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Effects of Agri-Silvopastoral Practices on Soil Physical and Chemical Properties in Machakos County, Kenya

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ABSTRACT

Background and Objective: Although agroforestry is known to enhance soil quality, the specific impacts of various agri-silvopastoral systems on the physical and chemical properties of soils, particularly in the tropical regions of Sub-Saharan Africa, remain insufficiently understood. This study investigated the influence of agri-silvopastoral practices on soil physical and chemical parameters. **Materials and Methods:** Soil was sampled from 73 different farmers with different agri-silvopastoral practices using a soil auger. Soil physical properties measured were sand, clay, and bulk density. The soil chemical properties included pH, total nitrogen, total phosphorus, total organic carbon, as well as carbon-to-nitrogen ratio (C/N). In addition, exchangeable bases such as potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), as well as micronutrients including manganese (Mn), copper (Cu), iron (Fe), and zinc (Zn), were also analyzed. Differences in time among agri-silvopastoral practices were evaluated using One-way Analysis of Variance (ANOVA). Statistical significance was set at $p<0.05$. **Results:** Agroforestry practices such as boundary cropping and scattered tree planting significantly increased the sand content in soils, while alley cropping, followed by woodlots, increased silt content. Adjacent to boundary planting, as well as scattered tree planting, was higher bulk density in soils. The TN was highest in alley cropping and woodlots, while elevated TOC and C/N ratios occurred in soils where alley cropping was practiced. The concentration of Ca occurred in soils where alley cropping and scattered tree planting were practiced, Mg and Na were highest in soils practicing alley cropping and woodlots. The highest concentration of Mn, Cu, and Zn occurred in soils practicing hedgerow and alley cropping, and was lowest in soils practicing scattered tree planting and boundary. **Conclusion:** The physical and chemical attributes in the soil appeared to be affected by the type of agri-silvicultural practice. The study recommends adoption of silvopastoral activities in most of the dryland regions to improve soil parameters.

KEYWORDS

Agri-silvopastoral, agroforestry, soil physical properties, soil chemical properties, silvopastoral systems, soil fertility, tropical soils

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INTRODUCTION

Agroforestry involves deliberate interactions between agriculture, namely, crops and livestock, and forestry, occurring at multiple spatial and temporal scales[1]. It typically entails the simultaneous cultivation of trees on the same land where crops are grown and livestock is raised. The tree species involved are often woody perennials, while the associated crops may be either subsistence or cash crops, enabling both ecological interaction and commercial synergy[2]. Agroforestry is increasingly being recognized as a viable solution to critical global challenges such as food insecurity, land degradation, and climate change. The adoption of agroforestry technologies is being actively promoted for their dual role in both mitigation and adaptation strategies. These systems contribute significantly to carbon (C) sequestration, enhance food security, bolster climate resilience, and support the sustainability of rural livelihoods[3,4]. Today, agroforestry practices are widespread globally, offering multiple benefits including improved food security, diversified livelihoods, and enhanced environmental quality[5-7]. However, despite its promise, the adoption of agroforestry remains limited, particularly among smallholder farmers. In Sub-Saharan Africa (SSA), where a majority of farms are under 2 ha, much of the land remains underutilized[8].

Agri-silvopastoral is a specific type of agroforestry system that integrates livestock rearing with the cultivation of trees and food crops such as vegetables, shrubs, vines, mushrooms, and fodder species[9]. This practice may involve combinations ranging from a single tree and crop to complex polycultures involving multiple tree and crop species, where the crops benefit from the microclimatic and edaphic modifications provided by the trees[10]. Various methods exist under agri-silvopastoral systems. These include alley cropping, where rows of trees are planted with crops in between; windbreaks, involving one or more rows of trees along field edges to protect crops and structures from wind; the improved fallow method, which alternates the cultivation of trees and crops to restore soil fertility; and hedgerow intercropping, where nitrogen-fixing shrubs are grown alongside annual crops[11]. Another common form is the woodlot, an area designated for tree cultivation for products such as firewood, timber, or other forest resources[12].

