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Review

Mitigating N_2O emissions from agriculture: A review of the current knowledge on soil system modelling, environmental factors and management practices influencing emissions

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The AgriGES project is a Concerted Research Action lead by Gembloux Agro-Bio Tech, aiming to quantify methane and nitrous oxide emission from pastures and crop fields, respectively. Besides quantification, a second important goal of the AgriGES project is to study the flux dynamics and to gain a better understanding of the biophysical processes coming into play. We focus here on N_2O fluxes and first propose an overview of the current modelling efforts. Two main weaknesses of these models have been identified, and potential new developments are suggested to mitigate these issues, with an emphasis on the denitrification process. Secondly, we propose a review of the current knowledge on the main environmental factors influencing nitrous oxide emission. Several mitigation options are also explored.

Key words: Nitrous oxide emission, environmental factors, modeling.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report (Stocker et al., 2013b), nitrous oxide (N_2O) concentration in the atmosphere was 324 ppb in 2011, being 20% higher than in the pre-industrial period. This greenhouse gas (GHG) concentration is still increasing at an approximately constant rate of 0.8 ppb/year since the 1980s. N_2O concentrations are far below other GHG concentrations, e.g. CO_2 but it has a global warming potential 298 times higher than CO_2 over 100 years. N_2O is thought to be responsible for around 7.5% of the total radiative forcing induced by GHG (Stocker et al., 2013b). Nitrous oxide emissions caused by human activities represent more than two thirds of the total emissions. N_2O emitted from agricultural soil is known to be a major source (about 60%) of these

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anthropogenic emissions (Mosier et al., 1998; Syakila and Kroeze, 2011).

The physical and biological processes responsible for nitrous oxide production in soil and its emission to the atmosphere lead to an extreme spatial and temporal variability of fluxes. Concerning the latter, it is commonly assumed that N_2O emission is composed of a background flux mainly due to the nitrification process, while high emission peaks occur due to denitrification in times of anaerobiosis e.g. after a rainfall. On an annual basis, these peaks generally account for about 50% of the total N_2O emissions, while representing only a minor part (about 10%) of the time (Groffman et al., 2009; Molodovskaya et al., 2012). The occurrence and magnitude of these peaks are also dependent on other variables influenced by human activities (mainly N-availability) enhanced by fertilization practices.

In this context, more and more attention is being given to the identification of the main environmental factors driving nitrous oxide emission, as well as to mitigation strategies to be applied in agriculture. Any mitigation options proposed to farmers need to be based on scientific evidence. This includes experimental tests at field scale, but this may also be done via the soil system modelling, provided that the model has been validated on experimental data.

Several models have been developed to predict N_2O emissions from soils. This paper first aims to identify why so many models have been proposed. Secondly, special attention will be paid to denitrification (NO_3-reduction to N_2) as it is the main biogeochemical process responsible for nitrous oxide emission from soils. Finally, a review of the current knowledge on environmental factors (soil pH, moisture, temperature, nitrogen (N) and carbon (C) content) and, to a lesser extent, a review of the explored mitigation strategies (e.g. reduced tillage, cover crop, lower fertilizer input) is also proposed.

Two main bottlenecks have been identified in current modelling: competition between the different steps of denitrification is never taken into account; and soil physics - particularly gaseous transports in soils - is poorly represented in most of the models. Some models assume direct emission of the produced gases to the atmosphere, thus bypassing all other reactions that may occur during the gas transport. Implementing new developments would be a great contribution to improving existing models.

PROPOSED MODELS

Despite the existence of well-known concurrent models (Blagodatsky and Smith, 2012) such as (this list is non-exhaustive) DNDC (Li et al., 1992a, b), ECOSYS (Grant et al., 1993a, b), STICS (Brisson et al., 2003, 1998, 2002), and DAYCENT (Parton et al., 1998, 2001), many different groups continue to develop new ones (e.g. MiCNiT (Blagodatsky et al., 2011), TOUGHREACT-N (Maggi et al., 2008)) or try to refine existing approaches, such as NLOSS which is based on DNDC (Riley and Matson, 2000).

There are several reasons for this:

1. From a historical point of view, some models have been designed for specific goals (e.g. DAYCENT for CO_2 emissions, STICS for crop yield), and later applied to other subsidiary outputs such as N_2O emissions.
2. A lack of cooperation between research groups attached to different research fields such as soil biology, soil physics, or agronomy (Blagodatsky and Smith, 2012; Sutton et al., 2011). The multidisciplinary nature of process-based approaches makes communication between researchers difficult. They may use different terminologies to refer to a same process or event, e.g. “dissimilatory nitrate reduction to ammonia” and “nitrate ammonification”.
3. A lack of modular implementation, which makes it difficult to insert new developments into old models. Rubol et al. (2013), for instance, have implemented a new model to take nitrate ammonification into account because of growing experimental evidence of the importance of this process.
4. The need for models applicable to a wide range of temporal and spatial scales (Manzoni and Porporato, 2009). The scale of models ranges from days to decades and from experimental plots to the whole planet. At large regional or national scales, simple experimental models with few parameters are preferable to more complex mechanistic ones, because the number of parameters tends to increase with the model complexity. Lots of these parameters in mechanistic models are site and climate specific (Saggar et al., 2013), and need to be initialized from experimental measurements.

The up-scaling of process-based models is still problematic, but they nevertheless have a great advantage over simpler ones in that their modelling scheme is closer to reality, thus giving the opportunity for a deeper understanding of the biophysical processes influencing N2O emissions, and a better simulation of mitigation options at the farm scale.

Heinen (2006) makes a distinction between two different types of process-based models: microbial growth models and soil structural models. The former models focus on the dynamics of the microbial organisms for the N-cycling processes and often assume immediate transfer of the produced gases from the soil to the atmosphere. The latter consider gaseous transport in soils in more detail, simulating the anoxic fraction of the pore volumes in which denitrification occurs (Blagodatsky and Smith, 2012). Meanwhile,

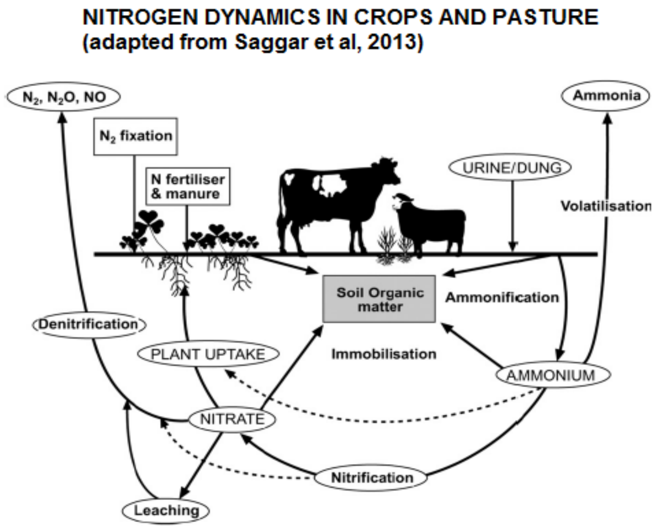

Figure 1. Basic N-cycle.

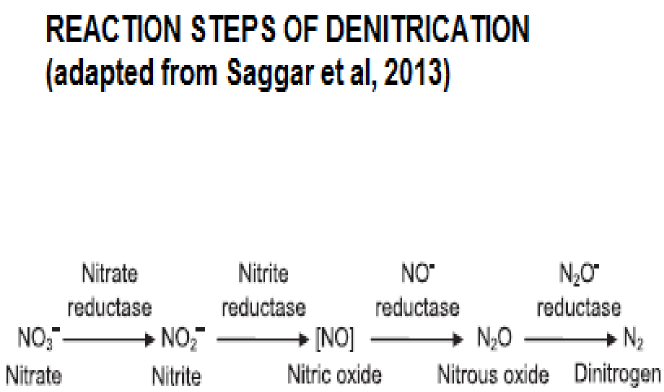

Figure 2. Reaction steps of denitrification.

most models consider simple dependencies of environmental variables (temperature, moisture) on the production of gases, and completely neglect the microbial nature of the C and N cycles.

Chen et al. (2008) provided a very comprehensive comparison of the most widely used models. The vast majority of these models are to be classified as microbial growth models (e.g. DNDC, DAYCENT, STICS). Most of the soil structural models have been tested in laboratory experiments, such as that of Arah and Vinten (1995), while a few attempts to up-scale them are worth noting (Langeveld and Leffelaar, 2002). There is probably a huge knowledge gap to fill, that is coupling a microbial growth model and a soil structural model into one. Since both mechanisms occur over the same timescale, their interaction cannot be neglected (Blagodatsky and Smith, 2012). This would be difficult to insert into the implementation of older models, justifying some new attempts such as MiCNit (Blagodatsky et al., 2011) and PASTIS-CANTIS (Cannavo et al., 2006) to combine these two aspects.

DENITRIFICATION

Denitrification is a natural microbial process and is an essential part of the nitrogen cycle, briefly illustrated in Figure 1. Denitrification is the stepwise reduction of nitrate (NO_3^-) to nitrogen (N_2) via nitrite (NO_2-), nitric oxide (NO) and nitrous oxide (N_2O) (Figure 2). Denitrification is performed by facultative anaerobic bacteria. In conditions of oxygen (O_2) depletion, these bacteria use nitrate as a substitute electron acceptor for adenosine triphosphate (ATP) generation, which is the energy source for cell processes. Each of the four steps of denitrification is catalyzed by a specific enzyme (nitrate reductase: Nar; nitrite reductase: Nir; nitric oxide reductase: Nor; nitrous oxide reductase: Nos). Since NO is highly cytotoxic, all denitrifiers have the gene to code Nor. On the other hand, some denitrifiers lack the gene to code Nos, therefore N_2O is their final product of denitrification. The complete denitrification cycle is mainly a symbiotic process, with bacteria coding Nos performing the last step.

There is growing evidence for competition among the different steps of denitrification. The experiment from Pan et al. (2013a) strongly suggests that this competition plays on the available electron donors (labile carbon). Whereas it is commonly thought that this competition only occurs under carbon-limiting conditions, their results tend to prove that it also occurs with high available carbon content.

According to them, the limiting step that triggers the competition is that the Nir, Nor and Nos use the same pathway to receive electrons, that is they all use the cytochrome c550 coenzyme, while Nar uses the ubiquinone/ubiquinol pool. This may explain their observations, showing a greater competition between Nir and Nos than between Nar and Nos or Nar and Nir. Under carbon-limiting conditions, Nir is highly favoured over Nos, leading to high nitrous oxide emissions.

Other experimental studies have indicated that an increasing nitrate concentration tends to enhance N_2O emission, provided that there is enough available labile carbon (Senbayram et al., 2012). Other molecules are also known to regulate enzyme activity and production, including intermediates from denitrification. Indeed, an increase in NO concentration favours NO-reductase production (Thomson et al., 2012; Zumft, 1997). This makes great sense in terms of biological evolution, since bacteria produce this enzyme to reduce a lethal component (NO) in response to its increase in concentration. It is also worth noting that N_2O reduction to N_2 is energetically less favourable compared to the other steps in denitrification (Senbayram et al., 2012),

their implementation to make them fit in to the geometric structure. Moreover, including a 3-

which may also explain why bacteria tend to favour the previous steps in denitrification, resulting in greater N_2O emission and comparatively less N_2 produced.

Denitrification can also be performed by some fungi. The mechanisms and the relative importance of fungal denitrification have not yet been fully addressed, even though a few authors have found experimental evidence that fungi comprise the majority of denitrifying organisms in grassland soils (Laughlin and Stevens, 2002). The reaction steps are quite similar to bacterial denitrification, but the enzymes involved are different and are not inhibited by O_2. Another important difference is that none of these fungi have the gene to code N_2O-reductase.

An overview by Heinen (2006) assesses more than fifty simplified denitrification models. The majority of these models are to be used at a regional scale. Denitrification is considered as a first order decay process, which is inadequate to explain observed non-linearities in soil N-dynamics (e.g. non-linear response of N_2O emission on quantity of N-fertilizer input (Kim et al., 2013).

Following the pioneering work of Leffelaar and Wessel (1988), most process-based models (e.g. DNDC and TOUGHREACT-N) consider denitrification as a 4-step chain reaction, each step being independent of the others, except that the product of a previous reaction is the reactant of the next one. It is assumed that each reaction follows Michaelis-Menten kinetics. In this regard, STICS constitutes an exception by using a simplified sub-model of denitrification, namely NOE (Bessou et al., 2010; Henault et al., 2005). Very few attempts have been made so far to model the competition between the different reaction steps. As another example of the multidisciplinary nature of this topic, efforts have been made by researchers in waste water treatment, where denitrification is a crucial process.

