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# SOIL AGGREGATE FRACTIONS AND ORGANIC CARBON POOLS AS INFLUENCED BY TREE DIVERSITY IN FOREST RESERVE OF SEMI ARID NIGERIA

# [INFLUENCIA DE LA DIVERSIDAD DE ARBOLES EN UNA RESERVA FORESTAL SOBRE LAS FRACCIONES DE AGREGADOS DEL SUELO Y DEPÓSITOS DE CARBONO ORGÁNICO EN LA REGIÓN SEMI ÁRIDA DE NIGERIA]

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## SUMMARY

The ability of trees to sequester carbon vary from species to species, this study therefore evaluates the influence of seven tree species (*Acacia senegal, Azadirachta indica, Eucalyptus camadulensis, Khaya senegalensis, Prosopis africana, Tamarindus indica* and *Tectona grandis*) on soil aggregate fractions and various pools of carbon in soil at three soil depth (0-5, 5-15 and 15-25cm). Results revealed that most soil quality enhancing properties concentrated more at the soil surface (0-5cm) relative to other depths. Soil planted to *T. indica* stood out in possessing high proportion of large and small macro aggregates, mean weight diameter (MWD) and least proportion of silt plus clay particles. High proportion of fine particulate organic carbon, particulate organic carbon, silt plus clay associated organic carbon and non hydrolysable organic carbons were attributed to soil under *T. indica*. *Tamarindus indica* might be a better choice of the seven tree species in mitigating green house effects by sequestering atmospheric carbon and improving soil aggregate stability.

**Key words**: Leaf litter; soil aggregate stability; organic carbon pools; carbon sequestration; savanna.

## RESUMEN

La habilidad de los árboles para secuestrar carbono varía de especie en especie. Este estudio evaluó la influencia de siete especies de árboles (*Acacia senegal, Azadirachta indica, Eucalyptus camadulensis, Khaya senegalensis, Prosopis africana, Tamarindus indica* y*Tectona grandis*) en fracciones de agregados del suelo y varios depósitos de carbono en el suelo a tres profundidades (0-5, 5-15 y 15 a 25 cm). Los resultados mostraron que la mayoría de los efectos de los árboles para mejorar el suelo se concentran en la superficie (0-5cm) en comparación con otras profundidades. Los suelos plantados con *T. indica* sobresalieron por poseer una alta proporción de macro agregados grandes y pequeños, y la menor proporción de limo más arcilla. Una alta proporción de partículas finas de carbono orgánico, partículas de carbono orgánico, limo más arcilla asociado a carbono orgánico y carbono orgánico no hidrolizable fueron encontrados en suelos con *T. indica*. Se concluye que *T. indica* es la mejor elección entre los siete arboles evaluados para la mitigación de los efectos invernadero debido a su capacidad de secuestro de carbono y mejora de la estabilidad de los agregados del suelo.

**Palabras clave:** Hojarasca; estabilidad de agregados del suelo; depósitos de carbono orgánico; secuestro de carbono; sabana.

## INTRODUCTION

Human activities such as fossil fuel burning, bush burning, deforestation and land use change in the past few decades have increased the amount of carbon dioxide, (CO$_2$) by about 30% and other greenhouse gases (GHGs) in the atmosphere; leading to extreme climate change that may have devastating effects on global economy and life forms.

The Kyoto protocol on climate change of 1997, established the principle that carbon sequestration can be used by participating nations to help meet their respective net emission reduction targets for $CO_2$ and other GHGs by the year 2012 (Kyoto protocol, 1997). Growing trees to sequester $CO_2$ could provide relatively net emission reduction because trees act as sinks for atmospheric $CO_2$ through photosynthesis. Litters on forest floor upon undergoing the process of decomposition to add carbon to the soil and consequently improve soil aggregate stability, since the soil has a greater potential to sequester carbon compared to vegetation and atmosphere (Swift, 2001). Hence non disturbance of forest soils increases the potential for C to remain relatively longer in such soils thus, mitigating green house effect (Six *et al*., 2002).