In drylands and degraded marginal lands, agri-silvopastoral systems offer substantial ecological and economic benefits. Historically, woody hedgerows have been used to delineate land boundaries[13]. Besides serving as living fences, hedgerows can provide fodder, fuelwood, and additional harvestable resources[14]. Woodlots commonly consist of multipurpose tree species such as pine, eucalyptus, and acacia, cultivated for biomass energy, timber, and fodder production[15]. In some cases, woodlots are integrated with fruit trees, berries, legumes (e.g., beans), and shrubs to diversify yields and ecological benefits[16]. These systems can also support livestock production while supplying secondary products like mushrooms, berries, resins, herbs, and even Christmas trees. During early establishment phases, trees are often intercropped with cash crops to generate supplemental income. Additionally, woodlots are widely used for beekeeping, contributing to high-quality honey and other apicultural products.

Interest is growing in the influence of agroforestry on soil physical and chemical properties. Agri-silvicultural systems have been shown to enhance soil health by increasing both aboveground and belowground organic matter pools[17-19]. A detailed evaluation of soil parameters such as bulk density, porosity, water retention, and nutrient content is critical for understanding these effects. In Sub-Saharan Africa, such practices have demonstrably improved soil quality, thereby contributing to sustainable land productivity over the long term[20,21]. However, targeted research on these impacts in dryland regions remains limited. Therefore, this study aims to evaluate the effects of agri-silvopastoral practices on selected soil physical and chemical properties in Machakos County, Kenya.

MATERIALS AND METHODS

Study area: This study was conducted in Machakos County between February and June, 2024. Machakos County occurs at an altitude ranging from 1,000 to 2,100 m.a.s.l. The county is situated between Latitudes 0°45' South and 1°31' South, and Longitudes 36°45' East and 37°45´ East. Predominantly semi-arid, Machakos County had a population of 1,421,932 according to the 2019 Kenya National Census[22]. The initial administrate boundary covers 11 divisions, which are politically eight constituencies. These divisions and constituencies often overlap and are commonly referred to as sub-counties. The research was conducted in four agroforestry sites: Mua (including Mavoko, Machakos Town, and Kathiani), Iveti Hills (covering Machakos Central and Kathiani), as well as Kima-Kimwe and Kalama, all located within Machakos Constituency.

The landscape includes hilltops that rise between 1,594 and 2,100 m. The average rainfall in the area is about 1,000 mm (500 to 1,300 mm) in a bimodal pattern of short rains between October to December and long rains from March to May[23]. Temperatures typically range from 18.7 to 29.7°C. In Machakos, the main soil groups are alfisols, ferrasols, acrosols, ultisols, nitosols, and oxisols[24,25]. Soils found on hilltops are typically shallow, well-drained, and characterized by a dark red volcanic composition, whereas the plains are predominantly composed of clay-rich soils. Irrigation is primarily supported by permanent rivers and streams that originate from nearby highland areas, enabling a consistent water supply for agricultural use. A broad range of crops is cultivated in the area, encompassing cereals, legumes, vegetables, and fruits. A wide range of crops are cultivated in the region, mainly maize, beans, coffee, avocado, pawpaw, mango, cassava, sweet potatoes, and tomatoes. Livestock production is also widespread, with the main animals kept being dairy cattle, beef cattle, sheep, and goats.

Soil sampling and analysis: Soil samples were obtained using soil auger from adopters of agri-silvopastoral (n = 43) and baseline, the non-adopters (n = 30). Soil was extracted to a depth of 15 cm using the auger. A minimum of five subsamples were taken from each farm and thoroughly mixed to create a composite sample for analysis. The collected soil samples were placed in khaki paper bags, each weighing two kilograms, and transported to Kenyatta University and at the Kenya Agricultural and Livestock Research Organization (KALRO) laboratories for analysis.