Based on their previous experimental results (2013a), Pan et al. (2013b) have proposed a new model in which denitrification steps are thought to be mediated by electron carriers going through cell membranes, and competition among the different steps is modelled as a competition for these electron carriers. Each reaction rate is multiplied by a Michaelis-Menten term regarding the carrier concentration, with different affinity constants for each reaction. This seems to be a promising approach to account for the inhibition of nitrous oxide reduction by nitrite and nitrate.

A MODEL OF SOIL STRUCTURE

Directly representing the soil pore space structure in current models might be a tricky task, because it would involve a review of all simulated processes, changing

dimensional (3D) representation of the soil structure in a model is likely to incur time and computer memory consumption issues (Blagodatsky and Smith, 2012).

Another approach involves using soil structural models as a pre-process tool to provide pedotransfer functions to be later used in a more generic model. In this regard, the pore-solid-fractal approach (PSF) derived by Perrier et al. (1999) has proved to be a powerful tool that is able to account for a wide variety of soil physical properties (Ghanbarian-Alavijeh et al., 2011; Perfect and Kay, 1995), such as the theoretical water retention curve derived by Wang and Zhang (2011).

Rappoldt and Crawford (1999) used the 3D-soil space resulting from the PSF model in order to solve the oxygen diffusion-respiration equation in soils. In relation to denitrification, their results can be used to simulate the soil anoxic fraction as a function of its water content in a given depth layer. This, together with a model of denitrification rate as a function of the soil depth (most likely decreasing with depth because of the decrease of the microbial community), may potentially lead to a better simulation of the N_2O emission peak dynamics, both in magnitude and temporal occurrence.

MAIN DRIVERS

Several environmental factors are known to play a key role in greenhouse gas emission from soils. In general, complete denitrification is favoured by high water content, neutral to slightly basic pH, high temperature, low O_2 diffusion, and labile C availability. While each individual influence is quite well researched, there is still a lack of complete comprehension of some mechanisms by which these factors (e.g. pH) act on emissions, and a fully comprehensive scheme of their interactions is thought to be unrealistic (Butterbach-Bahl et al., 2013). Several authors have provided reviews of the current knowledge on these driving factors. Of particular interest are: Butterbach-Bahl et al. (2013), Giles et al. (2012), and Saggar et al. (2013).

The timescales at which these factors influence N_2O emission from soils vary in a very wide range, from hours to decades. For instance, water content is known to regulate the anoxic volume of soils in a very direct way, while soil pH may have a long-term effect via microbial community adaptation. Long-term feedback effects are also reported, e.g. the increase of soil temperature due to the global warming will probably enhance greenhouse gas emission from soils in the coming decades.

Soil pH

Soil pH is known to be a key variable in soil biogeochemical processes, although its influence is not yet well understood (Liu et al., 2010; Simek and Cooper, 2002; Van den Heuvel et al., 2011). Regarding nitrous oxide emissions, it is globally accepted that acidic conditions (lower pH) tend to increase N_2O:N_2 emission ratio while decreasing total N_2O and N_2 emission (Liu et al., 2010). To minimize N_2O emission, a neutral to slightly alkaline soil pH seems to be optimal (Giles et al., 2012), dependent on other soil characteristics.

Soil pH affects denitrification in many different ways. Both direct and indirect effects of pH on denitrification rates, denitrification end product, and denitrifier community have been reported. Liu et al. (2010) have shown that a pH-dependent effect on denitrification enzyme activity occurs at a post-transcriptional level. They suggested that pH may disable the protein assembly, or influence its shape, leading to unusable active site. Bakken et al. (2012) working with a specific bacteria (*Paracoccus denitrificans*), observed that at pH 7, nearly no N_2O was emitted from batch cultures, while at pH 6, N_2O-reductase activity was drastically reduced, leading to high N_2O emissions.

Indirect effects of soil pH on denitrification may include changes in organic carbon availability and nitrogen mineralization rates (Simek and Cooper, 2002). These two variables tend to decrease under acidic conditions, leading to a smaller microbial community, which in turn leads to lower denitrification rates in soils (Van den Heuvel et al., 2011). Meanwhile, this effect could be counterbalanced by a long term adaptation of the microbial community.

Soil moisture and oxygen availability

Soil water content may influence gaseous emissions from soils in many different ways. For instance, water presence in soil is necessary for plant and microbial growth, which in turn can influence biochemical reaction rates and enhance nitrate uptake by crops. However, soil water content is particularly studied for its key role in the development of anaerobic conditions in soils. Indeed, most of the models (e.g. DNDC) use the water filled pore space (WFPS) of soils as a proxy to define periods of activation and inhibition of the denitrification process.

Several experimental studies, e.g. Bateman and Baggs (2005), have shown the existence of a WFPS threshold value above which denitrification rates increase sharply with soil water content, and under which denitrification rates are low and seem unrelated to WFPS. DNDC uses a threshold value of 60%, and this value differs according to soil type. After reaching a maximum around 70 to 80% WFPS, nitrous oxide emission generally tends to decrease. This is thought to be caused by a lower gas diffusion into soils, thus giving more time for denitrifiers to reduce N_2O (Smith et al., 2003).

De Klein and Van Logtestijn (1996) suggest that the WFPS threshold value is equivalent to or slightly higher than field capacity. This makes sense in several ways: at field capacity, micro-pores are still filled with water; whereas these pores are also thought to be the privileged location of microorganisms (including denitrifiers) in soils (Or et al., 2007). In addition, Saggar et al. (2013) report a duration of 24 to 48 h after a rainfall for N_2O emissions to return to their background level. The experimental definition of the field capacity is indeed the soil water content 48 h after its saturation.

This threshold value may also be related to several models describing the anoxic fraction of soils as a function of its water content (Arah and Vinten, 1995; Rappoldt and Crawford, 1999; Schurgers et al., 2006). These models show a highly non-linear response of soil anoxic fraction to soil WFPS, with the anoxic fraction notably increasing above a certain threshold value which may be compared to the observed threshold value for the denitrification activity. The threshold values computed by Rappoldt and Crawford (1999) and Schurgers et al. (2006) are in accordance with the WFPS threshold range given by Bateman and Baggs (2005).

Soil temperature

Soil temperature most significantly influences gas emission via its role in microbial growth and activity (Braker et al., 2010). Denitrification occurs across a wide temperature range (near 0 to 75°C), and is limited by water availability (freezing below 0°C) and microbial death at too high a temperature (Saggar et al., 2013). Optimal temperatures for denitrification rates have been reported from 25 to 30°C (Braker et al., 2010).

Of particular interest are fluctuations of temperature around 00, which lead to freeze-thaw cycles with high emission peaks reported in numerous studies, e.g. (Mørkved et al., 2006). Several explanations have been proposed for these peaks (de Bruijn et al., 2009). N_2O may accumulate in frozen phases due to lower gas diffusion and be released on thawing. It has also been suggested that substrate availability may be more important in winter because of low plant uptake during this period.

Increasing temperature may also cause higher oxygen consumption, thus leading to an increase in the anoxic fraction of the soil pores as less oxygen is available (Smith et al., 2003).

At a seasonal scale, Wolf and Brumme (2002) reported a linear relation between temperature and nitrous oxide emission on a bare soil with WFPS kept constant at field capacity. On a larger time scale, global warming (and consequent soil warming) is likely to have an important positive feedback on CO_2, CH_4 and N_2O emission from soils in the coming decades (Arneth et al., 2010; Stocker et al., 2013a; van Groenigen et al., 2011), mainly resulting from an enhanced microbial activity.

Soil carbon and nitrogen content

As electron donors and electron acceptors for denitrification respectively, both labile organic carbon and nitrate play a key role in nitrous oxide emissions. Besides the direct effect of providing supplies for the denitrifiers, other indirect effects have also been reported (Giles et al., 2012). For instance, the presence of carbon stimulates heterotrophic respiration, hence favouring anaerobic conditions in soils.

Several studies focus on the C:N ratio of fertilizers as well as on the applied rate to reach maximum crop yield while limiting N_2O emission. In their meta-analysis, Van Groenigen et al. (2010) reported a sharp increase in nitrous oxide emission when the N-fertilizer input leads to nitrogen saturation (excess of N compared to plant and microbial maximum demand) of soils, which may indicate that a precise control of N-input is a straightforward and effective option to reduce nitrous oxide emission.

The incubation experiment led by Senbayram et al. (2012) found that, for soils with low nitrate content, the nitrous oxide emission can be- substantially lowered by the addition of organic matter with high content of labile C, by promoting the reduction of N_2O to N_2. Alternatively, for soils with high nitrate content, labile organic C enhanced nitrous oxide emission, most likely due to an inhibitory effect of NO_3- on the N_2O-reductase.

Explored mitigation options

Strategies to reduce greenhouse gas emissions from agriculture mainly rely on our knowledge of the main drivers, with the aim to influence these factors (e.g. pH and liming, soil carbon and nitrogen content and fertilization practices) in order to decrease the emission levels as much as possible. These strategies have to be placed in a wider context, considering other constraints that best management practicess assessments should also acknowledge:

1. Productivity must be kept at a sustainable level in order to ensure food security.

2. Avoidance of nitrate leaching to maintain water quality. Moreover, this nitrate will eventually end in waste water treatment plants where denitrifiers are used to remove it from water, also leading to nitrous oxide emissions (Cui et al., 2014; Pan et al., 2013b).

3. The greenhouse gas budget of an agricultural farm should also take into account GHG emission from agricultural machinery, GHG emission for the production and transport of inputs (pesticides, fertilizers, lime, etc.). Promoting less intensive crop systems and reducing inputs to the field results in the saving of a considerable amount of GHG emissions upstream of the cropping itself (Smith et al., 2008).

4. The need to compute greenhouse gas emissions for a complete sequence of crops, which is more relevant than for a single crop as a previous crop affects the following one because of its influence on soil nutrients (Lehuger et al., 2011).

Several mitigation options for direct nitrous oxide emissions from the field are discussed hereafter. It is most likely that the best way to reduce these emissions involve a mix of these different practices, as they influence each other.

Fertilizers

As shown experimentally by Van Groenigen et al. (2010), nitrous oxide emission increases exponentially with excess N-fertilizer compared to plant demand. According to their study, lowering N-input to match the crop demand would be a straightforward and effective way to reduce N_2O emission per crop yield. Once this is done, if soil nitrate content remains at a relatively low level, addition of labile organic carbon may also be a way to enhance reduction of N_2O to N_2, thus also leading to a reduction of nitrous oxide emission. In this regard, combining both organic and synthetic fertilizers would be an efficient mitigation option (Senbayram et al., 2012).

Changing spatial and temporal location of N-input may also be an important factor in improving their efficiency. For instance, in the UK, avoiding manure application during autumn and early spring may be an effective way to reduce yearly emissions, since it often rains a lot during these periods leading to high denitrification rates in soils. This mitigation scenario has been tested with DNDC and shows promising results.

Technical progress has (Cardenas et al., 2013) also been made in the manufacture of slow- (or “controlled-”) release fertilizers, that is, fertilizers which decompose more slowly than traditional ones, thus providing nutrients more homogeneously over time (Azeem et al., 2014). The use of slow-release fertilizers seems to be a promising way to increase N-use efficiency, but their cost remains prohibitive.

Enzymatic regulations

While all of the enzymes involved in the denitrification process are influenced by environmental factors, explored mitigation options focus mainly on the N_2O-reductase. Enhancing N_2O-reductase activity is expected to decrease the $N_2O:N_2$ ratio. Liming of acidic soil is a way to achieve this, but it also leads to higher total N_2O+N_2 emission (Bakken et al., 2012).

Meanwhile, this additional direct loss of N-input is thought to be largely compensated by the decrease of nitrate leaching, since nitrate is consumed by denitrifiers. Another key variable for the N_2O-reductase enzyme is the soil copper content. Indeed, copper (Cu) is a mandatory and irreplaceable cofactor in order for this enzyme to be active. Thus, addition of Cu in copper-poor soil may also decrease $N_2O:N_2$ ratio, without disturbing the total N_2O+N_2 emission (Richardson et al., 2009; Thomson et al., 2012)

Regarding other biogeochemical processes, the use of nitrification (oxidation of ammonia to nitrate) inhibitors together with ammonium-based fertilizers has also been addressed (Liu et al., 2013). Inhibiting nitrification is expected to reduce nitrate losses by leaching and denitrification, while still leaving a usable form of N (rhat is, ammonium) for plant uptake. Liu et al. (2013) reported an increase of crop yield, and a better nitrogen use efficiency, as well as a reduction of N_2O emissions. Meanwhile, a phytotoxic effect associated with excessive inhibitor application rates was also reported, as well as a subsequent yield reduction.