Soil aggregation is important for soil to stay productive, it maintains the surface integrity of the soil and facilitates infiltration rather runoff (Franzluebbers et al., 2000) in addition to enhancing root growth and movement of soil water and gases. Carbon in plant residues and tree litter is sequestered in soil through decomposition and conversion into soil organic carbon in aggregates. It has been documented that aggregation and soil organic carbon (SOC) sequestration are suitable indicators for evaluating changes in soil quality (Unger, 1997). Forestation improves SOC storage (Six et al., 2000; Solomon et al., 2002). Since litter on forest floor promote the formation and stabilization of soil macro aggregates and facilitate SOC sequestration.

Organic matter (OM) stored in macro aggregates can become physically protected from decomposition by isolating OM resources from the activity of soil fauna (Beare *et al*., 1994; Elliot 1986). Furthermore, litter returned to the soil are exposed to variety of decomposition step processes contributing to a gradient in soil biochemical potential from active to passive (Paul *et al*., 2003). Mineralizable C and N are active components that can be use to characterized biochemical availability of organic resources.

Newly planted or regenerated forests, in the absence of major disturbance, will continue to take up carbon for 20 to 50 years or more after establishment, depending on the species and site conditions (IPCC, 2000). The complex relationship between soil organic carbon (SOC) sequestration and aggregate stability is crucial to understand SOC dynamics and turnover. Understanding how plant specie influences soil organic matter dynamics is important to predicting how soil carbon sequestration and fertility will respond to management decisions and global environment changes/mitigation of GHGs. There is a dearth of information on the effect of tree species on soil aggregate characteristics in the tropical environment. This study therefore assessed the influence of tree diversity on soil aggregate fractions and various concentrations / pools of carbon in varying aggregates sizes.

## MATERIALS AND METHODS

### Site description

The study was carried out at Afaka Forest Reserve in Kaduna State, Northern Guinea Savanna ecological zone (Keay, 1959) of Nigeria. It has a mean annual rainfall of 1270 mm and lies between coordinates 10$^o$ 33’ and 10$^o$ 40’ North and 07$^o$ 15’ East, altitude 593 m above sea level. The natural vegetation cover consist of *Isoberlina doka* as the dominant tree species on the deeper soils, *Monoles kerstingii* on the eroded areas bordering gully formations. While *Uapaca togoensis* and *parinari curatellifora* were common (Tomlison, 1957). The topography has a <2% slope and the soil type is Alfisol; plinthustalfs, sandy loam soil.

### Soil Sampling

Soil samples were collected from seven selected 19years old tree species, the tree species and the land area they occupied in parenthesis are as listed below:

*Eucalyptus camadulensis* (2.20ha); *Acacia senegal* (1.95ha); *Prosopis Africana* (2.00ha); *Tamarindus indica* (1.48ha); *Khaya senegalensis* (1.72ha); *Azadirachta indica* (1.75ha); *Tectona grandis* (2.00ha).

A stratified random sampling method was adopted to collect composite soil samples from three (3) subplots which represented three replications, soil were collected from 0-5 cm, 5-15 cm and 15-25 cm depth using a traditional hoe and bucket auger.

### Water stable aggregates

Aggregate stability was determined by wet sieving (Elliot, 1986). A 200 g of air dried bulk soil (which had been sieved through a 5 mm sieve) was wetted by rapid immersion then passed through 2 mm, 0.25 mm and 0.053 mm sieves, with an average stroke per minute of 36, 14 and 3 for each of the sieve sizes respectively.

The <0.053mm aggregate fraction was allowed to settle down and the water was decanted gently. The fractionated aggregates were oven dried at 60$^o$C to a constant weight. Aggregate fractions >0.053mm were corrected for sand and mean weight diameter determined (MWD). However, large macro aggregate

>2mm were not used in computing or calculating MWD, being that the proportion of aggregates >2mm recovered after the wet sieving were too small in weight to be corrected for sand (sand free fraction). The proportional weight of sand free aggregates is given as:

$$\frac{\text{Weight of fractioned aggregate - \% sand content}}{\text{Weight of bulk soil - \% sand content}}$$

Equation 1 (Masri and Ryan, 2006)

Mean weight diameter (MWD) was determined thus:

$$\text{MWD} = \sum_{1=1}^{n} xi \;\; wi$$

Equation 2

Where:
$xi$ = mean diameter of sieve proceeding and preceding
$Wi$ = proportional weight of sand free aggregates