The soil texture was analyzed by determining the relative proportions of sand, silt, and clay using standard particle size analysis procedures[26]. Bulk density was measured in triplicate for each study plot using a polyvinyl chloride (PVC) soil corer with a diameter of 42.2 mm. To minimize soil compaction, the corer was carefully inserted vertically into the ground to extract intact core samples. The collected soil cores were then oven-dried at 105°C for 24 hrs until a constant weight was achieved. Bulk density (g/cm^3) was calculated as the ratio of oven-dried soil mass to the core volume. Soil pH was determined *in situ* using a soil pH meter (Hanna Instruments HI 99121 Soil pH Tester, Hanna Instruments, Woonsocket/United State) following the manufacturer's protocol. Total nitrogen (TN) content was quantified by the Kjeldahl method using the wet-oxidation procedure[27]. Total phosphorus (TP) was quantified using the rapid perchloric acid digestion method[28]. Total Organic Carbon (TOC) was analyzed using the Walkley and Black wet oxidation method[29]. Exchangeable base cations (K, Na, Ca, and Mg) extraction using 1 M ammonium acetate (NH_4OAc) solution at pH 7.0. Sodium and potassium concentrations were analyzed using a flame photometer (Jenway PFP7 Flame Photometer, Jenway, Essex/United Kingdom), whereas calcium and magnesium levels were assessed from the same extract via atomic absorption spectrophotometry (AAS). Micronutrients (Fe, Mn, Zn, and Cu) were extracted using diethylene triamine penta-acetic acid (DTPA) and quantified by AAS[30].

Statistical analysis: The normality of data was examined by normal plots[31]. Results indicated that all data were normally distributed. To assess differences among agri-silvopastoral practices, One-Way Analysis of Variance (ANOVA) was conducted. Significant differences were further explored using Duncan's Multiple Range Test as a *post hoc* analysis. Statistical significance was set at $p<0.05$.

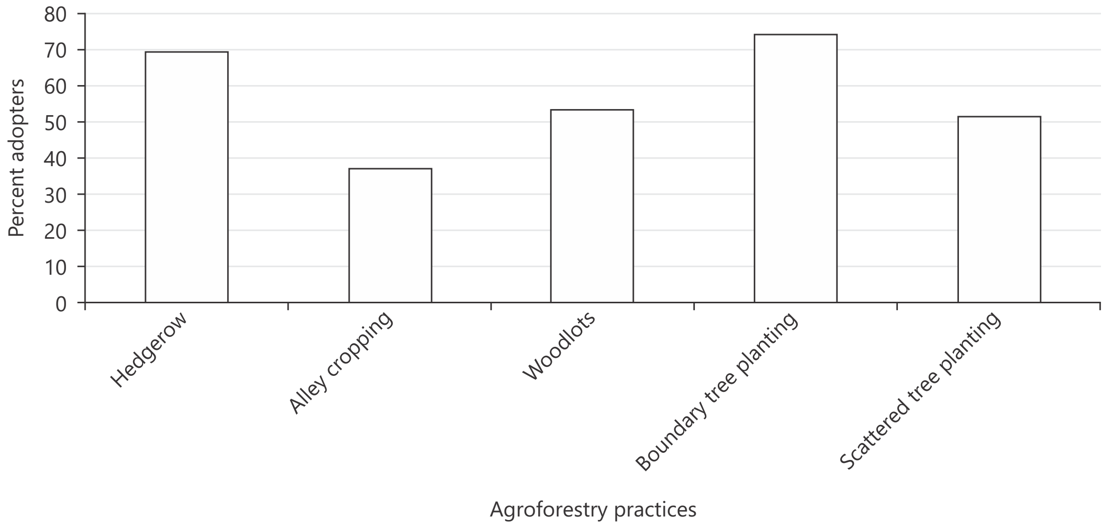

Fig. 1: Types of agroforestry practiced by the local community members adopted the practice during the study period

RESULTS

Agri-silvopastoral systems: During the study, 32.3% of respondents practicing agroforestry adopted agri-silvopastoral practices. The types of agri-silvopastoral practices identified in the study area are illustrated in Fig. 1. Among these, boundary planting was the most commonly adopted practice, embraced by 73.8% of the farmers, followed by hedgerow planting at 69.4%, and scattered planting at 51.2%. Alley cropping was the least preferred practice, adopted by only 37.1% of the respondents.

Physical soil parameters: Table 1 presents the physical soil properties from farmers employing different agri-silvopastoral practices. Significant differences ($p<0.05$) were found in sand content, influenced by both the type and age of the agri-silvopastoral system. Soils from boundary cropping and scattered tree planting contained the highest sand proportions, followed by woodlots and alley cropping, while hedgerows had the lowest sand content. Clay content ranged between 28.2 and 28.98% among the various practices but did not show significant differences ($p>0.05$). Silt content varied significantly ($p<0.05$), with alley cropping having the greatest silt percentage, followed by woodlots, and the least found in scattered tree planting. Bulk density also differed significantly ($p<0.05$), being highest in soils from boundary and scattered tree planting systems, intermediate in woodlots, and lowest in alley cropping.

