Phenological Characteristics, Wool Yield and Quality of Three Selected Provenances of *Calotropis procera* (Ait) in the South Eastern Drylands of Kenya

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DECLARATION

I understand that plagiarism is an offence and I therefore declare that this thesis is my original work and has not been presented to any other institution for any other award.

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DEDICATION

This work is dedicated to my dear children Caroline Ndungwa Mbatha and Samuel Mutiso Mbatha.

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ACRONYMS AND ABBREVIATIONS

ICRAF	International Centre for Research in Agroforestry
WAC	World Agroforestry Centre
SEKU	South Eastern Kenya University
ASALs	Arid and Semi-Arid Lands
GI	Germination Index
VI	Vigor Index
GV	Germination Velocity
MGT	Mean Germination Time
SB	Shoot Biomass
RB	Root Biomass
TL	Taproot Length
FGP	Final Germination Percentage
FRP	Fiber Reinforced Polymer
Ha	Hectare
GV	Germination Value
DGS	Daily Germination Speed
PV	Peak Value
GP	Germination Percent
GEI	Germination Energy Index
MDG	Mean Daily Germination
GS	Germination Speed
DMRT	Duncan Multiple Range Test
ANOVA	Analysis of Variance
EC	Electrical Conductivity
DBH	Diameter at Breast Height
DNA	Deoxyribonucleic acid

ABSTRACT

Calotropis procera is a dryland species which produces wool. In order to domesticate the species for wool production, a study was undertaken to evaluate growth, phenology and wool productivity of selected provenances of *C. procera* in the drylands of South Eastern Kenya. The research site was located at South Eastern Kenya University (SEKU) off Kwa Vonza, Kitui County, Kenya. Geographically, it lies at 01.31358^{0}S, 037.75546^{0}E & 01.31422^{0}S, 037.75576^{0}E at an elevation of 1173m above sea level (a.s.l.). The objectives of the study were to: i) determine the germination and early growth of three *C. procera* provenances in three soil types under nursery conditions, ii) to determine growth and phenological characteristics of three provenances under field conditions and at different spacing, iii) to quantify seasonal wool yield and quality from three provenances and iv) determine soil chemical characterization of the study site. The experiments were done at nursery and field levels. The experiments were done at nursery and field levels. The nursery and field experiments were laid out in a randomized complete block design and replicated three times. The nursery media treatments were three provenances and three soil media while field treatments were three provenances and three spacing levels. At the nursery, data on germination energy, energy period, germination rate, germination value and seedlings mortality were collected. Field data included growth data, phenological data, soil data and plant tissue data. Charts were generated to depict germination attributes. Computations of germination values were done using Czabator and Djavanshir and Pourbeik methods. Correlation analysis of germination attributes were also done. Seedling leaf production and height data were subjected to analysis of variance (ANOVA) and means separated using Tukey's test (post hoc, $p < 0.05$). The field data was subjected to ANOVA to detect significant statistical differences ($p < 0.05$). Wool quantification and wool quality analysis were done in the laboratory. ANOVA was applied to assess the significance of variations in the soil chemical properties, plant tissue data, *C. procera* provenances and spacing variables in relation to the field plots. Tharaka provenance and sand soil had the highest germination energy of 76% and 83%, respectively, and a similarly high germination value of 87.67% and 86.21%, respectively. Analysis of Variances for branching indicated significant differences ($p<0.05$) with Baringo provenance recording a p-value of 0.043, Kibwezi, 0.01 and Tharaka, 0.0001. Dancun Multiple Range Test (DMRT) showed no significant differences in diameter growth for all the three provenances though height growth was significant ($p < 0.05$). All the three provenances showed strong and positive correlations (Pearson, $p <0.01$) for branching, DBH and height with Baringo recording $r_s=0.975$, Kibwezi ($r_s=0.988$) and Tharaka ($r_s=0.996$). Flowering was characterized by clear-cut phenophases. Spearman rank correlations between wet seasons and flowering ranged from 0.89-0.96 and were highly significant. Growth, flowering and fruiting was impeded by periodic attack by *Aphis nerii*. 1.5*1.5m spacing level had highest wool production per Ha, followed by 2*2m then 3*3m, while 3*3m spacing gave the highest amount of wool per plant. Despite the fact that *C. procera* wool quality compared relatively well with that of cotton, spinning of the wool presented a challenge. There were no significant differences in subplots soil chemical properties. The study concluded that *C. procera* can be grown as a plantation crop with 1.5*1.5m spacing being the most appropriate from the economic perspective. Attack of *C.*

procera by *Aphis nerii* is a major challenge in adopting the species as a plantation crop while failure of the fibres to separate during spinning presents a challenge in large scale use of the wool in textile industry. The study strongly recommends use of normal nursery soil (forest soil) due to its ability to promote early growth. Further, seeds for raising plantation stock should be obtained from the nearest source to reduce effects of seed transfer distance. Further research on improvement of the spinning properties of the wool is strongly recommended.

CHAPTER ONE

1.0: Introduction

This chapter gives background information on *C. procera* and the concept of plant domestication. It gives the statement of the problem, research objectives and hypothesis used for this study. The significance of the study including the key outputs are also explained in this section.

1.1 Background Information

Increase in population and depletion of natural resources has led to the exploration of new plant resources to meet the increasing demand of communities for plant-based goods and services (Dansi *et al*., 2009; Vodouhè *et al*., 2011). While there is increased expoitation pressure on common plant resources, there are many little known and therefore under-utilised plant resources. The focus on under-utilised plant resources is driven by the need to achieve self-reliance, economic gains, diversification, nutrition, and energy independence. Barbieri *et al*. (2014) and Dansi *et al*. (2012) stressed on the importance of conservation and use of neglected and under-utilized plant species. Similarly, Galluzzi and Noriega (2014) and Akpagana and Foucault (2009) advocated on the importance of use and conservation of under-utilized plant species to solve challenges such as sustainable agriculture, food security and creation of climate change resilience pathways.

C. procera is one among the many under-utilized plant species with a wide range of economic and ecological uses. Among the many economic benefits of *C. procera*, wool production is the focus of this study. The species has been reported as a potential source of natural fibre as well as an alternative to polmer based fibres. Natural sources of fibres are renewable, biodegradable and do not cause environmental pollution. However, polymer-based fibres are cheap but are non-renewable, non-biodegradable and are associated with environmental pollution. Hassanzadeh and Hasani (2015) have documented the unique properties of *C. procera* as a source of natural fibre. According to Batello *et al*. (2004), Orwa *et al*. (2009) and Yasin *et al*. (2012), *C. procera* is a potential substitute for silk. Akhtar *et al*. (2014) has documented that *C. procera* has adequate potential for making natural fibre-reinforced composites. Ecologically, *C. procera* has the potential of phytoremediation of soils contaminated with heavy metals thus reducing environmental pollution. D'Souza *et al*. (2010), Alyemeni *et al*. (2011) and Galal *et al*. (2015a) have reported the ability of *C. procera* to pyto-extract heavy metals from the soil and concentrate them in their above-ground tissues.

C. procera has a global distribution especially in tropical and sub-tropical regions. It is native to India, Pakistan, Nepal, Afghanistan, Algeria, Iran, Iraq, Israel, Kenya, Kuwait, Niger, Nigeria, Oman, Saudi Arabia, United Arab Emirates, Vietnam, Yemen and Zimbabwe (Kumar *et al.*, 2013). In Asian countries, the species is grown for biofuel production especially in India. In India and China, many researches have been going on the medicinal application of the species. In Africa, the species is widely found in many countries where it is mostly used as a traditional medicine. The species has unique medicinal properties (Meena *et al.*, 2011). According to Orwa *et al.* (2009) and Galal *et al.* (2015b), *C. procera* has wide range of uses such as production of wool, medicinal uses while bark and latex are used in brewing and to curdle milk. Latex is used for tannin, dyestuff and a source of poison for arrows and spears. The young pods provide fodder and stems produce good charcoal and fibre. The species improves soil fertility and is important in pollution control by monitoring sulphur dioxide emissions in the air as well as a suitable indicator of exhausted soils.

In Kenya, *C. procera* wildly grows in Kitui, Machakos, Makueni, Tharaka, Baringo, Kibwezi, Turkana, Wajir, Isiolo, Mandera among other arid and semi-arid lands (ASALs). In Kitui County, the species is common in the eight Sub-Counties. In Kitui rural Sub-County, which houses the study site, the species is common in Kwa Vonza, Kiusyani, Mbitini and Kanyangi. In Kwa Vonza locality, which neighbours the study site, the local people use *C. procera* latex to remove thorns and spikes from flesh. In the recent past International Centre for Research in Agroforestry (ICRAF) in partnership with local farmers has been collecting the silky wool from the wild mainly for export to China. However, the quantity from the wild has failed to meet the market demand for the wool. According to Dansi *et al.* (2009) and Vodouhè *et al.* (2011), domestication of wild cultivars is driven by difficulties of getting them in time, quality and quantity when needed. To bridge the gap between demand and supply of the *C. procera* wool, a study was done with the aim of subjecting the species to specific but critical steps of the domestication process. The study focused on collecting the species' seeds from the wild, growing them in a nursery to understand germination and early growth and finally growing the seedlings in a typical farm setting with a view to understanding the species growth characterization, phenology and wool production and wool quality. These diverse experiments are critical stages in the domestication process since they aid in the mastery of mass production of the species in the future.

1.2 Statement of the Problem and Justification

The World Agroforestry Center, in partnership with the local communities in ASAL areas, has been collecting the wool from the wild to sell to China. However, the quantities collected are low to meet the market demand. Domestication of the species may be the key in bridging the quality and quantity demands for wool. However, information on its cultivation is scanty while that on its domestication process is lacking. Documentation of such information are a key step towards domestication of the species. Further, polymer-based sources of fibres have been causing environmental degradation since they are non-biodegradable and are non-renewable. As such, engineers in the textile industry have been focusing their attention on natural sources of fibres that do not pollute the environment, are biodegradable and renewable. *C. procera* falls under the category of natural sources of fibre/wool and there is need to exploit it as a potential source of polymer-based fibres in the textile industry.

In order to bridge the existing gaps in supply of *C. procera* wool, increase agricultural productivition in ASALs as well as reduce environmental pollution by substituting polymer-based sources of fibre with natural sources, domestication of *C. procera* is critcal. In this study, focus was given to selected initial but critical steps in the domestication process involving seed collection, raising the seedlings in the nursery and subsequent planting in a field trial plot. *C. procera* seeds were collected from the wild from diverse geographical zones in Kenya. The seeds were subjected to diverse nursery and field experiments. The nursery experiments were geared towards understanding the germination and early growth of the species. This is an important exercise in the domestication process since it documents the best practices that can be adopted by farmers after domestication of the species. The field experiment mainly focused on understanding the growth, phenology and productivity of the species in a typical farm setting. This step is very critical in the domestication process since at this stage, the reproductive biology of the species is understood and challenges of growing the species in a farm setting are documented.

1.3 Objectives of the Study

1.3.1 General Objective

To evaluate growth, phenology and wool productivity of selected provenances of *C. procera* under domestication in drylands of South Eastern Kenya

1.3.2 Specific Objectives

i. To determine germination and early growth capacities of three *C. procera* provenances under three soil types in the nursery.
ii. To determine growth parameters and phenological events of three provenances of *C. procera* at three spacing levels under field conditions.
iii. To assess seasonal wool yield quantities and quality from selected and domesticated *C. procera* provenances under three spacings.
iv. To determine the soil chemical characteristics of the study site

1.3 Research Hypotheses

i. **H_0**: There are no significant differences in germination and early growth capacities of *C. procera* provenances under three soil types in the nursery
  H_1: There are significant differences in germination and early growth capacities of *C. procera* provenances under three soil types in the nursery
ii. **H_0:** There are no significant differences in growth parameters and phonological events of three provenances of *C. procera* at three spacing levels under field conditions
  H_1: There are significant differences in growth parameters and phonological events of three provenances of *C. procera* at three spacing levels under field conditions
iii. **H_0:** There are no significant differences in seasonal wool yield quantities and quality from selected and domesticated *C. procera* provenances under three spacings.
  H_1: There are significant differences in seasonal wool yield quantities and quality from selected and domesticated *C. procera* provenances under three spacings.
iv**. H_0:** There are no significant differences in soil chemical characteristics at the

study site

H_1: There are significant differences in soil chemical characteristics at the study site

1.4 Significance of the Study

This study focused on understanding growth, phenology, productivity and wool quality of the under-utilized *C. procera* with the aim of domesticating the plant species for wool production. Dansi *et al*. (2012) and Mayes *et al*. (2012) documented that many plants across the world are neglected and under-utilized despite their economic importance. Further, according to Dansi *et al*. (2009) there is increasing pressure from a burgeoning human population and fast depletion of natural resources and as such there is need to explore the possibilities of exploiting new plant resources in order to meet the growing human needs. Similarly, Narendra *et al*. (2012) advocated for priotizing of domestication of under-utilized tree species for use by smallholder farmers. This study, therefore, greatly contributes towards exploitation of *C. procera* as one of the under-utilized plant species. It forms scientific basis for possible domestication of the species for wool production. Orwa *et al*. (2009) and Hafiza *et al*. (2010) reported that the wool of *C. procera* can be used as a substitute to *Gossypium hirsutum* wool for surgical purposes. Further, Somnath *et al*. (2013) documented that *C. procera* wool is used for preparation of cloth and insulating material.

Currently, *C. procera* wool is collected by members of the local communities from the wild and sold to countries such as China. However, collection from the wild does not meet the market demand. To increase supply and bridge the demand gap, this study sought to explore possibilities of domesticating the species by subjecting it to key domestication steps as outlined by Dansi *et al*. (2009) and Vodouhè *et al*. (2011). Extension agents and policy makers in the drylands can use results of this study. In Kenya, local farmers in dryland areas mainly depend on *Gossypium hirsutum* (cotton) as a cash crop. Since *C. procera* and *Gossypium hirsutum* both can produce wool, adoption of the former by local farmers will result to cash crop diversification hence improved farm incomes and livelihoods. It is important to note that diversification of germplasm is one of the key drivers of plant domestication. Padulosi *et al*. (2014) and Galluzzi and Noriega (2014) documented the importance of use and conservation of underutilized plant species to address challenges of agricultural sustainability, food security, self-reliance and development of resilience pathways to climate change.

The study will contribute greatly to the scientific world. Several scientific papers on *C. procera* growth, phenology and wool productivity were published for a wider scientific dissemination. This PhD thesis is a key output of the study.

1.5 Limitations of the Study

The study encountered two main limitations. These included: -

i. Occassional severe attack by *Aphis nerii* which was attacking the leaves, flowers and fruits. Though the study had identified *Aphis nerii* as one of the pests for *C. procera*, there was no documentation of its severity in a farm setting. However, these severe attacks were well managed by application of local pesticides.

ii. Poor spinning properties of *C. procera* wool during lab wool quality analysis. This was very critical in analyzing wool quality in details. Efforts to spin the wool in two major laboratories in Kenya failed to achieve the required results. Further efforts were made where the wool was sent to a laboratory in China for analysis. However, efforts by the laboratory management to get a student to do the analysis failed.

CHAPTER TWO

2.0 Literature Review

2.1 Introduction

This Chapter gives a review of relevant literature related to the study with a major focus on the domestication process of plants, ecology of *C. procera* as well as its botanical description and distribution. It also covers literature on *C. procera* propagation, phenology, wool production as well as challenges of pest and diseases.

2.2 Plant domestication process

Plant domestication is the process whereby wild plants have been evolved into crop plants through artificial selection. This usually involves an early hybridization event followed by selective breeding. It ensures that the products of a given plant are obtained in quality and quantity when needed. Different steps exist in the plant domestication process (Dansi *et al*., 2009 and Vodouhè *et al*., 2011). The steps are as summarized below: -

Step 0: The species is growing in the wild and collected only when need arises

Step 1: During land preparation, the wild species is left intentionally in the farm because of its uses and scarcity in quantity and quality when need arises

Step 2: A kind of ownership starts with farmers giving a lot of attention to the preserved plant by protecting it to ensure its survival and normal growth.

Step 3: Ownership of the species is rigorous whereby reproductive biology is known and farmers do multiplication and cultivation of the species. At this stage, farmers conduct experiments on planting date, spacing, pests and diseases management with the aim of mastering mass production in future.

Step 4: Farmers apply traditional methods to cultivate and harvest the species.

Step 5: Species quality improvement initiatives start with farmers applying specific criteria to select the best cultivar that meets the society's demands. At this stage, best variety is selected for development and multiplication based on product quality, resistant to diseases and pests. At this stage, access to market and traditional post-harvest preservation and processing are considered in order to meet the end users' needs.

Step 6: Selection initiatives for the best cultivar continues with a lot of attention paid to product use qualities as well as resistance to pests and diseases in the farm and in storage.

At this stage, varieties that meet consumers' preferences based on income and market demands are selected and produced.

2.3 Distribution and Ecology of *C. procera*

Calotropis procera (Aiton) W.T (Asclepiadaceae) is a xerophytic perennial shrub or small tree that is common in ASAL countries (Hassan *et al*., 2015). According to Farahat *et al*. (2015), the species is a perennial xerophytic shrub or small tree that grows in wastelands and has medicinal value. Its native homeland includes tropical and subtropical Africa and Asia including Middle East (Parsons & Cuthbertson 1992; Lottermose, 2011; Frosi *et al*., 2012) as well as Latin America. The species reproduces by seeds. *C. procera* can tolerate adverse climatic conditions and poor soils (Parsons & Cuthbertson 1992; Lottermoser, 2011; Kumar *et al*., 2013; Galal, 2015c). It is evergreen (Frosi *et al.,* 2012) and does well in saline soils with low soil moisture content and has a tendency of forming mono-specific stands (El-Midany, 2014). In Kenya, it is widely distributed in ASALs. In Kitui County, where the study site was located, the species occurs in many parts of the County including Kwa Vonza locality, which is adjacent to the study site. Frosi *et al.* (2013) described *C. procera* as a perennial shrub common in Asia and reproduces by seeds.

