ANALYSIS OF THE ECOLOGICAL PERFORMANCE OF MULTI- AND SINGLE-TAXA RESTORATION APPROACHES IN THE EASTERN MAU FOREST RESERVE, KENYA

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DECLARATION AND RECOMMENDATION

Declaration:

This thesis is my original work and has not been presented in this university or any other for the award of a degree.

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Recommendation:

This thesis has been submitted with our approval as university supervisors.

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DEDICATION

This thesis is dedicated to my grandmother Violet Simiyu, mother Scholastica Nambengere and my beloved son Dreymond Mudi.

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ABSTRACT

Anthropogenic pressure and climate change has spurred a global push for more innovative approaches to restore tropical forests, recognizing their crucial role in combating biodiversity loss. In the Eastern Mau Forest in Kenya both single- and multi-species tree restoration methods have been implemented since 2017; however, understanding of ecological performance and their benefits to forest ecosystem remains limited. A comparative study was conducted to assess tree species diversity and soil properties in Eastern Mau forest of the greater Mau complex, one of the five main water towers in Kenya. The experiment focused on *Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis,* and *Prunus africana*. Using Line Intersect sampling, study plots were divided into four 10 m x 10 m quadrats. Soil samples, collected from six points in each quadrat at depths of 0-15 cm and 15-30 cm, were combined for analysis of soil organic carbon (SOC), potassium (K), nitrogen (N), and available phosphorus (P). A calibrated rode was used to measure individual tree height while diameter at breast height measured by the use of calibrated diameter tapes in the defined six sample plots and the values were recorded in metres. The multi-species stands showed higher species recruitment with an average stand volume of 1.19 m^3 compared to single-species stands (0.85 m^3). There was also a 60% increase in forest-specialist species recovery. *H. abyssinica* showed high dominance (> 5 cm DBH), while the DBH of *P. gracilior, J. procera,* and *P. africana* were below 5cm. *J. procera* in single-species stands exhibited straight, tapered, and thick boles, contrasting with the multi-species approach where *H. abyssinica* and *O. capensis* displayed (> 5 cm DBH) and *P. gracilior* showed smaller sizes with higher mortality rates. *P. africana* experienced moderate mortality (~20% loss). Analysis of soil samples from the two stands revealed significant differences in organic carbon, nitrogen, and phosphorus concentrations between single and multi-species approaches ($p < 0.05$). There were significant differences in Soil Organic Carbon, Nitrogen, and Phosphorus among soil profiles ($p < 0.05$). Additionally, a statistical negative correlation was found between soil organic carbon and nitrogen concentrations ($r = 0.759$, $p = 0.0238$), indicating a dependency of nitrogen on soil organic carbon levels across sampled soil depth layers. These findings will inform better forest restoration by highlighting species approach benefits for soil health and biodiversity.

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LIST OF ABBREVIATIONS AND ACRONYMS

BEF	Biodiversity and Ecosystem Functioning
CFA	Community Forest Association
DBH	Diameter at breast height
EMF	Eastern Mau Forest
FAO	Food and Agriculture Organization
FLR	Forest Landscape Restoration
GDP	Gross Domestic Product
GEO	Global Environment Outlook
KEFRI	Kenya Forestry Research Institute
KFS	Kenya Forest Service
MFC	Mau Forest Complex
NEMA	National Environment Management Authority
PFM	Participatory Forest Management
SOC	Soil Organic Carbon
TOC	Total Organic Carbon

CHAPTER ONE
INTRODUCTION

1.1 Background information

Forest restoration is becoming more popular around the globe as a means of restoring biodiversity lost, and mitigating the negative consequences of climate change. This global effort to restore degraded ecosystems echoes the United Nations General Assembly's declaration of 2021–2030 as the "Decade on Ecosystem Restoration". Forest and land degradation have been a major issue, particularly in developing countries with significant population growth and narrowed options for livelihood sources. It is estimated that between 1 to 6 billion hectares of mosaic forests and agricultural landscapes have experienced degradation globally. The financial implications of this land use change are significant, with the annual loss of ecosystem services valued between USD 4.3 trillion and USD 20.2 trillion globally during the period from 1997 to 2011 (Ziadat *et al.*, 2021).

Over the last few decades, the world has experienced a troubling trend of biodiversity loss and environmental degradation, which has been fuelled by a variety of factors such as population growth and changes in land use patterns (Cheboiwo *et al.*, 2018). These changes were most prominent between 1997 and 2020, with major losses seen in agricultural landscapes and natural habitats around the world (Butet *et al*., 2022). As a result, there is a growing awareness of the critical need for conservation efforts and ecological restoration activities. Forest restoration has emerged as an important strategy because of its ability to solve numerous environmental issues at a large scale. Forests not only protect a large amount of the Earth's biodiversity, but also play important roles in carbon sequestration, water control, and soil stabilisation.

According to the United Nations Food and Agricultural Organization, the global forest area shrank by an annual average of 3.3 million hectares between 2010 and 2015, with most losses in tropics. While still significant, the rate of annual net loss of forests slowed from 0.18% to 0.08%. However, this is largely because of an increase in forest cover in temperate and boreal regions. In Africa and Latin America, the rate of loss was significantly higher, approximately at 0.54% and 0.43% respectively (Silva Junior *et al*., 2021). An example is the Amazon Basin in South America which is one of the world's most important ecological systems. It contains the Earth's greatest collections of biological diversity which have undergone significant land use changes with noticeable levels of degradation posing a long-term threat on the sustainability of the ecosystem and the multiple goods and services.

Kenya has been listed among the least forested countries in Sub-Saharan Africa with a cover of 8.83%, equivalent to 4,195,051 ha (Ministry of Environment and Forestry, 2020). The tropical forest belts such as Mount Kenya, Aberdares, Mau Forest complex, Karura, Cherengani and Mount Elgon ecosystems had experienced significant pressure both on its products and the conversion to agricultural lands, thereby threatening conservation and catchment protection functions (Buckner *et al*., 2016).

Landscape degradation in Kenya resulted in declining flows of ecosystem services such as water, food, medicine, fuel wood, fodder, timber, biodiversity, watershed protection, soil protection, and mitigation of global change and thus increased the risks of natural calamities such as drought especially in dry land ecosystems. There is a concern that continued landscape degradation would have long-term impacts on the overall human wellbeing and some initiatives were mooted to address and minimize impacts of degradation (Jebiwott *et al.*, 2021).

The Eastern Mau Forest is a biodiversity hotspot, home to rich flora and fauna that has experienced significant degradation. Anthropogenic activities and environmental pressures led to enormous changes in the Eastern Mau Forest Reserve. It experienced wanton destruction and degradation since the 1990s due to illegal logging, encroachments, and charcoal burning as well as ill-advised political decisions, particularly the excision of ~61,023 ha for human settlement in 2001 (Duguma *et al.*, 2019). As a major water tower, the impact of this loss was evident in lowered water levels in the rivers that emanated from this forest and increased temperatures. In addition are the economic losses in agriculture, tourism and energy sectors that affected the livelihoods of the people not just in the areas adjacent to the forest but also in the neighbouring communities (Mutugi, 2015).

Restoration efforts in the Eastern Mau Forest involved diverse strategies to protect endangered biodiversity, preserve water catchment integrity, and rehabilitate degraded areas. This study compared two methods: the Miyawaki method, using a multi-taxa approach, and the conventional method, focusing on single taxa. Developed by Japanese botanist Akira Miyawaki in the 1970s, the Miyawaki method accelerates forest regeneration by densely planting native species, promoting interspecies competition to rapidly restore ecosystems (Meguro *et al*., 2021; Miyawaki, 2014).

In September 2017, the Kenya Forest Service applied this method in the Sururu Forest, planting diverse species such as *Hagenia abyssinica, Podocarpus gracilior,* and *Juniperus procera* at varying intervals. This approach aimed to boost biodiversity recovery and soil carbon sequestration. The conventional method, used in the Green Zone Development Support project, focused on planting *Juniperus procera* at 2.5 x 2.5-meter intervals, emphasising simplicity and climate resilience (Mutugi, 2015). Both methods contributed to sustainable forest management.

Restoration methods profoundly impact forest soil dynamics, essential for the recovery of plant communities and improved soil health. Forest soils are complex ecosystems where nutrient cycling, organic matter decomposition, and microbial activity sustain vegetation and ecosystem functions. Effective restoration influences these processes, affecting vital nutrients like soil organic carbon (SOC), nitrogen, potassium, and phosphorus, which are critical for plant growth and soil fertility (Wei *et al*., 2023). Soil organic carbon is a key indicator of soil health, contributing to soil structure, water retention, and nutrient cycling. Restoration methods that increase SOC not only enhance plant growth but also support carbon sequestration, mitigating climate change. Similarly, nitrogen, potassium, and phosphorus drive plant productivity and ecosystem recovery.

Comparing the Miyawaki method and conventional techniques offers insights into their effects on soil nutrients. The Miyawaki method, through dense planting of native species, promotes biodiversity, nutrient cycling, and improved soil structure. In contrast, conventional methods may lead to slower nutrient replenishment due to reduced species diversity and organic matter (Miyawaki, 2004). By examining their effects on organic carbon, nitrogen, potassium and phosphorus, this study emphasises the importance of choosing the right restoration approach to enhance soil health and biodiversity for sustainable forest recovery (Miyawaki, 2004).

1.2 Statement of the problem

Eastern Mau Forest has experienced significant degradation as natural mixed-species forests are increasingly replaced by mono-species plantations, raising concerns about the ecological functionalities of these two systems. This study investigated the ecological differences and similarities between mixed-species forests and mono-species plantations, aiming to fill a critical knowledge gap regarding the effectiveness of various restoration approaches. Despite global efforts to implement innovative strategies for tropical forest restoration, recent endeavours in the Eastern Mau Forest have yielded minimal impacts, highlighting the necessity to understand tree phytosociological parameters and soil biochemical elements that are essential for enhancing biodiversity and ecosystem health. By examining which restoration method optimally supports these ecological functions, this research sought to provide valuable insights that would inform effective restoration strategies, promote sustainable land management practices, and bolster forest protection efforts.

1.3 Objectives

1.3.1 Broad objective

To contribute to the enhancement of ecological restoration success by providing insights on ecological performance of multi versus single-taxa approaches on soil physico-chemical properties and tree attributes

1.3.2 Specific objectives

i. To assess the phytosociological attributes within the sites restored using single and multi-taxa approaches.

ii. To compare the soil physico-chemical properties (SOC, N, P and K) in single and multi-taxa approach.

1.4 Research hypotheses

i. Ho_1: Restoration methods have no significant influence on the tree phytosociological attributes.

ii. Ho_2: There is no significant difference in soil physico-chemical properties between single and multi-taxa approaches.

1.5 Justification of the study

Forests hold immense global and national importance, contributing approximately 3.6% to GDP (KFS 2018). However, forests and land degradation pose significant global concerns, particularly in developing countries grappling with rapid population growth and high unemployment rates (Obati & Breckling, 2015). Forest landscape restoration (FLR) is increasingly championed as a key solution to combat climate change, biodiversity loss, land degradation, poverty, and food insecurity (Jebiwott *et al*., 2021). Thus, the necessity for research on restoration remains crucial in addressing these urgent challenges.

This study holds relevance within the contemporary discourse on forest restoration as it aligns with the 15th Sustainable Development Goal (SDG) of life on land, aiming to sustainably manage forests, combat desertification, reverse land degradation, and halt biodiversity loss. Additionally, it intersects with other pertinent SDGs such as 1 - 'No poverty' and 13 - 'Climate Action'. The overarching objective of the Sustainable Development Goals is to conserve and restore the use of terrestrial ecosystems like forests by 2030 to mitigate the loss of natural habitats and biodiversity.

The findings of this study would be invaluable to forest managers, stakeholders from the Kenya Forestry Research Institute (KEFRI) and Kenya Forest Service (KFS), as well as researchers, facilitating the adoption of a convenient, cost-effective, and sustainable restoration approach for Eastern Mau forest and beyond. The study outcomes, including the evaluation of restoration success between Single and Multi-taxa approaches, and the assessment of soil organic carbon (SOC), potassium (K), phosphorus (P), and nitrogen (N) content, contribute significantly to understanding soil health. These elements play a pivotal role in supporting plant growth and ecosystem functioning. By elucidating the dynamic balance and ecological significance of these soil components, the study enhances our ability to predict and manage soil quality, thereby fostering sustainable forest management practices and ecosystem resilience.

1.6 Scope of the study

The study was conducted in Eastern Mau Forest, situated in Mau Narok, with a primary focus on the Sururu block where the Miyawaki method was implemented to restore land previously ravaged by fire and other factors like deforestation, land disputes, settlement, and agriculture. The conventional approach was also evaluated in the same location. The study involved identifying the species planted during the program's initiation. Restoration success was assessed by comparing the two methods in terms of vegetation recovery, forest establishment rate, and the restoration of soil organic carbon levels. Phytosociological parameters, including tree heights, diameter breast height, canopy cover, and soil organic carbon, were measured to evaluate growth and assess the impact of these methods on forest restoration. Trees and soil samples were obtained from established quadrats in areas where the methods were applied.

1.7 Limitations and delimitation of the study

i. Constrained accessibility to certain study sites was encountered due to steep and rugged terrain. To facilitate navigation on such terrain, a four-wheeled double cabin vehicle was employed. Additionally, the use of protective gear, including gumboots and dust coats, was imperative during the data collection process.

ii. Unpredictable weather patterns, especially excessive rainfall, rendered roads to certain sites impassable. Data collection was conducted on non-rainy days to mitigate the inconveniences and uncertainties associated with adverse weather conditions.

1.8 Operational definition of terms

Afforestation: The establishment of a forest or stand of trees in an area where there was previously no tree cover, aimed at creating new forested ecosystems.

Biodiversity: The variety and variability among living organisms within forest ecosystems, encompassing different species, genes, and ecosystems, contributing to the resilience and stability of ecosystems.

Carbon sequestration: A natural or artificial process by which carbon dioxide is removed from the atmosphere and stored in solid or liquid forms, such as within plants, soils, or geological formations, thereby mitigating climate change.

Climate change: Refers to changes in climate patterns attributed directly or indirectly to human activities that alter the composition of the global atmosphere, in addition to natural climate variability observed over comparable time periods (UNFCCC).

Conventional method: A traditional approach to reforestation involving fixed spacing between planted seedlings across the entire area, with any initiatives deviating from this pattern considered alternatives.

Ecosystem: A geographical area comprising all organisms and the physical environment with which they interact, functioning as a complex and interconnected system.

Forest degradation: The reduction in the capacity of forests to provide ecosystem services, such as carbon storage and wood products, resulting from anthropogenic and environmental changes.

Forest reclamation: The process of restoring disturbed forest land to its former state or to another desired condition through various interventions.

Forest restoration: Actions undertaken to reinstate ecological processes that accelerate the recovery of forest structure, ecological functioning, and biodiversity levels toward those typical of climax forests.

Glade: An open area within a forest, often characterised by grassy meadows under the canopy of deciduous trees.

Landscape ecology: The study of the pattern and interaction between ecosystems within a region of interest, and how these interactions affect ecological processes, particularly focusing on the unique effects of spatial heterogeneity.

Miyawaki approach: A restoration concept based on potential natural vegetation, determined from ecological scenarios using the main species of natural forests, enabling the restoration of the original ecosystem.

Phytosociology: A branch of ecology concerned with the structure, composition, and interrelationships of plant communities, focusing on the ecological aspects of plant populations and their associations.

Phytosociological parameters: Tree attributes such as species diversity, relative density, frequency, relative dominance, and importance value index, used to assess the structure and composition of plant communities.