### Soil organic matter fractionation

Soil organic carbon content was determined in the aggregate fractions (2-0.25 mm, 0.25-0.053 mm, <0.053 mm) and the bulk soil by the dichromate (wet) oxidation method of Nelson and Sommers (1982). The organic carbon in the aggregate fractions in parenthesis, were referred to as Fine particulate organic carbon, FPOC, (2 – 0.25mm), Intra-aggregate pParticulate organic carbon, IPOC (0.25 – 0.053mm) and silt plus clay associated organic carbon (< 0.053mm). Sand free carbon concentration was thereafter calculated in aggregate fractions greater than 0.053 mm as:

$$\text{Sand free C fraction} = \frac{\text{C fraction}}{\text{1-[sand proportion] fraction}}$$

Equation 3 (Denef *et.al;* 2001)

Acid hydrolysis was employed to determine the Non hydrolysable carbon (NHC) (Tan *et al*., 2004). One gram of the bulk soil sample was passed through a 250 $\mu m$ sieve and digested with 25 ml of 6N HCl (Paul *et al*., 2001) Using a digestion block at a temperature of 100$^{o}$C until only the soil residue was left. The residue was centrifuged twice with 40 ml of distilled water for 30 minutes, to remove HCl. The residue was dried at 60$^{o}$C over night and weighed, after which carbon was determined in the acid hydrolyzed samples by dichromate (wet) oxidation method (Nelson and Sommers, 1982).

### Data analysis

Data collected in this study were subjected to statistical analysis of variance as described by Snedecor and Cochran (1967). Using the SAS computer package (SAS, 1998) the differences between the treatment means were evaluated using Duncan's Multiple Range Test (DMRT) (Duncan, 1955).

## RESULTS AND DISCUSSION

### Water stable aggregate

The effects of sampling depth and tree diversity on water stable aggregates (WSA) is presented in Table 1, statistical analysis of data revealed no significant difference among the evaluated depths with respect to large macro aggregates (>2mm) and mean weight diameter (MWD). Small macro aggregates (>0.25mm) decrease by 10.3% with increase in sampling depth from 5 – 15cm to 15 – 25cm. The high proportion of smaller macro aggregates at 0-5 and 5 – 15cm depth may be due to accumulation and non removal of residues on soil surfaces, which serve as mulch and seemed to improve soil aggregation. Beare *et al.* (1994) also observed that accumulation of residues at soil surfaces improved soil aggregation and reduced losses of soil organic matter. Litter on the forest floor may provides uniform temperature and moisture conditions which could encourages earthworm activities and lead to the production of burrows or biopores, thereby increasing infiltration rate and decreasing runoff which would consequently enhance soil aggregation. Furthermore the presence of organic matter at these depths in the form of leaf litter and decaying roots exert profound influence on the physical chemical and biological properties of soil, due to the non humic substances produced during decomposition of organic matter which plays a vital role in soil aggregation. It was also found that the proportion of micro aggregate (>0.053mm) and silt and clay aggregate fractions (<0.053mm) increased significantly ($P \geq 0.01$) by 12.8% and 20.3% respectively, with increasing sampling depth from 5 – 15cm to 15 - 25cm. This could be ascribed to reduced organic matter contents at these depths since the translocation of deposited leaf litter into the subsurface soil is slow, thus the influence of leaf residue in binding soil aggregate at this sub depth is limited. Furthermore, at lower depths there could also be the possibility that fragments of plant materials becomes encrusted with clay particles and microbial products to form micro aggregates, as clay was found to increase with depth in these soils (Six *et. al.* 2004).

The effects of tree diversity on water stable aggregates (Table 2) revealed that soils planted to