C. procera can tolerate adverse climatic conditions and poor soils (Parsons & Cuthbertson 1992; Lottermoser, 2011; Kumar *et al*., 2013). It is evergreen (Frosi *et al.*, 2012) and does well in saline soils with low soil moisture content and has a tendency of forming mono-specific stands (El-Midany, 2014). *C. procera* is drought and salt tolerant, xerophytic and is capable of surviving in a wide range of soil types. It prefers habitats that are open and characterized by overgrazing and poor soils (Kumar *et al*., 2013; Galal, 2015c). Dietmar (2005) reported *C. procera* as an environmentally invasive species that establishes quickly in degraded roadsides and in overgrazed native pastures. The species prefers low rainfall, sandy soils and areas subjected to over-cultivation. Kumar *et al*. (2013) suggested that the species does not require cultivation practices since it grows naturally in abandoned farmlands. Information on its cultivation is, however, scanty while that on its domestication process is lacking. According to Dansi *et al.* (2009) and Vodouhè *et al.* (2011), the collection of plants from the wild for cultivation on farm is a common practice continuously occurring. Many varieties, landraces and cultivars of plants have been developed and domesticated through this process to meet human needs for food, fibre, medicine and building materials amongst others (Sweeney & McCouch, 2007).

2. 4 Botanical description of *C. procera*

Morphologically, *Calotropis procera* (Ait) occurs as a single or multi-stemmed soft-wooded shrub, and occasionally a tree reaching upto 6m (Plate 2.1). All parts of the plant produce milky latex when cut (Roy *et al*., 2008 and Kumar *et al*., 2013). The botanical description of *C. procera* includes the following parts:

Plate 2.1: ***C. procera*** **growing in the wild in Mwingi Central, Kitui County, Kenya**

(*Source: Plate by Mutiso, 2017*)

2.4.1 Bark and Branches

The bark is usually thick, rough and corky and yellow-brown in colour (Kumar *et al*., 2013). The twigs are green and fleshy and may be covered by tomentum (white fur like hairs).

2.4.2 Leaves

Leaves are usually opposite-decussate, simple, ovate to obovate with 4-6 pairs of subopposite nerves prominent on the abaxial surface, an acute apex, sessile base, have pale green colour, and quite large, about 30*25 cm (Sharma *et al*., 2011) as shown in Plate 2.2.

Plate 2.2: The morphology and arrangement of *C. procera* leaves

(*Source: Plate by Mutiso, 2015*)

2.4.3 Inflorescences

C. procera inflorescence arises from the base of the leaves in pedunculate (7cm) cymes of 3-20 (Plate 2.3). Each inflorescence contains 3–15 flowers. The clusters are surrounded by involucres of several small oblong, pointed scaly caduceus bracts. The main stalk of the flower clusters is 20–55 mm long, and each flower has a pedicel about 15–25 mm long (Hassan *et al.*, 2015).

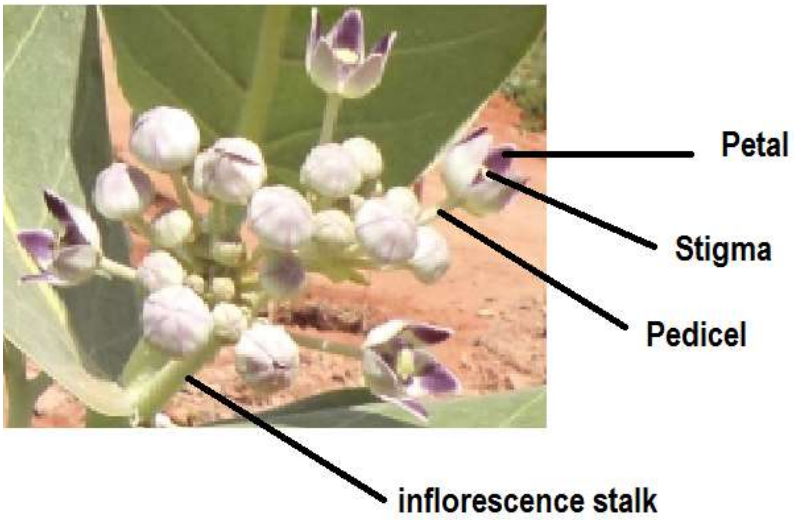

Plate 2.3: The morphology of *C. procera* inflorescence

(*Source: Plate by Mutiso, 2016*)

2.4.4 Flowers

The flowers of *C. procera* are regular, bisexual, liliac or pale rose, purple or light greenish yellow and have a faint odour. Flowers are arranged in simple or rarely compound cymose corymbs at the ends of laterally placed or interpetiolar peduncles arising from alternate sides of the nodes. Each cluster is surrounded by an involucre of several small oblong pointed scaly caducous bracts (Hafiza *et al.*, 2010). Flower buds are ovoid (Plate 2.4).

Plate 2.4: Appearance of leaves, inflorescence and flowers of *C. procera* in the wild along Sorohindi stream in Mandera

(*Source: Plate by Mutiso, 2017*)

2.4.5 Fruits

Fruits consist of green, spongy ovoid fruits, up to 15cm long by 10cm wide (Plate 2.5). The fruits split open to release plumed, papery light brown seeds with a pappus of white filaments upto 6cm long on one side (Fandohan *et al.*, 2015). The main flowering period is from March to October.

Plate 2.5: Fruiting of *C. procera* in Kibwezi, Makueni County, Kenya

(*Source: Plate by Mutiso, 2017*)

2.4.6 Roots

The bark of *C. procera* is separated from the wood 0.5-2.0cm in diameter bearing rootlets with diameter varying from 0.2 to 0.5cm externally whitish grey in colour and wrinkled in the fresh condition. Plenty of whitish latex exudes from cuts or wounds in the bark (Sharma *et al*., 2011).

2.4.7 Root bark

The taproots have prominent tops with rounded head with the rest of the portion being spirally curved (Sharma *et al*., 2011). These hard roots are greyish white in colour and exhibit sap exudations at the places where bark has been cut. The bark of the older roots is cracked at some places. The bark is yellowish grey outside and yellowish white inside. The upper cork portion is spongy and rough while the inner portion of bark is smooth and mucilaginous. The bark is bitter to taste when dried.

2.4.8 Calyx

Calyx of *C. procera* has five lobes broadly ovate with small fleshy teeth-like glands within the base. The sepals are 7–8 mm long; ovate acute, hairy outside; while petals are 2–3 cm wide, and white with purple tips internally (Hassan *et al*., 2015).

2.4.9 Corolla

C. procera corolla is regular, gamopetalous, pale rose purple or liliac, subcordate to broadly sub-campanulate with a short tube and five broad ovate, lanceolate, valvate, spreading lobes (Kumar *et al*., 2013).

2.4.10 Stamens

The stamens of *C. procera* are five, inserted at the base of the corolla. Filaments are united to form a large staminal column provided with five conspicuous radiating coronal appendages that are completely adnate to, but slightly shorter than the column (Hafiza *et al.*, 2010). Anthers are short, broad, somewhat horny with broadly triangular membranous anther tips that are inflexed over the sides of the stigmatic hood.

2.5 Propagation and Management Methods

C. procera is easily propagated by seeds and natural regeneration is common (Manikandan & Arumugam, 2010). Vegetative propagation using half stumps is common and helps in faster multiplication of the parent genotype with superior characters. In large-scale multiplication of the superior genotypes, vegetative propagation is done using stem and root cuttings (Kumar *et al*., 2013). According to Parsons and Cuthbertson (1992), Yasin *et al*. (2012) and Zhang (2012), *C. procera* regenerates primarily by wind dispersed seeds and water though asexual propagation occurs through root suckerings. Typically, each *C. procera* stem produces thousands of seeds annually. Further, Singh (2010) also demonstrated the excellent coppicing ability of *C. procera* after cutting or burning (Plate 2.6).

Plate 2.6: Coppicing of *C. procera* in Sorohindi, Mandera County, Kenya

(*Source: Plate by Mutiso, 2017*)

2.6 Seed germination of *C. procera*

In natural ecosystems, environmental factors such as temperature, light, soil moisture and salinity affect the germination and establishment of *C. procera* seedlings (Baskin & Baskins, 1998; Donohue *et al*., 2010 and Leal *et al*., 2013). According to Khaef *et al*. (2011), seeds of *C. procera* have poor germination rate under field conditions. Zhang (2012) observed reduced germination with decreasing osmotic potential, light intensity and increased salinity with temperature significantly affecting germination index, germination velocity, vigor index, mean germination time, shoot biomass, root biomass, and taproot length, but not significantly affecting the final germination percentage. In a study by Khaef *et al*. (2011) in Iran, temperature of >30^{o}C and <20^{o}C negatively affected germination of *C. procera* seeds.

Seed germination is a critical stage of plant survival. Leal *et al.* (2013) observed high germination with the mean germination time averaging less than 5 days. However, Silvia *et al.* (2009) documented high germination percent of *C. procera* seeds after long period especially in dry areas. Generally, seed germination and seedling establishment of *C. procera* seems to be very short (Khaef *et al*., 2011). Kalita and Saikia (2001) also recorded variations in seed germination of seeds from different geographical location whereby germination percentages obtained were 98, 96, 94, 88 and 86%. However, Yakubu *et al.* (2009) recorded different percentage germination rate for three provenances as 68.50 %, 61.25 % and 54.50 %. Further, the germination percentages fall below the minimum 75% standard for plantation species.

According to Francis (2002), a mature *C. procera* plant can produce thousands of seeds annually while Manikandan and Arumugam (2010) reported about 100,000 *C. procera* seeds/kg with germination rates reaching 89% 64 days after sowing. The germination period of 64 days is very long and contradicts what many researchers have documented for *C. procera*. Additionally, such a prolonged germination period distorts nursery operations such as pricking out and transplanting schedules. However, the maximum length of time the seeds can remain viable in the soil seed bank is unknown (Grace, 2006 & 2009). Though mass germination of seeds occurs at the start of wet season in the tropics, only a few survive the first season (Grace, 2006 & 2009). According to Francis (2002), *C. procera* has a large taproot that gives the species coppicing ability after cutting or burning the stem. Orwa *et al.* (2009) documented that the species has a taproot that can go upto 3-4m deep and a secondary root system with woody lateral roots that when damaged may readily coppice.

2.7 Flowering and Fruiting

Flowering of *C. procera* in temperate regions begins in winter when the plant is at least two years old (Csurhes & Edwards, 1998; Parsons & Cuthbertson, 1992). The number of fruits varies between 1-3 fruits per flower cluster. Plate 2.7 shows a *C. procera* stem growing in the wild in Mwingi, Kitui County, Kenya with a maximum of three and a minimum of one fruit per flowering cluster. Each plant had an average of 23 fruits per fruiting season. However, some stems can bear hundreds of fruits depending on plant size as indicated in plate 2.7. *C. procera* attains maximum fruit length of 7.5-9.5cm in 20-25 days.

Plate 2.7: Number of fruits per flowering site in a *C. procera* plant in Mwingi, Kitui County, Kenya (*Source: Plate by Mutiso, 2017*)

C. procera fruit has a maturity period of 30-35 days (Hafiza *et al*., 2010). Silvia *et al*. (2009), Leal *et al*. (2013) and Mellissa *et al*. (2013) recorded continuous flowering with annual peaks. Long flowering periods is an important characteristic of invasive species (Lloret *et al*., 2005; Godoy *et al*., 2009 and Mellissa *et al*., 2013). In Israel, *C. procera* flowering occurs for six months with possible slight variations resulting from temperature changes (Eisikowitch, 1986). Temperature conditions determine the distribution of *C. procera* due to "thermophilic" nature of the species (Eisikowitch, 1986). Elsewhere in Saudi Arabia, *C. procera* flowering period was found to be four months and starts early in the spring and ends after two or three weeks (El-Ghani, 1997). However, these seasoned mediated flowering driven by temperature variations may not be applicable in the tropics including the study site where no clear cut winter-summer change of seasons occur but rather flowering is largely influenced by rainfall regimes.

2.8 Wool and Fibre Production

C. procera produces seed floss with silky hairs measuring 3.2 cm (Louis & Andrews, 1995). Orwa *et al*. (2009) and Dietmar (2005) documented that the wool, which measures 2-3.5cm long, is silky and strong. According to Kumar *et al*. (2013) and Meena *et al*.

(2011), the wool measures 3cm or more in length. The silky hairs are largely for wind dispersal of *C. procera* seeds (Mellissa *et al*., 2013). According to Orwa *et al*. (2009) and Hafiza *et al*. (2010), the silky wool can serve as a substitute for *Gossypium hirsutum* wool for surgical purposes. Further, the silky wool of *C. procera* is used to make cloth and in preparation of insulating material (Somnath *et al*., 2013). Earlier on, usage of the fiber from the inner bark to make cloth for the nobility existed while the silky wool served as a stuffing material for mattresses and pillows including weaving into a strong cloth (Orwa *et al*., 2009; Chandrawat & Sharma, 2015). Further**,** Batello *et al*. (2004) and Yasin *et al*. (2012) stated that the silky floss is a potential substitute of silk.

Fibre length from the stem of *C. procera* measures between 0.6 – 1.04mm and this compares well with that of other species used in the pulp and paper industry such as *Gmelina arborea* and *Eucalyptus spp* whose fibre length measures 1mm (Yakubu *et al*., 2009). According to Bajwa *et al*. (2013), the stem of *C. procera* provides natural cellulosic bast fibres with valuable properties such as cellulose content, fiber strength and fiber elongation being intermediate between those of cotton (*Gossypium hirsutum*) and linen. Further, the fibres of *C. procera* have high tensile and abrasive strength as well as more weight per square meter than *Gossypium hirsutum* fibres.

2.9 *C. procera* wool quality

Farmers in the cotton industry use physical grading of wool based on clarity. Classification of the wool into grade 1 and 2 helps in marketing of the cotton wool. Typically, grade 1 is usually of higher quality and fetches better prices. This physical grading is usually cheap and does not require technical knowhow. However, other fibre mechanical properties such as fibre length are important in wool quality. For instance, Orwa *et al*. (2009) and Dietmar (2005) documented that the silky wool of *C. procera* is strong and measures 2-3.5cm in length while Kumar *et al*. (2013) and Meena *et al*. (2011) documented wool length of ≥3cm. Since *C. procera* depends on wind for seed dispersal, the silky hairs aid in wind dispersal (Mellissa *et al*., 2013) by acting as wings. The wool may also substitute *Gossypium hirsutum* wool especially for surgical purposes (Orwa *et al*., 2009; Hafiza *et al*., 2010 and Akhtar *et al*., 2014).

C. procera produces durable fibre known as bowstrings (Srinivas & Babu, 2013) while the seeds have very fine silky wool that measures between 2.5-4.5cm in length depending on their position within the fruit. The fibres are botanically single celled seed trichomes attached within the fruiting body. According to Akhtar *et al*. (2014), research has been done on *C. procera* fibre properties for application in making clothes at a 1:1 ratio with cotton (*Gossypium hirsutum)* fibre and results have indicated that the fibres have adequate potential for application in natural fibre-reinforced composites as well as other industrial textile applications. Results of agrobacterium-mediated transformation of *C. procera* fibres showed a more amplified effect on trichome density and length (Aslam *et al*., 2013). The characteristics of cloth made from *C. procera* fibres have shown that it has high tensile and abrasion strength as well as more weight per square metre than *Gossypium hirsutum* cloth (Varshney, 1987).

Research has also shown that *C. procera* fibre makes high quality composites. The Composites are mainly advanced materials made of a combination of two fibre types. The properties of composites change based on the type of constituent materials, their size, percentage composition as well as the processing methods. For instance, according to Akhtar *et al*. (2014), a combination of *C. procera* fibre and saline produces a composite with high quality mechanical properties. In addition, since *C. procera* fibre is a renewable natural resource, it can substitute synthetic sources of composites.

According to Pratik *et al*. (2016), industrial applications and research on natural fibre reinforced polymer composite materials has been rapidly growing as researchers, engineers and scientists pay more attention to natural composite sources to substitute reinforcement for fibre reinforced polymer composites. The natural fibre composites have unique properties that make them attractive as a substitute for convectional fibres. Some of their unique characters include bio-degradability, high specific strength, low cost amongst others. For instance, a combination of *C. gigantea* fibres and other polymers formed composites with properties such as excellent tensile strength and tensile modulus, flexural strength and flexural modulus, impact strength and density (Srinivas & Babu, 2013).

2.10 Biomass Production

The world derives a fifth of its energy from renewable resources with biomass generating 13-14% and hydro sources accounting for 6% (Kumar, 1998 & 2001). In some developing countries, 90% of their energy comes from biomass. After 17 years of using *C. procera* as a source of bio-fuel in semi-arid regions, Kalita & Saikia (2001) reported high potential of the species in bio-fuel production and noted that efforts for large-scale cultivation and improvement of *C. procera* in semi-arid region of Rajasthan are going on. It is also important to note that use of biomass energy can play a critical role in substitution of petroleum-based energy sources thus contributing to reduction greenhouse gas emmissions as well as promotong sustainable development.