Reforestation: The action of renewing forest cover through natural seeding or artificial planting of seeds or young seedlings, aimed at restoring forest ecosystems.

Soil organic carbon: A measurable component of soil organic matter, comprising carbon-containing compounds derived from decaying plant and animal matter, as well as microbial biomass.

Soil organic matter: The organic component of soil, consisting of plant and animal detritus at various stages of decomposition, soil microbes, and synthesised substances, playing a crucial role in soil fertility and ecosystem functioning.

Species diversity: The number of different species present in an ecosystem, along with the relative abundance of each species, influences ecosystem stability and resilience.

CHAPTER TWO
LITERATURE REVIEW

2.1 Forest restoration

Globally, forests cover approximately one-third of the Earth's land surface and play a critical role as habitats for more than 80% of terrestrial biodiversity. However, there is growing concern over the diminishing size and quality of forested areas, which poses threats to biodiversity and disrupts ecosystem functions (Jebiwott *et al.*, 2021). With population growth exerting increasing pressure on natural resources, it is essential not only to protect existing forests but also to embark on initiatives aimed at restoring forest ecosystems (Aerts & Honnay, 2011). Forest landscape restoration (FLR) is rooted in the principle of conserving eco-regions and involves deliberate efforts to restore ecological balance and enhance human well-being in areas affected by deforestation or degradation (Dimson & Gillespie, 2020).

Forest landscape restoration (FLR) is a strategic approach aimed at restoring ecological integrity and improving human well-being in deforested or degraded landscapes (Elias *et al.*, 2021). Unlike traditional reforestation efforts, FLR adopts a holistic approach that considers the entire landscape, including forest and non-forest areas (Wanyama *et al.*, 2023). The primary objective of FLR is to restore ecological functions and services while enhancing socio-economic conditions (Wanyama *et al*., 2023). This includes activities such as restoring forest cover, enhancing biodiversity, improving water and soil quality, mitigating climate change, and promoting sustainable land use practices (Chepkemoi, 2023). Active engagement with local stakeholders, including indigenous communities, government agencies, and non-governmental organisations, is essential for the success and long-term sustainability of FLR initiatives (Ronoh *et al*., 2018). FLR contributes to biodiversity conservation, poverty alleviation, climate change mitigation, and sustainable development goals (Aerts & Honnay, 2011). However, successful FLR requires careful planning, governance, funding, and robust monitoring and evaluation mechanisms to ensure effectiveness and adaptability (Kassa, 2018).

Such an approach facilitates achieving a balance between human needs and biodiversity conservation. In the context of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (2015), forest landscape restoration has been delineated as intensified efforts to safeguard forests, substantially restore degraded forests, peat lands, and agricultural lands, and to promote low-carbon rural development. According to the Food and Agriculture Organization (FAO, 2015), forest landscape restoration also encompasses actions aimed at bolstering the resilience and ecological integrity of landscapes through the active participation of local communities.

Forest restoration generally seeks to balance the requirements of humans with those of biodiversity, striving to restore diverse forest functions while recognizing and handling the trade-offs between them (Lamb & Gilmour, 2005). It integrates various ecological principles to guide its implementation, such as refraining from converting natural ecosystems, practicing adaptive management by modifying restoration strategies based on environmental conditions, human understanding, and societal preferences, adjusting to suit local socio-economic and ecological circumstances, and involving relevant stakeholders actively in decision-making concerning restoration objectives, methodologies, and compromises.

Moreover, the depletion and deterioration of forests compound both local and global challenges concerning sustenance and income, access to clean water, air quality, and climate stability. Impoverished landscapes also face heightened susceptibility to natural calamities and extreme weather events, including intense precipitation, flooding, and landslides (Bolan *et al*., 2024). Forest landscape restoration holds significant promise in tackling these concerns by revitalising landscapes to yield enduring advantages such as enhanced local climate moderation, enhanced flood and erosion mitigation, expanded access to food and non-food resources, and economic prospects for indigenous communities.

Forest restoration serves as a crucial instrument for bolstering climate resilience and minimising disaster risks (Wanyama *et al*., 2023). By enhancing forests, their resources, and associated processes, it mitigates hazards like floods, droughts, wildfires, landslides, and pest outbreaks, thereby supporting climate change mitigation and adaptation efforts while enriching ecological and socioeconomic values for the landscape and its inhabitants. Over time, this can lead to enhanced well-being and heightened resilience among local communities reliant on forests. Furthermore, the provision of landscape commodities such as food, water, timber, and medicinal resources promotes sustainable livelihoods, offering forest-dependent communities opportunities for income generation (Muthuri *et al*., 2023).

Loss of forest biodiversity poses a significant threat to the functioning of forest ecosystems, including vital processes like organic matter decomposition, soil nutrient cycling, and water retention, ultimately impacting the provision of ecosystem services (Rey Benayas *et al.*, 2009). Forest restoration plays a crucial role in reinstating biodiversity sanctuaries and ensuring the continued delivery of ecosystem services. However, given the escalating human population and the increasing demand for forest-derived goods and services, simply conserving existing forests may not suffice. Large-scale forest restoration, whether through passive or active means, emerges as a viable long-term solution to meet the growing needs for ecosystem services while preserving biodiversity, functions, and services of forests.

Establishing short-rotation single or multiple-species plantations on degraded soils, restoration plantings in secondary forests or assisted regeneration in selectively logged forest are a few examples of the wide spectrum of forest restoration approaches (Wekesa *et al*., 2018). Ecological restoration is therefore an important practice that may increase levels of biodiversity in human-altered ecosystems, protect soil properties, vegetative structure and physical components of biota and in the long run mitigate the impact of climate change (Dokata *et al*., 2023). Restoration presents a formidable challenge, as it entails halting the destructive cycle of degradation caused by excessive exploitation and initiating a positive cycle of forest restoration methods (Noulèkoun *et al*., 2021). Forest Landscape Restoration (FLR) is a comprehensive approach that requires involvement from various stakeholders, each contributing diverse technical insights, interests, and values. These include considerations such as land rights, cultural preservation, biodiversity conservation, water management, timber resources, and ecotourism (Zhou *et al*., 2018). These aspects are interconnected; for instance, ensuring clarity and security in land rights and tenure is essential for effective forest management practices and other FLR interventions.

There exist significant direct costs associated with the coordination, stakeholder engagement, and implementation of FLR interventions. These costs include foregone opportunities such as reduced harvests or lost income due to transitioning from existing land use practices, which vary among stakeholder groups and may ultimately prove ineffective in the long term (Noulèkoun *et al*., 2021). Marginalised groups may face immediate restrictions in resource access and use as a result of FLR, potentially jeopardising the success of the initiative. Furthermore, quantifying the goods and services derived from the restoration process poses a challenge (Lin *et al.*, 2024). While economic tools can aid in quantifying non-monetary benefits and costs, many ecosystem goods and services resist market valuation despite their ecological or social values. This complicates discussions and negotiations among stakeholders regarding FLR priorities.

Future uncertainty also presents a challenge to the success of restoration efforts (Noulèkoun *et al.*, 2021). Factors such as market forces, climate change, natural disasters, and political directions can evolve over time, making it exceedingly difficult to understand and manage the complexity of FLR projects or programs for positive long-term outcomes (Weiskopf *et al*., 2020). Restoring a matrix of forests within larger landscapes to meet diverse needs is a significant challenge (Ronoh *et al*., 2018). At this broader spatial scale, various influences, pressures, stakeholders, and habitats coexist, increasing the complexity of restoration efforts.

Balancing conservation priorities with other aspects of sustainable development requires negotiating trade-offs among a wide range of stakeholders (Chazdon *et al.*, 2021). This complexity necessitates a shift from site-based approaches focusing on individual forest benefits to broader-scale conceptualization, planning, and implementation. Achieving a balance between the various goods and services required from restored forest ecosystems demands planning and implementation on a broader scale (Ndubi, 2018). Identifying areas where forests are most beneficial and determining the type of forest suitable for specific locations are essential. Even in specialised conservation areas, cultural landscapes may be desired due to long-standing biodiversity adaptations or space constraints.

2.2 Restoration approaches in Eastern Mau Forest

In the context of Eastern Mau Forest in Kenya, efforts towards forest restoration have been underway for the past twenty years, spearheaded by the Kenyan government and key stakeholders such as the Kenya Forest Service (KFS) and the Kenya Forestry Research Institute (KEFRI). These endeavours have primarily aimed at reversing severe degradation through a multifaceted approach. While tree planting is a crucial component, restoration efforts also encompass protecting land from activities that contribute to deforestation and degradation (Kundu *et al*., 2003). Moreover, conservation measures are integral to allow for natural regeneration, thereby restoring vital ecosystem services like soil fertility, water filtration, and biodiversity preservation. Despite these initiatives, achieving forest restoration targets has been challenging due to various factors, including a lack of comprehensive knowledge on sustainable restoration techniques.

The selection of restoration approaches is contingent upon several factors, including the extent of degradation, available resources, and the desired restoration goals (Schirone *et al*., 2011). In the case of Kenyan forests, restoration mechanisms are broadly categorised into passive and active approaches (McLain *et al*., 2021). In the Eastern Mau Forest, particular attention has been given to two distinct methods: the Conventional approach and the Miyawaki method.

The Conventional method involves traditional tree planting techniques and management practices, while the Miyawaki method, named after Japanese botanist Akira Miyawaki, emphasises native species selection and dense planting to accelerate forest growth and biodiversity restoration (Schirone *et al*., 2011). These approaches have been implemented in specific sections of the Eastern Mau Forest, each tailored to address the unique ecological and social contexts of the area. However, despite the adoption of these strategies, significant challenges persist, highlighting the need for continuous research, adaptive management, and stakeholder collaboration to ensure the long-term success of forest restoration efforts in the region.

In addition to the Conventional and Miyawaki methods, other innovative approaches have also been explored in the restoration efforts within the Eastern Mau Forest. For instance, community-based restoration initiatives have gained traction as a means to not only restore degraded areas but also to foster local stewardship and livelihood improvement. These initiatives involve active participation and engagement of local communities in decision-making processes, implementation, and monitoring of restoration activities.

Furthermore, the integration of agroforestry practices within the forest restoration framework has emerged as a promising strategy in the Eastern Mau Forest. Agroforestry systems, which combine trees with agricultural crops or livestock, not only contribute to biodiversity conservation and soil restoration but also offer economic benefits to local communities. By promoting sustainable land management practices that enhance both ecological resilience and human well-being, agroforestry has the potential to complement traditional restoration approaches and address multiple objectives simultaneously. Moreover, recognizing the interconnectedness of ecosystems beyond the boundaries of protected areas, landscape-level approaches have gained importance in the restoration agenda for the Eastern Mau Forest including the Sururu block. Integrated landscape management strategies seek to reconcile competing land uses and interests across diverse stakeholders while promoting ecological integrity and sustainable development. By adopting a holistic perspective that considers not only forested areas but also adjacent lands and watersheds, landscape-level restoration initiatives aim to enhance ecosystem connectivity, resilience, and adaptive capacity in the face of ongoing environmental changes and human pressures.

In summary, the restoration efforts in the Sururu block encompass a spectrum of approaches ranging from traditional methods to innovative, community-driven, and landscape-scale initiatives. By leveraging diverse restoration techniques and engaging stakeholders at multiple levels, there is potential to overcome the complex challenges associated with forest degradation and achieve sustainable outcomes that benefit both nature and society.

2.2.1 Single-taxa approach (conventional method)

The conventional restoration approach, often referred to as the traditional method, is characterised by reforestation across a total area with fixed spacing between planted seedlings, typically focusing on single taxa or pure stands of fauna (Njue *et al*., 2016). While delineating precisely what constitutes traditional versus alternative approaches in forest restoration is challenging, traditional methods generally adhere to this fixed-spacing pattern, whereas alternative methods diverge from it. This traditional intervention tends to be most effective in areas undergoing active restoration and exhibiting less degradation, with a good capacity for spontaneous natural regeneration, a condition not met in the Eastern Mau. However, this approach exhibits biases in its reliance on silvicultural and agronomic techniques, influenced by local degradation levels, landscape characteristics, seed availability, and restoration costs across different regions (Edwards *et al*., 2021).

Heterogeneous reforestation with seedlings of native species, while mirroring forestry techniques used for *Eucalyptus spp* and *Pinus spp* does not seek to criticise or diminish the socioeconomic and environmental significance of these species for timber production. However, simply transplanting seedlings with specific spacing and fertilisation, as often done in Eucalyptus reforestation, may not fully replicate the complexity and ecological functions of native forests (Obati & Breckling, 2015).

Native forests' diversity and species arrangement are regulated by ecological processes such as dispersal, predation, competition, and nutrient cycling, encompassing various life forms besides tree species. Consequently, assuming that forests under traditional restoration can maintain planting alignment and a sparsely populated understory with a high density of regenerating shrub-trees is overly simplistic (Kweyu *et al*., 2020). Given the escalating impacts of climate change on terrestrial ecosystems, the conventional approach exhibits limited potential in rapidly producing forest cover and delivering substantial benefits for carbon sequestration, soil organic carbon, and biodiversity recovery.

The Green Zone Development Support Project in the Eastern Mau Forest (Sururu block), was initiated to enhance ecological restoration and improve land management practices in the region. This project aimed to address environmental degradation and promote sustainable agricultural practices by integrating local communities into the restoration efforts. The project emphasised community involvement, recognizing that local stakeholders play a crucial role in successful restoration initiatives. It sought to improve the quality of ecosystems while providing economic benefits to the communities involved. Despite these efforts, there remains uncertainty regarding the achievement of its restoration goals, highlighting the challenges faced in effectively implementing such projects in complex ecological and socio-economic contexts. Overall, while the Green Zone Development Support Project was a step towards ecological restoration, its long-term effectiveness and sustainability are still under evaluation (Bojie *et al*., 2023 ; Simonson *et al*., 2021).

2.2.2 Multi-taxa approach (Miyawaki system)

The Miyawaki method of reforestation, pioneered by Japanese Botanist Akira Miyawaki over four decades ago, has garnered significant attention well into the 21st century due to its distinctive features. This approach serves as an innovative tool for environmental reforestation, facilitating the rapid restoration of degraded areas by leveraging the concept of potential natural vegetation. This concept, rooted in ecology-based scientific scenarios using the primary species of natural forests, enables the restoration of the original ecosystem (Miyawaki, 2014).

At the core of the Miyawaki method lies dense planting and subsequent natural selection through competition, which collectively facilitate the creation of a diverse natural forest. The methodology entails planting seedlings of numerous main trees from the potential natural vegetation, predominantly canopy tree species native to the region. Additionally, the process incorporates mulching to enhance soil fertility and sustainability. Mulching serves various purposes, including mitigating soil dryness, preventing erosion on steep slopes, suppressing weed growth, providing insulation against cold temperatures, and serving as organic fertiliser as the materials decompose (Miyawaki, 2004).

The Miyawaki tree planting method commences with a comprehensive phytosociological survey aimed at obtaining a detailed environmental profile of the designated site. This survey facilitates the identification and classification of vegetation types into natural and substitute vegetation categories. Subsequently, the survey of potential natural vegetation is conducted, along with the preparation of an actual vegetation map for the area (Miyawaki, 2004). Following this initial phase, the planning for planting commences, wherein the selection of suitable species for planting is determined based on the actual vegetation map (Miyawaki, 2014).

Preserving the topsoil is of paramount importance during the preparation of the selected planting area. To achieve this, soil surveying, examination, and improvement processes are initiated, leading to the reconstruction of the topsoil. Concurrently, the production or procurement of young plants for planting is undertaken. Upon completion of the topsoil reconstruction, the planting area is covered with straw for mulching purposes, facilitating the dense and mixed planting of main tree species from the potential natural vegetation. These saplings are then nurtured for the initial three years through the provision of manure and weeding activities. Subsequently, they become self-sustaining, and within a span of 10 to 20 years, the area evolves into a native forest (Miyawaki, 2004).