*Prosopis africana* and *Tectona grandis*, significantly increased large macro aggregate fraction (>2mm) which was statistically similar with soils planted to *Tamarindus indica* and *Eucalyptus camadulensis.* However, *Acacia senegal Azadirachta indica* and *Khaya senegalensis* had the lowest level of macro aggregation. Soils under *Azadirachta indica* and *T. indica* had significantly higher small range macro aggregates (>0.25mm). Different tree species had no significant influence on the content of micro aggregates (>0.053mm). However, the least proportion of silt and clay aggregates (<0.053mm) was recorded in soil planted to *T. indica*. The MWD was significantly higher in *Azadirachta indica* and was found to be statistically similar with that of *T. indica* plantations. The consistency of *T. indica* to be among the tree species, recording high proportions of large and small macro aggregates, MWD and least proportion of silt and clay aggregates could be attributed to the numerous small dense foliage of *T. indica* which may decompose rapidly. Furthermore, the evergreen nature of the tree would sustain the soil organic matter content through higher level of deposition and decomposition of deposited litter, thereby increasing the rate of organic matter addition to soil as well as organic matter derived binding agent, and consequently, an improvement in soil aggregation. This supports the findings of Paul *et al.* (2003) and Six *et al.* (2002). They reported that soil aggregation was enhanced as soil organic matter increased, due to increased production of organic matter derived binding agent resulting from the activity of microbes on deposited residues in soils. More so, the strong correlation ($P \leq 0.01$) between these various aggregate fractions and their aggregate associated carbon may have been responsible for their better soil aggregate stability.

The proportions of micro aggregate (>0.053mm) was not affected by tree diversity. Six *et al.* (2004) asserted that micro aggregate stability is less dependent on agricultural management because of their binding agent and hierarchical order. The high proportion of silt and clay aggregate as well as the least MWD in soil planted to *Tectona grandis* (Table 2) despite its deciduous nature, could be attributed to the production and deposition of large leathery/fibrous leaves of the tree species (Keay, 1989), which are properties of non-easily decomposable litter. Hence, the production of organic matter derived binding agent in its underlying soils will be very slow and consequently lower soil aggregation relative to the other tree species evaluated in this study even after 19 years of establishment.

Table 1. Effect of sampling depth on water stable soil aggregates of a forested ecosystem.

| | Proportional Weight of sand free aggregate fractions | | | | |
|---|---|---|---|---|---|
| Depth (cm) | >2mm | >0.25mm | >0.053mm | <0.053mm | MWD |
| 0 – 5 | 0.196 | 0.396a | 0.258b | 0.140b | 0.488 |
| 5 – 15 | 0.175 | 0.400a | 0.264b | 0.135b | 0.479 |
| 15 – 25 | 0.174 | 0.359b | 0.298a | 0.162a | 0.452 |
| SE± | 0.0127 | 0.00785 | 0.0111 | 0.00489 | 0.0129 |
| Significant level | NS | ** | * | ** | NS |

Means followed by the same letter(s) within the same column are not significant at 5% level of probability.
** = Significant at 1% level of probability

NS = Not significant
MWD= Mean weight diameter (mm)

Table 2. Effect of tree diversity on water stable aggregates of a forested ecosystem.

| | Proportional Weight of sand free aggregate fractions | | | | |
|---|---|---|---|---|---|
| Tree specie | >2mm | >0.25mm | >0.053mm | <0.053mm | MWD |
| *Acacia senegal* | 0.127b | 0.375b | 0.323 | 0.170a | 0.472bc |
| *Azadirachta indica* | 0.135b | 0.456a | 0.252 | 0.131c | 0.552a |
| *Eucalyptus camadulensis* | 0.189ab | 0.377b | 0.303 | 0.138bc | 0.471bc |
| *Khaya senegalensis* | 0.159b | 0.362b | 0.279 | 0.151abc | 0.457cd |
| *Prosopis africana* | 0.241a | 0.355b | 0.245 | 0.159ab | 0.441cd |
| *Tamarindus indica* | 0.183ab | 0.426a | 0.257 | 0.108d | 0.521ab |
| *Tectona grandis* | 0.237a | 0.344b | 0.254 | 0.162a | 0.400d |
| SE± | 0.0195 | 0.0I20 | 0.0169 | 0.00747 | 0.0198 |
| Significant level | ** | ** | NS | ** | * |

Means followed by the same letter(s) within the same column are not significant at 5% level of probability.

** = Significant at 1% level of probability

NS = Not significant

MWD = Mean weight diameter (mm)

**Soil organic carbon pools**

The soil organic carbon in the top soil (0-5cm layer) decreased significantly with increasing depth for all aggregate associated carbon (Fine particulate, intra aggregate particulate and silt plus clay), except for Non hydrolysable carbon (NHC) fraction where further increase in sampling depth had no significant influence on SOC (Table 3). The high SOC content of the top soil (0 – 5cm) could be ascribed to deposition of leaf litter on the forest floor, in addition to non cultivation of the soil, which allowed accumulation of OM on soil surface. This agreed with Hubbert *et al.* (2001) who reported that most significant chemical changes associated with plantation forestry occurred at or near the surface of the soil, and is related to the supply of organic matter.