Nowadays, significant efforts to integrate biomass energy with agriculture, forestry and climate change related policies due to renewability and bio-degradability of biomass is common. For instance, according to Kalita & Saikia (2001), if a stocking level of 10,000 plants/ha at a spacing level of 1m*1m is adopted, the average plant weight will be 20kg giving a fresh biomass of 200,000kg/ha/annum and dry biomass of 40,000kg and this will yield 4-4.8 tonnes/ha/annum maximum biocrude translating to 10-12% recovery. Another research showed that *C. procera* yields 180 tonnes/annum of biomass making the species a potential source of renewable energy (Parsons & Cuthbertson, 1992; Yasin *et al.*, 2012). In other examples biomass production using *C. procera*, yielded 2–40 tonnes/ha of dry biomass depending on the agro-climatic conditions (Manikandan & Arumugam, 2010).

2.11 Cultivation of *C. procera*

C. procera grows naturally in the wild though not fully domesticated. In the study site environs, isolated stems of *C. procera* occur especially along the road reserves while naturally occurring stands occurs in Kwa Vonza and the neighbourhood Kiusyani. According to Sweeney and Couch (2007), domestication is generally the end-point of a continuum. The process starts with exploitation of selected wild plants and continues through cultivation and ends with the adaptation of the selected plants to the agro ecology. Selection initiatives that lead to genetic differences characterize the domestication process. Many plant varieties, landraces and cultivars have been developed through the domestication process principally to meet human and animal needs for food, fibre, medicine, building materials (Sweeney & Couch, 2007), fodder amongst others.

C. procera has a wide range of geographical distribution, mostly in semi-arid areas (Melo *et al*., 2001). Wagner *et al.* (1999) and Dietmar (2005) opined that C. *procera* is probably an environmental invasive species that escaped from cultivation in Hawaii. The species has a high dispersal capacity and largely depends on wind with the silky wool aiding in the dispersal process. Richardson *et al*. (2000) stated that when such species with high dispersal capacity move from their native homeland and are introduced in new habitats, chances are that they may find suitable microclimatic and ecological conditions leading to establishment of viable populations.

In some areas such as semi-arid regions of Rajasthan in India, *C. procera* has been tried in large-scale cultivation and improvement (Kalita & Saikia, 2001). Research has shown that although the species germinates throughout the year, the best sowing time is May-June. The species does not need deep tillage and the best sowing depth is 3-4cm. In some cases, if the soil moisture is not adequate, there is need to water once immediately after sowing. Weeds affect the growth of *C. procera* and as such weeding should be done 45 days after sowing. First harvest may occur 3-4 months after sowing (Kalita & Saikia, 2001).

In America and the Caribbean Islands, *C. procera* is cultivated for the production of fibre. When *C. procera* is cultivated, yields of upto 500kg/ha/annum are expected (Orwa *et al*., 2009). Although *C. procera* harvesting occurs twice or thrice per season, Kumar *et al*. (2013) recommended single harvest per season since it will lead to energy saving on the farm and in the processing plant. *C. procera* is best suited for intensive energy farming in arid or semi-arid regions where frost is not a limiting factor (Manikandan & Arumugam, 2010). In Kenya including the study site environs, the *C. procera* grows naturally though ICRAF has initiated on-farm cultivation of the species in Tharaka.

2.12 Spacing and Tree Management

Several spacing levels apply in planting of *C. procera.* Where adequate rainfall exists, a stocking level of 10,000 plants/ha can be used at a spacing level of 1m*1m but the mostly recommended stocking is 5,000 plants/ha at a spacing of 2m*1m. Though no watering is required during rainy seasons, it is reccommended to water during dry seasons. Although there is no documentation on nutrient requirements for optimum biofuel production, adding organic and inorganic fertilizers results in best performance. Leaf litter and prunings from the plantation can also contribute to improving the organic matter content of the soil (Kalita & Saikia, 2001) in *C. procera* stands.

In a study on phenology of *C. procera*, Andrade *et al*. (2005) used three spacing levels of 1.0m*1.5m, 1.5m*2.0m and 2.0m*2.0m and five planting ages of 30, 60, 90, 120 and 150 days. The results indicated that the management systems of the soil and the spacing did not affect the phenology of the species but significantly affected the studied age cohorts. According to Sharma and Sharma (2000) and Kumar *et al*. (2013), *C. procera* has been cultivated in South America and on the Caribbean Islands at a spacing level of 1-1.5 m and harvesting of different parts such as the roots, leaves and bark of young and older plants is done all year round. Sharma and Sharma (2000) further stated that ripe fruits are picked and opened to access the seed floss, then the seed are rubbed lightly against the palm of the hand making them to fall off readily from the wool.

2.13 Soil Requirement

C. procera grows in a wide range of soil types. In plantations for biofuel production, the species requires well-drained soils and at least 500mm annual rainfall. The species is drought-resistant and salt-tolerant capable of growing in open habitats and on poor soils devoid of competition. Kumar *et al*. (2013) noted that the species does well in poor soils preferably sandy soil and in areas devoid of competition from grasses or those subjected to overcultivation Orwa *et al*. (2009).

Soil disturbances promote regeneration of *C. procera* and hence the species is common along newly constructed roadsides amongst other disturbed habitats. It is deep-rooted (Orwa *et al*., 2009) and as such, it requires deep soils. It is capable of surving in soils of all textures. In India, the species occurs upto 1000m altitude (Parrotta, 2001) though in other geographical regions it is found at altitudes ranging from exposed coastal sites to medium altitudes of up to 1300m a.s.l.

2.14 Pests and Diseases of *C. procera*

C. procera has been reported to be vulnerable to attack by cutworms namely *Agrotis ypsilon* and *Agrotis flammatra*. Marugan *et al*. (2000) documented attacks by *Aphis nerii* resulting to defoliation of the plants, death of branches and abortion of flowers and fruits.

They further documented *Menochilus sexmaculatus* as the main control agent of *Aphis nerii*. Elsewhere, Dhafer *et al*. (2012), in a study in Saudi Arabia, documented key pests of *C. procera* to be *Semitocossus Johannes, Contigaspis zilla* and *Aphis nerii*. *C. procera* is attacked by *Aphis nerii* which forms mutualistic association with ants (Chandra *et al*. 2011; Navas, 2014; Kataria & Kumar *et al*., 2013; Amritphale & Sharma, 2007 and Styrsky & Eubanks, 2007)**.** According to Salau and Nasiru (2015), key insects associated with *C. procera* are *Apis mellifera, Anthophora* species, *Componotum perrisi, Trichius fasciatus, Physopelata famelica, Antherenus scrophulariae, Cerceris spincaudata* and *Dysdercus chrypsippus.*

Tahir and Jamaluddin (1993) documented leaf spot attack, a fungal infection in *C. procera,* caused by *Colletotrichum dematium.* In other studies, leaf spots in *C. procera* and *C. gigantea* were reported to be caused by *Alternaria alternata, which* is a fungal pathogen. Meanwhile, Sain *et al*. (2009) reported leaf spot in *C. gigantea*, which was causing extensive defoliation. Kumar and Khurana (2017) isolated *Alternaria alternata* as the causative agent of leaf spots in *C. procera.* In Pakistan, Mukhtar *et al.* (2013) reported leaf spots on *C. gigantea* and identified the causative agent as *Passalora calotropidis*. Stem canker also attacks *C. procera* leading to dieback of leader stem. Hood (2007) documented similar dieback of leader stems and lateral shoots due to attack by stem canker.

2.2 Conceptual Framework

Dansi *et al.* (2009) summarized the domestication process into six critical steps that start with the species growing in the wild and end with subjecting the species to selection initiatives based on qualities, protection against pests and diseases, income generation, market demands and consumers' preferences. Varieties that meet this criteria are selected and produced. Figure 2.1 below shows a conceptual framework developed to guide this study based on modification of Dansi *et al.* (2009) domestication model.

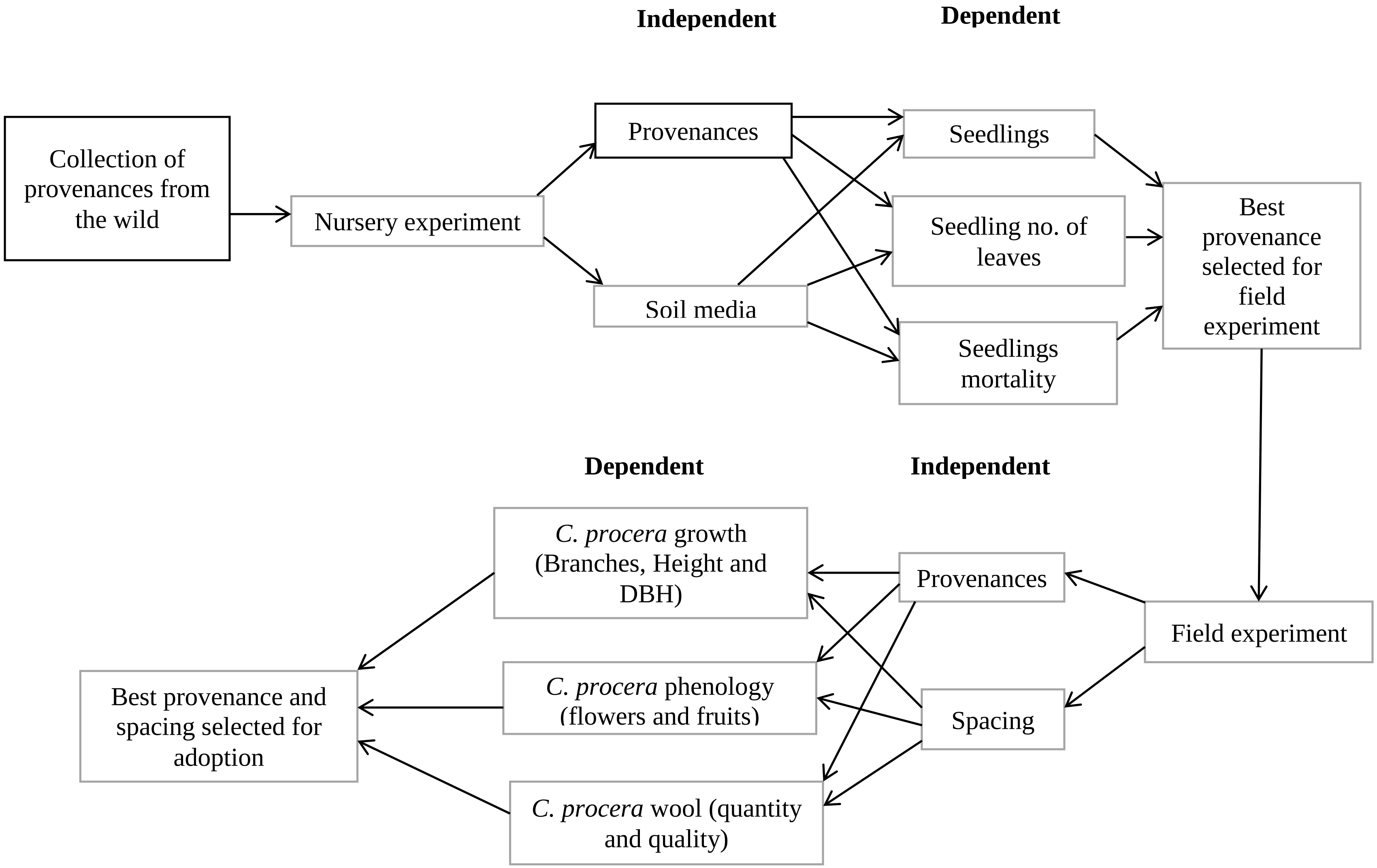

Figure 2.1: A modification of Dansi *et al*. (2009) basic theoretical conceptual framework of the domestication process

CHAPTER THREE

3.0 Materials and Methods

3.1 Introduction

This section describes the study site and the criteria used to select it. It elaborates on the experimental design and procedures used for data collection and analyses approaches.

3.2 Description of the Study Site

3.2.1 Geography

South Eastern Kenya University (SEKU), situated in Kitui County, Kenya, served as the study site. The research site was located 15 Kilometers off Kwa Vonza Market, along the Kitui-Machakos main road, Kwa Vonza/Yatta ward, Kitui Rural Sub-County, Kitui County. Geographically, the research plot was located at 01.31358^{0}S, 037.75546^{0}E and 01.31422^{0}S, 037.75576^{0}E at a general elevation of 1173m a.s.l (Figure 3.1).

3.2.2 Climate of the study site

The study site falls in agroecological zone IV and the climate is semi-arid characterized by very erratic and unreliable rainfall. The rainfall pattern is bimodal with the short rainy season occurring between November and December and the long rains between April and May. According to Pauw *et al*. (2008), the short rains are more reliable than the long rains with a mean annual rainfall of 500-1050 mm and 40 percent reliability. High temperatures ranging from 16^{0}C to 34^0 C characterize the site throughout the year (Pauw *et al*., 2008).

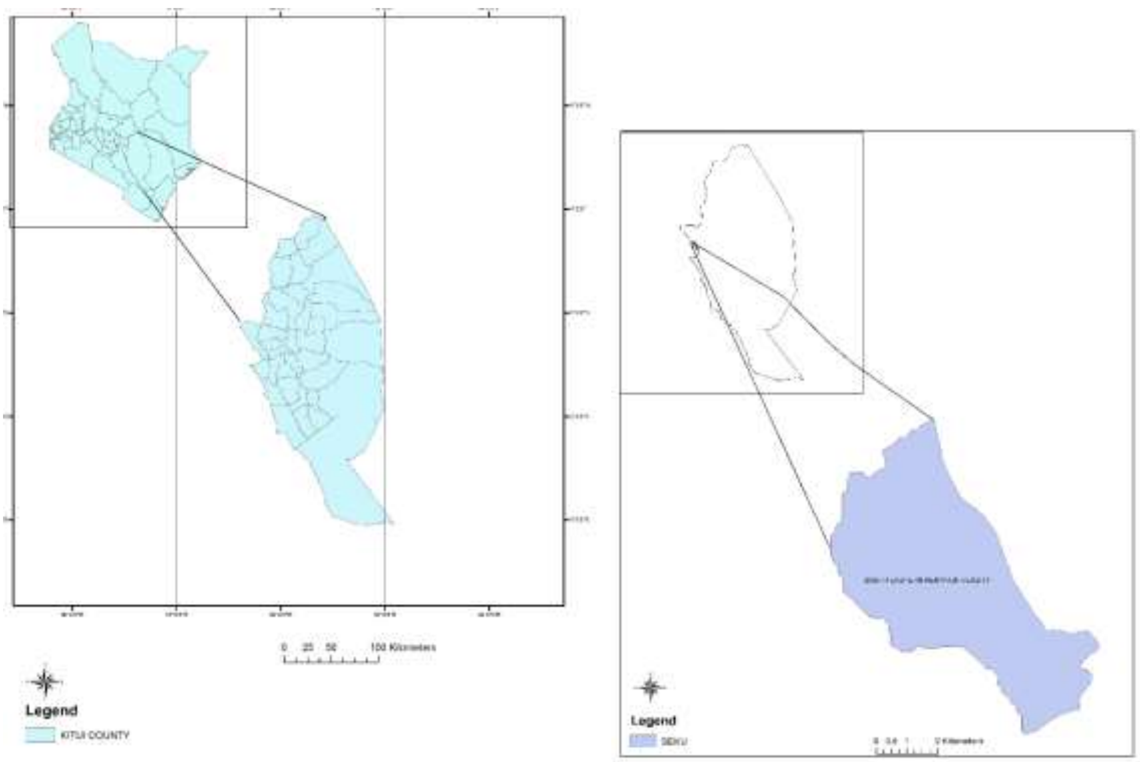

Figure 3.1: Location of the study site in South Eastern Kenya University, Kitui County (*Source: Mutiso et al., 2017*)

3.2.3 Hydrology and water resources

The research site and its environs are characteried by limited water resources. Mikuyuni and Mwita Syano seasonal rivers are the main water bodies. All the seasonal rivers and streams in the research area and its environs drain into the Tana River drainage basin, which is Kenya's largest river that drains the Eastern flank of the Aberdares and the Southern slopes of Mount Kenya (Borst & de Haas, 2006).

The rivers and streams in the study site are characterised by very low base flows in dry season and high flows during short and long rainy seasons. Most of the ephemeral streams generally become dry within one month after the rainy season (Borst & de Haas, 2006). High turbidity due to high sediment loads characterizes the river flows at the research site and its environs. The site and its environs are prone to fast flows and associated soil erosion. Sand and earth dams exist along Mwita Syano and Mikuyuni rivers. These water structures play a significant role in providing water for domestic and livestock particularly during dry seasons. Most of the sand and earth dams are small in size and end up drying during extended dry spells. Further, high water abstraction is common in the area.

3.2.4 Soils and geology

Soils at the study site are predominantly sandy to loamy sand texture. The soils are prone to soil erosion and have low capacity for water and nutrient retention. Lixisols is the predominant soil type at the study area and its environs while fluvisols occur in isolated patches along rivers, streams and on hill slopes (Borst & de Haas, 2006). Further, red well-drained sandy loam soils, which have quartz and feldspar grains and felsic gravel rock fragments are found in some areas of the research site. Soil depths vary from between 1.2m (upslope) to nearly 2.0m at the downslope side of the study site. High-grade regional metamorphic granitoid granulites characterize the geology of the research site and its environs. These are composed of quartz, feldspars of over 90%, mafic hornblende, and pyroxenes of approximately 10% (Winkler & Sen, 1973).