The Miyawaki forests, characterised by several notable peculiarities, represent a distinctive approach to environmental reforestation. Firstly, the concept of Potential Natural Vegetation forms the foundation of the Miyawaki Method, wherein rigorous field investigations of local vegetation and ecological theories guide the restoration and reconstruction of forests indigenous to the habitat (Miyawaki, 2014). These native forests typically exhibit multi-stratal composition, comprising distinct layers such as an overstory tree layer, an understory tree layer, a shrub layer, herbaceous layer, and often a moss layer.

One key advantage of Miyawaki forests is their ability to defend against natural calamities, with trees indigenous to the area playing a crucial role in functions like flood control. Additionally, the Miyawaki method facilitates the rapid restoration and regeneration of ecologically diverse forests, contrasting with the lengthy timeframe required by classical succession theory (Miyawaki, 2004). While natural vegetation typically takes over 200 years to develop into forests, the Miyawaki method can yield quasi-native forests within just 25-30 years, promoting sustainable development of human society through ecological restoration (Miyawaki, 2004).

Moreover, native forests foster environmental preservation and mitigate impacts such as noise, dust, and air pollution while maintaining water quality. This becomes increasingly critical in addressing global environmental challenges like climate change, where fast-tracking solutions are imperative. The Miyawaki method has demonstrated success across diverse geographical zones, from cold-temperate to tropical forest zones, offering a highly effective means of restoration (Miyawaki, 1998).

Furthermore, Miyawaki forests entail minimal post-planting costs, as nature manages itself through natural selection after the initial three years, leading to noteworthy forest quality compared to traditional reforestation techniques (Miyawaki, 2004). Additionally, the preservation and regeneration of native forests can contribute to local economic activities, permitting selective cutting and selling after several decades (Miyawaki, 2014).

Despite these remarkable advantages, the Miyawaki method is not without its drawbacks. Dense planting may impede wildlife movement in fully matured forests, while competition for space and nutrients can lead to vertical growth and vulnerability to environmental hazards like wind, pesticides, and flooding (Miyawaki, 2014). Moreover, Miyawaki forests are highly flammable, posing a risk of rapid destruction in the event of fire outbreaks (Miyawaki, 2014). Consequently, while the Miyawaki method offers significant benefits in carbon sequestration and soil organic carbon storage, it is best implemented on a small scale, often near urban areas, to supplement and complement natural ecosystems rather than replace them.

Ultimately, the creation of native forests through the Miyawaki method represents a crucial and effective measure in reducing carbon dioxide levels and mitigating global warming, owing to their substantial carbon sequestration capacity and long-term carbon fixation in biomass (Miyawaki, 2014). Thus, while Miyawaki forests offer tremendous potential in environmental restoration, it is essential to carefully consider their limitations and complementary role within broader conservation strategies.

2.3 Response of phytosociological attributes to forest restoration approaches

The restoration of landscapes aims to reinstate ecosystem services, making them functional and productive while meeting the needs of dependent populations. Evaluating indicators from restoration efforts is crucial for gauging success (Kundu *et al*., 2003). However, assessing restoration success involves comparing outcomes against a broad set of pre-agreed-upon criteria.

The Society of Ecological Restoration International (SER) delineated nine ecosystem attributes for measuring restoration success, encompassing diversity, presence of indigenous species, functional groups, physical environment capacity, functioning, landscape integration, threat elimination, resilience, and self-sustainability (Buckner *et al*., 2016). While measuring these attributes provides a comprehensive assessment, financial constraints and the need for long-term studies limit their widespread application. Furthermore, estimates of many attributes often require detailed long-term studies, but the monitoring phase of most restoration projects rarely lasts for more than 5 years.

Phytosociological parameters, such as species diversity, relative density, frequency, dominance, and importance value index of trees, offer valuable insights into restoration progress. Vegetation diversity and structure, measured by richness, abundance, cover, density, biomass, and profiles, reflect ecosystem resilience and succession direction (Ruiz-Jaén & Aide, 2005). Ecological processes such as nutrient cycling and biological interactions (e.g., mycorrhizal, herbivory) are important because they provide information on the resilience of the restored ecosystem (Jebiwott *et al*., 2021).

The evaluation of diversity, vegetation structures such as tree heights, canopy covers, and diameter-breast height alongside ecological processes can be used to reflect the recovery trajectory and self-maintenance of restored ecosystems. Quantifying tree structure is an important aspect of understanding how trees respond to ecological restoration (Jebiwott *et al*., 2021). Diameter-breast height is also an important variable in relation to restoration evaluation.

It is a standard method of expressing the diameter of the trunk or bole of a standing tree. Diameter at breast height is specifically defined as the point around the trunk at 4.5 feet above the forest floor on the upper hill side of the tree. It is measured either using diameter tapes or callipers.

The most common methods for the field measurements of dbh are the use of callipers or diameter tapes (Kinyanjui, 2009). Diameter tapes are more commonly employed for permanent sample plots because they are perceived as being more consistent for repeated measures (Omoro *et al*., 2013). However, callipers are often used and preferred for dbh measurements in temporary plots or when measuring large numbers of trees, as they are quick and efficient to use (Kinyanjui, 2009). This feature is vital as it is used to calculate the volume, site index and carbon storage of the vegetation within a local ecosystem.

Comparing attributes in restored sites with reference sites in similar life zones and exposed to similar disturbances is essential for gauging restoration success (Kundu *et al*., 2003). Multiple reference sites mitigate variation and enhance accuracy but increase costs. In conclusion, monitoring phytosociological attributes is crucial for assessing the efficacy of forest restoration approaches. These parameters provide insights into diversity, structure, ecological processes, and stand characteristics, facilitating the evaluation of restoration success. Incorporating reference sites enhances accuracy but necessitates careful planning and increased costs.

2.4 Bio-chemical properties of soil

2.4.1 Potassium

Potassium (K) serves as a fundamental element in plant physiology, exerting significant influence over various growth, developmental, and stress response processes. Sardans and Peñuelas (2021) delineated the multifaceted roles of potassium, including its contributions to disease resistance, structural integrity, photosynthesis, root development, drought tolerance, starch synthesis, protein formation, water regulation, and enzymatic activities. Within forest ecosystems, comprehending potassium dynamics assumes paramount importance, particularly concerning land degradation and the promotion of ecosystem resilience in the Mau Forest Complex.

The presence of potassium in soil manifests in four primary forms: water-soluble, exchangeable, non-exchangeable, and mineral (Kaur, 2019). These forms collectively dictate potassium's availability to plants, with the water-soluble fraction being directly accessible for uptake. Exchangeable potassium functions as a reservoir, replenishing water-soluble potassium as plants utilise it. Under conditions of depletion, non-exchangeable potassium may convert to exchangeable forms, while mineral potassium constitutes a significant portion of soil potassium, releasing slowly due to soil weathering processes.

Various restoration methodologies employed in the Mau Forest, such as reforestation and soil management practices, exert notable impacts on potassium dynamics by modulating soil properties and nutrient cycling processes. Several studies underscore the significance of incorporating potassium sources, such as manure, crop residues, or fertilisers, to bolster potassium redistribution among soil forms, thereby enhancing plant uptake. Nonetheless, the availability of potassium to plants remains subject to intricate factors, including soil speciation and release kinetics, accentuating the nuanced nature of potassium dynamics within forest ecosystems (Andrews *et al*., 2021).

Potassium deficiency in plants manifests through discernible symptoms, such as chlorosis of leaf margins and tips, typically commencing from lower leaves and progressing upwards, culminating in overall yellowing and leaf abscission. Furthermore, potassium deficiency impairs growth, leading to reduced branch development and diminished vigour (Kant & Kafkafi, 2002; Sardans & Peñuelas, 2021). Soil potassium levels are typically evaluated via extraction methods employing compounds like ammonium acetate, facilitating the leaching of potassium ions from the soil and enabling the quantification of available forms for plant uptake.

In summation, potassium assumes a pivotal role in forest ecosystem dynamics, profoundly influencing plant health, productivity, and resilience. Restoration endeavours in the Mau Forest wield significant influence over potassium availability through modifications to soil properties, nutrient cycling, and management practices. A comprehensive understanding of potassium dynamics and its interplay with other soil nutrients is indispensable for devising efficacious restoration strategies aimed at mitigating land degradation and fostering ecosystem sustainability within the Mau Forest Complex. Subsequent research endeavours should aim to explore innovative potassium management approaches tailored to the specific exigencies of forest restoration within degraded landscapes.

2.4.2 Soil organic carbon

Changes in soil organic carbon (SOC) influenced by climatic factors and vegetation have attracted significant attention in assessing the impact of global change on ecosystem carbon balance and in formulating strategies for carbon dioxide (CO_2) sequestration using natural systems. Soil, which holds approximately three-quarters of the organic carbon found in terrestrial ecosystems, plays a crucial role in regulating atmospheric CO_2 levels. The process of forest restoration also plays a vital role in this carbon cycle.

Forest restoration efforts aim to increase forest cover and promote healthy ecosystems, thereby enhancing carbon sequestration capacity. By restoring degraded forests, we not only mitigate carbon emissions but also contribute to the accumulation of soil organic carbon. Consequently, understanding the dynamics of SOC in restored forests is essential for evaluating the effectiveness of restoration efforts in mitigating climate change and maintaining ecosystem carbon balance.

Forests serve as the primary terrestrial reservoir of carbon, accounting for approximately 90% of all terrestrial biota biomass (Lin *et al.*, 2022). This equates to around 2.4 gigatons of carbon being withdrawn from the atmosphere annually. Forests play a crucial role in regulating the global carbon balance by sequestering carbon and emitting carbon dioxide (Njana *et al*., 2021). Their contribution to controlling atmospheric carbon flux, which includes the accumulation of soil organic carbon (SOC), is widely recognized as one of the most critical ecosystem services. Soil organic carbon (SOC) levels typically exceed vegetation carbon levels by 1.5 to 3 times, emphasising the importance of organic matter in forest soils for assessing land management practices and soil fertility (Kimaro *et al*., 2024; Mayer *et al*., 2020).

Nonetheless, increasing rates of deforestation and forest degradation have resulted in a reduction in forest coverage, reducing their ability to retain carbon. According to the Food and Agriculture Organization (FAO), forest biomass experienced an annual decline of 1.1 gigatons of carbon from 1990 to 2005, followed by an additional decrease of 0.5 gigatons per year from 2005 to 2010 (Asiva Noor Rachmayani, 2015). In recent years, there has been a growing global emphasis on assessing SOC, acknowledging its critical role in evaluating soil fertility and ecosystem functioning.

Several factors can influence soil organic carbon (SOC) stocks and composition. Climate plays a crucial role in shaping forest SOC dynamics by affecting both input, such as changes in plant productivity, and output, including alterations in soil microbial and faunal metabolism. The overall response of SOC to climate change hinges on the balance between these two processes (Wei *et al*., 2023). However, the majority of research on the response of SOC to warming has predominantly focused on decomposition, often overlooking the contribution of SOC input. The impacts of forest restoration practices on SOC fractions and chemical structures remain a topic of ongoing debate, highlighting the need for further investigation into their effects.

Soil organic carbon (SOC) is a crucial component in understanding the effects of carbon emissions resulting from land-use changes in the context of global climate change. The spatial distribution of carbon density is vital in assessing the impact of anthropogenic activities on ecosystems. Soil organic carbon levels are highly sensitive to various forms of soil degradation, including lopping, pollarding, deforestation, land use/land cover (LULC) changes, accelerated soil erosion, runoff leading to soil degradation, biomass burning, environmental pollution, and land use patterns and practices.

Furthermore, SOC serves as an indicative factor for assessing the soil's ability to provide favourable environmental conditions for vegetation growth and development. It reflects a comprehensive understanding of soil physical, chemical, and biological properties (Tarus *et al*., 2019). As such, it plays a pivotal role in ecological restoration efforts. Forest restoration, particularly through afforestation, emerges as a highly effective means of ecological restoration. Afforestation can help prevent wind and sand fixation, reduce water and soil loss, enhance land productivity, and improve the ecological environment. By restoring degraded forest lands, afforestation initiatives contribute to SOC sequestration, thus aiding in climate change mitigation efforts.

Continuous biotic interference is recognized as a significant driver of forest degradation, often affecting larger areas than deforestation itself. While forest cover monitoring in Eastern Mau has received considerable attention and has remained relatively unchanged over the past two decades, less focus has been placed on assessing soil carbon stocks, particularly in forest soils post-rehabilitation. Changes in vegetation density, whether gradual or sudden, can adversely impact the physicochemical characteristics of exposed soils, leading to variations in soil carbon reserves.

Forest degradation processes manifest in various forms, including reductions in forest crown cover, tree density (both measurable through remotely sensed data), biomass density, and biodiversity loss, among others. Furthermore, forest degradation is intricately linked to soil degradation, quality, and erosion. Therefore, quantifying soil organic carbon (SOC) is essential for understanding ecosystem sustainability and predicting productivity. It has been hypothesised that SOC density varies with forest cover type and density and is influenced by biotic pressures.

Forest restoration activities play a crucial role in combating land degradation. Deforestation and unsustainable land management practices lead to soil erosion, loss of soil fertility, and degradation of ecosystem services. Through afforestation and reforestation, degraded lands can be rehabilitated, soil erosion can be mitigated, and the overall health and resilience of ecosystems can be restored. It aims at restoring degraded grassland, has been touted as a useful approach to protect vegetation and exposed soil against wind and water erosion. It is fundamentally important to understand the effect of ecological restoration on plant community characteristics and soil quality to evaluate the effectiveness of ecological restoration measures.

Soil physicochemical and biochemical properties have become important indicators for evaluating soil quality. Soil microbial biomass and enzyme activities, especially those of enzymes involved in the Carbon cycle, play essential roles in nutrient mineralization, the decomposition of organic matter, and nutrient cycling. Thus, these soil microbiological properties are valuable metrics for evaluating the effects of restoration on soil function in terrestrial ecosystems and assessing the effectiveness of different restoration measures.

Several studies highlight the potential of the Miyawaki approach in enhancing plant growth and soil properties, particularly in China and Japan. Successfully implementing this ecological restoration measure in Mau and other Kenyan forests could be instrumental in accumulating soil nutrients, enhancing microbial biomass, activating enzyme activities, and ultimately conserving higher levels of soil organic carbon. The positive outcomes observed in other regions suggest that adopting the Miyawaki approach in the context of Mau and similar ecosystems could contribute significantly to the overall ecological restoration and sustainability of soil health in these areas.

2.4.3 Nitrogen

Nitrogen, as an essential nutrient for plant growth, plays a critical role in the functioning of forest ecosystems. Its deficiency can have significant implications for plant health and ecosystem dynamics. This deficiency often manifests in various symptoms, including chlorosis and leaf loss, ultimately impacting forest productivity and resilience (Heo & Park, 2022; Lu *et al*., 2021). In forest soils, nitrogen availability is influenced by a variety of factors, including land use changes, climate change, and soil degradation.

The Mau Forest Complex in Kenya, a vital ecosystem in East Africa, has experienced significant land degradation and deforestation, leading to nitrogen depletion in soils (Duguma *et al*., 2019). This depletion has far-reaching consequences for forest health, biodiversity, and ecosystem services. Climate change exacerbates nitrogen limitations in forest soils, altering precipitation patterns and increasing temperatures. These changes can disrupt nitrogen cycling processes, further reducing nitrogen availability for plant uptake (Hui *et al*., 2024). Additionally, land degradation practices, such as deforestation and agricultural expansion, contribute to soil erosion and nutrient loss, exacerbating nitrogen deficiencies in the forest ecosystem.