Moreover, several key points have not been addressed yet concerning the use of nitrification inhibitors, e.g. the GHG emission resulting from their manufacture and their long-term impact on the soil microbial community.

Cover crops

Cover crops, also known as catch crops, are mainly used during winter to avoid soil erosion by the structural effect of roots preventing soil loss, and nitrate leaching by plant uptake. N sequestered by cover crops is then made available for the main crops during the growth season, which enhances the yearly N-use efficiency of the crop rotation. Given this dual effect, cover crops are often considered as a win-win practice for N-management (Constantin et al., 2010), and their use is thought to reduce reliance on fertilizer input. In drier lands the positive impact of cover crops is less pronounced, since there is naturally less nitrate leaching in winter in these areas.

There are also concerns about water and nitrogen stress induced by cover crops, resulting in yield reduction issues for the main crop (Celette and Gary, 2013; Celette et al., 2008).

Conservation tillage

It is widely thought that conventional tillage is the primary cause of the decrease in soil organic carbon content. Many soils have lost up to 40% of the C they contained before cultivation (Baker et al., 2007). The first intent of reduced or no-till practices is to promote soil C sequestration, thus allowing soils to refill in order to act as a reservoir. In addition to this potential for sequestration, an increased soil C content can also promote the reduction of N_2O to N_2, provided that soil nitrate remains at a relatively low level. In order to control nitrate content, conservation tillage is often used in combination with other management practices, such as lower N-fertilizer application rates and the use of winter cover crops (Constantin et al., 2010; Petersen et al., 2011). A higher soil organic carbon content is also thought to enhance plant uptake, but this effect may be counterbalanced by a greater soil compaction, leading to a difficult root growth.

Nevertheless, a few authors have pointed out that evidence of soil C sequestration induced by reduced tillage is not that obvious. Baker et al. (2007) argued that the sampling depth in most of the experimental studies is not deep enough. Conservation tillage may change the C distribution in soils, thus increasing the C content in the first 30 cm layer, but at deeper depths some studies show a decrease in soil C content.

~~Conventional tillage practices have been concomitant to the soil C loss in the last few decades, but this does not necessarily mean that they are the main cause for this loss. Other major soil alterations induced by cultivation (e.g. loss of perennial vegetation with higher annual C assimilation than crops, and drainage of wetlands favouring microbial oxidation of organic carbon) may be the primary causes of the observed soil C loss. In the end, tillage practices may not be the key point to address when trying to reduce soil C loss.~~

~~Meanwhile, reduced and no-till practices still offer several great advantages compared to conventional tillage. This approach protects soils against erosion, reduces production costs, saves time and reduces GHG emission due to lower machinery use. There also are drawbacks worth mentioning (e.g. weeds and regrowth in no-till have to be eliminated, which is most often realized using herbicides), but the~~

~~overall balance looks positive regarding the GHG budget (~~**Error! Hyperlink reference not valid.**~~; ~~**Error! Hyperlink reference not valid.**~~).~~

CONCLUSIONS AND PERSPECTIVES

In this paper, the current knowledge on the main driving factors influencing nitrous oxide emissions from cultivated fields has been reviewed. While many environmental factors have been studied (such as soil pH, water content, temperature), there is still progress to be made to gain a complete comprehension of the influence of soil physical properties on GHG production and emission.

In this regard, a fractal model of soils seems a promising approach to give a consistent theoretical basis that is able to account for a wide variety of soil physical properties (Ghanbarian-Alavijeh et al., 2011; Perfect and Kay, 1995). In particular, the pore-solid-fractal approach (Perrier et al., 1999) allows derivation of a theoretical water retention curve (Wang and Zhang, 2011) and provides a 3D-space in which to simulate several key processes, including the temporal dynamics of the anoxic fraction of the pore volume (Rappoldt and Crawford, 1999).

Another key process which is not taken into account in current modelling efforts is the competition among the different steps of denitrification. The approach from Pan et al. (2013b) seems promising, but needs to be tested in a wider range of anaerobic conditions.

These potential developments need to be incorporated in a more general process-based model of soil C and N cycles which will need to be chosen from the different existing models, based on their current performance in agricultural and meteorological conditions encountered in our region.

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Abbreviations: ATP, adenine triphosphate; C, carbon; CANTIS, carbon and nitrogen transport in soil; CH4, methane; CO2, carbon dioxide; Cu, copper; DNDC, denitrification-decomposition; GHG, greenhouse gas; IPCC, intergovernmental panel on climate change; MiC-NiT, microbial carbon and nitrogen turnover; N, nitrogen; N2, dinitrogen; Nar, nitrate reductase; Nir, nitrite reductase; N2O, nitrous oxide; NO2-, nitric oxide; NO3-, nitrate; NOE, nitrous oxide emissions; Nor, nitric oxide reductase; Nos, nitrous oxide reductase; PASTIS, predicting agricultural solute transport in soils; PSF, pore-solid-fractal; STICS, simulateur multidisciplinaire pour les cultures standard ; UK, United Kingdom; WFPS, water filled pore space.

Conflict of Interest

The authors have not declared any conflict of interest.

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Soil properties and carbon sequestration under desert date (*Balanites aegyptiaca*) in the lowlands of Northern Ethiopia

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This study assessed the effect of *Balanites aegyptiaca* on soil properties and carbon sequestration. A 100 × 100 m plot of entirely the same biophysical setting was delineated. Nine trees of relatively the same diameter at breast height (DBH) were selected to study the effect of the tree on soil properties. In total, 81 soil samples were collected from three radii distances from each tree, that is 0 - 2, 2 - 4, and 4 – 8 m at three soil depths of 0 - 20, 21 - 50 and 51 – 100 cm. Soil analysis was carried out following routine laboratory procedures. The carbon sequestration potential of the tree was determined by taking 0.5 g sample specimen from each tree. The highest productivity was observed at the radial distance of 0 - 2 followed by 2 - 4 and 4 – 8 m with the productivity indices of 0.74, 0.63 and 0.58, respectively. The highest amount of CO_2^-e (235.7 kg tree^{-1}) was sequestered in older trees with a DBH range of 17 - 19 cm as compared to younger ones (56.9 kg tree^{-1}) with the DBH range of 8 - 10 cm. Therefore, this tree has a significant effect on soil fertility improvement and climate change mitigation through carbon sequestration and as a result, it is important to retain *B. agyptiaca* on farmlands.

Key words: *Balanites aegyptiaca*, soil properties, carbon sequestration, Kafta Humera Woreda.

INTRODUCTION

Parkland agroforestry is one of the agrosilvicultural systems known in agroforestry systems. It is defined as the integration of scattered trees in a cultivated land or rangeland where trees are deliberately associated with the agricultural environment because of their specific use (ICRAF 2008). It is one of the three types of agroforestry systems that are known in the drylands of Ethiopia Involving mixed cereal-tree-livestock, cereal-trees and tree-livestock systems as described by Kindeya (2004). Therefore, parkland agroforestry system can be characterized as a cereal-tree agroforestry system. There are often both economic and ecological interactions between trees and other components of the system. The ecological interaction can be understood as the existence of trees on farms that help maintain soil nutrient status through protection against leaching, translocation of

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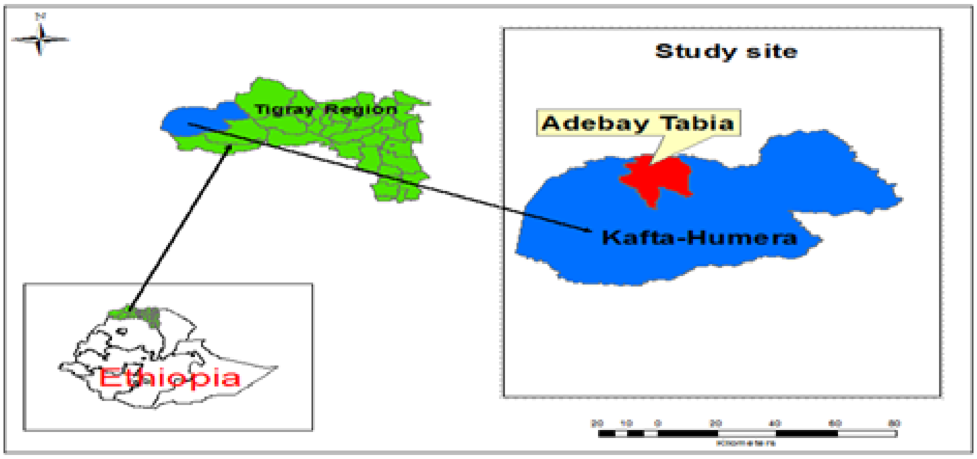

Figure 1. Geographical location of *Kafta Humera.*

nutrients from deeper soil layers to the surface and accumulation of plant litter, which creates a temporary nutrient pool at the soil surface below the canopies (Nair et al., 2009). The tree shades its leaves during the peak growing season and plays a great role in organic matter improvement and stays evergreen the whole year (Terra 2009). *Balanites aegyptiaca,* commonly known as desert date, is a small to medium sized dryland tree, which belongs to the family Zygophyllaceae (Clement, 2011).

It is found in most African countries stretching from arid and semi arid regions to sub humid Savannah (Orwa 2009). As a multi-purpose tree, *B. aegiptiaca* plays an important role in soil fertility maintenance, providing food, medicine, cosmetics, fodder, fuel wood and pesticides (Mansor et al., 2004). In lowlands of Tigray, *B. aegyptiaca* is traditionally retained on farmlands to get ecosystem benefits such as shading as described by Teklehaimanot (2011).

Small-scale farmers in *Kafta Humera Woreda* have long been experienced retaining *B.aegyptiaca* on their farmlands. However, due to the inadequate information available on the role of *B. aegyptiaca* in soil fertility management and climate change mitigation, farmers are clearing the tree for other socioeconomic uses like fuelwood and construction. Therefore, this study come up with clear findings that could help understand the role of *B. aegyptiaca* in soil properties and carbon sequestration, which at the same time enhances their awareness in retaining the existing trees and planting new seedlings on their farmlands.

MATERIALS AND METHODS

Study area description

The study was conducted in *Kafta Humera Woreda* located between 13°40′′ to 14° 27′′ N latitude and 36°27′ to 37° 32′′ E longitude, Western Tigrayzone (Figure 1). It is located about 570 km northwest of *Mekelle* town. It is bordered with the Sudan in the West, *Tahitay Adyabo* in the East, *Wolkayt* and the *Amhara* region in the South and Eritrea in the North.

Study site selection criteria

In selecting the study site, the natures of *B. aegyptiaca* dominated environment of all farmlands enabled understand the paramount significance of the tree. Secondly, the number of trees retained in each farms ranged from 23 to 55 where taking 47 trees for the purpose of this study was found representative. Finally, the proximity of the study site to access labor force and necessary materials was the other criteria used.

Experiment I: Examining the effect of *B. aegyptica* on soil properties

Experimental design and layout

In the experiment, a 100 × 100 m (1 ha) plot was laid out first where the total number of trees inside it were found to be 47. The DBH of all trees were measured and four DBH classes were then identified, namely 8 - 10, 11 - 13, 14 - 16 and 17 – 19 cm to study the effect of *B. aegyptiaca* on soil properties. DBH classification was made to minimize the variability in the desired variable due to wider age differences and make tree sampling easier.

A total of nine trees, which also were replications, were then randomly selected from the same diameter class. The two factors identified to cause variability in the response variable were tree radial distances (that is, 0 - 2, 2 - 4 and 4-8 m) and soil depths (that is, 0 - 20, 21 - 50 and 51 - 100 cm). As a result, complete randomized factorial design (CRFD) was used for laying out the experiment.

Soil sampling methods

A total of 81 composite soil samples were collected from three radii; namely 0 - 2, 2 - 4 and 4 - 8 m at three soil depths that is, 0 - 20; 21 - 50 and 51 - 90 cm. All the soil samples were air-dried, ground and passed through a 2 mm sieve for soil physico-chemical analysis.

Table 1. Effect of *B. aegyptiaca* on physical soil properties.