3.3 Selection of the Study Site

The selection of the study site was subjective based on the following criteria. Firstly, the study site is a typical semi-arid area hence a good representation of many drylands in Kenya. Secondly, the study site had adequate space and associated utilities that were critical for setting up nursery and field experiments.

3.4 Selection of *C. procera* Provenances

To select the study provenances, the seed sources had to have similar semi-arid climatic conditions as the study site. Based on this criterion, Baringo, Kibwezi and Tharaka Nithi met the conditions for seed sources.

3.5 Experiment Levels

The study entailed two experiments at the nursery and field levels. The nursery experiment aimed at selecting the best germination and growth media for *C. procera* based on germination parameters and seedlings early growth performance. Field experiment aimed at identifying the best provenance and optimum field spacing for *C. procera* for optimum growth and wool production.

3.5.1 Nursery experiment

At the nursery, sand, black cotton and normal nursery (soil collected from a forested area) soil were collected from the research site locality. The soil was thoroughly mixed to form potting mixes. Each soil type was potted into 288 polythene tubes of size 5cm*8cm. *C. procera* seeds were sown into the pots. Only one seed was sown per pot. Uniformity in sowing depth was maintained. The experiment was laid out in a randomized complete block design (RCBD) and replicated three times for each soil type and provenance to give nine treatment combinations as indicated in appendices 1 and 2. Data collected in the nursery experiment included germination energy, energy period, germination value, germination rate and seedlings mortality. This data was collected after germination for four weeks until the seedlings were transplanted to the field trails.

3.5.1.1 Germination energy, energy period, germination value and germination rate

To determine germination, seed germination was monitored and direct counts of germinated seeds taken on a daily basis for different provenances under the three different germination media. Germination rate data was used to plot graphs to capture germination energy and energy period. Germination percent and energy period were calculated using the following formula:

$$\boldsymbol{Germination}\,\% = \frac{\boldsymbol{Number\ of\ Germinated\ seed}}{\boldsymbol{Total\ number\ of\ seed\ sown}}\%$$

$$\boldsymbol{Germination\ energy} = \frac{\sum \boldsymbol{Germinates}\ (\boldsymbol{peak})}{\boldsymbol{Total\ number\ of\ seed\ sown}}\%$$

Czabator method (1962) and Djavanshir and Pourbeik method (1976) were used to compute germination values for the three provenances under the three germination media. Two methods were used to calculate germination value:

Czabator method: $\boldsymbol{GV} = \ (\boldsymbol{final})\boldsymbol{DGS} * \boldsymbol{PV}$

Where: GV = Germination value, DGS = Daily Germination Speed, PV = Peak value

Djavanshir and Pourbeik method:

$$\boldsymbol{GV = \sum (DGS/N) * \frac{GP}{10}}$$

Where:

GP = Germination percent at the end of the test,

DGS = Daily germination speed, obtained by dividing the cumulative germination percent by the number of days since sowing,

∑DGS = The total obtained by adding every DGS figure obtained from the daily counts and

N = The number of daily counts, starting from the date of first germination.

Pearson correlation analysis was done to establish existence of relationships between germination attributes (germination value, germination energy index and germination speed) in the three provenances of *C. procera.* Germination rates under different germination media were subjected to Duncan Multiple Range Test (DMRT) to establish existence of statistically significant differences. Spearman correlation analysis was done to determine existence of any relationships between daily germination rates and the number of days since germination started in the three germination media.

3.5.1.2. Seedlings mortality

Seedlings mortality was monitored. This was done by daily direct counts of dead seedlings in each provenance and soil type. Pearson correlation analysis was done to establish the existence of relationship between seedling mortality rate and seedling age in the three provenances and the three germination media. Symptoms and signs shown by affected seedlings were qualitatively described to establish whether mortality was as a result of pest or disease attack.

3.5.1.3 Seedlings early growth

Key growth parameters monitored included the number of leaves per seedling and the height. The measurements started two weeks after sowing and subsequent measurements were done after every three days until the seedlings were transplanted (after two months). The number of leaves were recorded after direct counts while height was measured using a 30cm ruler.

Leaf production by the three provenances was subjected to Test of Homogeneity of Variances and means separation done using Tukey's test (post hoc, $p < 0.05$) to test for statistically significant differences. Seedlings height was subjected to Duncan Multiple Range Test (DMRT) and Pair-wise analyses using Tukey's post hoc test. Pearson correlation analysis was used to determine existence of relationship between seedlings height and leaf production for the three provenances under the three germination media.

3.5.2 Field experiment

Monitoring of growth, phenological characteristics and wool productivity of *C. procera* was carried out in a typical farm setting. A 60m by 80m plot was cleared and levelled. 27 subplots were demarcated within the main plot. The subplots were laid out in a randomized complete block design within the main plot. In each of the subplot, 12 planting pits (1ft by 1ft) were dug but at different spacing. For each provenance, three spacing types, 1.5m by 1.5m, 2m by 2m and 3m by 3m were used. These were replicated three times to give a total of 9 treatment combinations (appendices 3 and 4). The spacing between subplots was 4m. The seedlings were transplanted and watering was done when enough moisture was not available in the first one month after transplanting. The main plot was weeded 2 weeks after transplanting. Subsequent weeding was done depending on the intensity of the weeds until the plants were fully established to withstand competition from weeds. In the field, the following data were collected: survival count, height and diameter growth, phenological characterization and wool production and quality.

3.5.2.1 Survival count

Survival count was done 21 days after transplanting. This was done to capture incidences of seedling establishment failure in the field. However, no replacement was done for dead seedlings to avoid data distortion in the research plot. Survival percent for each provenance was calculated. Survival count data was transformed, separated by provenance as well as spacing then subjected to analysis of variance to establish existence of statistically significant differences.

3.5.2.2 Growth parameters

One month after transplanting, four plants from each treatment were selected randomly at the centre core of each subplot and tagged. Boundary plants were avoided. Growth parameters (number of branches, diameter and height) were monitored and recorded for two years (four seasons). A veneer calliper and a ruler were used to measure diameter and height respectively. As the plants grew big, the veneer calliper and the ruler were replaced with a diameter tape and height rod/suunto hypsometer respectively. Subsequent growth measurements were done on the tagged plants every month for four seasons (two years).

Charts were generated to depict the levels of branching across the three provenances. Branching data was subjected to Test of Homogeneity of Variances to detect existence of significant differences among the three provenances. Diameter and height data were used to generate DBH and height growth curves respectively for the three provenances. Diameter and height data were further subjected to Duncan Multiple Range Test (DMRT) to test for statistically significant differences across the three provenances. Pearson correlation analysis was used to establish existence of relationships across the growth parameters in the three *C. procera* provenances under different spacing levels.

3.5.2.3 Phenological characterization

Tagged plants were monitored and phenological characteristics such as flowering, fruiting and ripening of fruits were captured. Monthly monitoring of the tagged plants included collection of data on the number of flowers (number of inflorescences and number of flowers per inflorescence) and number of fruits per inflorescence and per plant. The length and diameter of the fruits at maturity were also measured.

Phenological data (flowering and fruiting) was used to generate charts that depicted the flowering and fruiting phenophases for the three provenances under different spacing level in four seasons (two years). Phenological data was subjected to Test of Homogeneity of Variances to test existence of statistically significant differences across the three provenances under different spacing levels. Spearman correlation analysis was done to isolate existence of significant relationship in occurrence of phenological events (flowering and fruiting). Phenological phenophases were tabulated.

3.5.2.4 Wool production and quality

The fruits of the tagged plants were harvested for four seasons (two years) and the diameter and length of fruits were measured. Mean fruit diameter and length was calculated. For the three provenances, fruits whose pericarps had shown signs of dehiscence at the ventral suture were collected, put in Khaki paper bags and left to fully dehiscence in the lab. The wool length at three different locations within the fruiting body (head, middle and tail-end) was measured. The mean wool length was calculated and staple length identified. The silky floss was separated from the seeds to estimate wool productivity. Quantification of wool productivity per plant for different provenances under different spacing was done for four seasons. The data was extrapolated to get productivity on per hectare basis. In the laboratory, the wool was classified into grade 1, 2 and 3 based on wool clarity where the clearest was classified as grade 1. In the laboratory, the wool was put in a spinning machine to separate the fibres for further analysis of fibre mechanical properties.

3.5.3 Analysis of plant tissue and soil nutrient composition

A site where *C. procera* naturally grows was identified at Kwa Vonza, Kitui Rural Sub-County, Kitui County. Soil samples were collected from the natural stand of *C. procera* and soil chemical characterization was done. Similar samples were taken from each of the 27 subplots in the research trial plot and soil chemical characterization was done. In addition, plant tissue analysis was done in each of the 27 subplots.

3.5.3.1 Soil sampling and analysis

In the site where the *C. procera* naturally grows, sampling was done according to Kimiti *et al*. (2016) whereby a 100m by 100m sampling plot was established. A diagonal transect was ran across the sampling plot. Three soil sampling points were identified and marked; one at the centre and two at the edges of the diagonal transect. At each point, three plants of *C. procera* were identified and from each plant, soil samples were collected by auguring at 30cm deep and 1m away from the plant base. The soil cores were pooled, mixed and subsamples taken for laboratory analysis.

In each of the 27 subplots, the zigzag sampling method was used to collect four soil samples that were pooled, mixed and subsamples taken for laboratory analysis. Soil extracts were prepared to meet the requirements for the different parameters, 1:5 (w/v) soils (g): distilled water (ml). This extract was used to determine pH values using a glass electrode pH meter (Model 9107 BN, ORION type) and electrical conductivity (EC) with (conductivity meter 60 Sensor Operating Instruction Corning). Carbonates and bicarbonates were determined by titration against 0.1 N HCl using phenol phthalein and methyl orange as indicators. Total N was estimated using Micro-Kjeldahl method, while total P using a spectrophotometer (CECIL CE 1021) by applying Indo-Phenol blue and molybdenum blue methods, respectively. Sodium and potassium were determined using flame photometer. Zinc, copper, iron, manganese, were determined using Atomic Absorption ectrophotometer (Shimadzu, AA-6200).

One-way ANOVA was used to test the significance of variations in the soil chemical properties (pH, total N, P and K), Plant tissue data (total N, P, K, OC, Zn, Cu and Fe) of *C. procera* provenances and spacing treatment in relation to the field plots. Pearson simple linear correlation coefficient (r) was calculated for assessing the type of relationship between the study site and the natural stand of *C. procera* in relation to the soil chemical properties.

3.5.3.2 Plant tissue sampling and analysis

From the four tagged plants in each subplot, plant tissue samples were collected by harvesting the leaves. For each subplot, the harvested leaves were thoroughly mixed to form a bulk sample. For each subplot, a 500g sample (wet weight) was measured using a digital weighing balance. The samples were taken to the laboratory for complete chemical properties analyses (total organic carbon, nitrogen, phosphorus, potassium, zinc, copper, manganese and iron).

CHAPTER FOUR

4.0 Results

4.1 Seed germination and seedlings' early growth

4.1.1 Germination energy, energy period, germination rate and germination value

A total of 864 seeds were sown and each of the three soil media had a total of 288 seeds. Germination started on the fourth day, peaked on the 8th day and ended on 12th day. Twenty two (22) seeds representing 2.55% of all sown seeds failed to germinate. Of the 22 seeds that failed to germinate, 7 belonged to Kibwezi, 9 Baringo and 6 Tharaka provenances. In terms of germination media, 11 seeds in black cotton soil, 9 in normal nursery soil and 2 in sandy soil failed to germinate (Table 4.1).

Table 4.1: Number of seeds from three provenances that failed to germinate in three soil media

Provenances	***Soil media***			**Total no. in each provenance**
	Sand soil	Black cotton soil	Nursery soil	
Kibwezi	0	4	3	7
Tharaka	1	3	2	6
Baringo	1	4	4	9
Total no. in each soil media	2	11	9	22

All the three provenances recorded a high germination percent with Tharaka recording 97.92% followed by Kibwezi (97.57%) then Baringo (96.88%). The germination percentages showed no statistically significant differences among the three provenances ($F_{0.05;\ 8}$ = 0.302). In terms of germination media, sand soil had the highest germination percent of 99.31%, followed by normal nursery soil (96.88%) then black cotton soil (96.18%). The energy period was attained on the 8th day when all provenances and the different germination media showed peak germination (Figure 4.1a and 4.1b). In sand soil, germination ended on 11th day while in nursery and black cotton soil it ended on 12th day

(Figure 4.1b). Black cotton soil showed a high delayed germination after the peak period (Figure 4.1b).

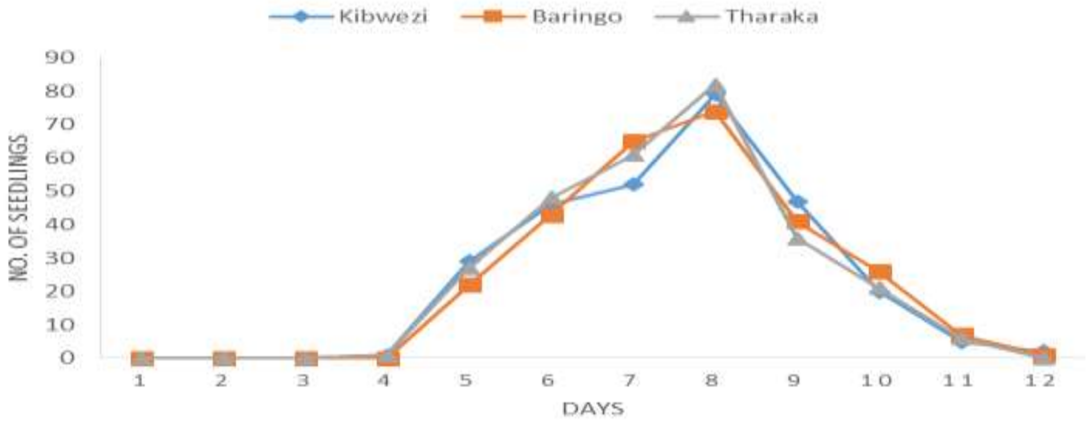

Figure 4.1a: Seedlings germination period by provenances

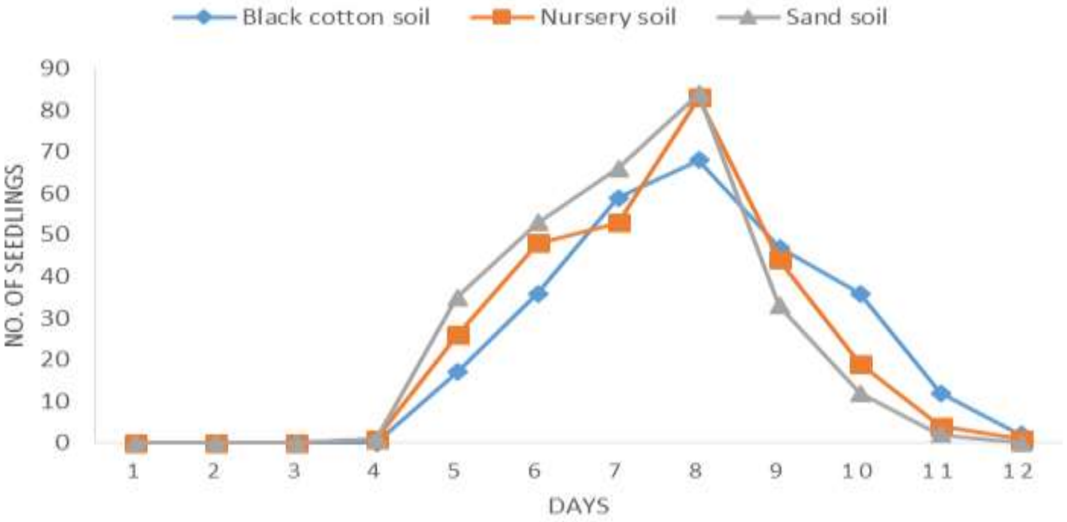

Figure 4.1b: Seedlings germination period by soil media

Tharaka provenance recorded the highest germination energy (76%) followed by Kibwezi (71%) then Baringo (70.8%). For germination media, sand soil had the highest germination energy (83.0%) followed by normal nursery soil (73.3%) and finally black cotton soil (62.5%) as shown in Figures 4.2a and 4.2b.