*Tamarindus indica* plantation had highest total organic carbon (TOC) content followed by *Eucalyptus camadulensis* and *Prosopis Africana* (Table 4). Soil under *T. indica* was among soils with significantly high fine particulate organic carbon,intra aggregate particulate organic carbon and silt plus clay associated organic carbon. It was better than soils planted to *Khaya senegalensis* in all the carbon pools (fine particulate, intra aggregate particulate and silt plus clay organic carbon) except for NHC pool, where *T. indica* and *K. senegalensis we*re statistically similar. The several months of flowering (i.e November – December and May to August) of *T. Indica* producing flowers with fleshy slender stalk and hairy ovaries, in addition to its numerous non-leathery leaflets (Keay, 1989; ICRAF, 1992), increased the propensity of *T. indica* biomass to decomposition, thus releasing nutrients into the underlying soil as well as increasing organic carbon content. Furthermore the evergreen dense foliage of *T. indica* may be responsible for its high carbon content, through increased potential of photosynthesis by enhancing atmospheric carbon ($CO_2$) utilization thus stimulating carbon allocation to soil (Silvola and Ahlholm, 1995). In addition, this may encourage high carbon sequestration through the biomass of *T. Indica,* which when returned to soil as leaf litter and tree branches on forest floor, would improve carbon pools and consequently, the $CO_2$ effect in the environment is mitigated.

Table 3. Effect of sampling depth on organic carbon content in soil of a forested ecosystem.

| | Soil organic carbon (gkg$^{-1}$) | | | | |
|---|---|---|---|---|---|
| Depth (cm) | Total organic carbon | Fine particulate | Intra aggregate particulate | Silt plus clay | Non hydrolysable |
| 0 – 5 | 9. 22a | 20.91a | 16.93a | 10.78a | 4.02a |
| 5 – 15 | 7.57b | 13.55b | 12.67b | 8.90a | 3.37ab |
| 15 – 25 | 6.08c | 7.22c | 8.38c | 6.47b | 2.78b |
| SE± | 0.271 | 1.458 | 0.991 | 0.068 | 0.076 |
| Significant level | ** | ** | ** | ** | ** |

Means followed by the same letter(s) within the same column are not significant at 5% level of probability.

* = Significant at 5% level of probability

** = Significant at 1% level of probability

Table 4. Effect of Tree diversity on organic carbon content in soil of a forested ecosystem.

| | Soil organic carbon (gkg$^{-1}$) | | | | |
|---|---|---|---|---|---|
| Tree species | Total organic carbon | Fine particulate | Intra aggregate particulate | Silt plus clay | Non hydrolysable |
| *Acacia senegal* | 6.41d | 15.85a | 12.86ab | 8.96a | 3.62ab |
| *Azadirachta indica* | 6.75d | 13.14ab | 12.84ab | 9.51a | 3.16b |
| *Eucalyptus camadulensis* | 8.89b | 19.40a | 15.31ab | 8.90a | 3.11b |
| *Khaya senegalensis* | 6.01d | 7.91b | 5.41c | 6.11b | 3.62ab |
| *Prosopis Africana* | 8.04bc | 12.46ab | 13.65ab | 8.60a | 4.43ab |
| *Tamarindus indica* | 10.31a | 14.68ab | 16.97a | 9.51a | 4.81a |
| *Tectona grandis* | 6.92cd | 13.81ab | 11.57b | 8.71a | 1.83c |
| SE± | 0.414 | 2.227 | 1.514 | 0.104 | 0.116 |
| Significant level | ** | * | ** | * | ** |

Means followed by the same letter(s) within the same column are not significant at 5% level of probability.

* = Significant at 5% level of probability

** = Significant at 1% level of probability

The least carbon content was obtained from soils under *Khaya senegalensis.* Though the crown of this tree is evergreen, but it possesses a non-easily decomposable biomass, such as its larger, dark shiny leathery foliage, and its production of hard woody fruits compared to *T. indica*. These features of *K. senegalensis* would not allow its biomass deposited on forest floor to be easily accessible to microbes and therefore will culminate to its less organic matter turnover in soil, and consequently less SOC sequestrations, as indicated in its total and all other aggregate associated carbon pools (Table 4). Hobbie *et al.* (2007) observed that tree species have differing effects on soil C and N cycling through litter due to inter specific variation in litter chemistry.