Forest restoration efforts in East Africa, including the Mau Forest, aim to address these challenges by restoring degraded landscapes and enhancing ecosystem resilience. The

Miyawaki approach, a restoration method that emphasises dense planting of native species, has shown promise in promoting biodiversity and soil health in forest ecosystems (Meguro *et al*., 2021). By restoring vegetation cover and enhancing nutrient cycling, this approach can help alleviate nitrogen deficiencies in forest soils.

Implementing sustainable land management practices is crucial for improving nitrogen availability and soil fertility in forest restoration projects. Techniques such as agroforestry, organic matter addition, and cover cropping can enhance nitrogen retention and cycling, supporting long-term ecosystem health and productivity (Were *et al*., 2015). These practices also contribute to climate change mitigation by sequestering carbon and enhancing soil organic carbon levels. Furthermore, community involvement and stakeholder engagement are essential components of successful forest restoration initiatives. Engaging local communities in restoration activities fosters a sense of ownership and promotes sustainable land management practices. In the context of the Mau Forest, community-based approaches to restoration have been shown to enhance project sustainability and effectiveness (UNFCCC, 2003).

2.4.4 Phosphorus

The role of restoration methods in influencing phosphorus dynamics within forest ecosystems is a critical aspect of forest management and conservation. In recent years, researchers have extensively studied the impact of different restoration approaches on phosphorus availability and its interactions with other soil nutrients. This literature review aims to explore the relationship between restoration methods, phosphorus availability, and other key soil nutrients in forest ecosystems, focusing on the Eastern Mau Forest in Kenya. The Miyawaki method, developed by Akira Miyawaki, emphasises dense planting of native species to accelerate forest regeneration.

This approach promotes biodiversity and ecosystem resilience, which can have implications for soil nutrient dynamics, including phosphorus. Studies by Johan *et al*. (2021) have shown that the Miyawaki method enhances soil organic matter content, leading to improved phosphorus retention and availability in degraded forest soils. By fostering a diverse plant community, the Miyawaki method creates favourable conditions for nutrient cycling and soil organic carbon accumulation, ultimately benefiting phosphorus availability in the ecosystem.

Conventional restoration practices, on the other hand, often focus on reforestation with economically valuable species. While these practices may contribute to ecosystem stability, they may not prioritise soil nutrient dynamics as explicitly as the Miyawaki method. However, research by Fahad *et al*. (2022) suggests that targeted soil amendments and fertilisation can enhance phosphorus availability in conventionally restored forest areas. By incorporating phosphorus-rich organic matter or applying fertilisers, restoration practitioners can replenish nutrient-depleted soils and support plant growth and ecosystem recovery.

Phosphorus availability in forest soils varies with soil depth, influencing plant nutrient uptake and ecosystem productivity. Studies have shown that phosphorus tends to accumulate in surface soil layers due to organic matter decomposition and root activity (Spohn, 2024). Therefore, restoration methods that promote soil organic matter accumulation, such as the Miyawaki method, may enhance phosphorus availability in surface soils, supporting plant growth and establishment.

The availability of phosphorus in forest soils is intricately linked to other essential nutrients, including nitrogen (N) and potassium (K). Soil nutrient interactions influence plant nutrient uptake and ecosystem functioning, with implications for forest health and productivity. Other researches have also highlighted the importance of balanced nutrient availability for optimal plant growth and development. In degraded forest ecosystems, imbalances in nutrient availability, such as phosphorus deficiency, can limit plant productivity and ecosystem resilience.

In conclusion, the choice of restoration method can significantly influence phosphorus dynamics and soil nutrient interactions in forest ecosystems. The Miyawaki method promotes biodiversity and soil organic matter accumulation, leading to enhanced phosphorus availability and ecosystem resilience. Conventional restoration practices can also improve phosphorus availability through targeted soil amendments and fertilisation. Understanding the complex interactions between restoration methods, phosphorus availability, and other soil nutrients is essential for designing effective forest restoration strategies in the Eastern Mau Forest and beyond. Further research is needed to explore innovative approaches to phosphorus management tailored to the specific challenges of forest restoration in degraded landscapes.

2.5 Theoretical framework

Forest restoration relies on a multidisciplinary approach influenced by various factors, primarily ecosystem-related. Succession theory plays a crucial role in predicting the evolution of ecological communities over time, including their trajectory back to a pre-disturbed state (Choi, 2004). While there are debates about its accuracy, succession theory is extensively employed in restorative conservation efforts aimed at degraded habitats or those recovering from disturbances, providing a conceptual framework to guide practices and procedures. Succession entails the continuous, unidirectional change in species composition within natural communities, typically initiated by disturbances.

Succession theory is not limited to describing natural processes but also encompasses artificially induced disturbances. Despite differing opinions on the predictability and utility of successional trajectories, temporal shifts in community composition reflect changes in species presence and relative abundance across environments. Although commonly associated with plant communities, succession theory is applicable to shifts in populations of various organisms (Poorter *et al*., 2023). Succession occurs in diverse settings and can vary in rate depending on the intensity and scale of the disturbance, ranging from volcanic eruptions to abandoned urban lots to glacial retreats.

Succession occurs when disturbances render an area devoid of vegetation, whether due to natural phenomena or human activities (Poorter *et al*., 2023). Disturbances manifest in various forms, from catastrophic events like volcanic eruptions to more localised incidents such as tree mortality. The pace of recovery differs between primary and secondary succession, with primary succession characterised by the slow establishment of communities following the complete loss of vegetation and soil profile, whereas secondary succession occurs after less severe disturbances, allowing for quicker recolonization (Coradini *et al*., 2022).

Successional communities can be categorised as early or late, with early communities establishing rapidly and late communities developing over time (Hanusch *et al*., 2022). Understanding succession theory is essential for ecological restoration efforts, as it provides insights into the dynamics of ecological community changes over time (Chang & HilleRisLambers, 2016). Ecological restoration typically involves two stages: colonisation, where slow-growing, adaptable species are selected and introduced, and ecosystem development, which involves the accumulation of nutrients in the soil, altering soil structure, and reducing toxicity. By aligning species introductions with appropriate successional stages, restoration efforts can be more efficient and effective.

Despite its limitations, succession theory remains widely utilised in restoration conservation due to its conceptual utility. Rooted in the ideas of community progression over time, succession theory enables researchers to describe and predict community structure changes through observation. Although Clements' original model had its inaccuracies, it laid the groundwork for subsequent models of succession. Disturbance regimes, whether natural or human-induced, uniformly affect community composition and are central to understanding ecosystem dynamics.

2.6 Research gaps

Even though many studies have been done on evaluating forest restoration methods and their influence on vegetation structures, there still exist insufficient pool of information on how various approaches such as multi-taxa thrive as compared to single taxa approach, their influence on phytosociological attributes and soil mineral content (SOC, N, P, and K). Studies conducted in Mau Forest have been those on disturbances caused by humans (Kinyanjui, 2009; Ronoh *et al.,* 2018) no recent study has been done evaluating the existing restoration approaches and their impact on regeneration rate (Hopkinson *et al*., 2020). Therefore, this study will focus on comparison between single-taxa and multi-taxa approaches by assessing the growth attributes and chemical soil properties in Eastern Mau Forest.

The Miyawaki method has been adopted by forest managers in India, Japan, China, Amazonian rainforests in Brazil, Mt Kenya forest as well as Eastern Mau in Kenya and has covered over 3000 projects worldwide (Padilla & Pugnaire, 2006). However, the literature does not provide a substantial threshold of evaluating the effectiveness of this approach in the Eastern Mau Forest. Most studies conducted are limited to self-evaluation rather than comparison. Most of the literature focus on natural potential that the approach offers and their influence on carbon stocks with very little attempt on other mineral elements such as Nitrogen, Phosphorus, Potassium and their implication on soil health.

Studies in Mau forest have focused on natural and artificial disturbances according to Ronoh *et al*. (2018), human encroachment and their influence on vegetation structure (Kinyanjui, 2009), resource based conflicts , assessment of the challenges and opportunities of restoring the Eastern Mau Forest (Chepkemoi, 2023) and the effect of forest management types on soil carbon stocks in Eastern Mau Forest in Kenya (Tarus *et al*., 2019). Less has been done on comparing various restoration approaches, growth attributes and soil minerals. Therefore, there is a need to provide information for policy formulation to decision makers and forest managers on the best approach to be incorporated for specified objectives of restoration in order to conserve biodiversity and to increase forest cover in Kenya.

Table 2.1: Research gaps

Author(s) and year of publication	Research topic/focus	Research gaps
Chepkemoi (2023)	Assessment of the challenges and opportunities of restoring the Eastern Mau Forest emphasised on underlying.	The author emphasised on underlying challenges & opportunities towards forest restoration, with little focus on the evaluation of the restoration success and soil influence through restoration
Kinyanjui (2009)	The effect of human encroachment on forest cover, composition and structure in the Western and Eastern Blocks of the Mau Forest Complex.	The study focused only on the structure, composition and forest dynamics as a result of human encroachment. Restoration approach not indicated.
Tarus *et al*. (2019)	The effect of forest management types on soil carbon stocks in Eastern Mau Forest in Kenya.	Even though this study took place in Eastern Mau, the element of focus was SOC, with little evaluation on N, P and K.
Poddar (2021)	Miyawaki technique of afforestation in India and Mediterranean, Mediterranean and parts of Malaysia and far East	The study only evaluates the Miyawaki method after 8 years of initiation, it is further constrained to SOC & canopy cover.

2.7 Conceptual framework

This section explained the interrelationships among the forest restoration techniques, phytosociological attributes and soil chemical properties. The multi-taxa approach represented the Miyawaki method of restoration. It is an innovative tool for environmental reforestation that allows rapid restoration of degraded areas. The concept is based on potential natural vegetation, which is determined from ecology-based scientific scenarios using the main species of natural forests, enabling restoration of the original ecosystem (Miyawaki, 2014). The method involves dense planting and subsequent natural selection through competition, resulting in the creation of a diverse natural forest (Miyawaki, 2004). Mixed stands of *Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis and Prunus* africana were planted in Eastern Mau Forest in 2017 with 3-5 species/square metre.

The second independent variable in this study was the conventional method of restoration, which is commonly known as the traditional restoration method. This approach typically involves planting tree seedlings at fixed spacings of 2.5 metres by 2.5 to 3.0 metres. In most cases, this method focuses on the use of single taxa, resulting in pure stands of a single species at a time. The regeneration process of forest ecosystems is driven by ecological succession. This process is initiated by seeds present in the soil seed bank, as well as by seeds dispersed through seed rain. Additionally, the growth of stalks and root buds from various life forms plays a crucial role, often forming regeneration nuclei. Phytosociological were the dependent variable which related to tree attributes such as tree heights and diameter-breast height, these measures were useful for predicting the direction of plant succession. Quantifying tree structure is an important aspect of understanding how trees respond to ecological restoration. Diameter at breast height (DBH) is vital as it is used to calculate the volume, site index and carbon storage of the vegetation within a local ecosystem.

Tree heights were used as indicators to determine site's ability to sustain plantation, stand growth and productivity, site index and as the most important factor for estimating wood volume. In addition to evaluate these attributes in the restored site, it was necessary to compare them with values from reference sites to estimate the level of restoration success sites should occur in the same life zone, close to the restoration project, and should be exposed to similar natural disturbances. Forest regeneration or succession is dependent on various factors which represent intervening variables in this case. Regeneration degree, forest management activities, soil horizons and soil health status, climate variability, vegetation vigour and species variation. These variables depict the direction of restoration success in relation to the method of use, tree attributes and soil contents of SOC, N, K and P.

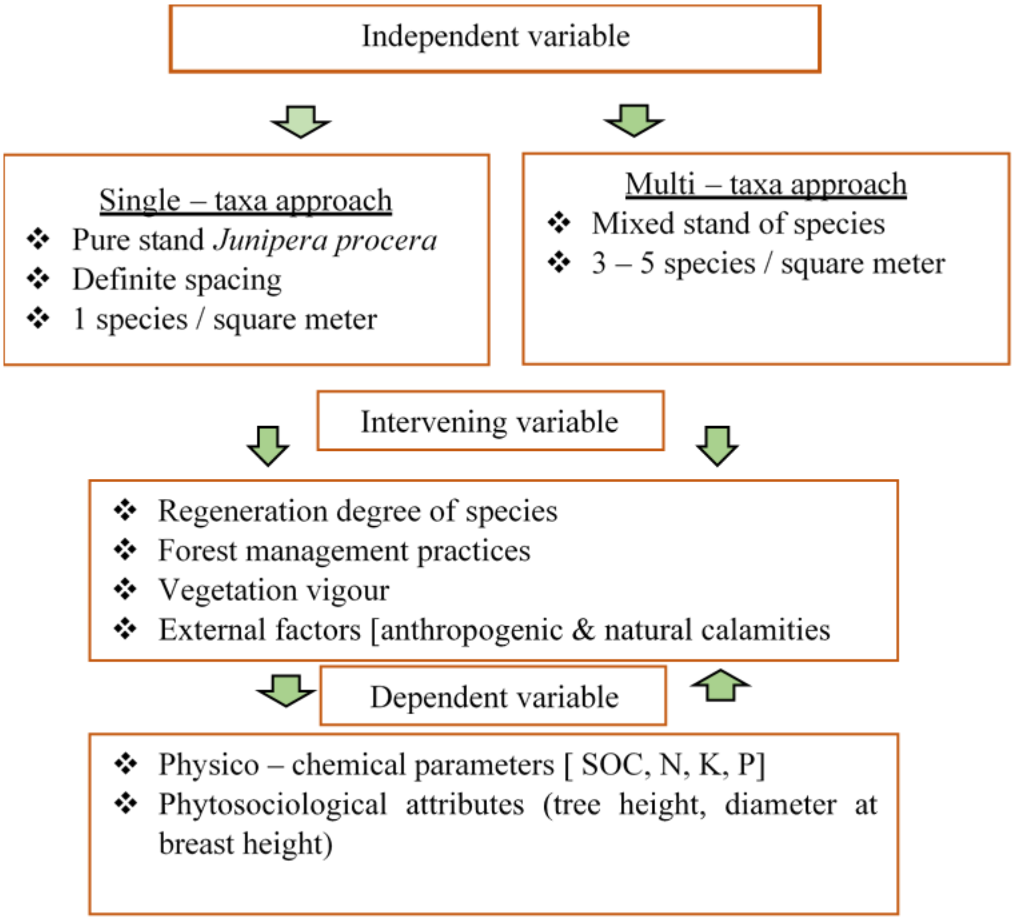

Figure 2.1: Schematic presentation of the conceptual framework (Source – Researcher)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Location of the study area

The study was carried out within the Sururu forest block, nestled within the Eastern Mau forest reserve, precisely situated between latitudes 0°31'15" S - 0°36'30" S and longitudes 36°0'10" E - 36°4'25" E. Encompassing an area of approximately 13,364.4 hectares, Sururu forest block plays a pivotal role as a vital watershed, contributing significantly to the hydrological dynamics of key regional lakes, including Victoria, Nakuru, Baringo, and Natron. This verdant expanse hosts a rich tapestry of tree species, prominently featuring *Aningeria adolfi-friedericii* and *Strombosia scheffleri,* both of which are integral to the intricate ecological balance of the area. The forest's biodiversity flourishes with an array of wildlife, including elephants, antelopes, and primates, underscoring Sururu's status as a vibrant ecological hub within the expansive Mau Forest Complex.