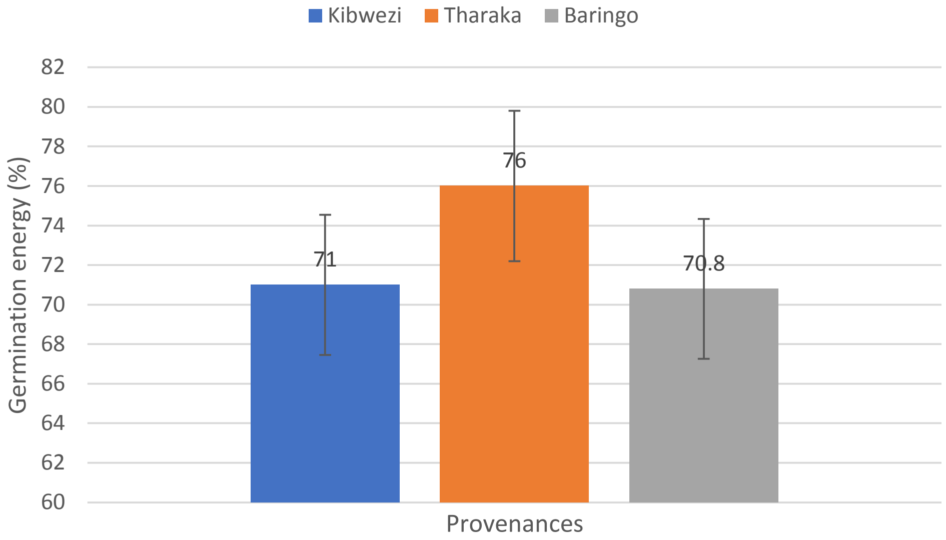

Figure 4.2a: Seedlings germination energy by provenances

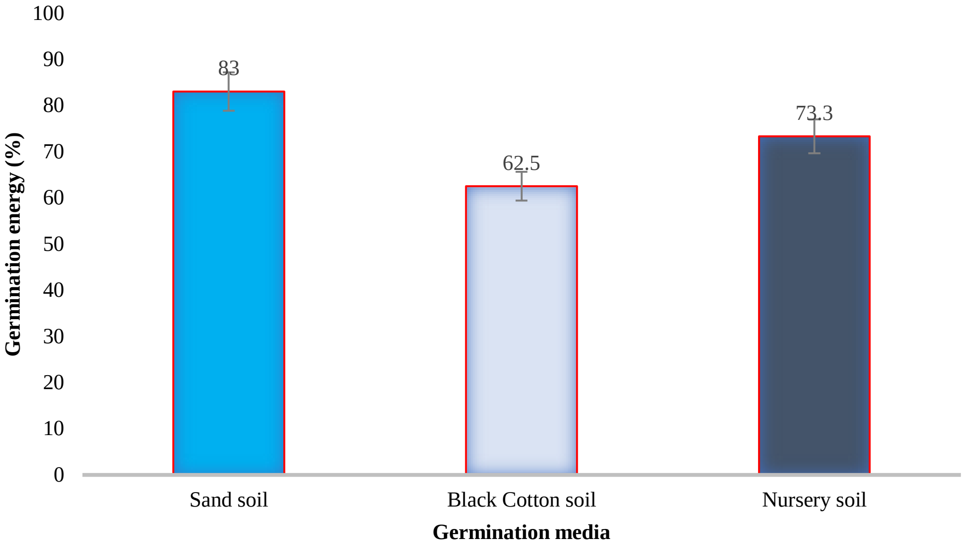

Figure 4.2b: Seedlings germination energy by soil media

All the provenances achieved a germination rate of ≥50% by the 8th day. However, sand soil achieved a germination rate of 53.8% by the 7th day. According to Czabator method (1962), Tharaka had the highest germination value (87.67) followed by Kibwezi (79.75) and then Baringo (76.07) being the least (Computed from Tables 4.2, 4.4 & 4.6 respectively). Djavanshir & Pourbeik method (1976) gave germination values of 83.40, 284.02 and 534.17 for Tharaka, Kibwezi and Baringo (Computed from Tables 4.2, 4.4 & 4.6) respectively.

Table 4.2: Germination values for Tharaka provenance seeds using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	*Daily Germ. %*	*Cumulative Germ. %*	*Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)*	*∑ DGS*	*No. of counts*	*∑ DGS/N (Col.5 ÷ Col.6)*
1	2	3	4	5	6	7
4	0.3	0.3	0.1	0.1	1	0.1
5	9.4	9.7	1.9	2.0	27	0.1
6	16.7	26.4	4.4	6.4	48	0.1
7	21.2	47.6	6.8	13.2	61	0.2
8	8.5	76.1	9.5	22.7	82	0.3
9	12.5	88.6	<u>9.8</u>	32.6	36	0.9
10	7.3	95.9	9.6	42.2	21	2.0
11	2.1	<u>98</u>	<u>8.9</u>	51.1	6	<u>8.5</u>

(1) Czabator method (1962)

Germination value = Final DGS × Peak Value DGS = 8.91 × 9.84 = 87.67

(2) Djavanshir and Pourbeik method (1976)

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 8.51 × 9.8 = 83.40.

A strong positive correlation was obtained for germination value (GV), germination energy index (GEI), mean daily germination (MDG) and germination speed (GS) for all the three provenances of *C. procera* (Table 4.3, 4.5 and 4.7). The correlations were statistically significant ($P<0.05$) for all the germination attributes for the three provenances. Tharaka provenance showed the strongest correlation between germination value (GV) and

Germination energy index (GEI) (Pearson, r = +0.976, $p < 0.05$) followed by Kibwezi (r = + 0.968) then Baringo (r = + 0.967) as shown in tables 4.3, 4.5 and 4.7.

Table 4.3: Correlation matrix for germination attributes of *C. procera* from Tharaka provenance

	GV	*GEI*	*MDG*	*GS*
GV	1			
GEI	0.976*	1		
MDG	0.924*	0.912*	1	
GS	0.938*	0.887*	0.938*	1

* = $P \leq 0.05$

Where: GV = Germination value, GEI = Germination Energy Index and GS = Germination speed

Table 4.4 below shows computations of germination attributes from the start of germination (4th day) to the end of germination (12th day) for Kibwezi provenance. Application of the Czabator method gave a germination value of 79.75 while Djavanshir and Pourbeik gave a germination value of 284.02.

Table 4.4: Germination values for Kibwezi provenance seeds using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	***Daily Germ. %***	***Cumulative Germ. %***	***Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)***	***∑ DGS***	***No. of counts***	***∑ DGS/N (Col.5 ÷ Col.6)***
1	2	3	4	5	6	7
4	0.35	0.35	0.09	0.09	1	0.09
5	10.1	10.45	2.09	2.18	29	0.08
6	16.0	26.45	4.40	6.58	46	0.14
7	18.1	44.55	6.36	12.94	52	0.25
8	27.4	71.95	8.99	21.93	79	0.28
9	16.3	88.25	9.81	31.74	47	0.68
10	6.9	95.15	9.52	41.26	20	2.06
11	1.7	96.85	8.80	50.06	5	10.01
12	0.7	97.55	8.13	58.19	2	29.10

(1) Czabator method

Germination value = Final DGS × Peak Value DGS = 8.13 × 9.81 = 79.75.

(2) Djavanshir and Pourbeik method

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 29.10 × 9.76 = 284.02.

When germination attributes (germination energy index, mean daily germination and germination speed) for Kibwezi provenance were subjected to Pearson correlation analysis, strong positive correlations (Pearson, $p < 0.05$) were obtained (Table 4.5).

Table 4.5: Correlation matrix for germination attributes of *C. procera* of Kibwezi provenance

	G.V	*GEI*	*MDG*	*GS*
G.V	1			
GEI	0.968*	1		
MDG	0.936*	0.892*	1	
GS	0.912*	0.897*	0.894*	1

* = P ≤ 0.05

Table 4.6 below shows computations of germination attributes for Baringo provenance from the start of germination (5th day since sowing) to the end of the test period (12th day). When Czabator method was applied, a germination value of 76.07 was obtained while Djavanshir and Pourbeik gave a germination value of 534.17.

Table 4.6: Germination values for Baringo provenance seeds using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	*Daily Germ. %*	*Cumulative Germ. %*	*Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)*	*∑ DGS*	*No. of counts*	*∑ DGS/N (Col.5 ÷ Col.6)*
1	2	3	4	5	6	7
5	7.6	7.6	0.54	0.54	22	0.02
6	14.9	22.5	3.75	4.29	43	0.10
7	2.6	45.1	6.44	10.73	65	0.17
8	25.7	70.8	8.85	19.58	74	0.26
9	4.2	85.0	9.44	29.02	41	0.71
10	9.0	94.0	9.40	38.42	26	1.48
11	2.4	96.4	8.76	47.18	7	6.74
12	0.3	96.7	8.06	55.24	1	55.24

(1) Czabator method (1962)

Germination value = Final DGS × Peak Value DGS = 8.06 × 9.44 = 76.07

(2) Djavanshir and Pourbeik method (1976)

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 55.24 × 9.67 = 534.17.

Table 4.7 below shows correlations between germination attributes (germination energy index, mean daily germination and germination speed) for Baringo provenance. Strong positive correlations (Pearson, $p < 0.05$) existed between the germination attributes.

Table 4.7: Correlation matrix for germination attributes of *C. procera* of Baringo provenance

	G.V	***GEI***	***MDG***	***GS***
G.V	1			
GEI	0.967*	1		
MDG	0.928*	0.923*	1	
GS	0.935*	0.868*	0.877*	1

* = $P \leq 0.05$

Sand soil had the highest germination value of 86.21 followed by normal nursery soil 79.33 while black cotton soil with a value of 73.22 had the least (Tables 4.8, 4.9 & 4.10 respectively).

Table 4.8: Germination values under sand soil using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	***Daily Germ. %***	***Cumulative Germ. %***	***Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)***	***∑ DGS***	***No. of counts***	***∑ DGS/N (Col.5 ÷ Col.6)***
1	2	3	4	5	6	7
4	0.3	0.3	0.08	0.08	1	0.08
5	12.2	9.3	1.86	1.94	35	0.06
6	18.4	26.0	4.33	6.27	53	0.12
7	22.9	44.4	6.34	12.61	66	0.91
8	9.2	73.2	9.15	21.76	84	0.26
9	11.5	88.5	9.83	31.59	33	0.96
10	4.2	95.1	9.51	41.1	12	3.42
11	0.7	96.5	8.77	49.87	2	24.94

(1) Czabator method (1962)

Germination value = Final DGS × Peak Value DGS = 8.77 × 9.83 = 86.21

(2) Djavanshir and Pourbeik method (1976)

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 24.94 × 9.65 = 240.67.

In seeds sown in normal nursery soil, germination started on the 4th day and ended on 12th day (Table 4.9). Germination attributes were computed for the entire test period. When Czabator and Djavanshir and Pourbeik methods were applied to compute germination values, 79.33 and 560.86 values were obtained respectively.

Table 4.9: Germination values from normal nursery soil using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	***Daily Germ. %***	***Cumulative Germ. %***	***Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)***	***∑ DGS***	***No. of counts***	***∑ DGS/N (Col.5 ÷ Col.6)***
1	2	3	4	5	6	7
4	0.3	0.3	0.08	0.08	1	0.08
5	9.0	9.3	1.86	1.94	26	0.07
6	16.7	26.0	4.33	6.27	48	0.13
7	18.4	44.4	6.34	12.61	53	0.24
8	28.8	73.2	9.15	21.76	83	0.26
9	15.3	88.5	9.83	31.59	44	0.72
10	6.6	95.1	9.51	41.1	19	2.16
11	1.4	96.5	8.77	49.87	4	12.47
12	0.3	96.8	8.07	57.94	1	57.94

(1) Czabator method (1962)

Germination value = Final DGS × Peak Value DGS = 8.07 × 9.83 = 79.33

(2) Djavanshir and Pourbeik method (1976)

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 57.94 × 9.68 = 560.86.

Black cotton soil showed delayed germination since germination started on the 5th day and ended on 12th day (Table 4.10). Germination attributes were computed for the entire test period and values obtained used to compute the germination value for the soil media. Czabator (1962) and Djavanshir and Pourbeik (1976) methods gave germination values of 73.22 and 254.35 respectively.

Table 4.10: Germination values from black cotton soil using Czabator (1) and Djavanshir and Pourbeik (2) methods

Days since sowing	*Daily Germ. %*	*Cumulative Germ. %*	*Daily Germ. Speed (or Mean Germ.) (Col. 3 ÷ Col. 1)*	*∑ DGS*	*No. of counts*	*∑ DGS/ N (Col.5 ÷ Col.6)*
1	2	3	4	5	6	7
5	5.9	5.9	1.84	1.84	17	0.11
6	12.5	18.4	3.07	4.91	36	0.14
7	20.5	38.9	5.56	10.47	59	0.18
8	23.6	62.5	7.81	18.28	68	0.27
9	16.3	78.8	8.76	27.04	47	0.58
10	12.5	91.3	9.13	36.17	36	1.00
11	4.2	95.5	8.68	44.85	12	3.74
12	0.7	96.2	8.02	52.87	2	26.44

(1) Czabator method (1962)

Germination value = Final DGS × Peak Value DGS = 8.02 × 9.13 = 73.22

(2) Djavanshir and Pourbeik method (1976)

Germination value = (Final ∑ DGS (N) × (Final Cumulative Germination %/10) = 26.44 × 9.62 = 254.35.

Duncan Multiple Range Test (DMRT) showed significant statistical differences ($P<0.05$) in germination rates among the different soil media used. The three soil media showed positive correlation between germination rates and the number of days up to peak value and a negative correlation from the peak value date to the end of the test period (Table 4.11). Black cotton soil showed a strong positive correlation (Spearman correlation, 0.731, $p<0.05$) at the initial germination period and a relatively strong negative correlation (Spearman correlation, -0.756, $P<0.05$) towards the end of the test period. On the contrary, sand soil showed very strong positive correlations at the initial and peak period of the test (Spearman correlation, 0.946 and 1.000 respectively, $p<0.01$) and a similarly strong but negative correlation (Spearman correlation, -0.945, p<0.01) towards the end of the test period (Table 4.11).

Table 4.11: Correlation matrix between germination rates and number of days

	Initial stages of test period (4-6th day)	*Peak of the test period (8th day)*	*Final stages of test period (10-12th day)*
Sand soil	0.946*	1.000*	-0.945*
Black cotton soil	0.731*	0.834*	-0.756*
Nursery soil	0.826*	0.923*	-0.831*

* = $p \leq 0.05$

The high germination rates among the three provenances and in the three germination media were as a result of the uniform germination observed. Strong positive correlations between germination rates and the number of days at the initial and peak germination period as well as strong but negative correlations were also evidence of uniformity in seedlings germination (Plate 4.1).

Plate 4.1: Uniformity of germination of the three provenances in three germination media (*Source: Plate by Mutiso, 2015*)

4.1.2 Seedlings mortality

A total of 16 seedlings representing 1.9% of the germinated seedlings died before transplanting. Of the 16 seedlings, 5 belonged to Kibwezi, 4 Baringo and 7 Tharaka provenances (Table 4.12). The highest mortality (8 seedlings) was recorded in normal nursery soil, followed by black cotton soil (5) and sand soil (3).

Table 4.12: Seedlings mortality by provenance and soil media

Provenances	***Soil media***			**Total no. of dead seedlings in each provenance**
	Sand soil	Black cotton soil	Nursery soil	
Kibwezi	1	1	3	5
Tharaka	2	3	2	7
Baringo	0	1	3	4
Total number of dead seedlings in each soil media	3	5	8	16

The mortality occurred in the first two weeks after germination. Examination of the dead seedlings showed a clean cut at the root collar diameter is some seedlings and soaky decaying root collar (Plate 6) in others.

Plate 4.2: A seedling attacked at the root collar

(*Source: Plate by Mutiso, 2015*)

Some seedlings exhibited attack by lower stem canker (Plate 4.3). The canker did not cause outright killing of the affected seedlings. Wound healing followed the attack. In cases where the canker caused loss of apical dominance, coppicing occurred leading to a multi-stemmed seedling (Plate 4.3).

Plate 4.3: Seedling with lower stem canker followed by recovery and coppicing

(*Source: Plate by Mutiso, 2015*)

4.1.3 Seedlings early growth

Generally, Tharaka provenance recorded the highest number of leaves (mean) and seedlings mean height followed by Kibwezi provenance then Baringo provenance. Test of Homogeneity of Variances using DMRT showed that Tharaka provenance was the most significant in terms of leaf production from week 1 to week 4 (Table 4.13).

Table 4.13: Leaf production (average number) by provenances of *C. procera*

Provenances	Week 1	Week 2	Week 3	Week 4
Kibwezi	3.83a	4.33ab	6.08ab	6.92a
Tharaka	4.75b	6.58bc	7.75c	8.33c
Baringo	3.75a	4.75ab	5.5a	5.92b
Mean	4.11	5.22	6.44	7.06
CV (%)	10.8	13.74	16.94	18.58
P	<0.002	<0.001	<0.001	<0.001

**Means bearing the same letter in a column are not significantly different. Mean separation by Tukey's test (p <0.05, CMD = 1.23)*

Results indicate that growth performance was greatly influenced by soil type. Seedlings grown on normal nursery soil showed the best performance in terms of number of leaves per seedling, height and root collar diameter (Plate 4.4 and Figure 4.3). Black cotton soil ranked second while sand soil had the poorest performance. Test of homogeneity of variances showed statistically significant differences (p=0.03) at 5% level of probability in mean height across the three provenances. Similarly, Duncan Multiple Range Test (DMRT) showed significant differences (p=0.037) in seedlings height across the three provenances. Pair-wise analyses using Tukey's post hoc test showed significant differences (p<0.05). Pearson correlation analysis showed a strong positive correlation between seedling height and leaf production (Pearson, $r_s = 0.732^{**}$, p<0.01, N = 27) in the three provenances. The correlations were significant (p<0.001) for week 1 to week 4 when seedling on sand soil started showing stunted growth with yellowing and shedding of the old foliage towards transplanting time.