S/N	Factors	Physical soil properties						
		BD (Mg m^{-3})	MC (%)	AWC (cm cm^{-1})	Clay (%)	Sand (%)	Silt (%)	Texture
1	**Radii (m)**							
	0 - 2	1.26^b	16.3^a	0.14^b	57^b	20^a	20^a	Clay
	2 - 4	1.43^a	15.0^b	0.16^{ab}	59^{ab}	19^a	23^b	Clay
	4 - 8	1.46^a	9.0^c	0.17^a	60^a	19^a	24^b	Clay
	S (±)	0.15	2.3	0.04	4.3	4.3	5.5	
	P-value	< 0.001	< 0.001	0.01	0.024	0.911	0.125	
2	**Depth (cm)**							
	0 - 20	1.23^c	11.4^c	0.13^b	56^c	20^a	24^a	Clay
	21 - 50	1.37^b	13.4^b	0.16^a	59^b	20^a	21^{ab}	Clay
	51 - 100	1.54^a	15.5^a	0.18^a	63^a	19^a	18^b	Clay
	S (±)	0.12	3.5	0.03	3.5	4.4	5.1	
	P-value	< 0.001	< 0.001	< 0.001	< 0.001	0.557	0.001	
3	**Depth * Radii**							
	P-value	0.001	0.987	0.148	0.992	0.962	0.986	
	Rep.	9	9	9	9	9	9	
	DF	80	80	80	80	80	80	

BD = Bulk density; Mc = moisture content; AWC = available water holding capacity and values with the same superscript letter were not significantly different at (P < 0.05).

Laboratory soil analyses procedure

Total Nitrogen was analyzed using Kjeldahl procedure as described in Jackson (1958) by using oxidation method. Soil pH was measured in a 1:2.5 suspension of soil salt solution of 1 M $CaCl_2$ by using pH meter (Schofield and Taylor, 1955). Available phosphorus was determined by Olson method (Olsen and Sommers, 1982). Exchangeable potassium was measured using Flame Photometer following ammonium acetate extraction method (Jackson, 1958). The total organic carbon content of the soil was determined by wet oxidation method as described by Black and Walkley (1934). Electrical conductivity was determined using an EC meter in 1:5 soil water suspensions (Houba et al., 1989). The cation excange capacity of the soil was analyzed through ammonium acetate extraction with a pH adjusted to 7.0 by using Flame Photometer (Houba et al., 1989).

The bulk density was determined using a core sampler and the moisture content was measured gravimetrically (Blake and Hartge, 1986). Soil texture was measured using a Bouyoucos hydrometer as indicated in Gee and Bauder (1982). Water holding capacity of the soil was analyzed using 10 Ka for field capacity and 1500 Kpa for permanent wilting point (Stolte 1998).

Soil productivity index calculation

The productivity index is an algorithm based on the idea that crop yield is a function of root growth, including rooting depth, which is controlled by the soil environment (Nwite et al., 2008). The productivity index was calculated using normalized sufficiency factors of pH, bulk density, electrical conductivity and available water holding capacity as described by Nwite et al. (2008), for the three soil layers, namely 0 - 20, 21 - 50, and 51 - 100 cm (Equation 1).

$$PI = \sum_{i=1}^{n} (A_i \text{ x } B_i \text{ x } C_i \text{ x } D_i \text{ x } WF) \quad (1)$$

Where PI = Productivity Index of the soil, I = 1, 2, 3…..n^{th} soil layers, Ai = sufficiency factor for available water holding capacity, B_i = the sufficiency factor for bulk density, Ci = the sufficiency factor of pH, D_i = the sufficiency factor for electrical conductivity of the i^{th} soil layer. The four sufficiency factors were retrieved from Table 1. WF is the root weighting factor at different rooting depths given by Equation (2) and B is average tree biomass where the soil sample was taken.

$$WFi = (RD_m – D_1)^2 – (RD_m – D_2)^2 / RD_m^2 \quad (2)$$

Where RD_m = maximum depth of root system (100 cm), D1 = depth of the upper boundary (cm) and D2 = depth of the lower boundary (cm).

Statistical analysis

All the soil data were first checked for normality and equality of variance using Anderson Darling normality test and Bartlett's test for equality of variance, respectively. Then, a two-way analysis of variance (ANOVA) with a fixed effect model at P < 0.05 was used to see the effect of *B. aegyptiaca* (both at three radii and soil depths) on selected soil properties using JMP Version 5 and MINITAB Version 14. Treatments were further compared using LSD Tukey (Least square means difference Tukey test) for their average values at 5% level of probability. A simple correlation analysis was also employed to see the relationship between different soil properties.

The statistical model, used for data analysis of the two factors experiment (Radial distance and soil depth effect) and one factor experiment (soil depth) for SPI were:

$Y_{ijk} = \mu + A_i + B_j + AB_{ij} + e_{ijk}$

And

$Y_{ik} = \mu + A_i + e_{ik}$

Where: Y = the response variable, μ = overall mean, A_i = i^{th} level treatment effect of factor A (that is, soil depth), B_j = j^{th} level treatment effect of factor B (that is, Radii), AB_{ij} = ij^{th} interaction effect of A and B, e_{ijk} = the random error effect.

Experiment II: Assessing the carbon sequestration potential of *B.aegyptiaca*

Experimental design and layout

A 100 × 100 m (1 ha) plot, which was also used for experiment-I, was delineated to measure tree characteristics, where 47 *B. aegyptiaca* were counted. Then, all the *B. aegyptiaca* in one hectare area were measured for their DBH using a caliper, tree height using clinometers and crown height using a measuring tape (Abebe, 2001).

Tree selection procedure

DBH was considered as tree selection criteria. Hence, the DBH of all the forty-seven trees were measured using a Caliper. These trees were then classified in to four DBH classes, namely 8-10; 11-13, 14-16 and 17-19 cm to see the effect of DBH on total biomass production and carbon sequestration as well as carbon trading potential.

Total tree biomass estimation

Total tree biomass here was considered as the sum of the above ground biomass (AGB) and belowground biomass (BGB). The above ground biomass of the forty-seven trees was estimated using the allometric equation specific to *B. aegyptiaca* (Equation 3) as developed by Matieu et al. (2011):

$$\log10Y = (2.55 \times \log10(X)) + 0.07 \quad (3)$$

Where, Y = above ground biomass (AGB) in kg, x = diameter at breast height (cm), 2.55 and 0.07 = constants.

The below ground biomass of each tree was estimated from the AGB by multiplying it with a factor of 0.27 (root/shoot ratio) as described by IPCC (2003), which is summarized in Equation (4):

$$\text{BGB tree}^{-1} = 0.27 \times \text{AGB tree}^{-1} \quad (4)$$

Determination of carbon fraction in B. aegyptiaca

Three trees with different DBH classes were randomly selected from the total of forty-seven trees. They were felled using chainsaw. Then, composite specimens were taken from the leaf, branches, stems and roots. Then after, the specimens were oven dried at 65°C and weighed repeatedly until a constant reading was obtained. Further, specimens of each tree sample were then ground (milled) using a grinding machine and a 0.5 g sieved sample was weighed for ashing. It was done after burning the sample in a muffle furnace at 550°C for 8 h until a white ash was obtained (Ullah et al., 2008). Finally, the ash content and carbon fraction were calculated using Equations (5) and (6), respectively:

$$\text{Ash (\%)} = (W_3 - W_1) / (W_2 - W_1) * 100 \quad (5)$$

$$\text{CF (\%)} = (100 - \text{\%ash}) * 0.58 \quad (6)$$

Where; W_1 = weight of crucibles; W_2 = weight of oven dried tree samples + empty crucible weight; W_3 = weight of ash + empty crucible weight; CF = carbon fraction and 0.58 = a conversion factor.

Estimation of carbon stock in B. aegyptiaca

The carbon stock of both the above ground and below ground biomass was estimated by multiplying total biomass by the carbon fraction as described by IPCC (2003) and given in Equations (7) and (8):

$$C_{AGB} = AGB * CF \quad (7)$$

$$C_{BGB} = BGB * CF \quad (8)$$

Where, C_{AGB} = the carbon stock in the above ground biomass; C_{BGB} = carbon stock in the below ground biomass and CF = carbon fraction as described in Equation (6).
The total carbon stock of the tree is the sum of both the above ground and below ground carbon as described IPCC (2003) indicated in Equation (10).

$$TCS_T = B_{Total} \times CF \quad (9)$$

Where, TCS_T = total carbon stock of the tree; B_{Total} = total biomass; CF = carbon fraction.

Soil carbon stock estimation

Three composite soil samples were collected from each radii of 0 - 2, 2 - 4 and 4 - 8 m at 0 - 20, 21 -50 and 51 – 100 cm soil depths for total organic carbon (TOC) determination according to Black and Walkley (1934). Besides, undisturbed soil samples were collected using a core sampler to determine soil bulk density (Blake and Hartge, 1986). The coarse fragment proportion of the soil was determined as the ratio of weight of coarse fragment to the weight of the sum of both the coarse fragment and fine soil of the i^{th} soil layer in gm. At last, the soil carbon stock was calculated using Equation (10) as described by Andreas et al. (2012).

$$C_{soil} = \sum_{i=1}^{n} d_i * \rho b_i * OC_i * CFpi \quad (10)$$

Where, C_{soil} = soil carbon stock (t ha^{-1}); d = soil layer thickness in (cm), ρb = bulk density in (g cm^{-3}) of each sample depth, OC = carbon concentration (g g^{-1}) of each soil sample and CF_{pi} = correction factor for coarse fragments of the i^{th} layer > 2 mm.

The total carbon stock of the parkland agroforestry system was calculated by summing up the total carbon stock of the tree and the soil by using Equation (11) (IPCC, 2003).

$$TCS_{system} = CS_T + C_{soil} \quad (11)$$

Where, TCS_{system} = total carbon stock of the parkland agroforestry system; CS_T = carbon stock of the tree and C_{soil} = soil carbon stock. Then, the $CO_2{}^{-e}$ of the system was calculated by multiplying the total carbon stock of the system by a factor of 3.66 Equation (12) (IPCC, 2003).

$$CO_2{}^{-e} = TCSs_{ystem} \times 3.66 \quad (12)$$

The carbon price, which according to the European Union Emission Trading Scheme (*EU ETS*) is planned in three phases. Phase I was from 2005 to 2007, phase II from 2008 to 2012 and phase III from 2013 to 2020 where the carbon pricing was set to be 30, 10, and € 30 for one tone CO_2 for the three phases respectively. But the current (2013/2014) price rate is equivalent to € 4.94 $tone^{-1}$ (Elina, 2013). As a result, the carbon trading potential of the parkland agroforestry system of the *Tabia* was estimated using Equation (13) as described by Lal (2002).

$$C_{benefit} = CO_2{}^{-e} \times C_{price} \times \text{total area of the parkland} \quad (13)$$

Statistical analysis

A one way analysis of variance (ANOVA) was used with LSD (Least square means difference Tukey test) to compare the mean carbon stocks at different radii with a fixed effect model at (P<0.05). JMP version 5 was used for data analysis. The linear model used was:

$$Y_i = \mu + A_i + e_i,$$

Where, Y_i = is the response variable (that is, SCS), μ = overall mean, A_i = i^{th} treatment effect of factor A (that is, radii), and e_i = random variable error.

RESULTS AND DISCUSSION

Effect of *B. aegyptiaca* on physical soil properties

As presented in Table 1, the effect of *B. aegyptiaca* on bulk density showed a significant difference (P< 0.05) across the three radii and three soil depths. The highest BD was found in the open field (1.46 Mg m^{-3}), followed by the radial distances first at 0 - 2 m and then at 2 - 4 m where the respective BD were 1.26 and 1.43 Mg m^{-3}. Disturbance of the soil by livestock and organic matter availability contributed for the difference in BD both for the three radii and soil depths. Linnea (2006) reported that under tree canopies, lower bulk density was found than in the outside.

The moisture content of the soil was significantly different (P < 0.05) for the three radii (Table 1). The moisture content of the soil was found higher with increase in soil depth, which is due to a higher initial infiltration rate during the rainy season and relatively lower loss of moisture via evaporation and the mulching effect of the soil during the dry season. A study conducted by Bekelle (2003) also reported that, deeper soils under agroforestry systems have higher moisture content than the upper horizons.

The AWC was significantly different both across its radii and along soil depths. AWC ranged between 0.13 to 0.18 cm cm^{-1}. Open fields (0.17 cm cm^{-1}) held much water as compared to the soils under the tree canopy (0.14 cm cm^{-1}). This might be due to the higher water infiltrated in the open field than the amount trickled under the canopy. Furthermore, the highest AWC was obtained with increasing the soil depth. The highest AWC (0.18 cm cm^{-1}) was found in the deepest layer whereas the lowest AWC (0.13 cm cm^{-1}) was observed in the upper most layers. Nair et al. (2009) also concluded that a 15% increase in AWC was observed at deeper horizon (30-60 cm) than in the top soil (0 - 30 cm).