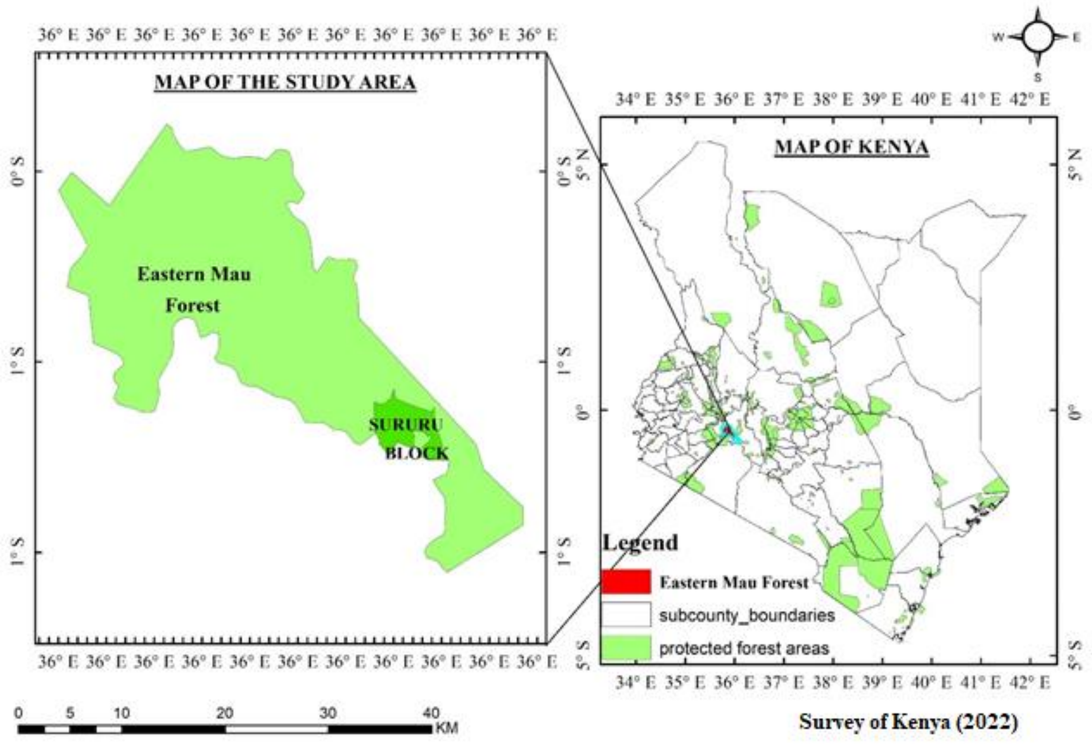

Figure 3.1: Map of Kenya showing Sururu block in Eastern Mau Forest (Modification from survey of Kenya, 2022)

3.1.1 Climate and soils

The Eastern Mau Forest, part of the larger Mau Forest Complex in Kenya, is characterised by a rich diversity of soil types and physicochemical properties shaped by its unique altitudinal zonation and climatic conditions. The region experiences a trimodal precipitation pattern, with annual rainfall averaging around 1,200 mm, leading to significant seasonal variations that impact soil moisture and nutrient dynamics (Kinyanjui, 2009). The soils are generally well-drained and deep, featuring a thick humic top horizon that supports various vegetation types, including lower montane forests transitioning to middle and upper montane ecosystems (Tarus *et al*., 2019).

The findings from previous studies indicated that soil organic carbon (SOC) stocks in the Eastern Mau Forest were significantly affected by forest management practices. Undisturbed natural forests exhibit higher mean SOC stocks compared to disturbed areas and mono-species plantations, with undisturbed natural forests recording approximately 135.17 Mg·C/ha versus 116.51 Mg·C/ha in mono-species plantations. This disparity underscores the critical role of biodiversity in maintaining soil health and nutrient availability (Tarus *et al*., 2019). Soil organic carbon serves not only as an indicator of soil health but also contributes to essential functions such as water retention, nutrient cycling, and habitat for microorganisms (Khambalkar *et al*., 2021).

The physicochemical properties of the soils reflect variations in nutrient content, with pH levels ranging from 5.6 to 6.4, conducive for nutrient availability (Kinyanjui, 2009). Nutrient analyses reveal significant variations in nitrogen (N), phosphorus (P), and potassium (K) levels based on land use and management practices. For example, the conversion from natural mixed-species forests to mono-species plantations has been linked to decreased nutrient retention and increased soil degradation (Widyati *et al*., 2022). Studies show that nitrogen levels are higher in mixed-species systems due to enhanced litter decomposition rates and microbial biomass associated with greater plant diversity. Soil microbial communities play a vital role in nutrient cycling within these ecosystems. The presence of arbuscular mycorrhizal fungi correlates positively with higher SOC levels and improved nutrient cycling in tropical forests (Xiao *et al*., 2023). This symbiotic relationship emphasises the importance of maintaining diverse plant communities for healthy soil ecosystems. Increased biodiversity also leads to greater functional redundancy within microbial communities, enhancing ecosystem resilience against disturbances (Zhang *et al*., 2023).

Understanding the physicochemical properties of soils in the Eastern Mau Forest is essential for developing effective restoration strategies. Evidence suggests that multi-taxa restoration approaches may be more effective than single-taxa methods in enhancing soil health and nutrient dynamics. A comparative study demonstrated that multi-taxa restoration improved SOC levels and overall biodiversity compared to mono-species plantations (Tinya *et al*., 2023). This research aims to provide insights for effective restoration strategies tailored to the unique ecological context of the Eastern Mau Forest, promoting sustainable land management practices and enhancing forest protection efforts.

3.2 Research design

The study employed descriptive-comparative and nested-experimental research design for data collection procedures. Two systematic blocks measuring 50 m by 50 m within each of the forest restoration approaches (Miyawaki and conventional) were established. In each block, four random plots measuring 10 m by 10 m were nested, and in each plot, six random soil auger points were identified for sampling in a zigzag way. In understanding the effect of depth on the availability of soil elements, samples were obtained at a depth of 0-15cm and 15-30cm. These designs were incorporated through a systematic identification; measurement and analysing the similarities and differences that existed in the tree phytosociological parameters such as tree heights and diameter breast height between the two sites. Thereafter, restoration success in Eastern Mau Forest was evaluated from the comparison of the dynamics and forest structures and soil elements (C, N, P, K and C/N).

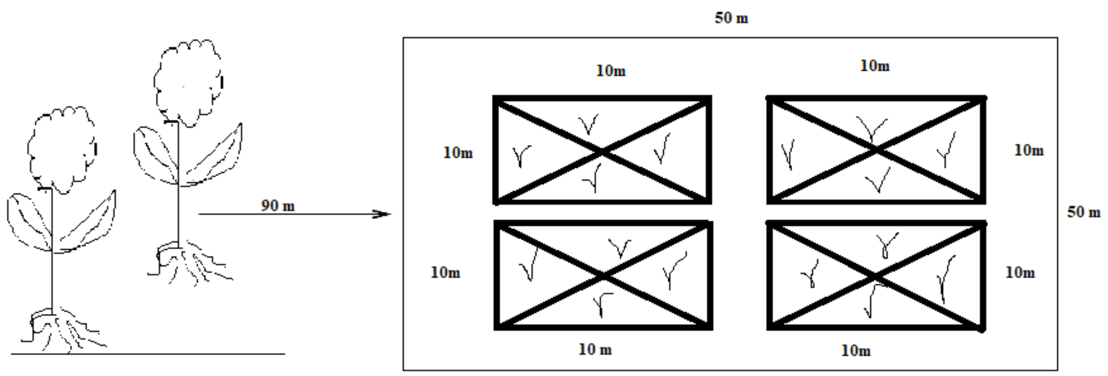

Figure 3.2: Schematic illustration of research design

3.3 Data collection

3.3.1 Measurement of the tree phytosociological attributes

The study employed Line Intersect sampling and nested experimental design to divide the study site in each restoration block, 50 m by 50 m in size. Four random plots measuring 10 m by 10 m in each block were nested. The first line transect was laid at 90 metres from the forest edge (cutline), sample plots were each separated with a distance of 10m from the other.

Identification of specific tree species of *Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis and Prunus africana* was done and their structural attributes i.e. tree heights and diameter breast height measured. A calibrated rode was used to measure individual tree height in the defined six sample plots and the heights were recorded in metres. Diameter breast-height of the trees was measured by use of a calibrated diameter tape alongside callipers and the values estimated on the callipers scale. The following procedure was followed on previously sampled trees;

i. Using a tape measure, 4.5 feet was measured up the tree trunk from the ground and a marker pen was used to mark the height on the tree.
ii. Measuring tape was wrapped around the tree trunk aligning with the mark
iii. Values were read and the circumference measurement was converted to diameter by dividing by pi (3.14)

    DBH= Circumference/pi

In multiple stemmed-trees, the size was determined by measuring all the trunks, and then adding the total diameter of the largest trunk to one-half the diameter of each additional trunk.

3.3.2 Field survey and soil sampling

Four sample plots measuring 10 m x10 m were nested in each restoration block of 50 m by 50m in size (Single and Multi-taxa). Soil samples were then obtained at six points in each plot at a depth of 0-15 cm and 0-30 cm in a zigzag way (2-vertical, 2-horizontal and 2- diagonal) by the use of a 5-cm diameter soil auger. Each soil sample was collected after removal of the surface litter and debris, and the sampling points were at least one metre away from the tree canopy. Soil samples collected from the respective sampling plots were thereafter mixed to form a composite sample relating to depth strata. Each site provided 24 soil samples, 12 from 0-15 cm and 12 from 0-30cm depth to give a total of 48 samples that were taken to the laboratory.

3.3.3 Soil pre-treatment

In the laboratory, extraneous materials were handpicked from the soil samples. This was followed by air-drying the soil samples on clean open trays for three days and homogenising them by grinding using a miller. The samples were then oven-dried to a constant 24 weight for 48 hours at 5°C then cooled. Large unwanted particles were removed by sieving using size 600 µm mesh. After sieving, the samples were grinded using an agate mortar and a pestle to particle sizes of nano-metres range. The powder obtained after sieving was stored in clean-labelled polythene bags in desiccators, ready for analysis. The procedure was repeated for the rest of the samples from each subplot. All the reagents and chemicals used for the study were of analytical grade and were used as obtained from the suppliers without further purification. Some of the required reagents were prepared in the laboratory as follows:

Solution A (acetic acid, 0.11 mol/l) was prepared by dissolving 3.3022 gram of acetic acid under fume cupboard to 500 ml volumetric flask and made up to the mark with distilled water to give an acetic acid solution of 0.11M.

Solution B (ascorbic acid, 0.2 mol/l) was prepared by dissolving 4.4033 grams of ascorbic acid in a 250ml volumetric flask then adding distilled water to the mark. The solution was then covered with aluminium foil and kept at 4°C in a refrigerator.

Solution C (hydrogen Sulphate, 8.8 mol/l) was prepared by transferring 67.4072 ml pure hydrogen Sulphate into a 250 ml volumetric flask and diluting to the mark with distilled water.

Solution D (ammonium acetate, 1.0 mol/l) was prepared by dissolving ammonium acetate (38.54 g) in 300 ml distilled water in a 500 ml volumetric flask. The pH of the solution was adjusted to around 2.0 with 0.1-degree fluctuation by using HNO_3 and filling it up with distilled water.

Soil samples were analysed for nitrogen and organic carbon at the Soil Science Laboratory in Egerton University while potassium and phosphorus at Chemistry laboratory both at Egerton University. The AAS measurements for potassium and phosphorus were carried out on a buck scientific 210 VGP atomic absorption spectrometer (Varian Spectra AA. 10 model) equipped with a hollow cathode lamp as the radiation source. An acetylene–nitrous oxide flame was used; the gas flow rates and the burner height were adjusted in order to obtain the maximum absorbance signal for each element. The AAS was calibrated using SY-3 rock standards for all the analysis done. Determination of nitrogen was done by Kjeldahl (AKA-11 model).

3.4 Soil analysis

3.4.1 Total organic carbon content

A soil sample (0.3 g), dried at 105 for 1 hour, was placed in a ceramic crucible, heated at 550 for 2 hours, cooled in desiccators then weighed. Quantification of the soil organic content was done for the 24 samples from each site to obtain Total Carbon Stocks (TOC) determined as per the Walkley and Black titration method by subjecting the soil to complete oxidation (Sulphuric acid and aqueous potassium dichromate mixture) followed by titration using ferrous Ammonium Sulphate on the unused potassium dichromate as outlined (Tarus *et al*., 2019). A blank titre was used as a controlled experiment. The difference between added and residual potassium dichromate therefore denoted a measure of organic carbon content in the soil samples.

The soil organic carbon (SOC) was derived using the following equation:

$$SOC = \frac{Initial\ weight\ (g) - Final\ weight\ (g)}{Initial\ weight\ (g)} \times 100 \quad \text{.............. Eqn (1)}$$

3.4.2 Determination of nitrogen content

Determination of nitrogen was done by the Kjeldahl method. This was done in order to ascertain the total nitrogen concentration. Nitrogen was converted into ammonium salts, from which the ammonia was given out on adding a non-volatile alkali (concentrated sodium hydroxide solution). After distillation, the determination of ammonia was done by titration. The initial decomposition of the soil organic compound was made possible by acid digestion in the presence of a Copper (II) Sulphate catalyst. Digestion stage was important and took several 3-5 hours during which the sample turned brown and eventually was decolorized.

3.4.3 Determination of phosphorus content

The extraction of total phosphorus in the 48 soil cores was done using Olsen's procedure (Silva *et al.,* 2015) (0.5M sodium bicarbonate, pH 8.5, 1:20 v/v soil: extractant ratio, 30 minutes extraction), thereafter, the extracted phosphate was determined by colorimetric and by the molybdenum blue procedure. Air-dried soil (0.3 g) was put into a 250 ml conical flask and 50 ml of Olsen's extracting solution (0.5M $NaHCO_3$, at pH 8.5) was added to each flask to achieve a 1:20 soil to extractant ratio. The extraction was achieved by having the mixture shaken in an electrical shaker for thirty minutes. The suspension that formed was filtered through Whatman no. 42 filter paper. Phosphorus concentration in the filtrate was then determined colorimetrically by the ascorbic acid method at 880 nm by a UV-VIS Spectrometer, after which total phosphorus levels were read on the spectrometer.

3.5 Data analysis

3.5.1 Phytosociological attributes of tree species in restored sites

Descriptive statistical analysis was performed on the data obtained and the measures of central tendency (mean, range, median, standard error) reported for each tree species in both single and multi-taxa approaches. The analysed data were summarised in tables. A line graph was drawn to indicate the differences in the phytosociological attributes (height & diameter at breast-height among the tree species.

3.5.2 Assessment of soil elements between single and multi-taxa restored site in soil depth strata

Soil measurements were done in triplicate then means and averages calculated. Significance tests for the analytical methods in the differences of soil element in depth strata were done using One-way ANOVA test. Moreover, paired t-tests were performed to find a significance difference between single and multi-taxa approach of restoration. Pearson correlation analysis was performed to determine the relationships between Carbon and Nitrogen in the soil profiles. The data obtained was presented in tables and bar graphs. Descriptive statistics was also used to determine the mean as well as the spread in variations among soil properties in different soil profiles.

Table 3.1: Statistical analysis methods for each objective

Research Objectives	Research variables	Statistical data analysis method
To assess the phytosociological attributes within sites restored using single and multi-taxa approach	Tree height Diameter at Breast Height	Descriptive statistics, tables and graphs
To compare the soil physicochemical properties (SOC, N, P and K) between single and multi-taxa approach	SOC, N, P and K	2-sample t-test One-way ANOVA Pearson correlation analysis Tables and graphs

3.6 Ethical consideration

Before data collection began, Ethical clearance was obtained from Egerton University Institutional Scientific and Review Committee. A research permit was acquired from the National Commission for Science, Technology, and Innovation (NACOSTI) and permission was sought from Kenya Forestry Research Institute to obtain forest data.