Soil chemical properties: The chemical properties of the soils are summarized in Table 2. Soil pH showed no significant variation among the different agri-silvopastoral practices ($p>0.05$). Total nitrogen (TN) differed significantly ($p<0.05$), with the highest concentrations found in soils under alley cropping, followed by woodlots, and the lowest in boundary planting and hedgerows. Total phosphorus (TP) did not vary significantly across the different practices ($p>0.05$). Total organic carbon (TOC) exhibited significant differences ($p<0.05$), being highest in soils practicing alley cropping, followed by scattered tree planting, and lowest in hedgerows. Similarly, silvopastoral practice type ($p<0.05$), with the highest ratios in alley cropping, followed by scattered tree planting, and the lowest in boundary planting and hedgerows.

Exchangeable bases: The concentrations of exchangeable bases among soils from farmers practicing different forms of agri-silvopastoral are presented in Table 3. Calcium levels were significantly higher ($p<0.05$) in soils under alley cropping and scattered tree planting compared to those under hedgerows. Magnesium and sodium concentrations also varied significantly ($p<0.05$), with the highest values observed in soils practicing alley cropping and woodlots, and the lowest in hedgerow soils. Potassium content

Table 1: Variation in soil physical properties between farmers engaged in agroforestry and those who are not

Age of adoption	Sand (%)	Clay (%)	Silt (%)	Bulk density (kg/m^3)
Hedgerow	59.22±1.29^{a}	29.42±0.65	11.13±1.08^{b}	1247±96.5^{ab}
Alley cropping	63.35±1.11^{b}	28.39±0.53	12.71±1.28^{d}	1054±100.5^{a}
Woodlots	61.32±0.27^{b}	28.27±0.54	10.08±2.53^{c}	1386±92.1^{b}
Boundary planting	67.56±1.21^{c}	29.29±0.50	12.45±1.13^{d}	1464±84.4^{c}
Scattered tree planting	65.15±0.67^{c}	27.53±0.89	9.86±2.14^{a}	1449±83.4^{c}
ANOVA				
F	32.1132	0.764	8.577	31.4447
Df	4	4	4	4
p-value	<0.001	0.5427	0.0043	<0.001

Each column shows Mean Values±Standard Deviation. Values with different superscript letters within a column are significantly different (p<0.05)

Table 2: Soil chemical properties among farmers with different lengths of agroforestry adoption in machakos county

Age of adoption	pH	TN (g/kg)	TP (g/kg)	TOC (g/kg)	C/N
Hedgerow	6.33±0.34	0.78±0.16^{a}	8.38±2.19	10.9±2.53^{a}	10.6±2.7^{a}
Alley cropping	6.26±0.29	2.55±0.49^{d}	7.76±2.42	22.1±3.05^{d}	18.4±5.3^{c}
Woodlots	6.02±0.31	2.35±0.45^{c}	6.75±2.90	16.1±3.01^{b}	12.7±4.9^{b}
Boundary	6.06±0.27	0.81±0.24^{a}	7.49±1.92	19.7±2.49^{c}	9.0±2.3^{a}
Scattered tree planting	6.28±0.39	1.39±0.46^{b}	8.20±2.18	25.0±2.17^{c}	24.3±4.5^{d}
ANOVA					
F	2.343	58.345	1.132	265.234	22.324
df	4	4	4	4	4
p-value	0.3202	<0.001	0.3912	<0.001	<0.001

Each column shows Mean Values±Standard Deviation. Values with different superscript letters within a column are significantly different (p<0.05)

Table 3: Comparison of soil exchangeable base cations between farmers practicing agroforestry and those not, and their changes over time