The clay proportion of the soil was found to be significantly different (P < 0.05) for the three radii and the three soil layers. The result clay content was 57 and 60% for 0 - 2 and 4 - 8 m radii, respectively which was by far 3% higher than in the soils under the tree canopy. High proportions of clay particles might have been trapped by cracks of vertisols during the dry season that is accumulated due to wind erosion. Migration of clay particles down the soil profile might also have contributed for the increase in clay particles deep the soil horizon.

Effect of *B.aegyptiaca* on chemical soil properties

Table 2 presents the effect of *B. aegyptiaca* on the soil chemical property. *B. aegyptiaca* effect on TN, Av. P, OC, CEC and EC were significant at (P < 0.05) both along with the soil depth and radii. The pH was not significantly different at (P > 0.05) in both the three radii and three soil layers (Table 2). This could be due to the Calcareous nature of the parent material.

The total nitrogen content was highly significant at (P < 0.05) both at the three radii and soil layers (Table 2). The highest N content (0.1%) at 0 - 2 m radial distance, which was by 50% greater than in the open field (0.05%) that was located at 4 - 8 m radius. This was apparently due to *B. aegyptiaca* effect on increasing the organic matter through liter fall.

The available phosphorus was only significantly different between the three radii (P < 0.05). The available P was decreased with increasing the radial distance. It exhibited a 23% increase at a radius of 0 - 2 m and 16% increase at 2 - 4 m radius as compared to the open field (4 - 8 m). The available P content was rated as low as described by Marx et al. (1999). P availability in the soil depends on the soil pH where it is most available within the pH range of 6 to 7 and absorbed primarily by plants as orthophosphates. Accordingly, the available P decreased with increasing the radial distances. Issam

Table 2. Effect of *B. aegyptiaca* on chemical soil properties.

S/N	Factors	Chemical soil properties						
		pH	TN (%)	Av. P (ppm)	Ex. K (C. mol kg^{-1})	OC (%)	CEC (C. mol kg^{-1} soil)	EC (dS m^{-1})
1	**Radii (m)**							
	0 - 2	7.4^a	0.10^a	6.8^a	2.11^a	0.7^a	46.6^a	0.16^a
	2 - 4	7.4^a	0.09^b	6.1^a	1.99^a	0.7^a	45.8^{ab}	0.15^{ab}
	4 - 8	7.5^a	0.05^c	4.5^b	2.09^a	0.4^b	43.6^b	0.14^b
	S (±)	0.28	0.02	1.02	0.33	0.21	4.4	0.03
	P-value	0.142	< 0.001	< 0.001	0.170	< 0.001	0.009	0.015
2	**Depth (cm)**							
	0 - 20	7.5^a	0.10^a	5.7^a	1.72^c	0.8^a	46.6^a	0.13^c
	21 - 50	7.5^a	0.08^b	5.6^a	2.14^b	0.6^b	47.1^a	0.15^b
	51 - 100	7.4^a	0.06^c	6.1^a	2.33^a	0.4^c	42.3^b	0.18^a
	S (±)	0.28	0.03	1.4	0.25	0.19	4.02	0.02
	P-value	0.609	< 0.001	0.241	< 0.001	< 0.001	< 0.001	< 0.001
3	**Depth * Radii**							
	P-value	0.089	0.0002	0.856	0.978	0.039	0.013	0.273
	Rep.	9	9	9	9	9	9	9
	DF	80	80	80	80	80	80	80
	Range	1.5	0.13	5.9	1.5	1.04	20.3	0.12

pH = Acidity and alkalinity of the soil; TN = total nitrogen; Av.P = available phosphorus, Ex. K = exchangeable potassium, OC = organic carbon; CEC = cation exchange capacity; EC = electrical conductivity. Values with the same superscript letter were not significantly different at (P < 0.05).

(2007) also confirmed that arid and semi-arid soils have relatively low available phosphorus.

A significant difference was observed in exchangeable K between three soil depths at (P < 0.05). The deepest layer (51-100 cm) had 2.33 C. mol kg^{-1} and was found to be higher than the surface horizon (0- 20 cm), which had only 1.27 C.mol kg^{-1}. Exchangeable K increased with increasing the soil depth. The highest exchangeable K was observed in the deepest horizon, which could be due to the pumping effect of the deep root.

As presented in Table 2, the effect of *B. aegyptiaca* on OC was significantly different at (P<0.05) both for the three radii and soil depths. The open field constituted only 0.4% of organic carbon as compared to soils under the tree canopy of the two radii that had 0.7% for both. Similarly, the top soil constituted a higher organic carbon than the deeper soil profile which was due to the accumulation of higher organic matter under the canopy.

The CEC was significantly different at (P < 0.05) for the three radii and soil depths (Table 2). As Fassil and Charles (2009) reported that the CEC of Vertisols of the highlands of Ethiopia ranged from 25 to 45 C. mol kg^{-1}, this study revealed a lower CEC on open fields (43.6 C. mol kg^{-1} soil) than under the tree canopy with 46.6 C. mol kg^{-1} soil at 0 - 2 m radii where the difference could be due to the lower organic matter in open fields.

Electrical conductivity (EC) was significantly different (P < 0.05) for both the three radii and soil depths (Table 2). Across the radii, the highest EC was obtained under the tree crown at 0 - 2 m with a value 0.16 dS m^{-1} than in the open fields (0.14 dS m^{-1}), which was about 2% greater than in the open field soils. Depth wise also, a 5% increase in EC was observed in the third soil horizon (51-100 cm) having a value of 0.18 dS m^{-1} as compared to the first layer (0 - 20 cm) that had only 0.13 dS m^{-1}.

The highest EC in the deepest soil horizon might be due the basaltic parent material of the soil, the root pumping effect and leaching of soluble salts deep into the soil. The highest EC at a radius of 0-2 m could be due to the availability of old leaves on the surface of the soil, which are rich in calcium. The EC was therefore ranged between 0.1 to 0.2 dS m^{-1}, which according to Marx et al. (1999) was rated as low.

Correlation of major soil properties

As seen in Table 3, a simple correlation test between the relevant soil properties indicated that soil fertility under *B. eagyptica* was significant (P < 0.05). The soil organic carbon was positively and significantly correlated with total nitrogen (r = 0.982*; P = 0.04) and significantly contributed to available phosphorus (r = 0.955*; P < 0.05) across the three radii indicating total N and available P

Table 3. Correlation matrix between major soil properties at P<0.05 and n=81.

Correlation across radii	pH	TN (%)	AV.P (ppm)	Ex.K (C. mol kg^{-1})	OC (%)	CEC (C. mol kg^{-1} soil)	AWC (cm cm^{-1})	Clay (%)
pH	1.000							
TN (%)	-0.982	1.000						
Av. P (ppm)	-0.955	0.994*	1.000					
Ex. K (cmol kg^{-1})	0.359	-0.176	-0.066	1.000				
OC (%)	-0.987*	0.982*	0.955*	-0.359	1.000			
CEC	-0.966	0.998*	0.999*	-0.107	0.966	1.000		
AWC (cm cm^{-1})	0.866	-0.945*	-0.975	-0.156	-0.866	-0.966	1.000	
Clay (%)	-0.945	0.990	0.999*	-0.034	0.945	0.997*	-0.982	1.000
Correlation (depth)								
pH	1.000							
TN (%)	0.866	1.000						
Av. P (ppm)	-0.982	-0.756	1.000					
Ex. K (cmol kg^{-1})	-0.740	-0.136	0.599	1.000				
OC (%)	0.866	0.998*	-0.756	-0.977	1.000			
CEC	0.996	0.815	-0.995	-0.673	0.815	1.000		
AWC (cm cm^{-1})	-0.803	-0.993	0.676	0.995	-0.993	-0.743	1.000	
Clay (%)	-0.904	-0.997	0.807	0.956	-0.997	-0.860	0.981	1.000

*Significant at P < 0.05 otherwise no.

were increased as the soil organic matter increased. Available P was strongly and significantly correlated with CEC ($r = 0.999^*$; $P < 0.05$) and the clay content of the soil ($r = 0.999$; $p < 0.05$) across the three radii. The CEC also had a positive and strong correlation with the clay content ($r = 0.997^*$; $P < 0.05$) across the three radii. Whereas, the total N was strongly and negatively correlated with the available water holding capacity (r = -0.945*; $P < 0.05$) indicating that with increase in soil depth, total nitrogen was decreased and available water holding capacity was increased. However, along the soil depth, total nitrogen was strongly and positively correlated with organic carbon (r = 0.998*; $P < 0.05$) that showed an increase in organic matter increased the total N of the soil.

Effect of *B. aegyptiaca* on soil productivity Index

Table 4 presented the effect of *B. aegyptiaca* on soil productivity index. The result revealed that the PI ranged from 0.67 to 0.75 in the open fields at 4 - 8 m and at 0 - 2 m radius, respectively. However, PI was significantly different at $P < 0.05$ at the three radii. Nevertheless, a relatively higher PI was observed under the tree canopy at 0 - 2 m than the open fields (4 - 8 m), which could be due to the availability of optimum pH, lower EC, higher AWC and lower BD. All the soil productivity indices were rated as very high as described in Table 4. Hence, *B. aegyptiaca* positively affected the soil productivity.

Biomass of *B. aegyptiaca*as affected by age

The biomass of *B. aegyptiaca* at different age classes was significantly different ($P < 0.05$) as presented in Table 5. Trees with an age class of 3 to 4 years had an average above ground biomass (AGB) of 24.99 kg $tree^{-1}$and those older than 7 and 8 years had an average AGB of 103.47 kg $tree^{-1}$. Similarly, an increase in the below ground biomass (BGB) of *B. aegyptiaca* was observed. This clearly indicates that older aged trees produce higher biomass as compared to younger ones.

In addition, the total aboveground biomass was 2936.78 kg ha^{-1} while the total belowground biomass of *B. aegyptiaca* was 792.62 kg ha^{-1} yielding a total biomass of 3729.4 kg ha^{-1}.

Carbon stock of *B. aegyptiaca*

The effect of *B. aegyptiaca* age on carbon stock was significantly different at ($P < 0.05$). Age classes of 5.1 to 7 and 7.1 to 8 years had the capacity to sequester more carbon in kg $tree^{-1}$ than the younger ones (3 to 4 and 4.1 to 5 yrs.). An age class of 3 to 4 yrs. had a total carbon stock of 15.55 kg $tree^{-1}$ and the oldest age class of 7.1 to8 years was able to sequester 64.39 kg C $tree^{-1}$ with a48.8% increase over the first age class (3 to 4 years.).

Table 4. Effect of *B. aegyptiaca* on soil productivity index.

Soil depth (cm)	PI (0-2 m)	PI (2-4 m)	PI (4-8 m)	S (±)	P-value
0-20	0.28[a]	0.20[b]	0.24[ab]	0.062	0.05
21-50	0.29[a]	0.23[b]	0.22[c]	0.068	0.01
51-100	0.17[ab]	0.20[a]	0.12[b]	0.066	0.02
PI	0.74[a]	0.63[b]	0.58[c]	0.16	0.002

PI = Productivity index; S (±) = plus or minus deviation of each observation from the average value; P-value = significance level of rejection at (P<0.05).

Table 5. Age effect on tree biomass.

DBH class (cm)	Age class (years)	AGB (kg tree^{-1})	BGB (kg tree^{-1})	Total Biomass (kg tree^{-1})
8 - 10	3 - 4	24.99[d]	6.74[d]	31.73[d]
11 - 13	4.1 - 5	46.43[c]	12.53[c]	58.97[c]
14 - 16	5.1 - 7	72.47[b]	19.56[b]	92.04[b]
17 - 19	7.1 - 8	103.47[a]	27.93[a]	131.41[a]
S (±)		26.7	7.21	33.92
R^2		91	91	91
P-value		< 0.001	< 0.001	< 0.001
DF		46	46	46

R^2 = total variability of the response variable; DF = degree of freedom; values designated by the same letter were not significantly different and P-value= significant level at (P<0.05).

Therefore, this study concluded that an older tree could be able to capture more carbon from the atmosphere than the younger ones and this could be due to variation in biomass weight (Table 6).

The total carbon stock in the aboveground biomass was 1.438 t ha^{-1} showing differences among different age classes where older trees (7.1 - 8 years) could capture more carbon than younger ones. The higher biomass production in older trees might have contributed to the difference. Similarly, the belowground biomass was able to sequester 0.388 t ha^{-1}. The total carbon stock of *B. aegyptiaca* of the study site was then 1.826 t ha^{-1} (Table 7).