CHAPTER FOUR

RESULTS

4.1 Single and multi-taxa approaches

Findings from single -taxa approach indicated that *Juniperus procera* species possessed straight, tapered and thick boles compared to the ones in multi-taxa approach. The data obtained from the site in this approach is shown in Table 4.1. The mean height of sampled trees was 2.55 ± 0.099285 m with diameter-breast height of 0.03 m. The minimum recorded height for *Juniperus procera* was 1.4 m, diameter breast height of 0.01 m. The lowest diameter breast height observed was 0.01 m and the mean stand volume was 0.186 m^3.

Findings from multi -taxa approach indicated that there was a stand variation in *Hagenia abyssinica* species density compared to other species (*Podocarpus gracilior, Juniperus procera, Olea capensis,* and *Prunus africana)* all found in the same locality. Among these species, *Hagenia abyssinica* and *Olea capensis* exhibited mature population structures, characterised by Diameter at Breast Height (DBH) classes exceeding 5 cm. Conversely, *Podocarpus gracilior*, *Juniperus procera*, and *Prunus africana* fell within lower DBH classes, indicative of younger individuals. Figure 4.1 is a line graph of volume (cm^3) different tree species in the multitaxa approach. It can be seen from the graph that *Hagenia abyssinica* (0.459 cm^3) had the largest volume and *Podocarpus gracilior* (0.091 cm^3) was the smallest in size.

Podocarpus gracilior displayed the least growth success, experiencing higher mortality rates and exhibiting diminished phytosociological attributes, particularly in terms of size and vitality. Approximately 20% of *Prunus africana* individuals were lost, evident from the cut stumps, indicating a moderate level of mortality within this species. These findings underscore the species-specific responses within the multi-taxa restoration context, suggesting differential success rates and population dynamics among the species included in the restoration effort. The data obtained from the single-taxa restoration approach is shown in Table 4.1 below.

Table 4.1: Descriptive statistics for phytosociological attributes in single and multi-taxa approaches

Species	Variable	Mean	S. E	Max	Min	Median	Skewness	Count
	Height	2.552	0.099	3.30	1.400	2.525	-0.434	
Juniperus procera (single - taxa)	DBH	0.032	0.003	0.06	0.010	0.030	0.283	20
	Volume	0.186	0.049	0.92	0.019	0.122	2.704	
	Height	5.143	0.339	7.38	3.500	5.100	0.556	
Hagenia abyssinica	DBH	0.064	0.004	0.085	0.044	0.066	0.049	14
	Volume	0.459	0.056	0.936	0.218	0.444	0.849	
	Height	2.040	0.209	2.500	1.300	2.200	-1.183	
Podocarpus gracilior	DBH	0.011	0.003	0.02	0.005	0.009	1.242	5
	Volume	0.091	0.061	0.333	0.025	0.031	2.232	
	Height	2.883	0.332	3.800	1.600	3.050	-0.711	
Prunus africana	DBH	0.040	0.004	0.052	0.027	0.039	-0.114	6
	Volume	0.166	0.029	0.253	0.064	0.163	-0.176	
	Height	3.700	0.383	4.700	2.500	3.800	-0.229	
Olea capensis	DBH	0.043	0.009	0.065	0.012	0.049	-0.634	6
	Vol	0.236	0.065	0.439	0.037	0.254	-0.150	
	Height	3.143	0.264	4.000	1.900	3.100	-0.711	
Juniperus procera (multi – taxa)	DBH	0.055	0.007	0.072	0.021	0.060	-1.271	7
	Volume	0.248	0.044	0.373	0.051	0.248	-0.753	

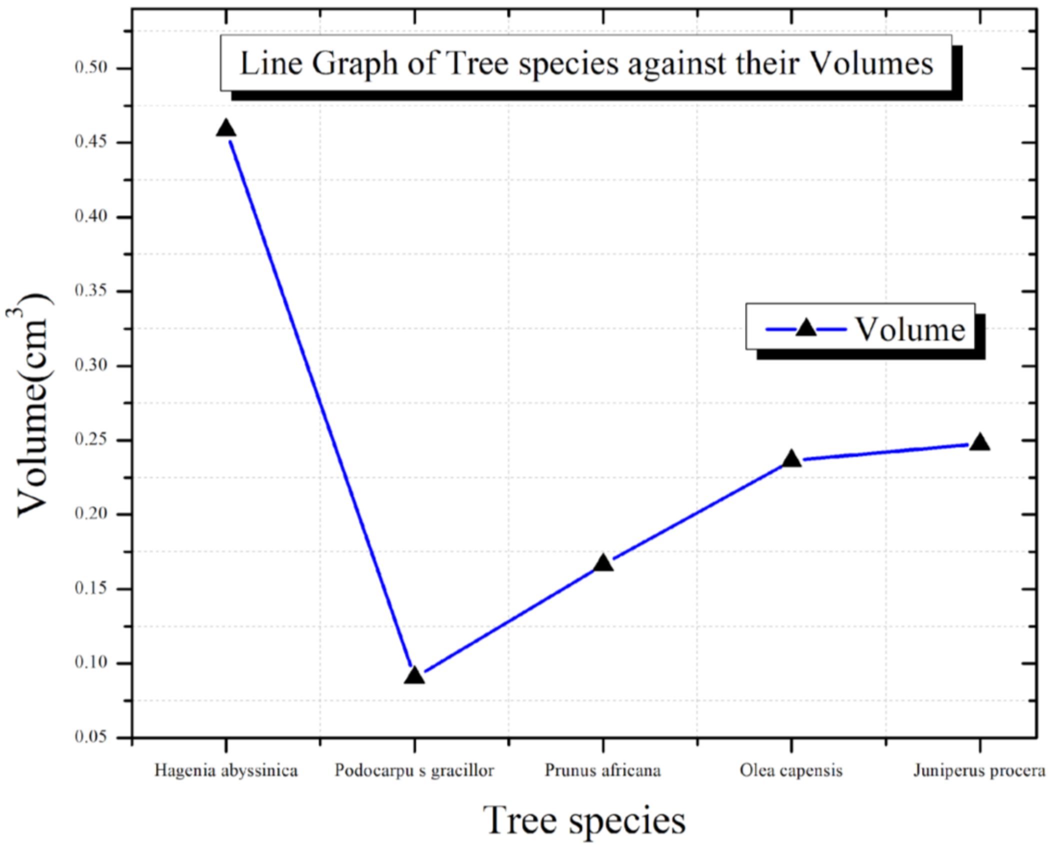

Figure 4.1: Phytosociological attributes (volume) of tree species

4.2 Variation between soil properties and soil profile

Soil samples from the two sites were for soil fertility index parameters and the results are presented as below:

4.2.1 Variation of soil elements in single-taxa and multi-taxa approach

In this study, the concentration levels of soil elements were investigated by subjecting normalised data to a 2-sample t-test at a 5% significance level. Treatments were structured such that combined average measurements for each approach were treated as distinct datasets for all elements irrespective of soil profiles. The analysis revealed higher concentrations of nitrogen, organic carbon, and phosphorus in the multi-taxa approach compared to the single-taxa approach. Conversely, potassium concentrations were higher in the single-taxa approach relative to the multi-taxa approach.

The concentrations (in ppm) of soil organic Carbon ranged from 0.507 ± 0.014 to 0.208 ± 0.015, Nitrogen ranged from 0.38 ± 0.015 to 0.331 ± 0.020, available Phosphorus ranged from 0.231 ± 0.005 to 0.187 ± 0.004, and available potassium ranged between 0.921 ± 0.025 and 0.937 ± 0.019. 2-sample t-test indicated significant differences in organic carbon, nitrogen, and phosphorus concentrations between the single and multi-taxa approaches, (2-Sample t-test, df=3, p=0.000).

Table 4.2: Mean concentration (ppm) of soil physico-chemical attributes among soil profiles (M15, S15, M30 and S30), where SOC represents Soil Organic Carbon, M15(0 – 15) and M30(16 – 30) n –Topsoil and subsoil in multitaxa respectively

	Element	SOC		Phosphorus		Potassium		Nitrogen	
	Profile (cm)	0 – 15	15 – 30	0 – 15	15 – 30	0 – 15	15 – 30	0 – 15	15 – 30
		Method							
Single taxa	Mean	0.238	0.178	0.198	0.175	0.946	0.927	0.367	0.295
	SEM	0.026	0.020	0.004	0.004	0.020	0.029	0.022	0.020
Multi-taxa	Mean	0.056	0.453	0.243	0.218	0.921	0.920	0.42	0.357
	SEM	0.034	0.020	0.011	0.007	0.033	0.034	0.020	0.022
	F-statistic	48.113		13.988		0.162		5.805	
	p-value	2.49E-9		3.82E-5		0.920		0.002	

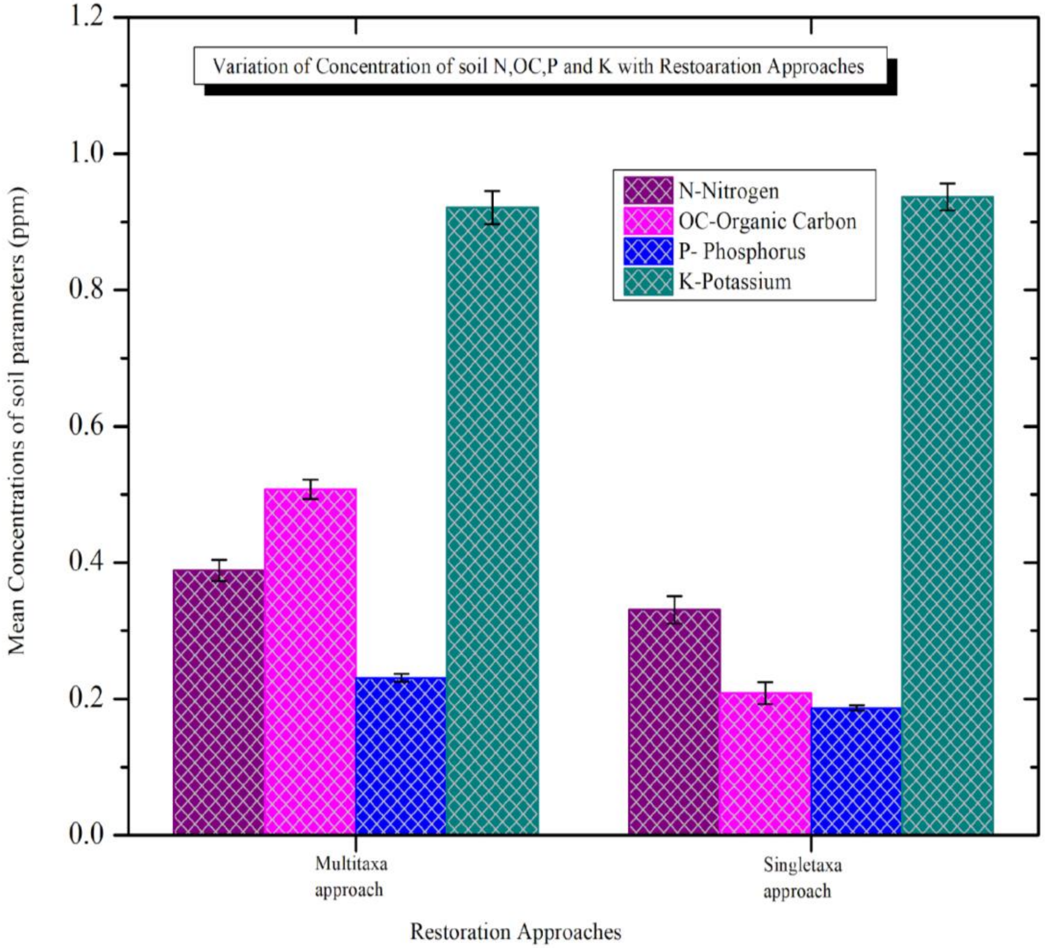

Figure 4.2: Variation of soil elements in single-taxa and multi-taxa approach

4.2.2 Vertical distribution of soil properties: nitrogen, soil organic carbon, potassium and phosphorus

In this experiment, the concentration levels of the soil elements were studied by subjecting the normalised data to one –way ANOVA at 5% significance level. The treatments were such that the individual measurements for both approaches at 0 - 15 and 16 -30 cm were considered as separate sets of data for all the elements. The element concentrations were observed to be higher in top-soils (0 -15 cm) as compared to sub-soils (15 - 30 cm). In all the sites, the concentration of potassium was highest while phosphorus was the least. Soil organic carbon ranged between 0.561 ± 0.034 and 0.178 ± 0.021, nitrogen ranged between 0.42 ± 0.019 to 0.295 ± 0.020, available phosphorus ranged between 0.243 ± 0.011 to 0.175 ± 0.004 ppm. Available potassium ranged between 0.946 ± 0.020 ppm and 0.920 ± 0.034 ppm as shown in Table 4.3 below. Results from One-way ANOVA revealed that there were significant differences in soil organic carbon, nitrogen and phosphorus among the four soil profiles, (ANOVA Test, df=3, p=0.00) as shown in Figure 4.3.

Table 4.3: Mean concentration (ppm) of soil physico-chemical attributes between restoration approaches

	Element	SOC	Phosphorous	Potassium	Nitrogen
		Method			
Single taxa	Mean	0.208	0.186	0.936	0.331
	SEM	0.015	0.004	0.019	0.020
Multi-taxa	Mean	0.507	0.231	0.921	0.388
	SEM	0.014	0.006	0.024	0.015
	t-statistic	13.963	6.343	-0.499	2.289
	p-value	6.94E-8	8.42E-5	0.635	0.032

Where SOC represents soil organic carbon.

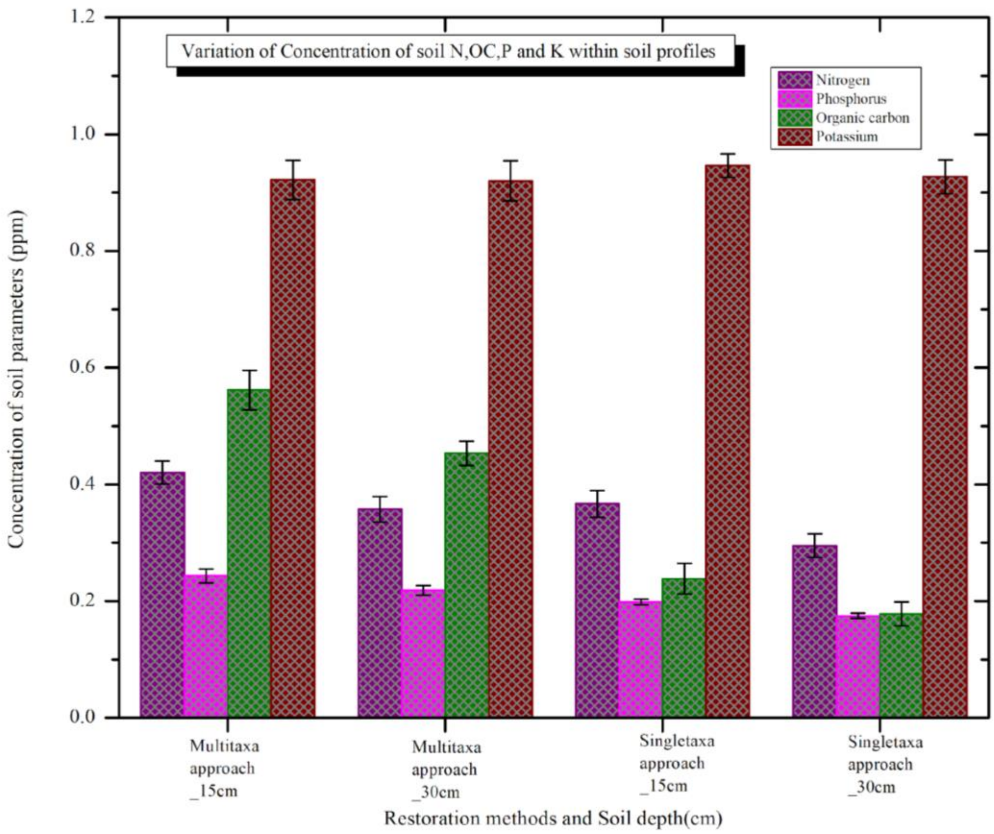

Figure 4.3: Vertical distribution of soil properties

((N - Nitrogen, SOC – soil organic carbon, K – potassium and P - phosphorus))

4.2.3 Carbon- nitrogen correlation

To determine the influence of soil organic carbon levels on nitrogen concentration trends, a graph was created plotting the logarithm of percent organic carbon against percent Nitrogen as indicated in Figure 4.4. It was established that these two soil elements exhibited negative correlation to each other, $r^2 = - 0.759$.