Age of adoption (years)	Calcium (Cmol$_c$/kg)	Magnesium (Cmol$_c$/kg)	Sodium (Cmol$_c$/kg)	Potassium (Cmol$_c$/kg)
Hedgerow	2.13± 0.33^{a}	1.83±0.33^{a}	0.15±0.09^{a}	0.31±0.02^{a}
Alley cropping	5.22±0.28^{c}	5.15±0.70^{d}	0.26±0.10^{c}	0.32±0.08^{a}
Woodlots	3.42±0.34^{b}	4.05±0.93^{d}	0.15±0.11^{a}	0.19±0.17^{a}
Boundary	3.21±0.22^{b}	3.01±0.99^{c}	0.12±0.12^{a}	0.21±0.23^{b}
Scattered tree planting	5.77±1.02^{c}	2.28±0.68^{b}	0. 21±0.32^{b}	0.44±0.14^{c}
ANOVA				
F	9. 2226	17. 4222	13.3115	19.443
df	4	4	4	4
p-value	<0.001	<0.001	<0.001	<0.001

Each column shows Mean Values±Standard Deviation. Values with different superscript letters within a column are significantly different (p<0.05)

Table 4: Concentrations of soil micronutrients among agroforestry adopters and non-adopters in machakos county

Age brackets (Years)	Manganese (mg/kg)	Copper (mg/kg)	Iron (mg/kg)	Zinc (mg/kg)
Hedgerow	1.24±0.04^{a}	8.59±3.87^{a}	351.54±83.33^{a}	32.22±5.44^{a}
Alley cropping	1.37±0.02^{b}	8.78b±1.42^{a}	353.67±102.78^{b}	32.58±3.29^{a}
Woodlots	1.38±0.03^{b}	8.11±1.21^{a}	547.45±100.37^{b}	52.43±5.38^{c}
Boundary	1.45±0.05^{c}	13.01±4.33^{b}	563.44±88.37^{d}	48.32±6.19^{b}
Scattered tree planting	1.48± 0.05^{c}	12.86±2.14^{c}	5782.52±65.71^{e}	59.47±5.87^{d}
ANOVA				
F	8.2334	9.113	12.344	7.4535
df	4	4	4	4
p-value	0.0008	0.0056	0.00112	0.01232

Each column shows Mean Values±Standard Deviation. Values with different superscript letters within a column are significantly different (p<0.05)

differed significantly as well (p<0.05), with the highest concentrations found in soils practicing scattered tree planting, followed by boundary cropping, while the lowest levels were in hedgerows, alley cropping, and woodlots.

Micro-nutrients: Micro-nutrient concentration among farmers practicing different forms of agri-silvopastoral practices is shown in Table 4. The Mn, Cu, Fe, and Zn differed significantly with agri-silvopastoral practices ($p<0.05$). Highest concentrations of Mn, Cu, and Zn occurred in soils practicing hedgerow and alley cropping, and were lowest in soils practicing scattered tree planting and boundary.

DISCUSSION

Adoption of agri-silvopastoral among the respondents was 32.3%, consistent with previous studies on agroforestry adoption in similar regions[32,33]. The feasibility of agri-silvopastoral in the area is primarily attributed to its dryland conditions, where limited moisture makes commercial agriculture less viable. Among the farmers who adopted agri-silvopastoral, the most common practices included boundary planting (73.8%), hedgerow planting (69.4%), and scattered tree planting (51.2%), while alley cropping was the least preferred practice (37.1%). The popularity of hedgerow agroforestry stems from its effectiveness in providing shelter and functioning as windbreaks[34,35]. Boundary planting was largely adopted to serve as windbreaks and to demarcate farm boundaries.

The physical properties of soils varied based on the type of agri-silvicultural system practiced. Soils from farms practicing boundary planting and scattered tree planting showed higher sand content, likely due to the direct impact of rainfall and compaction caused by livestock movement in search of pasture. These practices offer livestock more space, which may lead to greater soil compaction and uneven particle distribution. Conversely, the lowest sand content was observed in soils under alley cropping. Clay content ranged from 28.2 to 28.98%, with no significant differences across agri-silvopastoral systems. However, silt content varied significantly, with the highest levels found in alley cropping systems. The increased silt content in these systems is likely due to the buildup of organic matter, which contributes to the formation of silt and organic residues while reducing the relative proportion of sand[36]. Silt particles result from the decomposition of organic matter, input of external organic materials, and microbial and biochemical activity[37,38], processes particularly prevalent in alley cropping systems.