Plate 4.4: Growth performance of seedlings on sand, black cotton soil and normal nursery soil (*Source: Plate by Mutiso, 2015*)

Where: T2s – Sand, T1B – Black cotton soil and T3N – Normal nursery soil

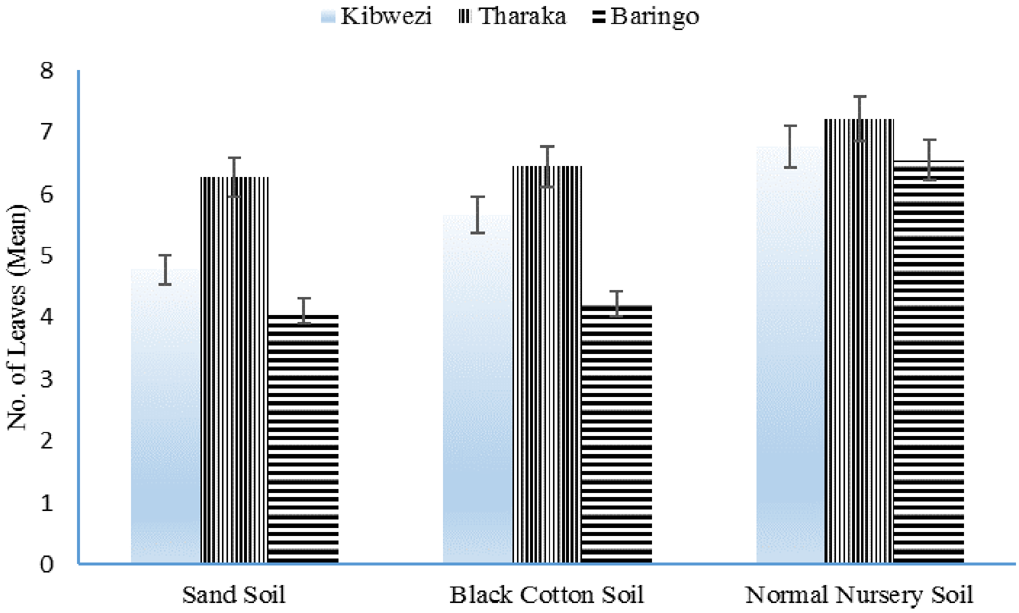

Figure 4.3: Leaf production by provenances and soil types

The highest number of leaves was recorded in normal nursery soil with a mean of 6.85 followed by black cotton soil with 5.44 and the least was sand soil with 5.06. Growth in height followed the same trend with normal nursery soil recording a mean height of 4.95cm followed by black cotton soil with 3.3cm and sand soil 2.47cm. In terms of provenances, Tharaka recorded the highest mean number of leaves and mean height followed by Kibwezi then Baringo in all the soil media (Table 4.14). Subjecting the results to analysis of variance showed significant differences for mean number of leaves (p=0.013) and the seedlings' height (p=0.006) at $\alpha = 5\%$ probability level across the three soil media. Spearman correlation analysis showed a strong positive correlation between seedling height and leaf production (Spearman, $r_s = 0.742^{**}$, $p<0.01$, N = 27, 2-tailed) across the three soil media.

Table 4.14: Seedlings leaf production and height by provenances and soil types

Provenances	*Parameters (mean)*	*Soil media*					
		Sand soil	SD	Black cotton soil	SD	Nursery soil	SD
Kibwezi	No. of leaves	5.0	2.23	6.0	1.22	7.0	0.70
	Height (cm)	1.7	0.16	2.5	0.21	6.2	0.35
Tharaka	No. of leaves	6.0	1.22	6.0	1.22	7.0	1.58
	Height (cm)	4.0	0.23	4.8	0.25	4.9	0.21
Baringo	No. of leaves	4.0	0.70	4.0	1.41	7.0	1.22
	Height (cm)	1.7	0.2	2.6	0.1	3.8	0.07

Nursery soil recorded the best performance in terms of seedling height (mean height value) and leaf production (mean leaf value) followed by black cotton soil while sand soil had the poorest (Table 4.14). Test of homogeneity of variances showed statistically significant differences (p=0.03) at 5% level of probability in mean height across the three provenances. Similarly, Duncan Multiple Range Test (DMRT) showed significant differences (p=0.037) in seedlings height across the three provenances. Pearson correlation analysis showed a strong positive correlation between seedling height and leaf production (Pearson, $r_s = 0.732$, $p<0.01$, N = 27) in the three provenances. Seedlings on sand soil started showing stunted growth with yellowing and shedding of the old foliage towards transplanting time.

4.2 Field establishment of *C. procera*

4.2.1 Field seedlings survival

Survival count showed excellent field establishment with Kibwezi provenance attaining 98% while Baringo and Tharaka had 97.5% (Table 4.15). Separation of survival count results by provenance and space and by space alone didn’t show significant statistical differences (p<0.05).

Table 4.15: Seedling survival rate by provenances of *C. procera*

Provenances	***Total seedlings***	***Survival rate***
Kibwezi	108	98% (106 seedlings)
Baringo	108	97.5% (105 seedlings)
Tharaka	108	97.5% (105 seedlings)

4.2.2 Growth performance of the three *C. procera* provenances

4.2.2.1 Production of branches by *C. procera*

It was observed that *C. procera* is generally a multi-stemmed plant (Plate 4.5). Emergence of branches occured immediately the plants were transplanted though there were cases where it started at the nursery, especially for seedlings affected by cutworms or other injuries that triggered resprouting of new shoots. Subsequent damage in the field by pests, diseases or physical injuries triggered massive branching with some plants taking a bush-like morphology (Plate 4.5). The bush-like plants were characterized by a minimum of 5 to a maximum of 40 branches.

Plate 4.5: Multi-stemmed morphology of *C. procera* at the study site

(*Source: Plate by Mutiso, 2017*)

By the age of 2 years, branching in the three provenances seemed to have levelled off (Figure 4.4). Tharaka provenance had the highest mean branching of 20.94 followed by Baringo (17.84) then Kibwezi (16.92) as shown in figure 4.4. When the branching data was subjected to Test of Homogeneity of Variances, significant statistical differences ($p<0.5$) were obtained with Baringo being the least significant (0.043), Kibwezi (0.01) and Tharaka (0.0001).

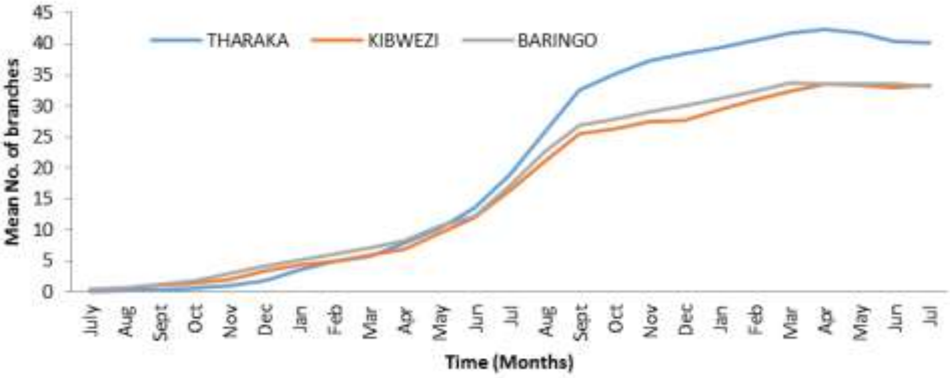

Figure 4.4: Average branching levels of *C. procera* provenances

4.2.2.2 Horizontal growth (DBH) of *C. procera* provenances

The three provenances showed minor variations in diameter growth in the first nine months of field growth. From the age of 16 months, all the three provenances showed minimal diameter increment (Figure 4.5) though complete levelling off of DBH growth curves was not evident by the end of the two year monitoring period. However, mean DBH growth followed a slightly different trend as captured under branching with Tharaka recording the highest (5.74cm), Kibwezi (5.49) and Baringo (5.23). Individual stems showed lack of homogeneity in diameter classes with Tharaka recording a range of 4.5-7.3cm, Kibwezi (3.8-7.3) and Baringo (3.7-7.4).

The observed diameter sizes (Plate 4.6) at the end of the monitoring period were generally low since a ground check in the course of this study captured a naturally growing *C. procera* plant that had a diameter of 25cm along Enziu river, Mui ward, Mwingi Central, Kitui County. Duncan Multiple Range Test (DMRT) showed no statistically significant differences ($p<0.5$) in diameter growth for the three provenances. However, when the data was subjected to Pearson correlation analysis, all the three provenances showed strong positive correlations (Pearson, $p<0.01$) between branching and DBH with Kibwezi recording $r_s = 0.975$, Baringo ($r_s = 0.988$) and Tharaka ($r_s = 0.996$).

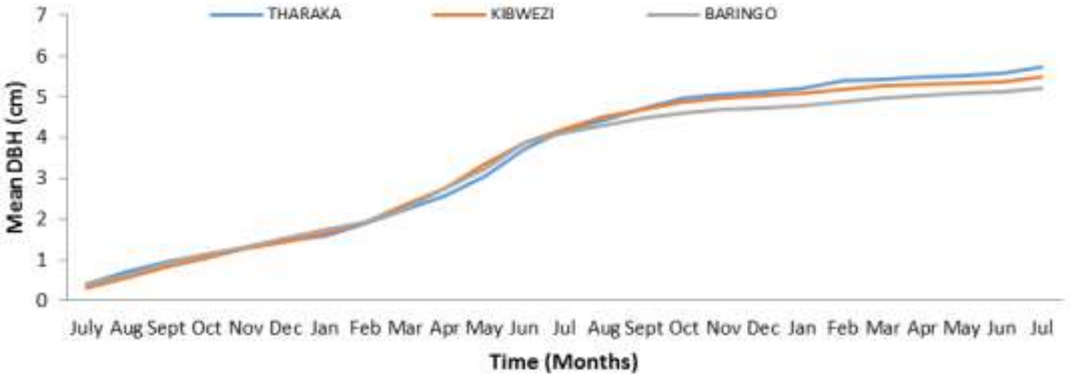

Figure 4.5: Mean DBH of *C. procera* provenances over two year period

Plate 4.6: ***C. procera*** **stem sizes at the study site**

(*Source: Plate by Mutiso, 2017*)

4.2.2.3 Height growth of *C. procera* provenances

In the first year of growth, Baringo provenance recorded the highest mean height (Figure 4.6). However, by the end of the two year period, Tharaka had the highest mean height of 368.24cm, Kibwezi (354.20) and Baringo (339.67) as shown in figure 4.6. Height growth lacked homogeneity typical in plantation crops with each provenance showing a range in height distribution (Tharaka 230-442cm, Kibwezi 233-448.5cm and Baringo 213.5-429cm). At the end of the two year monitoring period, the height growth had not levelled off. Test of homogeneity of variances showed significant statistical differences ($p<0.5$) with Baringo being the least significant (0.034), Kibwezi (0.022) and Tharaka (0.01). All the three provenances showed a strong positive correlation (Pearson, $P<0.01$) of branching, DBH and Height with Baringo recording $r_s = 0.975$, Kibwezi ($r_s = 0.988$) and Tharaka ($r_s = 0.996$).

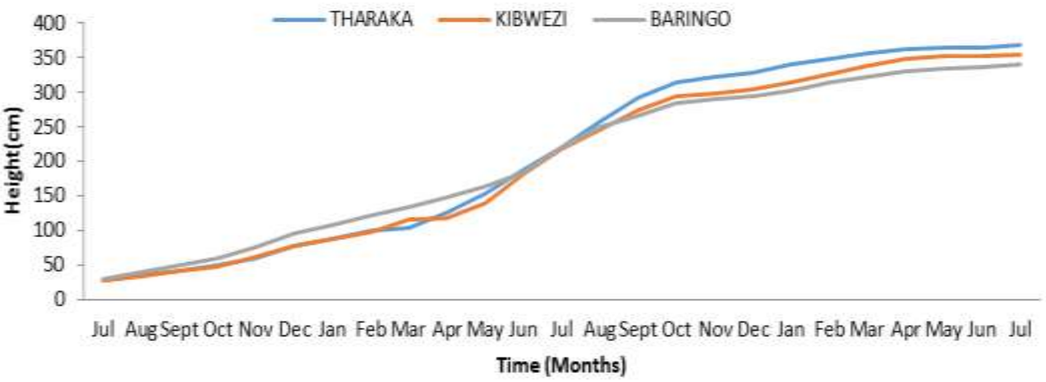

Figure 4.6: Height of *C. procera* provenances over a two year period

4.2.2.4 Flowering of the three provenances of *C. procera*

Flowering started when the plants were four months old in the month of October (Plate 4.7). At this stage, the plants were still juvenile. However, some plants did not flower. Flowering intensity was very low with individual plants bearing 1-5 flower clusters (Plate 4.7). Each cluster was characterized by 15-30 flowers (Plate 4.8). At this age, all the three provenances showed similar trends in flowering with no statistically significant differences ($P<0.05$). However, when the plants were 1 year old, differences in flowering rates started manifesting with Tharaka provenance showing a slightly higher number of flower clusters followed by Kibwezi and then Baringo (Figure 4.7).

Plate 4.7: Three flower clusters in a 4 months old *C. procera* plant

(*Source: Plate by Mutiso, 2015*)

Plate 4.8: Twenty three flowers in one flower cluster of *C. procera* at the study site

(*Source: Plate by Mutiso, 2017*)

Flowering seemed to occur throughout the year with mean annual peaks of flower cluster per plant in the month of March (Tharaka – 59, Kibwezi – 50 and Baringo – 49) and October (Tharaka – 45, Kibwezi – 43 and Baringo – 42) every year for the three provenances (Figure 4.7). On average, at peak flowering, a mature *C. procera* plant had at least 47 flower clusters translating to atleast 1,000 flowers. Flowering was lowest in the month of February (Tharaka – 3, Kibwezi – 1 and Baringo – 1) and June (Tharaka – 2, Kibwezi – 2 and Baringo – 2) every year for all the three provenances (Figure 4.7).

Peak flowering seemed to be sychronized to concide with the onset of long rains in the month of March and short rains in the month of October (Figure 4.7). Flowering duration and active phases seemed to be significantly longer and high ($p<0.001$) during the wet season. Further, spearman rank correlations between wet seasons and flowering ranged from 0.89 to 0.96 and were highly significant (r_s, pair-wise correlations, $p<0.0001$).

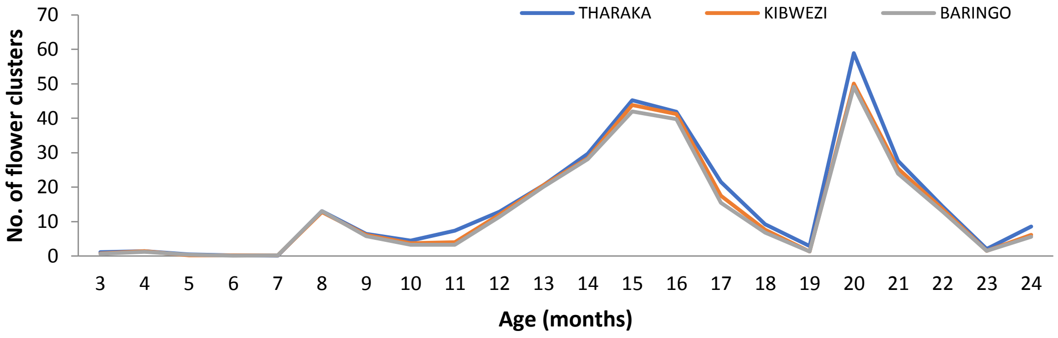

Figure 4.7: Flower clusters and flowering phenophases of *C. procera* provenances

In a typical year during the monitoring period, six flowering and fruiting phenophases were noted (Table 4.16). Though flowering phenophases were clear-cut, flowering occurred throughout the year though off season flowering was characterized by 1-2 flower clusters per plant.

Table 4.16: Flowering and fruiting phenophases of *C. procera*

No.	Sequential phenophases	
	Flowering	Fruiting
1	1-2 flower clusters and few flower buds	No fruits
2	1-2 flower clusters and many opening buds	No fruits
3	Opening flowers	Early fruits
4	Peak flowering	Green fruits
5	Few flowers and many withered flowers	Peak fruit maturation
6	1-2 flower clusters and many dried and withered flowers	Fruit dehiscence and seed dissemination

The three provenances did not show statistically significant differences in flowering though all of them portrayed very strong positive correlations (Pearson, $p<0.01$, 2-tailed, $n = 189$) in flowering across the year where Baringo had $r_s = 1$, Kibwezi ($r_s = 0.853$) and Tharaka ($r_s = 0.959$). However, flowering intensity in different months of the year was significantly different ($p<0.05$) for the three provenances with clear flowering phenophases (Figure 4.6). Peak flowering phenophases were characterized by massive flowering of the individual stems of *C. procera* (Plate 4.9).

Plate 4.9: Mass flowering during peak flowering phenophases

(*Source: Plate by Mutiso, 2017*)

Though the peak flowering phenophases were characterized by heavy flowering, massive flower abortion occurred all through with a limited number making it to the fruiting stage.

Attack of flowers by oleander aphid (*Aphis nerii*) was common during flowering period. In extreme cases, all the flower in a cluster failed (Plate 4.10a) but typically 1-4 flowers made it to fruiting stage (Plate 4.10b).

Plate 4.10a: Flower abortion in a whole cluster

Plate 4.10b: Two flowers transit to fruiting stage

(*Source: Plate by Mutiso, 2017*)

4.2.2.5 Fruiting of the three provenances of *C. procera*

Fruiting phenophases were evident each year with peak fruiting occuring in the month of April during the long rainy season and in the month of November during the short rainy season (Figure 4.8). A strong sychronization of fruiting and the rain seasons was evident. Fruiting durations and active phases seemed to be significantly longer and high ($p<0.001$) during the wet season. At the juvenile stages, fruiting levels in each provenance were almost negligible. Similarly, off season fruiting was negligible. A positive correlation was observed between fruiting and plant age; suggesting that the younger the plants, the lower the number of fruits. In the third and fourth seasons, Tharaka was the most significant in terms of fruit production with an average of 45 and 36 fruits respectively. In the same seasons (Figure 4.8), Kibwezi had an average of 39 and 31 respectively while Baringo had the least (37 and 30 fruits respectively). Spearman correlation analysis showed a strong positive relationship ($p<0.05$) between flowering and fruiting in all the provenances.