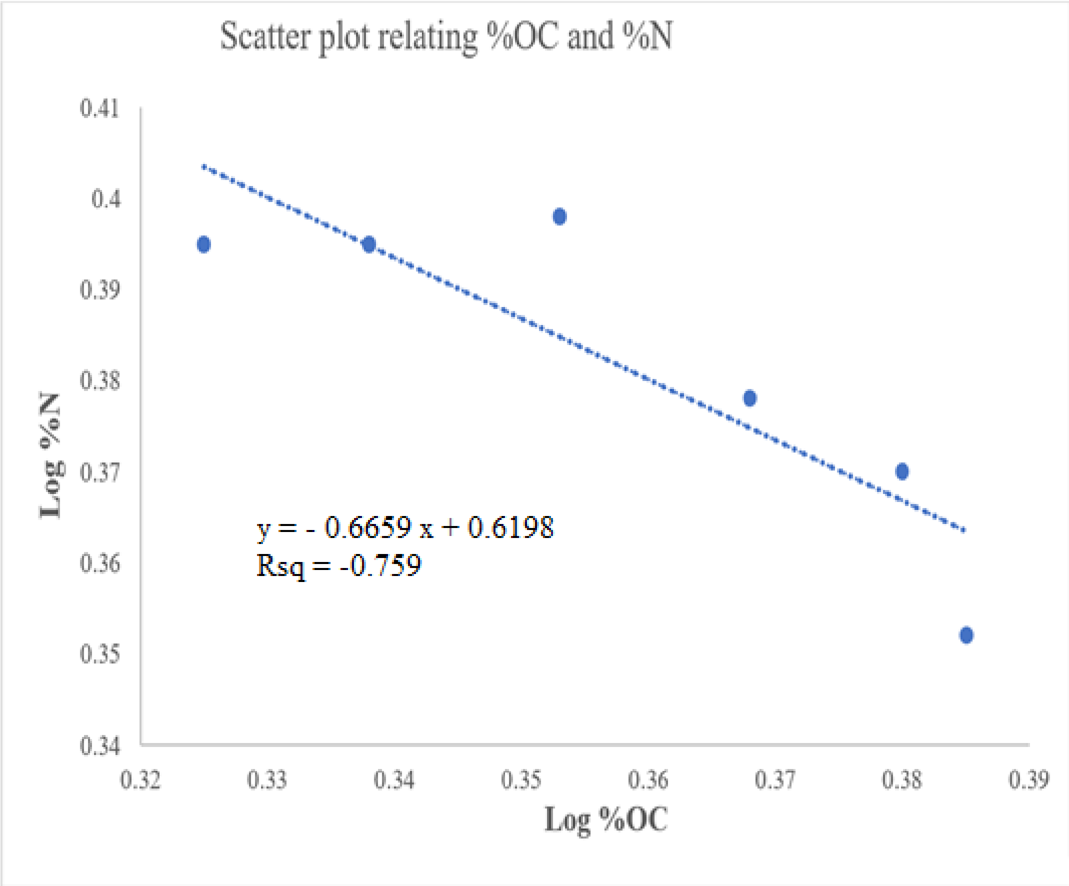

Figure 4.4: Relationship between % Nitrogen and % Soil organic Carbon in soil profiles

CHAPTER FIVE

DISCUSSION

5.1 Assessment of phytosociological parameters within single and multi-taxa restoration approaches

Restoration with multiple species promoted a greater recovery of forest-specialist species in the study sites groups, resulting in a greater abundance of these species. Stand structure (basal area, DBH, tree height) are reliable indicators of forest development (Liu et al., 2017). The mono plantation of *Juniperus procera* exhibited the highest basal area with total number of cut stumps being low while the mixed plantation of *Juniperus procera, Hagenia abyssinica, Olea capensis Prunus africana and Podocarpus gracilior* recorded the lowest basal area and with highest number of cut stumps, this is because some species had higher preference over the other (Muhesi *et al*., 2023). These observations coincide with (Kinyanjui, 2009) who noted a higher preference by the local communities in a high species diversity site than a mono stamp whose uses were monotonous in Mau Forest. The exploitation pattern could also be attributed to the economic, medicinal value and wood quality of a particular tree species, thus multiple harvesting of trees should be harmonised and stem density per class be reduced to avoid these indiscretions (Marini *et al*., 2021).

The obtained results emphasised on the important role that multiple use of species in restoration can play in mitigating the impact of habitat loss and degradation on the most vulnerable species, and in recovering ecological functions relevant to forest integrity. This highlights the need to conserve and protect mature forests, particularly near restoration sites and provide possible fencing (Dokata *et al*., 2023).

Similarly, Fikadu and Zewdu (2021) elucidated in their research the significant role played by tree canopies in modifying the abiotic environment for understory plants. Their investigation revealed that this modification occurred through direct impacts on factors such as light availability, temperature, and humidity, as well as indirect effects on soil processes. Substantiating these findings, (Harris *et al.*, 2024) provided additional support, indicating that tree canopies influenced micro environmental conditions. Their observations documented decreases in both air and soil temperature, wind speed, and irradiation, resulting in reduced soil evaporation and heightened relative humidity. These alterations, documented within a temperate forest setting in Canada, were linked to decreased survival rates of *Juniperus procera* seedlings.

Research conducted by Teshome *et al*. (2024) corroborated the shade intolerance of *Juniperus procera*, highlighting its preference for open, sunlit habitats. The study reported diminished growth and survival rates of *J. procera* individuals subjected to shaded conditions, underscoring the species' dependence on adequate sunlight for optimal performance. Furthermore, findings from a study by Wondimneh *et al.* (2024) reinforced the notion of *Juniperus procera's* shade intolerance. Their research emphasised the detrimental effects of prolonged shade exposure on the physiological processes and growth dynamics of *J. procera* saplings, elucidating the species' limited capacity to adapt to shaded environments.

In multi-taxa approach, the saplings were observed to have a low frequency as compared to the single-taxa approach, this is because the site was easily accessible to human disturbance and *Juniperus procera, Olea capensis* that were preferred for construction poles, *Podocarpus gracilior for* timber and medicinal use and *Prunus africana* as a purgative for cattle and donkey. An open canopy within a mixed stand forest facilitates disturbances and permits tree exploitation. This condition creates an environment where human activities such as logging, selective harvesting, and other forms of resource extraction can occur more easily due to increased accessibility and reduced obstruction from tree cover (Wanyama *et al.*, 2023).

Research conducted by Barrere *et al*. (2021) provided empirical evidence supporting the relationship between open canopy conditions and increased susceptibility to disturbances and exploitation within mixed stand forests. Their study examined the ecological consequences of canopy openness on forest dynamics and highlighted the implications for sustainable management practices. Furthermore, the presence of an open canopy alters the microenvironment within the forest, impacting factors such as light penetration, temperature, humidity, and nutrient availability. These changes can have cascading effects on ecosystem processes, species composition, and overall biodiversity.

The findings revealed that the multi-taxa forest, comprising a combination of these diverse species, exhibited higher stand volume compared to a single-taxa forest dominated solely by *Juniperus procera*. About 1.19 m^3 was attributed to multi and 0.85 m^3 to single-taxa approach. These results give a clear indication of the potential of the mixed stand versus a pure stand. Species diversity and richness acts as an indicator to the volume stand differences (Li *et al*., 2023). This observation aligns with the ecological principle that diverse forests, with a mix of tree species, tend to have increased stand volume due to complementary resource utilisation and niche partitioning among different taxa (Pretzsch *et al*., 2020).

According to Sheil and Bongers (2020), there exist a positive correlation between species diversity and stand volume in forest ecosystems. The presence of multiple species with varied ecological characteristics contributes to more efficient resource use and enhanced structural complexity, leading to higher stand volumes. Moreover, the findings from this study highlighted that *Hagenia abyssinica* played a significant role in contributing to the elevated stand volume in the multi-taxa forest.

The considerable contribution of *Hagenia abyssinica* to stand volume in comparison to other species like *Podocarpus gracilior, Juniperus procera, Olea capensis, and Prunus africana* can be linked to a number of ecological reasons. For starters, Hagenia abyssinica frequently creates thick stands due to its rapid regeneration and efficient colonisation of open spaces. This dense stand growth results in a high biomass concentration, which increases overall stand volume (Melkamu & Bitew, 2021). Furthermore, *Hagenia abyssinica* has a huge canopy and a broad root system, allowing it to absorb a significant quantity of sunlight and soil nutrients, all of which are necessary for development and volume accumulation. The species' vast root network also improves soil stability and nutrient cycling processes, which contributes to its ability to sustain huge stand volumes (Barrere *et al*., 2021).

In contrast, *Podocarpus gracilior* may contribute less to stand volume than *Hagenia abyssinica* because of its slower growth rate and smaller individual size. *Podocarpus gracilior* has a more scattered distribution and less dense stand formations, which results in lower biomass accumulation and, as a result, reduced stand volume. Furthermore, *Podocarpus gracilior* may have distinct habitat preferences or growth requirements that limit its ability to thrive and compete with other forest species (Negash, 2019).

Different tree species exhibit a range of growth characteristics, including variations in tree size and diameter at breast height (dbh), thereby yielding distinctive impacts on stand volume and density within Kenyan forests (Amara *et al.*, 2023). Diameter at breast height is a crucial factor in determining stand volume in mixed forests, emphasising the indispensable role of mature tree species in shaping ecosystem structure and biomass abundance (Melkamu & Bitew, 2021). Liu *et al*. (2022) delved into the impact of stand density, biodiversity, and spatial structure on stand basal area increment within natural spruce-fir-broadleaf mixed forests.

Although their research centred on various tree species, it provided valuable insights into the interplay between diameter at breast height (dbh) and stand volume in mixed forest environments. Their findings underscored the significant influence of stand density, biodiversity, and spatial structure on stand basal area increment, suggesting a potential correlation with dbh, consequently, stand volume in mixed stands. Similarly, Amara *et al*. (2023) explored the role of tree size and species in aboveground biomass across different land cover types in the Taita Hills, Southern Kenya. Their observations highlighted the substantial impact of tree size, as represented by DBH, on aboveground biomass, indicating a positive association between dbh and stand volume across diverse land cover types. It remains pertinent to understanding the dbh-stand volume relationship in mixed stands.

The findings from this study are also supported by studies conducted by Lee *et al*. (2021) which showed similar species growing in higher altitudes and in multiple approach, indicated that the species tended to decrease as the altitudes were getting to the peak, which was probably due to poor edaphic factors and the aspect of intra-competition. Advani, 2023 recommended that in order to implement conservation strategies of multiple species as the case in this study, efforts should focus on physiological factors and identifying favourable altitude thresholds to promote the species survival. Kibonde *et al*. (2020) also associated the growth of *Hagenia abyssinica* with fertile and moist soils as it was the case in Eastern Mau. Also, similar findings are reported in studies conducted by Lelamo (2021) which confirmed that *Olea capensis* was found to be highly threatened by prolonged drought throughout and was preferred for domestic use such as fencing when grown in a mixed stand.

5.2 Variation of soil elements in single-taxa and multi-taxa approach

Understanding the influence of tree stands, whether mixed or pure, on soil properties have been recognized as a pivotal aspect of sustainable forest management and ecosystem conservation. The manipulation of species composition within ecosystems can significantly impact soil properties due to variations in functional traits and interactions among species. Wu *et al*. (2024) and Yin *et al*. (2020) conducted experiments in grasslands, where they manipulated species composition, revealing that increased biodiversity led to enhanced productivity and improved soil health by facilitating the recovery of lost minerals. However, in forest ecosystems, reports on the effects of species richness on productivity have been contradictory. While some studies have demonstrated a positive influence of species richness on productivity in tree plantations and boreal forests, Mensah *et al*. (2023) emphasised that biodiversity might be considered less crucial in determining soil nutrient levels, particularly in temperate forests thriving in stable, productive environments. In such cases, the dominant species exert a noticeable influence, suggesting that the effect may not solely stem from the number of tree species but also from their abundance.

Over recent years, numerous studies have delved into how the composition of tree stands impacts soil nutrient levels, including nitrogen (N), phosphorus (P), carbon (C), and potassium (K). In addition to exploring the effects of tree stand composition on soil properties, restoration approaches have also garnered attention within the scientific community. Restoration efforts use either multi-taxa or single-taxa approaches, each with its own set of implications. Multi-taxa restoration approach aims to enhance ecosystem resilience and functionality by reinstating complex ecological interactions and nutrient cycling processes. Research has shown that multi-taxa restoration approaches can lead to improvements in soil health and nutrient levels by fostering diverse microbial communities, enhancing nutrient retention, and promoting symbiotic relationships among species. On the other hand, single-taxa may target keystone species or those with significant ecological roles, they may not necessarily promote overall biodiversity. However, single-taxa restoration approaches can still have notable impacts on soil properties, particularly if the chosen species possesses traits that facilitate nutrient accumulation, soil stabilisation, or organic matter decomposition.

This study elucidated substantial discrepancies in nitrogen dynamics, soil organic carbon sequestration, and phosphorus availability between mixed and pure tree stands, shedding light on the contrasting impacts of multi-taxa and single-taxa restoration approaches. Research conducted by Du *et al*. (2024) revealed that mixed stands, incorporating nitrogen-fixing tree species such as alder (Alnus spp.) and legumes, tend to exhibit elevated soil nitrogen levels compared to pure stands dominated by non-nitrogen-fixing species. This increase in soil nitrogen within mixed stands was attributed to the synergistic effects of various tree species on nitrogen cycling processes, encompassing fixation, mineralization, and immobilisation. Similarly, investigations by Devi (2021) and Du *et al*. (2024) underscored the significant contributions of both mixed and pure tree stands to carbon sequestration in soils. Mixed stands generally sequester more carbon due to heightened litter fall diversity, increased microbial activity, and enhanced soil structure.

Conversely, recent studies by Wu *et al*. (2019) emphasised the influence of tree stand composition on phosphorus and potassium availability in soils. Chen *et al*. (2024) observed that mixed stands with diverse tree species often exhibit higher levels of soil phosphorus due to variations in root morphological traits and mycorrhizal associations among different tree species within mixed stands. Similarly, Wu *et al*. (2019) noted that mixed stands tend to display more balanced potassium levels compared to pure stands, attributed to the complementary effects of different tree species on potassium cycling processes.