Bulk density also varied significantly among the practices. The highest bulk density was recorded in soils under woodlots, followed by scattered tree planting, while the lowest values were observed in boundary planting and hedgerow systems. In another comparative analysis, soils under boundary planting and scattered tree planting showed higher bulk density than woodlots, with the lowest values in hedgerow systems ($p<0.05$). The increased bulk density in boundary and scattered tree planting systems may be attributed to livestock-induced soil compaction and the addition of organic matter from decomposing leaves[39,40], as these systems often involve livestock grazing near homesteads. In contrast, the lower bulk density in alley cropping may result from the accumulation of wood debris, which supports organic matter decomposition and reduces compaction, as previously reported[41].

Total nitrogen (TN) levels in soil differed significantly among agri-silvicultural systems ($p<0.05$). The highest TN levels were found in soils under alley cropping, followed by woodlots, and the lowest in boundary planting and hedgerow systems. The elevated TN in alley cropping is attributed to the decomposition of leaf litter and contributions of native organic matter within the system. Similarly, total organic carbon (TOC) was significantly higher in soils under alley cropping, followed by scattered tree planting, with the lowest levels in hedgerow systems ($p<0.05$). This increase in TOC likely results from leaf litter decomposition. Moreover, root-derived carbon plays a crucial role in SOC accumulation, especially in deeper soil layers[42]. Research shows that root inputs may contribute 1.5 to more than 3 times more carbon to SOC than shoot-derived inputs[43].

The carbon-to-nitrogen (C/N) ratio also varied significantly across agri-silvopastoral practices ($p<0.05$), with the highest ratios observed in alley cropping, followed by scattered tree planting, and the lowest in boundary planting and hedgerow systems. The elevated C/N ratios in alley cropping reflect higher carbon accumulation relative to nitrogen, likely due to the combined effects of leaf litter decomposition and inorganic fertilizer application, which enhance nitrogen availability and promote SOC sequestration[44,45].

Micronutrient concentrations, including manganese (Mn), copper (Cu), and zinc (Zn) were highest in soils under hedgerow and alley cropping systems, and lowest in scattered tree and boundary planting systems. This pattern is linked to the higher organic matter content in hedgerow and alley cropping systems, as supported by prior studies[20]. Manganese in soil originates from plant wash-off, tissue leaching, and decomposition of plant residues and animal waste[46,47]. These processes, enriched in systems with high organic matter, increase the availability of exchangeable micronutrients. Similarly, practices that improve soil organic matter, such as manure application in agroforestry, are associated with elevated iron (Fe) content. These findings align with studies demonstrating significant increases in soil zinc levels under agroforestry systems, partly due to the use of zinc-containing fertilizers such as chelates, sulfates, and oxides[48].

CONCLUSION

The assessment of soil physical properties revealed that soils from farms practicing boundary cropping and scattered tree planting had the highest sand content, followed by those under woodlots and alley cropping systems. Conversely, soils from alley cropping systems exhibited the highest levels of silt and bulk density, with soils from woodlots ranking second, while those under scattered tree planting recorded the lowest silt content. In terms of chemical properties, soils under alley cropping demonstrated the highest concentrations of essential nutrients, followed by those in woodlot systems. These findings underscore the significant influence of agri-silvicultural practices on both the physical and chemical characteristics of soils. The study offers important insights into soil responses within integrated farming systems and contributes to the formulation of agroforestry-based strategies for soil rehabilitation and sustainable land management.

SIGNIFICANCE STATEMENT

This study discovered that different agri-silvopastoral practices distinctly influence soil health by altering its physical and chemical properties, which can be beneficial for designing site-specific land-use strategies in dryland farming systems. Practices such as boundary cropping and scattered tree planting were linked to higher sand proportions, while alley cropping and woodlots contributed to increased silt content and bulk density. In terms of chemical characteristics, alley cropping notably enhanced key nutrients, including nitrogen, organic carbon, calcium, magnesium, and trace elements like iron and zinc. These results provide valuable insights for improving soil productivity through agroforestry. This study will help the researchers to uncover the critical areas of soil response to integrated farming systems that many researchers were not able to explore. Thus, a new theory on agroforestry-driven soil rehabilitation may be arrived at. The study recommends the adoption of Silvopastoral activities in most of the dryland regions to improve soil parameters.

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