The least non hydrolysable SOC was observed in *Tectona grandis* plantation. Though the tree specie is deciduous in nature (not maintaining an ever green crown all year round); therefore, it may be possible that there is a reduction in its photosynthetic ability and hence less carbon may be sequester from the atmosphere for subsequent storage in soil. In addition, physical examination of litters indicates that, the very broad fibrous and leathery leaves (Keay,1989) shed on forest floor, is non-easily decomposable and consequently this will hinder rapid release of nutrient into the soil. This is further confirmed by the findings of Okoro and Osagie (1999). They reported lower organic carbon under *Tectona grandis* plantation than natural vegetation, which was attributed to slow mineralization of *T. grandis* litter.

**Interaction effect on soil Properties**

Generally, TOC decreased as the depth of soil sampling increases from 0 – 5 to 15 – 25 cm depth (Table 5). Expectedly TOC was higher at surface soil as leaves and other debris decompose on soil surface, though it may be leached down soil profile with time, but it will still remain higher on top soil, since debris and detritus are continually deposited and mineralized. Further more, there may be possibility of higher microbial activity at soil surface (Six *et al.*, 2002) due to the presence of abundant debris and detritus. At 0 – 5 cm depth, significantly higher TOC was found on plots grown to *Eucalyptus camadulensis, Prosopis africana* and *Tamarindus indica,* relative to *Acacia senegal, Azadirachta indica* and *Khaya senegalensis.* The lower TOC content in the latter tree species (*A. senegal and K. senegalensis*) could be ascribed to the poor decomposing properties (leathery leaves, drier debris, hard woody fruits, and xerophytic nature) of these trees which were observed via physical assessment of deposited litter. However at greater depths (5 – 15 and 15 – 25cm), TOC on field grown to *Tamarindus indica* was significantly higher than other tree species evaluated in this study. It may be possible that *T. indica* sloughs off more roots at greater soil depths relative to the other tree species studied. Balesdent and Balabane (1996) observed that roots sloughed off each year continually add C and N to the soil. More so rhizosphere deposition such as root exudates may be a significant source of SOC and may have great influence on SOC concentration.

Table 5. Interaction between sampling depth and tree species (D x S) on Total Organic Carbon (gkg$^{-1}$).

| | Depth (cm) | | |
|---|---|---|---|
| *Tree species* | 0 – 5 | 5 – 15 | 15 – 25 |
| *Acacia Senegal* | 7.66d-f | 6.25e-g | 5.33fg |
| *Azadirachta indica* | 7.73d-f | 6.45e-g | 6.07e-g |
| *Eucalyptus camadulensis* | 12.50a | 8.12c | 6.05e-g |
| *Khaya senegalensis* | 6.27e-g | 6.83d-g | 4.93g |
| *Prosopis Africana* | 10.44a-c | 7.65d-f | 6.02e-g |
| *Tamarindus indica* | 10.67ab | 11.07ab | 9.20bc |
| *Tectona grandis* | 9.24b-d | 6.58e-g | 4.93g |
| SE ± 0.71788 | | | |

Means followed by different letter(s) are significant at 5% level of probability.

## CONCLUSION

Soil organic carbon pools and aggregate stability indices were significantly enhanced at the top soil (0–5cm), These enhanced soil properties were attributed to the frequent and continual deposition of litters and debris on forest floor and the non incorporation of same into sub soil.

This study suggests that tree diversity have great influence on soil organic carbon and pools and aggregate stability and therefore their restorative ability. Tree species that increase carbon sequestration in soil will in turn improve soil quality and may provide a good opportunity to combat soil degradation and loss of biodiversity and improve food security. It was observed that the tissue chemistry of tree species particularly, that of the leaves may be an important mechanism contributing to ecosystem functions. Further research on this area with more trees will need to be pursued.

*Tamarindus indica* could be a better choice of tree, of seven tree species evaluated in this study. In regenerating a degraded soil by afforestation and consequently sequestering atmospheric carbon to reduce global warming, deciding on a good choice of tree species and planting the tree in time, will go a long way in addressing the rate at which soil degradation and green house effect will be mitigated.

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