Based on these findings, it is essential to explore the underlying reasons for the observed statistically significant differences in nitrogen dynamics and soil organic carbon sequestration between a multi-taxa restoration approach, including species such as *Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis,* and *Prunus africana,* and a single-taxa approach focused solely on *Juniperus procera*. The disparities in nitrogen dynamics, soil organic carbon sequestration, and phosphorus availability between these restoration approaches can be ascribed to the varied functional traits and interactions inherent in multi-species ecosystems. In multi-taxa restoration approaches, the inclusion of diverse species fosters complementary interactions that enhance ecosystem functioning and nutrient availability. However, in single-taxa restoration approaches, the limited diversity may constrain ecosystem functioning, resulting in lower nutrient levels and reduced soil health.

Notably, the observed differences in potassium concentration, where no statistical significance was found between multi-taxa and single-taxa restoration approaches, may be attributed to additional factors influencing potassium dynamics beyond species composition alone, such as soil properties and environmental conditions. In conclusion, considering tree stand composition is crucial in restoration efforts, with multi-taxa approaches offering enhanced soil health and advocating for climate resilience. In summary, the observed differences underscore the importance of considering tree stand composition in restoration efforts, with multi-taxa approaches offering enhanced ecosystem functioning and nutrient availability compared to single-taxa approaches. By promoting biodiversity and fostering complementary interactions among species, multi-taxa restoration approaches can effectively improve soil health and mitigate the impacts of climate change on ecosystems.

5.3 Vertical distribution of soil properties: nitrogen, soil organic carbon, potassium and phosphorus

The study's findings unveil a nuanced understanding of soil element concentrations within Kenyan soils, emphasising the intricate interplay between various factors influencing nutrient dynamics. The distinct concentration patterns observed between top-soils (0-15 cm) and sub-soils (15-30 cm) underscore the significance of soil depth in shaping nutrient distribution. This vertical stratification aligns with established ecological principles, highlighting the multifaceted influences of biological activity, soil structure, and leaching processes (Matano *et al*., 2015).

Potassium emerged as a prevalent element across all soil profiles, corroborating its pivotal role in soil fertility and plant growth, as emphasised in previous literature (Attia *et al*., 2022). Conversely, the relatively low concentration of phosphorus underscores its potential limitation in tropical soils, a critical consideration for sustainable agricultural practices (Opala *et al.*, 2012). Quantitative insights into soil element concentrations reveal a broad range of variability, particularly evident in soil organic carbon, nitrogen, and phosphorus levels. These variations underscore the heterogeneity of nutrient availability across soil profiles, highlighting the complexity of soil nutrient dynamics *(Gui et al*., 2022). Statistical analyses further elucidate the significance of differences in soil element concentrations, particularly notable in soil organic carbon, nitrogen, and phosphorus. The insignificance of potassium concentrations suggests its relative stability across soil profiles, indicative of its fundamental role in essential biochemical and physiological processes within soil ecosystems (Attia *et al.*, 2022).

Further contextualization of the study's findings within the broader literature reveals consistent patterns observed in previous studies conducted in forest and grassland systems. The influence of soil depth on nutrient distribution, as highlighted by Babur *et al*. (2021), underscored the importance of understanding the limitations imposed by soil permeability and microbial activity. Insights from Li *et al*. (2023), emphasised the influence of forest type and tree species on soil nutrient dynamics, particularly in promoting litter decomposition and nutrient retention within subsurface layers. Conversely, Adekiya *et al*. (2024) sheds light on the role of soil composition and mineralogy in influencing potassium distribution, underscoring the need for comprehensive understanding and management of soil elements within forest ecosystems.

5.4 Soil organic carbon: nitrogen correlation analysis

Pearson's correlation analysis revealed a strong correlation between the physicochemical soil properties under multi-taxa and single-taxa approach, at 0–15 cm and 15-30 cm soil depth. The SOC was positively correlated with N in both approaches and soil depths, ($r=0.759$). There was also a statistical difference in the correlation coefficient between %N and SOC, ($p= 0.0238$) i.e. there is dependency in the %N to the SOC levels, $p < 0.05$. Soil C/N ratio was an important parameter used to roughly evaluate the decomposition rates of soil organic matter. Soil C/N ratio in both soil profiles gradually decreased as soil depth increased, indicating that soil organic matter in deep soils was more easily decomposed and utilized. These findings correspond with those of Ding *et al.* (2022) who reported higher C: N and C: P ratios which reflected higher plant N and P use efficiency. Soil depth is an important factor influencing the contents of SOC and N.

The findings from this study showed a decreasing tendency in SOC, N, and other elements' contents; this could be explained by the decreasing inputs of Soil organic matter with rising soil depth from both above and below-ground litter fall (Xiong *et al.,* 2020), especially by the decreasing influence of the humus layer covering the soil surface. The most important reason might be the highest biological activity in the topsoil, characterised by the highest SOM content and associated nutrient. The C: N ratios could be used as indicators of the saturation or limitation of SOC and N (Rahman *et al.,* 2022) and to assess the structure, health, and function conditions of forests that influence the quality and quantity of litter/humus as well as their mineralization .This response was attributable to the large amounts of logging left on site, root mortality, and a successional pattern that included nitrogen fixers. The findings implied that the cumulative effects of such changes in terrestrial land use.

The observed variations of C: N ratios with soil depth and forest restoration approach in this study were consistent with other investigations. Based on the results, the soil ratios multi-taxa approach was higher than those for single-taxa approach, which could be associated with the element content changes, and litter decomposition rate (Gong *et al*., 2020).

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The main objective of this study was to compare the single-taxa to multi-taxa approach of forest restoration in regard to Phytosociological attributes and soil elements such as phosphorus, potassium, carbon and nitrogen in Eastern Mau Forest. Tree species for the experiment included; *Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis and Prunus africana*. In the context of this, the study makes the following conclusions:

I. The comparison of single and multi-taxa forest restoration methods in the Eastern Mau Forest showed that the multi-taxa approach enhances ecological performance by increasing species abundance and facilitating the recovery of forest-specialist species, particularly through the dominance of *Hagenia abyssinica*, which significantly boosts stand volume. In contrast, *Podocarpus gracilior* exhibited limited growth potential in single-species plantations, highlighting the importance of species diversity in restoration efforts.

II. The comparison of soil physicochemical properties in single and multi-taxa restoration approaches in the Eastern Mau Forest revealed that the multi-taxa method significantly improved nutrient dynamics, enhancing soil organic carbon (SOC), nitrogen (N), phosphorus (P), and potassium (K) levels. This approach not only increased overall nutrient content but also ensured a more effective distribution of these nutrients across soil layers, demonstrating its superiority for promoting sustainable ecosystem health compared to single-species methods.

6.2 Recommendations

In view of the findings and the conclusion drawn above, this study makes the following recommendations:

I. To enhance ecological performance in forest restoration, it is recommended to prioritise multi-taxa approaches that increase species diversity and promote the recovery of forest-specialist species, such as *Hagenia abyssinica*. This strategy should focus on integrating a variety of native tree species to improve stand volume and overall ecosystem resilience, while also considering the specific growth potentials of different species to maximise restoration success.

II. To enhance soil nutrient dynamics and promote sustainable ecosystem health in the Eastern Mau Forest, it is recommended to adopt multi-taxa restoration approaches. This strategy should prioritise species diversity to improve soil organic carbon (SOC), nitrogen (N), phosphorus (P), and potassium (K) levels, ensuring better nutrient distribution. Implementing holistic management practices that consider soil depth and biological activity will further support restoration efforts.

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APPENDICES

Appendix A: Publication

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Comparison of Soil Physicochemical Properties in Single and Multi-Taxa Forest Restoration Approaches in Eastern Mau Forest, Kenya

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Abstract

Climate change has spurred a global shift toward innovative strategies for tropical forest restoration, emphasizing their vital role in mitigating biodiversity loss. In the Eastern Mau Forest, both single-taxa (*Juniperus procera*) and multi-taxa; (*Hagenia abyssinica, Podocarpus gracilior, Juniperus procera, Olea capensis, and Prunus africana*) restoration approaches were employed; however, their effectiveness has been inconsistent. To address this, a comparative study was conducted, focusing on the variation of soil properties, specifically nitrogen (N), organic carbon (OC), potassium (K), and phosphorus (P). The study utilized Line Intersect sampling, dividing the sites into four 10m x 10m quadrats. Soil samples were collected from six points within each quadrat at depths of 0–15 cm and 15–30 cm and were subsequently combined for the analysis of SOC, N, K, and P in the laboratory. Statistical analyses, including a 2-sample t-test, revealed significant differences in SOC, N, and P concentrations between single-taxa and multi-taxa restoration approaches ($p < 0.05$). Additionally, a one-way ANOVA indicated significant differences in SOC, N, and P across soil profiles: M15, M30, S15 and M30 ($p < 0.05$), which was further corroborated by a post-hoc Tukey test. In contrast, potassium concentrations exhibited no significant variation ($p = 0$). Moreover, a statistically significant positive correlation was observed between SOC and N concentrations ($r = 0.759$, $p = 0.0238$), suggesting a dependency of nitrogen levels on SOC across the sampled soil depths. The study's findings offer critical insights into enhancing tropical forest restoration strategies, particularly regarding species diversity and soil nutrient management.

Index Terms - Climate change, Forest restoration, Physio-chemical, Single-taxa and Multi-taxa

I. Introduction

The restoration of forests is increasingly recognized globally as a crucial approach to halting biodiversity loss and mitigating the harmful effects of climate change particularly on forest ecosystem ((Cheboiwo *et al.,* 2018). This worldwide initiative aligns with the United Nations General Assembly's designation of 2021–2030 as the "Decade on Ecosystem Restoration."(UNFCCC, 2013). The degradation of forests and lands is a significant challenge, particularly in developing nations where rapid population growth and high unemployment rates exacerbate the problem (Langat *et al.,* 2021). It is estimated that between 1 and over 6 billion acres of mosaic forests and agricultural landscapes have been degraded globally. The economic value of ecosystem services lost due to land use changes was estimated at USD 4.3 to 20.2 trillion annually from 1997 to 2011 (Kundu *et al.,* 2021). Landscape degradation in Kenya resulted in declining flows of ecosystem services such as water, food, medicine, fuel wood, fodder, timber, biodiversity, watershed protection, soil protection, and mitigation of global change. It thus increased the risks of natural calamities such as drought, especially in dryland ecosystems (Jebiwott *et al.,* 2021).

The Mau Forest in Kenya, one of the largest closed-canopy forests in East Africa, is a critical component of the country's natural heritage and an essential water catchment area. However, this forest has been severely degraded over the years due to deforestation, illegal logging, and encroachment for agriculture and settlement (Kweyu *et al.,* 2020). The loss of forest cover in the Mau has disrupted soil physio-chemical properties, reducing fertility, altering nutrient cycling, and increasing erosion and nutrient leaching, thus weakening ecosystem resilience. Climate change and anthropogenic activities have intensified the degradation of this tropical forest spurring a global push for innovative restoration approaches (Kogo *et al.,* 2019). These efforts recognize the crucial role of tropical forests in mitigating biodiversity loss, regulating local and global climates, and supporting livelihoods. In the case of the Eastern Mau Forest, restoration initiatives focused on reforestation, sustainable land-use practices, and community involvement in forest management. The restoration of this forest is vital for the health of Kenya's ecosystems, water security, and the broader global fight against climate change. Forest restoration significantly impacts soil organic carbon (SOC), nitrogen, potassium, and phosphorus stocks, which are essential for maintaining soil health and ecosystem functionality. Research indicates that restoration practices can enhance

Appendix B: Research licence (NACOSTI)

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Appendix C: Ethical approval

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EU/RE/DIR/009
Approval No. EUISERC/APP/295/2023 *4th October* **2023**

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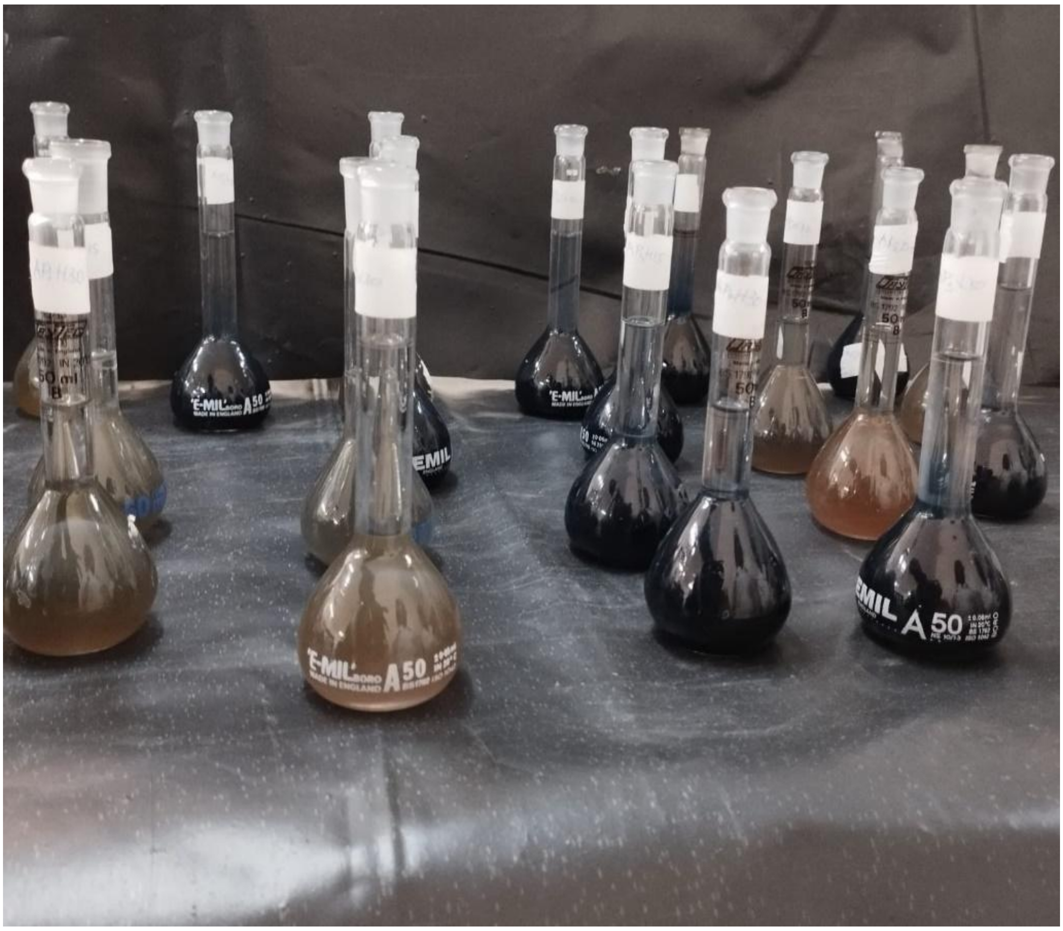
Dear Praxides,
RE: ETHICAL APPROVAL: A COMPARISON OF MIYAWAKI TO CONVENTIONAL RESTORATION METHODS IN EASTERN MAU FOREST, KENYA

This is to inform you that the *Egerton University Institutional Scientific and Ethics Review Committee* has reviewed and approved your above research proposal. Your application approval number is *EUISERC/APP/295/2023.* The approval period is *4th October, 2023 – 5th October, 2024*

This approval is subject to compliance with the following requirements;

i. Only approved documents including (informed consents, study instruments, MTA) will be used.
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by *Egerton University Institutional Scientific and Ethics Review Committee.*
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to *Egerton University Institutional Scientific and Ethics Review Committee* within 72 hours of notification iv. Any changes, anticipated or otherwise that may increase the risks or affect safety or welfare of study participants and others or affect the integrity of the research must be reported to *Egerton University Institutional Scientific and Ethics Review Committee* within 72 hours.
v. Clearance for Material Transfer of biological specimens must be obtained from relevant institutions.

Appendix D: Phosphorus samples at the laboratory



Appendix E: Diluting soil samples for soil organic test