Soil carbon stock

The total soil carbon stock was significantly different (P < 0.05) at the three radial distances as presented on Table 8. It ranged from 10.15 to 14.73 t ha^{-1}. In the open field (that is, 4-8 m) the smallest carbon stock (10.15 t ha^{-1}) was observed as compared to the radii at 0 - 2 m (14.32 t ha^{-1}) and at 2 - 4 m (13.23 t ha^{-1}). The difference could be due to the availability of higher organic matter under the tree canopy than outside it. This finding is supported by Asako (2007) that confirmed an increase in soil carbon stock around trees and three reasons were given for this evidence. Firstly, it has an effect on physical stabilization by micro-aggregation; secondly, the intimate association through soil particles and finally, biochemical stabilization by formation of resistant soil organic compounds.

CO_2 equivalents and C benefits of *B. aegyptiaca*

As seen in Tables 6 and 8, the soil could sequester more carbon (12.57 t ha^{-1}) comparing to the tree, which was only 1.83 t ha^{-1}. Therefore, although the soil carbon was larger than the carbon stock of *B. aegyptiaca*, the existence of the tree contributed to the higher carbon pool of the soil as explained previously. The total carbon stock of the parkland agroforestry system was then 14.4 t ha^{-1}.

The carbon trading potential of the parkland agroforestry system of the study site was estimated to be € 260.3. However, in total, € 1,457,680 could be obtained from the total of 5600 ha land of the parkland agroforestry system of the selected study area (Table 9). This is therefore an indication that, besides the environmental services, parkland agroforestry systems could serve as a source of money by trading carbon.

Conclusion

This study concludes that *B . aegyptiaca* significantly improved soil properties such as total nitrogen, available

Table 6. Tree age effects on Carbon stock in *B. aegyptiaca.*

DBH class (cm)	Age class (years)	No. of trees	TC_{AGB} (t. ha^{-1})	TC_{BGB} (t. ha^{-1})	TC (t. ha^{-1})
8 - 10	3 - 4	7	0.086	0.023	0.109
11 - 13	4.1 - 5	12	0.273	0.074	0.347
14 - 16	5.1 - 7	19	0.674	0.182	0.856
17 - 19	7.1 - 8	8	0.405	0.109	0.514
	Total C stock(t ha^{-1})		1.438	0.388	1.826

TC_{AGB} = total carbon in the above ground biomass, TC_{BGB} = total carbon in the below ground biomass, TOC = total carbon stock of *B. aegyptiaca.*

Table 7. Total carbon stock of *B. aegyptiaca* of the study site.

DBH class (cm)	Age class (years)	C_{AGB} (kg tree^{-1})	C_{BGB} (kg tree^{-1})	TOC (kg tree^{-1})	CO_2^-e
8 - 10	3 - 4	12.24^d	3.31^d	15.55^d	56.9
11 - 13	4.1 - 5	22.75^c	6.14^c	28.89^c	105.7
14 - 16	5.1 - 7	35.51^b	9.58^b	45.09^b	165.0
17 - 19	7.1 - 8	50.70^a	13.68^a	64.39^a	235.7
	S (±)	13.09	3.533	16.62	3.4
	R^2	91	91	91	91
	P-value	< 0.001	< 0.001	< 0.001	<0.001
	DF.	46	46	46	46

TC_{AGB} = Total carbon stock in the above ground biomass; TC_{BGB} = total carbon stock in the below ground biomass; TOC = total carbon stock; t ha^{-1} = tone per hectare.

Table 8. Effect of *B. aegyptiaca* on soil carbon stock.

Variable	Radii(m)			S (±)	P-value
	0-2	2-4	4-8		
SCS (t ha^{-1})	14.32^a	13.23^b	10.15^a	3.87	0.001

SCS = soil carbon stock; S = standard; P-value = significance level. Average values with the same superscript letters were not significantly different at (P<0.05).

Table 9. Carbon benefits of the parkland agroforestry system.

TCS_{tree} (t ha^{-1})	TCS_{soil} (t ha^{-1})	TCS_{PAS} (t ha^{-1})	CO_2 $^{-e}$ (t ha^{-1})	C price of the study site (€)	C price of the system (€)
1.83	12.57	14.4	52.7	260.3	1,457,680.00

TCS = total carbon stock; $CO_2$$^{-e}$ = carbon dioxide equivalents; C = Carbon; € = Euro.

phosphorus, exchangeable potassium, organic carbon, pH, bulk density and CEC. A very high productivity index (PI) of the soil has also been found under the tree canopy than outside it. The tree was able to contribute 5 and 2% of the available N that could have been supplied by Dap and Urea to the soil, respectively.

It also contributed in clean development mechanism through storing carbon in its biomass both through its above ground biomass and below ground biomass. A significant amount of carbon was also stored in the soil from respiration of microorganisms and decomposition of organic matter under the tree canopy.

The carbon benefit of the parkland agroforestry system was also paramount. With the current carbon price developed by EU ETS, the total amount of money generated from the parkland agroforestry system of the *Tabia* was € 1,457,680.

RECOMMENDATIONS

B. aegyptiaca is widely grown through natural regeneration in the Northern lowlands of Ethiopia. Hence, due to the lack of knowledge by local farmers, it is usually cleared during cultivation from farmlands. Therefore, awareness creation for concerned stakeholders on the role of the tree in soil fertility improvement and climate change mitigation needs to be done. In addition, farmland based seedling raising and micro-propagation is recommended. It can be recommended for all African countries of the same agroecological zones where no trees exist. More scientific researches on the tree physiology, anatomy, biology and adaptation must be conducted to maximize the benefits both economically and ecologically.

Conflict of Interest

The authors have not declared any conflict of interest.

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Variation in nutrient concentrations of basement complex and sedimentary rock of teak plantations in Ogun State, Southwest Nigeria

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This study examined the differences in the nutrient concentration of the parent material of teak plantations under basement and sedimentary rocks in south western Nigeria. Systematic line transect was employed to establish 18 plots (30 m x 30 m), each in Ilaro (sedimentary rock) and Olokemeji (basement complex rock) plantations which were 37, 40 and 42 years old while twelve rock samples each from 3 quadrants each of 30 m^2 were selected for rock nutrient analysis. Topsoil (0-15 cm) and subsoil (15-30 cm) samples, above-ground plant parts (leaf, bark, stem, twig and branch) and biomass parameters (bole height, girth, total height and crown diameter) were collected. The soil samples were analyzed for soil physicochemical and micronutrients while plant parts were analyzed for nutrient contents (nitrogen, phosphorous, potassium, calcium and magnesium) using standard procedures. Pearson's correlation and regression analysis were used to establish the type and level of association between soil properties and vegetation parameters respectively at $p<0.05$. The result indicates that there is no significant difference between the various minerals found in the rocks of the two locations. Secondary test indicate that there is significant difference among the three horizons A, B and C on the mean concentration of phosphorus and iron with $p = 0.008<0.05$ and $p = 0.046 < 0.05$ respectively. The multiple comparisons revealed that there is no statistical significant difference in phosphorous concentration between horizons A and B horizon but that there is a statistical significant difference between horizon A & C and B & C with $p = 0.005< 0.05$ for all.

Key words: Bedrock geology, parent rock materials, physical properties, physico-chemical properties, soil nutrients.

INTRODUCTION

In tropical region of Africa underlain by basement complex and sedimentary terrain, parent materials change when the rock type changes. Coastal Plain soils are formed from weathered and eroded rock particles that are moved by water and maybe alluvial or marine sediments. These sediments have similar minerals, so parent material differences are related to changes in the amounts of sand, silt, and clay. Properties of parent

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materials within the same landform vary if changes in texture occur. For example, a single floodplain may contain pockets of sands and clays at different locations. These differences produce changes in soil water holding capacity and fertility. Two different parent materials deposited side by side (same climate, biotic, topography, and age) will result in two soils having different properties Minerals are naturally occurring homogenous solid, inorganically formed, having a definite chemical composition and an orderly atomic arrangement. Most minerals have fairly definite physical properties such as crystal form, color, luster, hardness, specific gravity, and solubility.

Minerals are classified based on their origin and chemical composition. The need for exotic timber species like teak in Nigeria has been recognized since pre-colonial times and this has resulted in the planting of some plantations around existing natural forests with the planting of teak (*Tectona grandis*) and Gmelina (*Gmelina arborea*) being the most popular (Adejuwon and Ekanade, 1988).

Despite the fact that teak was introduced to Nigeria in 1902 along side other countries such as Ghana in 1905, Trinidad in 1913 and Cote d'Ivotre in 1929, the current productivity and supply level of this exotic tree species is far below the need of the market in comparison to other hard wood species such as Gmelina, Eucalyptus and Acacia (Perez and Kanninen, 2005). This has been a serious challenge to professionals in the field of forest management, which includes foresters, pedologist and geographers alike (Aborisade and Aweto, 1990).

Several studies have been conducted on the effects of cultivated tree plants on soil properties in the rainforest ecosystem of West Africa by Ekanade (1988) and Akpokodje (2007) which revealed that the levels of most soil nutrient properties were significantly lower under tree plants than under adjoining forests. So far, the findings have shown that different tree species have different interactions with soil properties. Findings in Nigeria have also shown that different tree crops have different interactions with soil properties and of significant importance are studies conducted on the effect of tree plants on soil characteristics in the forest areas of south-western Nigeria.

Some of these studies as conducted by, all focused on the influence of tree species on nutrient circling while several other studies by Egunjobi (1974) and Nwoboshi (1985) examined the effects of tree plants (in plantations) on forest soils, by comparing soil characteristics between adjoining forest and those under plantation condition.

What is conspicuously absent from the literature either in the tropical environment, temperate, Europe, America or other Africa countries is research on variation in the nutrient concentration of parent material and soil of teak plantation which is the gap my research intend to fill especially in the field of biogeography. In view of the above gap in the literature, this study investigated the influence of the parent materials and soil on the growth of teak under basement rock of Olokemeji and sedimentary sand stone rock of Ilaro formation in Southwest Nigeria.

The outcome of this study will form the basis for the formulation of better silviculture management for the cultivation of teak and to establish the best geological formations suitable for the growth of teak and which will recycle and restore soil nutrients on time. In addition, a monitoring system for detecting changes in critical site parameters (especially biophysical and chemical characteristics) under different geological formations is expected to be designed for silviculture monitoring purposes which is one of the major contribution this research intend to add to the study of bio-geomorphology (Juo and Manu, 1996).

METHODOLOGY

Study area

The teak stands used for this study were purposively selected from two forest reserves located in south-western Nigeria. The reserves fall within the humid tropics which support the tropical rainforest ecosystem (Richards, 1952). The two selected reserves are specifically located in Olokemeji and Ilaro, Ogun State, Nigeria. The two reserves are sources of enormous economic benefits to the state because of their rich wood resources (Adeyoju, 1971; Okali and Onyeachusim, 1991) (Figure 1).

Location and extent of Olokemeji and Ilaro plantations

The Olokemeji teak plantation is located in the heart of Olokemeji forest reserve located between latitudes 7° 05' and 7° 40'N and longitudes 3°15' and 3°46'E. According to Aminu-Kano and Marguba (2002), the plantation occupies a total land area of 58.88 km^2 (approximately 5,000 ha). The reserve, which was established in 1899 is the second forest reserve in Nigeria. It lies approximately 32 km west of Ibadan, and 35 km north-east of Abeokuta. It falls within the middle course of Ogun River, which drains the western half of the Basement Complex area of South Western Nigeria.

The second location (Ilaro) is bounded on the north by the Oyo Province, on the South by Lagos, on the east by the Egba Division and on the west by Dahomey (Republic of Benin). The boundary on the South is defined in the "Colony of Nigeria Boundaries Order in Council 1913" (Volume IV, page 311 of Laws of Nigeria). Ilaro forest reserve is defined roughly by latitude 06 38' 51.36 N and 06 57' 24.40 N and Longitude 02 49 06.12'E and 03 10 43.60 E. This reserve covers an area of about 34.2 by 39.9 km^2.