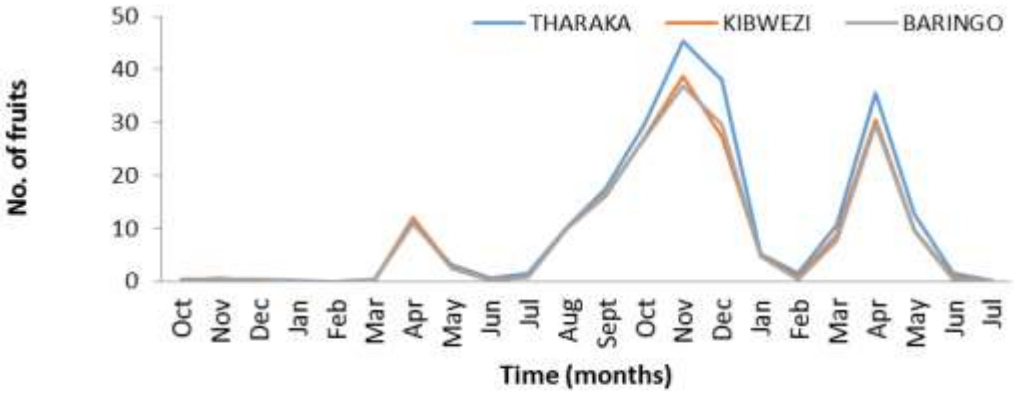

Figure 4.8: Fruiting phenophases of the three provenances of *C. procera*

Figure 4.9 shows the shift in flowering to fruiting as well as the number of flower clusters that make it to be fruits. This shows a very low transition rate given that each cluster had an average of 23 flowers.

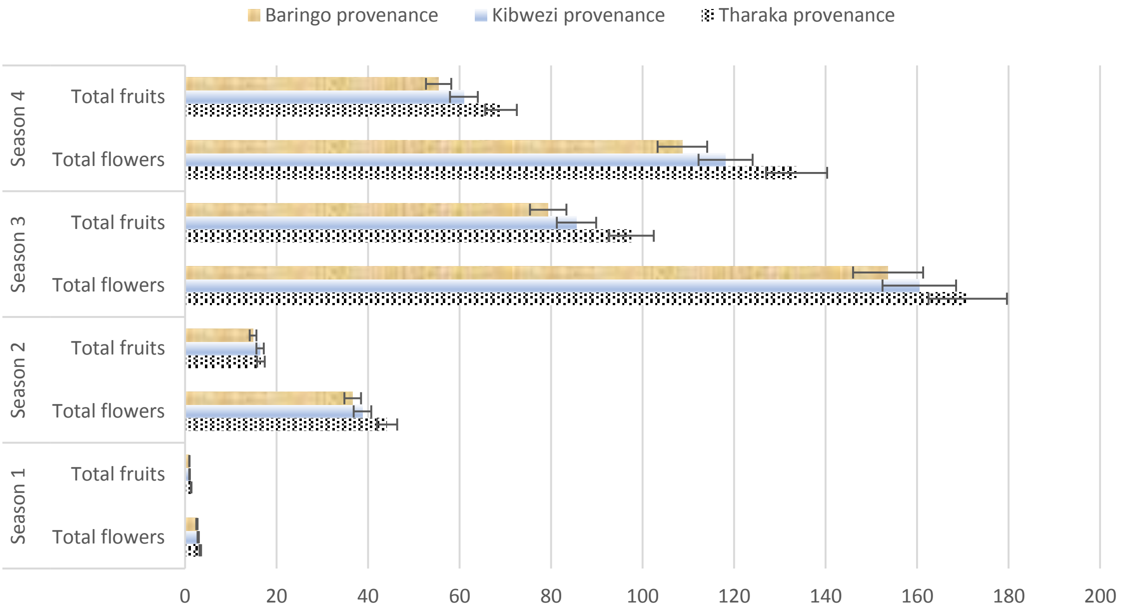

Figure 4.9: Transition of flower clusters to fruits

Figure 4.10 below shows the total number of fruits recorded and the number that was harvested for each provenance. In each season, the number of fruits that made to the harvesting stage was generally lower than the total recorded fruits. When the total recorded fruits and the harvested fruits were subjected to DMRT, significant differences were obtained for all the provenances in seasons two, three and four.

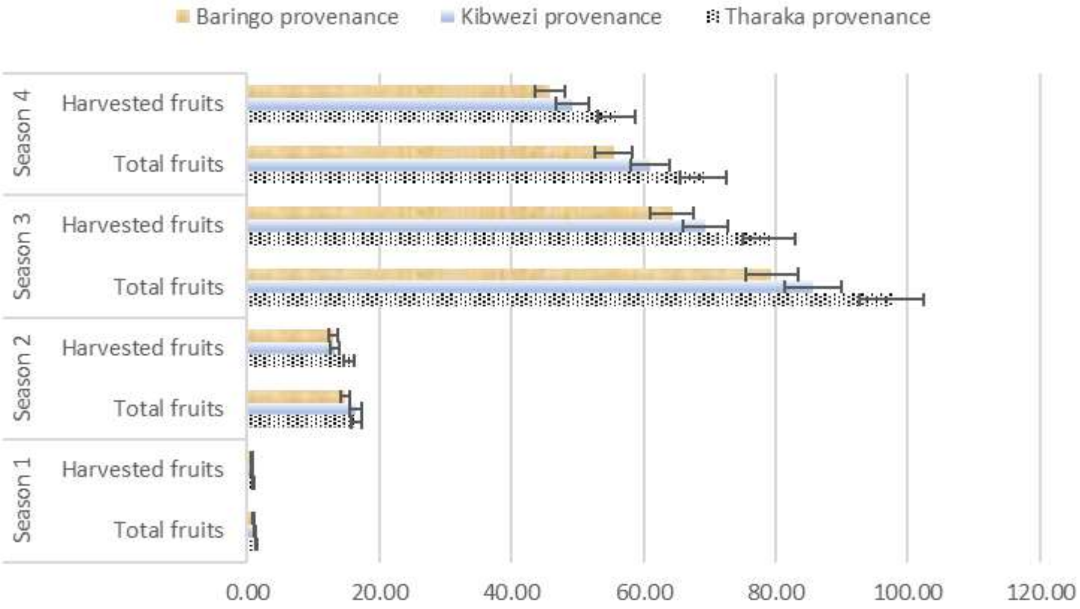

Figure 4.10: Seasonal fruit production and number of harvested fruits of *C. procera*

In some incidences, fruit abortion occurred at the initial stages of fruiting thereby reducing the total number of harvestable fruits. In other cases, fruits were heavily attacked by *Aphis nerii* (Plate 4.11) leading to premature death of the fruits.

Plate 4.11: Some fruits heavily attacked by the oleander aphids (*Aphis nerii*) at the study site (*Source: Plate by Mutiso, 2017*)

Despite the flower and fruit losses, heavy fruiting was common in all the provenances with individual plants having 1-3 fruits per flower cluster (Plate 4.12). The number of fruits per stems varied widely in the three provenances. Generally, in season 3 and 4, a minimum of 25 fruits and a maximum of 105 fruits was common in individual stems of the three provenances. Given that at peak flowering a single plant would bear at least 1000 flowers, the transition rate from flowers to fruits ranged between 2.5-10.5%. Generally, the flower to fruit ratio was very low. Concurrent flowering and fruiting was common in all provenances.

Plate 4.12: Concurrent flowering and fruiting of *C. procera* plants at the study site

(*Source: Plate by Mutiso, 2017*)

Fruits took an average of 30-40 days to ripen. Mature fruits had a diameter range of 8.4cm-11.3cm with a mean of 9.6cm. The fruit length at maturity ranged between 7.5cm-11.8cm with a mean of 9.7cm. Once ripe, the fruits split along the ventral suture releasing the wool and the seeds (Plate 4.13). In many cases, fruits maintained their green colour at maturity (Plate 4.13) making it difficult to differentiate mature and immature fruits. To avoid loss of wool, fruits were harvested shortly before they burst open or once the pericarp showed signs of dehiscence at the ventral suture. The harvested ripe fruits were stored in khaki bags in a laboratory for 1-3 days. When the fruits bursted open the silky floss (wool) was separated by hand from the seeds.

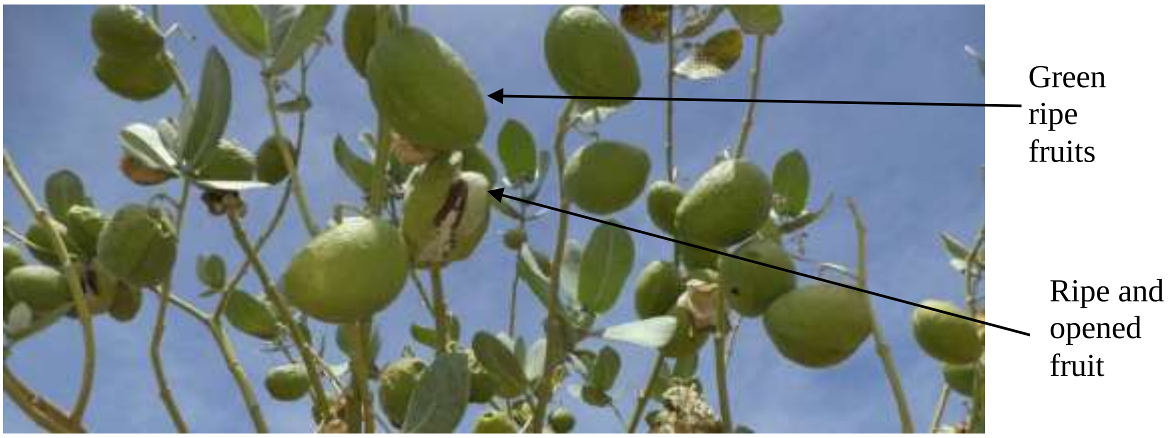

Plate 4.13: Ripe fruits of *C. procera* at the study site

(*Source: Plate by Mutiso, 2017*)

4.3 Effects of spacing on growth and phenology of *C. procera* provenances

4.3.1 Effects of spacing on branching of the three *C. procera* provenances

In the first nine months, all the three spacing levels showed no significant differences in the branching rates (Figure 4.11). However, the spacing levels had differences in the branching rate for the rest of the monitoring period with 3m*3m spacing being the most significant. By the end of the two year monitoring period, the branching curves for the three spacing levels were almost levelling off (Figure 4.11).

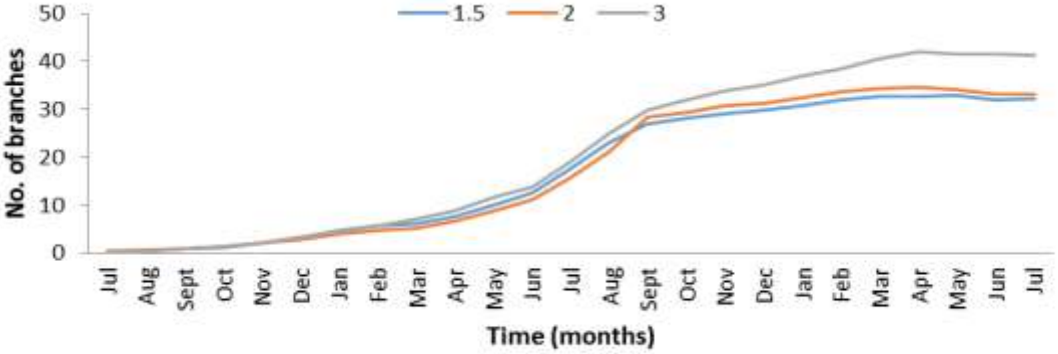

Figure 4.11: Branching rates of *C. procera* under different spacing levels

Pearson correlation analysis showed a weak to relatively strong negative correlation between branch production under different spacing levels and the age of the *C. procera* plants in the first 10 months but the relationship turned to be very strong and positive towards the end of the test period (Table 4.17)

Table 4.17: Correlation between branch production and age of *C. procera* under different spacing levels

	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
July	1.00																								
Aug	0.76	1																							
Sept	0.72	0.94	1.00																						
Oct	0.83	0.85	0.91	1.00																					
Nov	0.80	0.86	0.91	0.95	1.00																				
Dec	0.70	0.78	0.82	0.89	0.94	1.00																			
Jan	0.62	0.56	0.53	0.69	0.78	0.90	1.00																		
Feb	0.35	0.12	0.11	0.38	0.47	0.63	0.88	1.00																	
Mar	0.34	0.00	0.03	0.35	0.40	0.54	0.80	0.97	1.00																
Apr	0.07	-0.32	-0.30	0.05	0.08	0.23	0.56	0.88	0.93	1.00															
May	0.02	-0.32	-0.31	0.03	0.06	0.24	0.57	0.88	0.93	0.99	1.00														
Jun	-0.16	-0.51	-0.55	-0.22	-0.25	-0.04	0.34	0.71	0.76	0.91	0.94	1.00													
Jul	-0.18	-0.55	-0.58	-0.25	-0.25	-0.06	0.33	0.72	0.78	0.94	0.95	0.99	1.00												
Aug	-0.21	-0.60	-0.63	-0.30	-0.29	-0.14	0.25	0.67	0.72	0.92	0.91	0.97	0.98	1.00											
Sept	-0.23	-0.69	-0.78	-0.48	-0.51	-0.45	-0.07	0.36	0.42	0.70	0.67	0.82	0.83	0.90	1.00										
Oct	-0.34	-0.76	-0.82	-0.54	-0.56	-0.50	-0.13	0.33	0.40	0.69	0.67	0.81	0.83	0.91	0.99	1.00									
Nov	-0.34	-0.76	-0.82	-0.54	-0.57	-0.52	-0.15	0.31	0.39	0.68	0.65	0.81	0.82	0.90	0.99	1.00	1.00								
Dec	-0.31	-0.73	-0.79	-0.50	-0.52	-0.48	-0.12	0.34	0.42	0.70	0.67	0.81	0.83	0.91	0.99	1.00	1.00	1.00							
Jan	-0.30	-0.73	-0.78	-0.48	-0.51	-0.47	-0.10	0.35	0.44	0.72	0.69	0.82	0.84	0.91	0.98	0.99	1.00	1.00	1.00						
Feb	-0.26	-0.71	-0.77	-0.46	-0.50	-0.46	-0.09	0.36	0.45	0.73	0.70	0.83	0.85	0.91	0.98	0.99	0.99	0.99	1.00	1.00					
Mar	-0.25	-0.71	-0.74	-0.42	-0.48	-0.43	-0.08	0.36	0.47	0.74	0.71	0.83	0.85	0.91	0.96	0.97	0.98	0.98	0.99	1.00	1.00				
Apr	-0.28	-0.73	-0.74	-0.42	-0.51	-0.47	-0.15	0.29	0.42	0.69	0.67	0.80	0.81	0.87	0.93	0.95	0.95	0.96	0.97	0.98	0.99	1.00			
May	-0.26	-0.71	-0.72	-0.39	-0.48	-0.43	-0.11	0.33	0.46	0.72	0.70	0.82	0.83	0.88	0.93	0.94	0.95	0.95	0.97	0.98	0.99	1.00	1.00		
Jun	-0.23	-0.68	-0.67	-0.34	-0.43	-0.39	-0.07	0.35	0.49	0.74	0.72	0.82	0.83	0.88	0.90	0.92	0.92	0.93	0.95	0.96	0.98	0.99	1.00	1.00	
Jul	-0.24	-0.68	-0.68	-0.35	-0.45	-0.40	-0.09	0.33	0.47	0.72	0.70	0.81	0.82	0.86	0.89	0.91	0.91	0.92	0.94	0.96	0.98	0.99	1.00	1.00	1

The response of the three provenances to spacing was similar with a general increase in branching with increase in spacing (Figure 4.12). When the data was subjected to Test of Homogeinity of Variances, 3m*3m was the most significant ($p<0.05$) for the three provenances with 1.5m*1.5m and 2m*2m showing minimal variations.

