661.
24. Millaleo R, Diaz M, Ivanov AG, Mora ML, Alberd M. Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms. J. Soil Sci. Plant Nutr. 2010;10(4):470.
25. Clarkson DT. The uptake and translocation of manganese by plant roots. In: R.D. Graham, R.J. Hannam, N.J. Uren. (eds). Manganese in Soil and Plants. Kluwer Academic Publishers, Dordrecht. 1988; 101-111.
26. Miller HG. Dynamics of nutrient cycling in plantation ecosystems. In: Aldous, J.R., (ed). Wood for energy: The implications for harvesting, utilization and marketing. Edinburgh, Institute of Chartered Foresters. 1984;137-146.
27. Bouillet JP, Laclau JP, Gonçalves JM, Moreira MZ, Trivelin PO, Jourdan C, et al. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil 2: Nitrogen accumulation in the stands and biological N2 fixation. For. Ecol. Manag. 2008;255:3918-3930.
28. Liu X, Meng W, Liang G, Li K, Xu W. Available phosphorus in forest soil increases with soil nitrogen but not total phosphorus: Evidence from subtropical forests and a pot experiment. PLoS ONE. 2014;9(2):88070. DOI:https://doi.org/10.1371/journal.pone.0088070

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/23841