Plantation sampling techniques

Sampling design for this study was based on two premises, first, the need to spread sample sites objectively over the study area and second, the needs to ensure that plant and site characteristics are adequately depicted. Therefore, in order to obtain detailed soil and plant representation, one teak plantation each established on Basement Complex and Sedimentary formation parent rocks were purposefully selected and divided into plantation quadrants based on the information extracted from the forest resources study of Nigeria (FORMECU, 1999). The two teak stands are those established in Olokemeji and Ilaro forest reserves in Ogun State, Southwest Nigeria. The two selected teak stands were distinctively

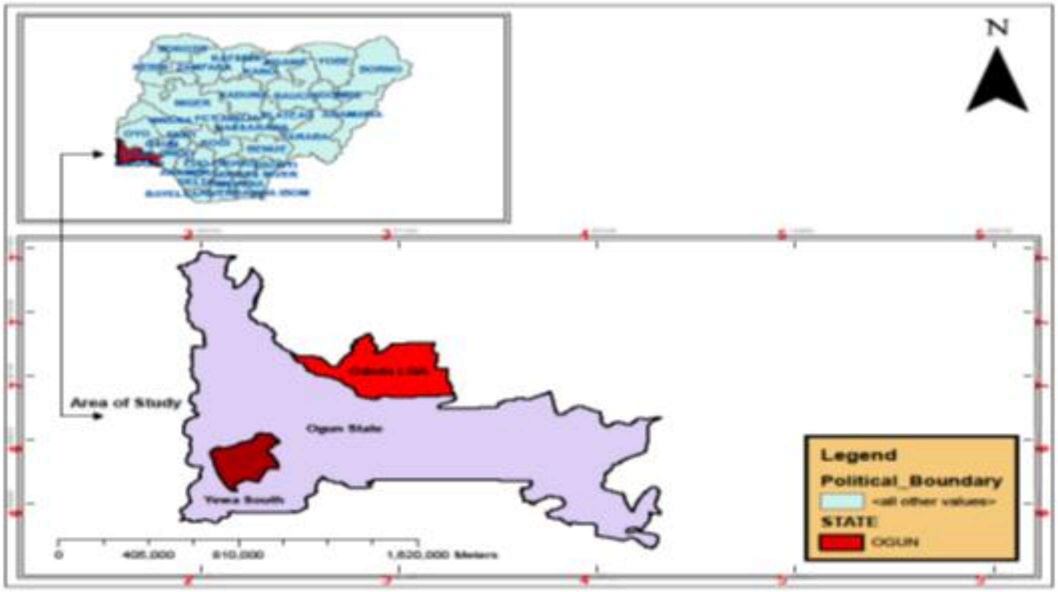

Figure 1. Map of Nigeria showing the study areas.

established under basement complex and sedimentary formation in Olokemeji and Ilaro respectively (Kogbe, 1976; Hushley, 1976). The choice of teak as the study species is because of its high quality as hardwood which led to its high demand (Raymond, 1996).

According to FORMECU (1999), Olokemeji forest reserve has 15 teak plantations of 50 ha (750 ha) while Ilaro forest has 11 teak plantations, also of 50 ha each (550 ha). The twenty-six teak plantations were established between 1970 and 1975 across the two sites. Therefore, due to the uniformity in the area sizes and the ages of the plantations, random and systematic sampling techniques were adopted to select the quadrant plots where various soil and plant samples were collected.

Rock and soil sampling techniques

Three soil profiles were sampled in each plantation from both existing road cuttings and dugged pits. From each soil profile and dugged pit, three soil samples were collected from three horizons of A, B and C making the total soil samples from each profile per plantation to be nine and 18 for both plantations. This was done for better understanding of the mineralogical composition of the bedrock geology underlying the basement complex and sedimentary formation. Rock samples were also collected from the sampled quandrant plots and road cuttings as well as the dugged pit using the geological Hammer from which tin sections and modal analysis were carried out in the petrological laboratory of the Department of Geology, University of Ibadan.

Systematic line transect was employed to establish 18 plots (30 m x 30 m), each in Ilaro (sedimentary rock) and Olokemeji (basement complex rock) plantations which were 37, 40 and 42 years old from June to August 2010. Topsoil (0-15 cm) and subsoil (15-30 cm) samples, above-ground plant parts (leaf, bark, stem, twig and branch) and biomass parameters (bole height, girth, total height and crown diameter) were collected. The soil samples were analyzed for soil physicochemical and micronutrients while plant parts were analyzed for nutrient contents (nitrogen, phosphorous, potassium, calcium and magnesium) using standard procedures.

Laboratory soil and statistical analytical procedures

The mechanical analysis was carried out on the soil samples by the Bouyoucos method to determine the various sizes of particles present in the fine earth (that is, particle < 2 mm) of the soil using international scale. For chemical analysis in the laboratory, available Phosphorus (P) was extracted with 0.1 M sulphuric acid and measured colourmetrically by the ascorbic acid blue method (Olsen et al., 1954). Exchangeable Ca and Mg were measured after extraction using 1 M ammonium acetate at pH 7.0. Concentrations for Ca and Mg in the extracts were analyzed using an atomic absorption spectrophotometer, while K was determined by flame photometry (Black et al., 1965). After extraction with neutral 1 N ammonium acetate, total N was also determined by the micro-Kjeldahl method (Schnitzer, 1982). Cation exchange capacity (CEC) was estimated titrametrically by distillation of ammonium that was displaced by sodium (Chapman, 1965). Descriptive statistics, such as arithmetic mean were applied in order to determine the general characteristics of all parameters and indices. In addition, pearsons correlation and stepwise multiple regression was employed to determine the effects of soil parameters on biomass. This method enables only potent variables to be retained for model formulation.

Statistical analysis

The data were subjected to different analytical tools:

Descriptive statistics: This include statistic such as the mean, Standard Deviation and Standard error of mean of each of the indices.

Generalized Linear Model: This was executed using the GLM of SAS version 9. Under this GLM, different sources of variation including both main and interaction effect were investigated. Where significant differences occurred, mean separation of the different sources of variation was done using Duncan Multiple Range Test. In addition, factor analysis was carried out using Principal

Plate 1. An extensive low lying outcrop of Migmatite in the OIokemeji forestry study area.

Plate 2. Redish sandy Clay on a road cutting at Ilaro.

Component Analysis of the MINITAB (version17). Specifically, one-way analysis of variance (ANOVA) was conducted for detecting statistically significant differences in soil physicochemical properties, biomass production and distribution, tree nutrient concentrations across geological formations at 0.05 and 0.001 significance levels.

RESULTS AND DISCUSSION

Description of rocks with their respective minerals

The quartz grains show high degree of roundness which is an evidence of far travelling before being deposited in Ilaro soil (Plate 1). In fact, the geology of the area suggests that the quartz were from the coastal plain sands and move into the study area during the marine incursion of the continent during the Cenomanian/Santonian).

The implication is that the grains sizes would not be able to hold the mineral component in the soil because the degree of interlocking of minerals grains of quart is weak, thereby allowing the passage of minerals in soluble component from the soil which should have been trapped. On the other hand at Olokemeji (Plate 2).

In tropical region of Africa which is underlain by basement complex and sedimentary terrain, parent materials change when the rock type changes. Coastal Plain soils are formed from weathered and eroded rock particles that are moved by water and may be alluvial or marine sediments. These sediments have similar minerals, so parent material differences are related to changes in the amounts of sand, silt, and clay. Properties of parent materials within the same landform vary if changes in texture occur. For example, a single floodplain may contain pockets of sands and clays at different locations. These differences produce changes in soil water holding capacity and fertility. Two different parent materials deposited side by side (same climate, biotic, topography, and age) will result in two soils having different properties.

Minerals are naturally occurring homogenous solid, inorganically formed, having a definite chemical composition and an orderly atomic arrangement. Most minerals have fairly definite physical properties such as crystal form, color, luster, hardness, specific gravity, and solubility. Minerals are classified as to their origin and chemical composition Based on origin, minerals may be primary and secondary. Minerals rocks are simply aggregates of two or more minerals.

Primary minerals

These are formed by the cooling and solidification of original molten material.

(1) Quartz: SiO_2

(i) Most common soil forming mineral
(ii) Make up 13% of earth's crust and from 30 to 40% of the average soil
(iii) Commonly a translucent milky-white color
(iv) Hard enough to scratch glass
(v) Resistant to weathering
(vi) Present in granite; absent from basalt
(vii) Present in almost all sandstone
(viii) Does not contribute plant nutrients to the soil

(2) Feldspar -alumino-silicates with bases of K, Na, and Ca

(i) Account for 60% of the earth's crust

(A) Orthoclase Feldspar---$KA1Si_3O_8$

(i) Slightly harder than glass
(ii) Commonly white, orange, or pink in color
(iii) Fine wavy lines may occur within crystals
(iv) Flat surfaces are common (intersecting at 88-90° angles)
(v) The most abundant mineral in granite
(vi) Is an important source of potassium

(B) Plagioclase feldspar--Na AlSi308↔Ca $Al_2Si_2O_8$

(i) Slightly harder than glass
(ii) Common gray color (from almost white to dark bluish gray)

(3) Horneblende --- $NaCa_2$ (Mg, Fe, Al)5 (Si, Al)8 O22 (OH)2

(i) Slightly harder than glass
(ii) Black, dark brown, or dark green in color

(4) Micas-alumino-silicates with K, Mg, and Fe basic components

(i) Easily spilt into thin flexible elastic plates
(ii) Has shiny surface

Secondary minerals

These are formed by the weathering of primary minerals

Gypsum - $CaSO_4$ $2H_2Q$

(i) Forms from evaporating calcium sulfate-bearing waters
(ii) Very soft and weathers fairly readily

Iron oxides

(i) Formed through chemical weathering
(ii) **Geothite** (FeOOH): gives yellow color in soils
(iii) **Hematite** (Fe_2O_3): responsible for red coloration in soils

Clay minerals (kaolinite)

(i) Highly colloidal
(ii) Formed primarily form chemical weathering of primary minerals
(iii) Ability to adsorb or hold nutrient ions on their surfaces.

Analysis of the mineralogy of the bedrock geology

The soil sampled from the profile on the Olokomeji soil revealed that the soil has higher enrichment for nutrients on the A-Horizon and show depletion through B-Horizon to C-Horizon (Table 1). Nitrogen shows maximum values of 5.60, 3.22 and 1.54 mg/g in A, B and C-Horizon respectively. OC, Mn, Fe and Zn follow the same trend with Nitrogen with Maximum values of 33.56, 21.20 and 9.45 mg/g, 126.11, 6.800 and 2.60 mg/g, 62.34, 43.23 and 28.11 mg/g and 7.60, 3.33 and 2.02 mg/g respectively. This is attributed to higher degree of weathering at the top soil which produces high enrichment of these nutrients at the A-Horizon. On the other hand P and K, show contrary values with higher enrichment at B-Horizon with Maximum values of 34.23, 36.07 and 16.20 mg/g; and 0.42, 1.23 and 0.18 mg/g in A, B and C-Horizons respectively.

Cu shows higher enrichment in the C-Horizon with maximum values of 1.19, 0.74 and 2.30 mg/g in A and B to C-Horizon. The enrichment of P and K in the B-Horizon could be attributed to their high solubility which allows their easy percolation when dissolved in water into deeper horizon as the porosity is expected to decrease with depth. Higher enrichment of Cu in the C-Horizon is as a result of higher resistant of Copper to weathering which in turn reduces its availability in A and B-Horizon. The literature from the previous works such as Aweto

Table 1. Summary of the result of chemical/nutrient analysis of the soil profile for Olokemeji Plantation.

Parameter	Olokemeji Horizon-A			N=3	Olokemeji Horizon-B			N=3	Olokemeji Horizon-C			N=3
	AV.	Min	Max	Std	AV.	Min	Max	Std	AV.	Min	Max	Std
N (mg/kg)	3.74	2.37	5.63	1.68	2.42	1.460	3.220	0.89	0.97	0.64	1.54	0.49
OC (mg/kg)	27.8	22.84	33.56	5.39	17.5	14.12	21.20	3.54	6.97	5.23	9.54	2.26
P (mg/kg)	28.5	25.14	34.23	4.94	31.7	27.10	36.07	4.49	15.1	13.60	16.20	1.36
K(Cmol/kg)	0.24	0.15	0.42	0.15	0.83	0.500	1.23	0.36	0.14	0.11	0.18	0.03
Mn (mg/g)	110	96.0	126.11	15.11	4.94	3.560	6.80	1.67	2.04	1.52	2.60	0.54
Fe (mg/g)	47.6	38.22	62.34	12.92	35.2	30.44	43.23	6.97	24.8	22.54	28.11	2.88
Cu (mg/g)	0.96	0.76	1.19	0.21	0.60	0.52	0.740	0.21	1.36	0.57	2.30	0.87
Zn (mg/g)	4.97	3.12	7.60	2.34	2.50	1.89	3.33	0.74	1.68	1.45	2.02	0.30

Table 2. Summary of the result of Chemical/Nutrient Analysis of the Soil Profile for Ilaro Plantation.

Parameter	Ilaro horizon-A			N=3	Ilaro horizon-B			N=3	Ilaro horizon-C			N=3
	Aver	Min	Max	stdev	Aver	Min	Max	Stdev	Aver	Min	Max	Stdev
N (mg/kg)	0.40	0.33	0.49	0.08	0.96	0.88	1.02	0.07	0.69	0.56	0.79	0.11
OC (mg/kg)	4.06	3.80	4.30	0.25	9.35	8.40	10.1	0.86	7.57	6.70	8.40	0.85
P (mg/kg)	33.21	28.4	41.2	6.96	31.50	28.6	34.2	2.80	11.5	10.9	12.5	0.88
K (Cmol/kg)	0.24	0.06	0.60	0.30	0.06	0.04	0.08	0.02	0.07	0.06	0.09	0.01
Mn (mg/g)	8.6	7.9	10.0	1.2	9.8	8.0	12.4	2.2	6.3	5.5	7.2	0.8
Fe (mg/g)	41.5	38.2	47.5	5.2	31.0	28.6	34.4	3.0	30.5	26.3	34.3	4.02
Cu (mg/g)	0.66	0.56	0.76	0.10	0.61	0.56	0.70	0.07	0.77	0.55	1.23	0.39
Zn (mg/g)	3.34	2.62	4.20	0.79	2.95	2.53	3.45	0.46	3.44	2.69	4.20	0.75

(1987), Ogidiolu (1988) and Gbadegesin (2004)) have all proven that soil originate from bedrocks/parent rock material, therefore the properties (both chemical and physical) are in no doubt depend on the properties of the parent rock with other abiotic factors such as climate, topography and organisms. Olokemeji Plantation is known to be underlain by basement rocks such as metamorphic and igneous rocks, the common rock forming minerals as evidenced from the above modal analysis include: Quartz, Orthoclase-Feldspar, Plagioclase-Feldspar, Muscovite Mica, Biotite Mica, Hornblende, Pyroxene and other accessory minerals.

Contrary to the observed trend in Olokemeji soil, the nutrients in the Ilaro soil profile revealed that Nitrogen (N), Organic Carbon (OC) and Manganese (Mn) show maximum values of (0.49, 1.02 and 0.79 mg/kg), (4.30, 10.100 and 8.400 mg/kg) and (10.00, 12.40 and 7.200 mg/g). P, K, Fe and Zn show maximum values of (41.20, 34.20 and 12.56 mg/kg), (0.60, 0.08 and 0.09 mg/kg), (47.51, 34.46 and 34.30 mg/g) and (4.20, 3.45 and 4.29 mg/g) respectively with Copper (Cu) recording the values of (0.76, 0.70 and 1.23 mg/g) in A through B to C-Horizon respectively (Table 2.). The enrichment of N, OC and Mn in B-Horizon could be attributed to the high porosity of marine sediment dominated by intercalation of sand and sandy clay materials of the Ilaro formation. Higher values of P, K, Fe and Zn in A-Horizon could be attributed to enrichment from oxidation, decay of plant materials and other surface reactions (Figures 2 to 6).

Analysis of the nutrient concentration of parent material using factor and component analysis

Origin of the nutrient/minerals in the soil can be further explained using the factor and component analysis. This approached has being employed by several workers in the past for classification of parameters base on characteristics/properties, origin, and other types of grouping in data analysis which signifies relevant association and similarity by reduction. In this work, data from each plantation site were subjected to component analysis separately from which three Components were derived as shown in Tables 3 and 4 Ilaro and Olokemeji respectively.

In Ilaro component analysis, C1 compose of assigned factor loading values ranges from -0.00 to 0.84 with extracted factor (factor percentage variance) and cumulative percentage of 29.84% in both cases. The loading variables include Nitrogen, Organic carbon and Potassium. C2 comprises of assigned factor loading values range from -0.26 to 0.80 with extracted factor

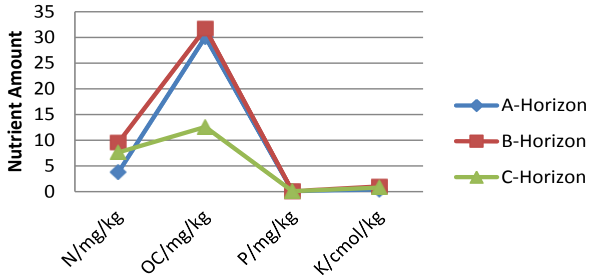

Figure 2. Ilaro macronutrients for profile 1.

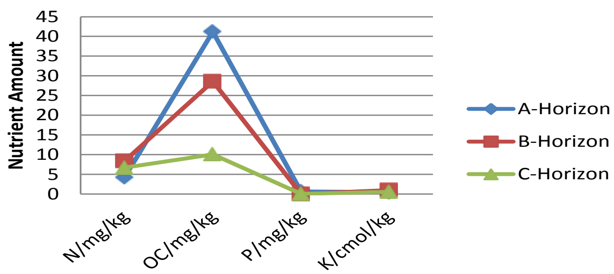

Figure 3. Ilaro macronutrients description of profile 2.

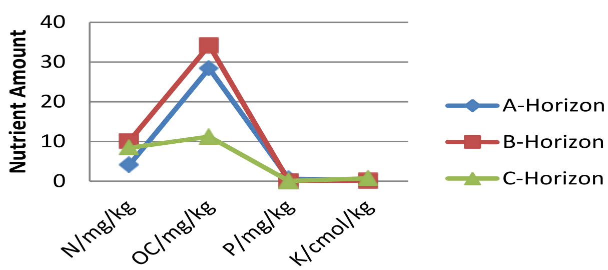

Figure 4. Ilaro macronutrients for profile 3.

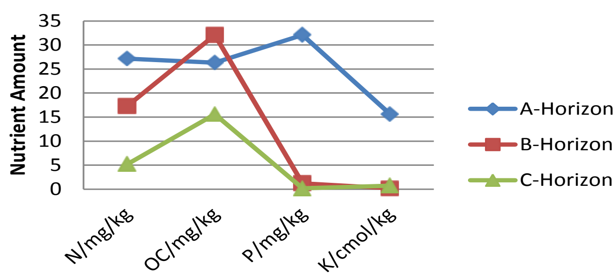

Figure 5. Olokemeji macronutrients for profile 2.

(factors percentage variance) and cumulative percentage of 21.94 and 51.79% with loading variables Phosphorous, Manganese and Copper. C3 comprises of assigned load values ranges from -0.55-0.66 with extracted factor

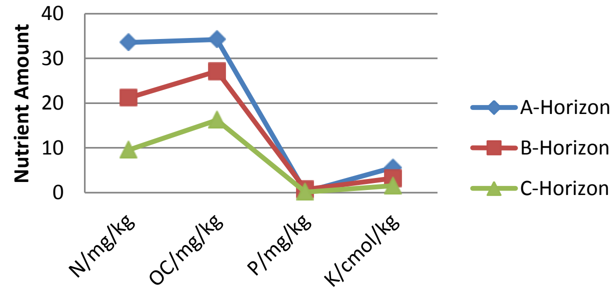

Figure 6. Olokemeji macronutrients for profile.

(factors percentage variance) and cumulative percentage of 16.65 and 68.45% with loading variable of Iron (Fe). Component C1 and C2 indicate soil enrichment from organic matter and parent rock contribution respectively while C3 implies influence of redox reaction which produces enrichment of Iron oxide in the soil.

The loading variables include Nitrogen, Organic carbon and Phosphorous, Potassium Manganese, Copper and Zinc. C2 comprises of assigned factor loading values range from -0.44 to 0.77 with extracted factor (factors percentage variance) and cumulative percentage of 17.20% and 73.25% with loading variable of Iron (Fe). C3 comprises of assigned load values ranges from -0.26-0.52 with extracted factor (factors percentage variance) and cumulative percentage of 12.12 and 85.37% with loading variable of Iron (Fe). Component one C1 implies influence of parent rocks and organic matter. This is more dynamic compare with that of Ilaro soil since the mineralogical complexity of the basement rock produce more mineral influence on the residual soil.

Mineral and nutrient analysis of the parent rock

The result of the hypothesis on nutrient concentrations in parent material indicates that there is no significant difference between the various minerals found in the rocks of the two locations. The result further revealed that there is significant difference among the three horizons A, B and C on the mean concentration of phosphorus and iron with $p<0.05$. The multiple comparisons revealed that there is no statistical significant difference in phosphorous concentration between horizons A and B horizon but that there is a statistical significant difference between horizon A & C and B & C with $p< 0.05$ for all. Hence, we conclude that the mean concentration of phosphorus is highest in B horizon with value of 35.625 followed by A with 30.892 and finally C with 13.343.

For Iron (Fe), the result revealed that there is no significant difference between A & B horizons and similarly between B & C but there is a statistical significant difference between the A & C horizons with $p< 0.05$. This shows that, the mean concentration of iron is

Table 3. Principal component analysis for Ilaro soil chemical data.

Parameter	Component		
	1	2	3
N	0.789	-0.172	-0.395
OC	0.840	-0.232	-0.306
P	-0.004	0.576	0.243
K	0.822	-0.020	0.218
Mn	0.475	0.647	0.444
Fe	0.370	-0.264	0.664
Cu	0.128	0.807	-0.169
Zn	0.080	0.448	-0.556
% of Variance	29.848	21.947	16.657
Cumulative %	29.848	51.795	68.452

Table 4. Principal component analysis for Olokemeji soil chemical data.

Parameter	Component		
	1	2	3
N	0.764	-0.446	0.461
OC	0.764	-0.446	0.462
P	0.660	0.159	-0.260
K	0.917	0.224	-0.121
Mn	0.877	-0.100	-0.360
Fe	-0.061	0.779	0.528
Cu	0.641	0.494	0.143
Zn	0.925	0.206	-0.182
% of Variance	56.048	17.208	12.121
Cumulative %	56.048	73..256	85.377

highest in A horizon with value of 44.55 followed by B horizon with 33.14 and finally by C horizon with 27.23. There are no statistical significant differences in the mean concentrations of other minerals such as Nitrogen, Organic carbon (OC), Potassium (K), Magnesium (Mg), Copper (cu) and Zinc (Zn) in the three horizons of A, B, & C on their mean concentrations. This revealed that, there are no significant differences in the mineral concentration of the parent rock in teak plantation under basement (Olokemeji) and sedimentary (Ilaro) rock formations in term of the mineral compositions.

DISCUSSION

The soil sampled from the profile on the Olokomeji Plantation revealed that the material sampled has higher enrichment for nutrients on the A-Horizon and show depletion through B-Horizon to C-Horizon for Nitrogen, OC, Mn, Fe and Zn. This is attributed to higher degree of weathering at the top soil which produces high enrichment of these nutrients at the A-Horizon. On the other hand P and K show contrary values with higher enrichment at B-Horizon, through C-Horizon. Copper (Cu) showed higher enrichment in the C Horizon. The enrichment of Phosphorous (P) and Potassium (K) in the B-Horizon could be attributed to their high solubility which allows their easy percolation when dissolved in water into deeper horizon as the porosity is expected to decrease with depth.

CONCLUSION AND RECOMMENDATIONS

Contrary to the observed trend in Olokemeji soil, the nutrients in the Ilaro soil profile revealed that Nitrogen (N), Organic Carbon (OC) and Manganese (Mn) show similar trend. Unlike in Olokemeji however, Copper (Cu) is higher at A through B to C-Horizon respectively. The enrichment of N, OC and Mn in B-Horizon could be attributed to the high porosity of marine sediment dominated by intercalation of sand and sandy clay materials of the Ilaro formation. Higher values of Phosphorous (P), Potassium (K), Iron (Fe) and Zinc (Zn) in A-Horizon could be attributed to enrichment from oxidation, decay of plant materials and other surfacial reactions.

The quartz grains show high degree of roundness which is an evidence of far travelling before being deposited. In fact, the geology of the area suggests that the quartz in horizon C were from the coastal plain sands and move into the study area during the marine incursion of the continent during the Cenomanian/Santonian.

The implication is that the grains sizes would not be able to hold the mineral component in the soil because the degree of interlocking of minerals grains of quart is weak, thereby allowing the passage of minerals in soluble component from the soil which should have been trapped. The results of this work have clearly shown that though, there are differences but the differences observed are not statistically significant under different parent materials in teak plantations of the two study sites. A critical geographical, pedological (lithological) and edaphic analysis and appraisal is required before siting a plantation other than common political consideration which are peculiar to developing nations in Africa.

Conflict of Interest

The authors have not declared any conflict of interest.

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