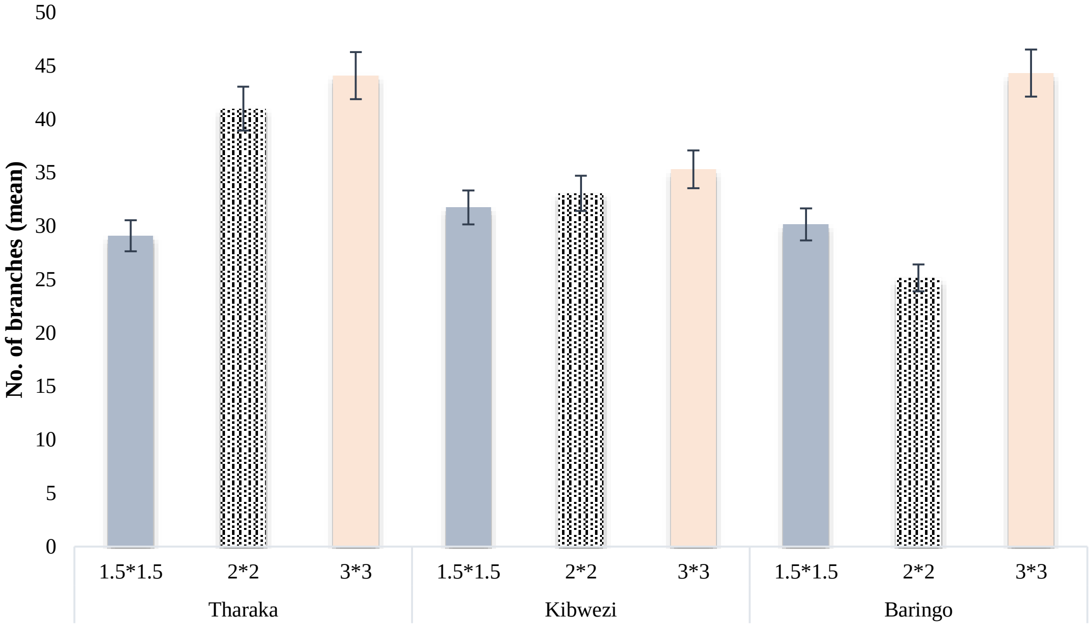

Figure 4.12: Branching levels by provenances and spacing levels

Under the 3m*3m spacing level, *C. procera* plants seemed to invest more on development of lateral branches giving a single plant a multi-stemmed and bushlike appearance (Plate 4.14). On the contrary, under closer spacing of 1.5m*1.5m, *C. procera* plants invested heavily on height growth and minimally on development of lateral branches (Plate 4.15). The study could not authoritatively explain why the number of branches for Baringo provenance under 2*2m spacing was generally low.

Plate 4.14: Investment in lateral branches production in 3m*3m spacing level (*Source: Plate by Mutiso, 2017*)

Plate 4.15: Investment in height growth in 1.5m*1.5m spacing level (*Source: Plate by Mutiso, 2017*)

4.3.2 Effects of spacing on vertical growth of the three *C. procera* provenances

In the first 15 months, height growth was independent of spacing levels with the *C. procera* plants showing an almost similar increment in height (Figure 4.13). However, with time, differences in height growth started emerging with 1.5m*1.5m recording a relatively higher mean stem height (366.55) followed by 2m*2m (358.75cm) then 3m*3m (335.98) at the end of the monitoring period (Figure 4.13). A 3m*3m spacing was not statistically significant (0.806, $p<0.05$) while 2x2 and 1.5x1.5 were significant at $p = 0.001$ and $p = 0.0001$ respectively. A positive correlation (Spearman, $p<0.01$) existed between height growth and age of the plants under different spacing levels with 1.5m*1.5m relating strongly ($r_s = 0.986$) followed by 2m*2m ($r_s = 0.9$) then 3m*3m ($r_s = 0.614$). Though by the end of the monitoring period the height increment had slowed down, complete levelling off of the vertical growth curves had not occurred (Figure 4.13).

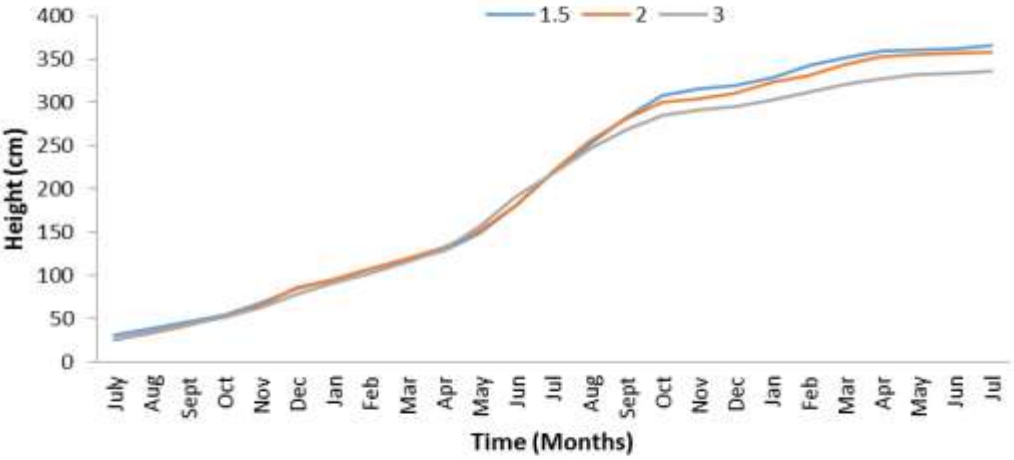

Figure 4.13: Vertical growth of *C. procera* under different spacing levels

DMRT showed significant differences ($p<0.05$) in height growth of the three provenances of *C. procera* under different spacing levels. Tharaka provenance had 1.5m*1.5m recording the highest height followed by 2m*2m then 3m*3m. Contrary, Kibwezi had 2m*2m recording a relatively higher mean stem hieght followed by 1.5m*1.5m then 3m*3m (Figure 4.14).

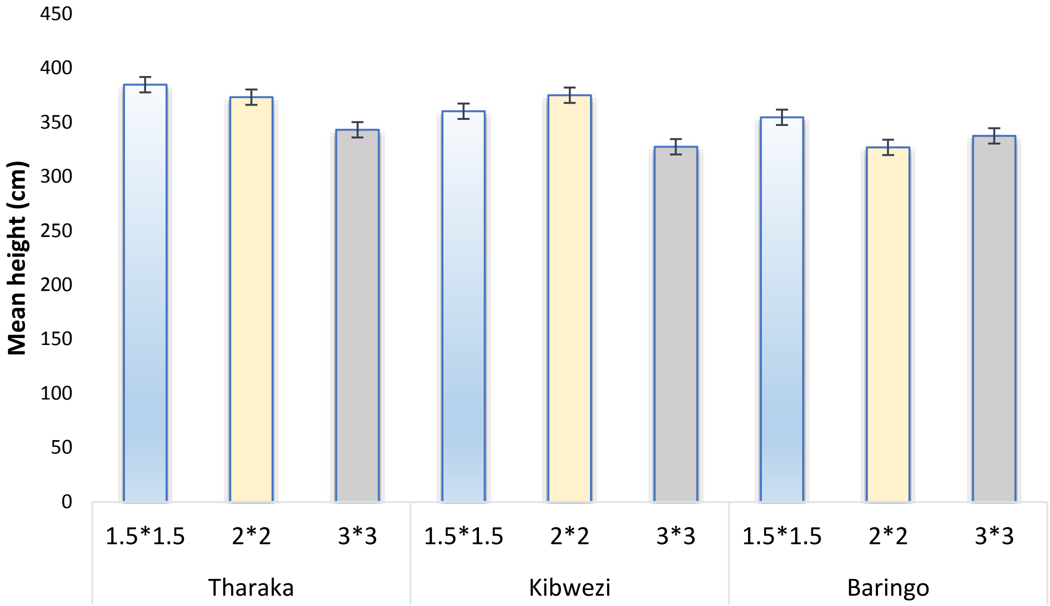

Figure 4.14: Plant height by provenances and spacing levels

4.3.3 Effects of spacing on horizontal growth of the three C. procera provenances

Differences in diameter increment in the first 7 months were almost negligible. As the *C. procera* plants aged, 3m*3m spacing level was the most significant in terms of horizontal growth (Figure 4.15) while 1.5m*1.5m and 2m*2m maintained an almost similar rate of horizontal growth. By the end of the monitoring period, the horizontal growth curves had not levelled off under the three spacing levels.

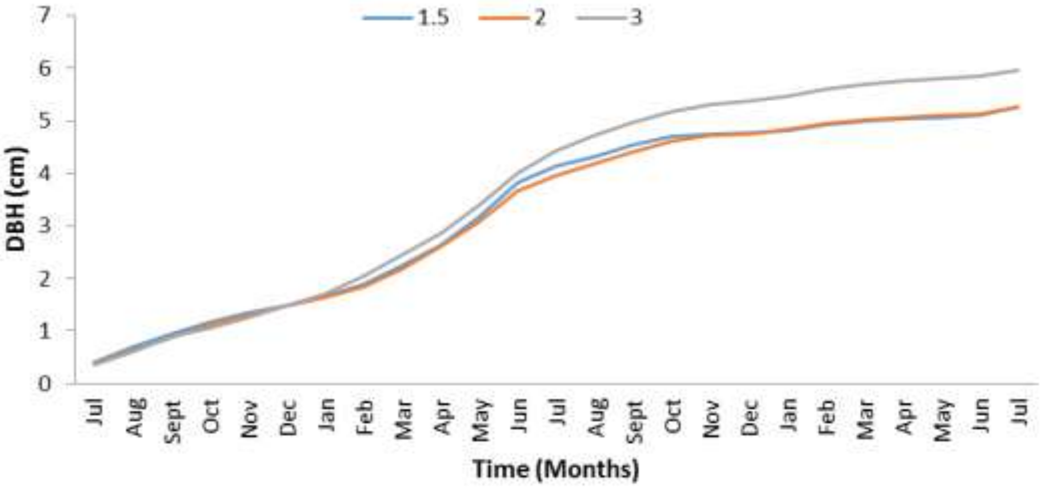

Figure 4.15: Horizontal growth of *C. procera* and different spacing levels

Spearman correlation analysis showed a strong positive relationship ($r_s = 0.973$) between spacing and diameter growth in the three provenances of *C. procera.* A general increment in spacing translated to a similar increment in diameter (Figure 4.16). Generally, 3m*3m spacing recorded the highest mean stem diameter in all the provenances (Figure 4.16).

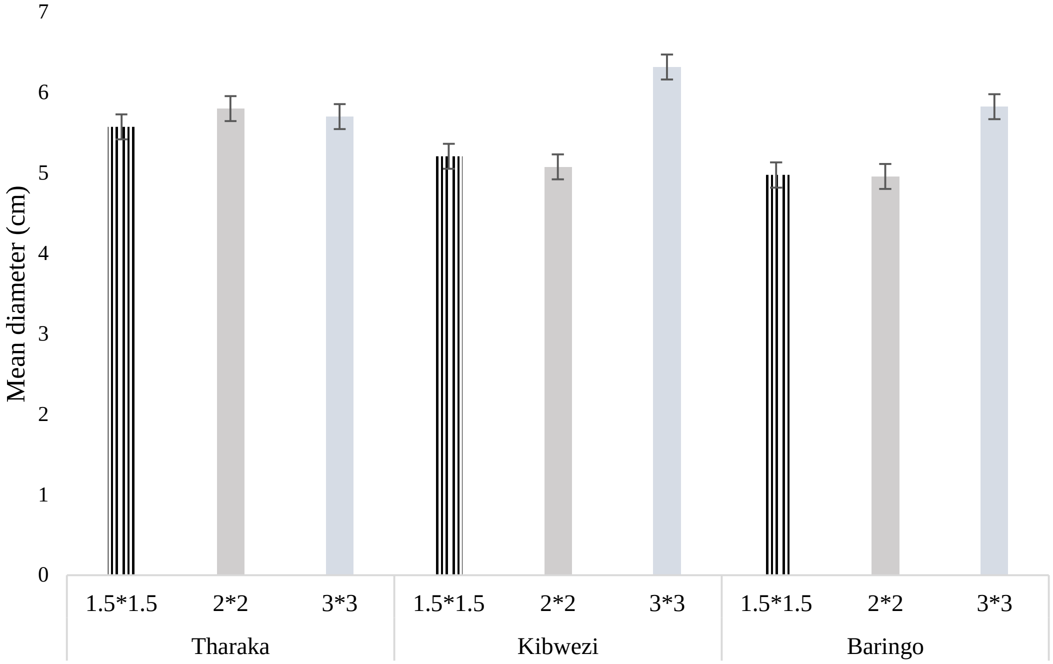

Figure 4.16: Diameter growth by provenances and spacing levels

4.3.4 Effects of spacing on flowering of *C. procera*

In the first and second peak flowering seasons, the different spacing levels did not affect the flowering rate though in the second season, 1.5m*1.5m recorded a slightly higher number of flower clusters. However, in the third season (October) and fourth season (March), 3m*3m spacing level recorded a significantly higher number of flower clusters (Figure 4.17) compared to 2m*2m and 1.5m*1.5m spacing levels.

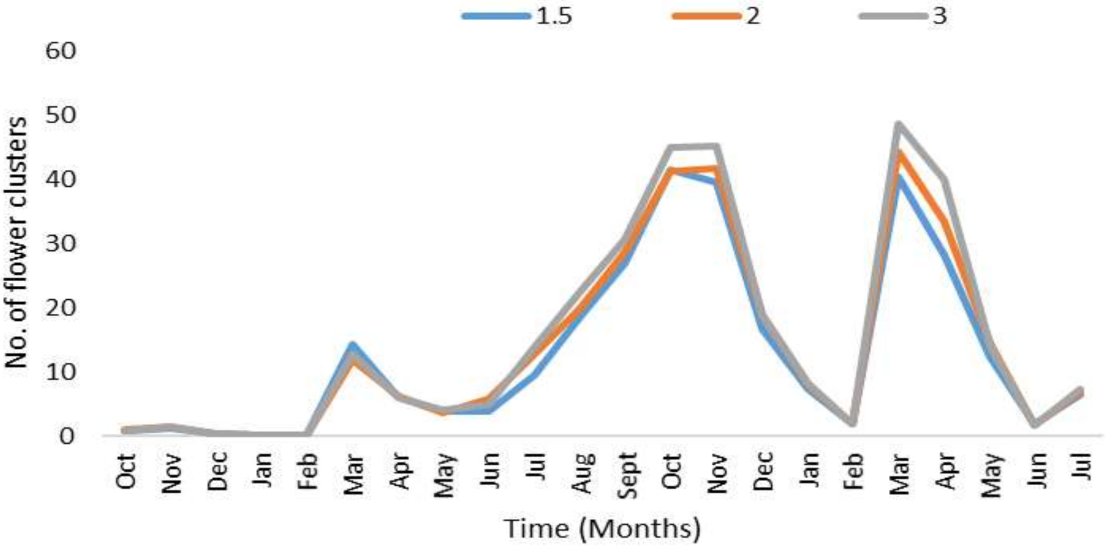

Figure 4.17: Flowering phenophases by spacing levels

The three *C. procera* provenances under different spacing generally portrayed a similar trend in flowering with all the provenances showing a relatively higher number of clusters under the 3m*3m spacing level (Figure 4.18). However, the differences in the number of flower clusters for the three provenances in 1.5m*1.5m and 2m*2m spacing levels were not significant.

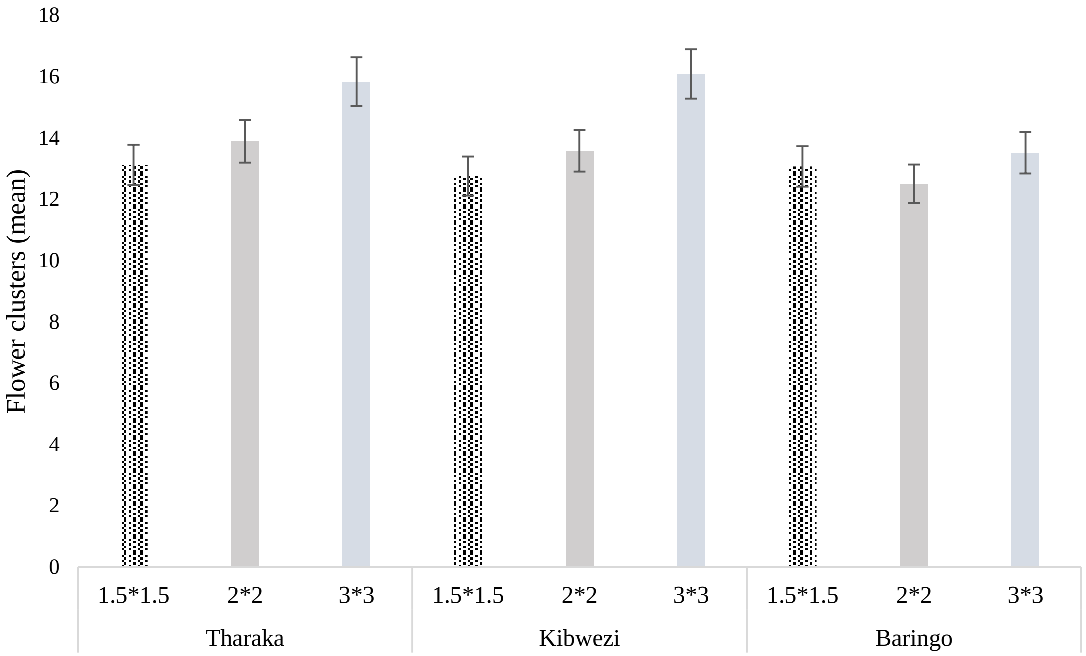

Figure 4.18: Flower clusters by provenances and spacing levels

4.3.5 Effects of spacing on fruiting of *C. procera*

In the first fruiting season (November-December), the number of fruits produced was very few and were independent of the spacing levels. In the second season (March-May), a substantial number of fruits was produced though the differences under the three spacing levels were not significant (Figure 4.19). However, in the third season (November-December), 3m*3m spacing recorded the highest number of fruits while 1.5m*1.5m and 2m*2m showed a similar trend in fruit production. In the fourth season (March-May), 3m*3m and 2m*2m recorded similar levels of fruit production with 1.5m*1.5m producing a relatively lower number of fruits (Figure 4.19). Pearson correlation analysis showed a very strong positive correlation (Pearson, $r_s = +0.924$, $p<0.05$) between flowering and fruiting under the three spacing levels.

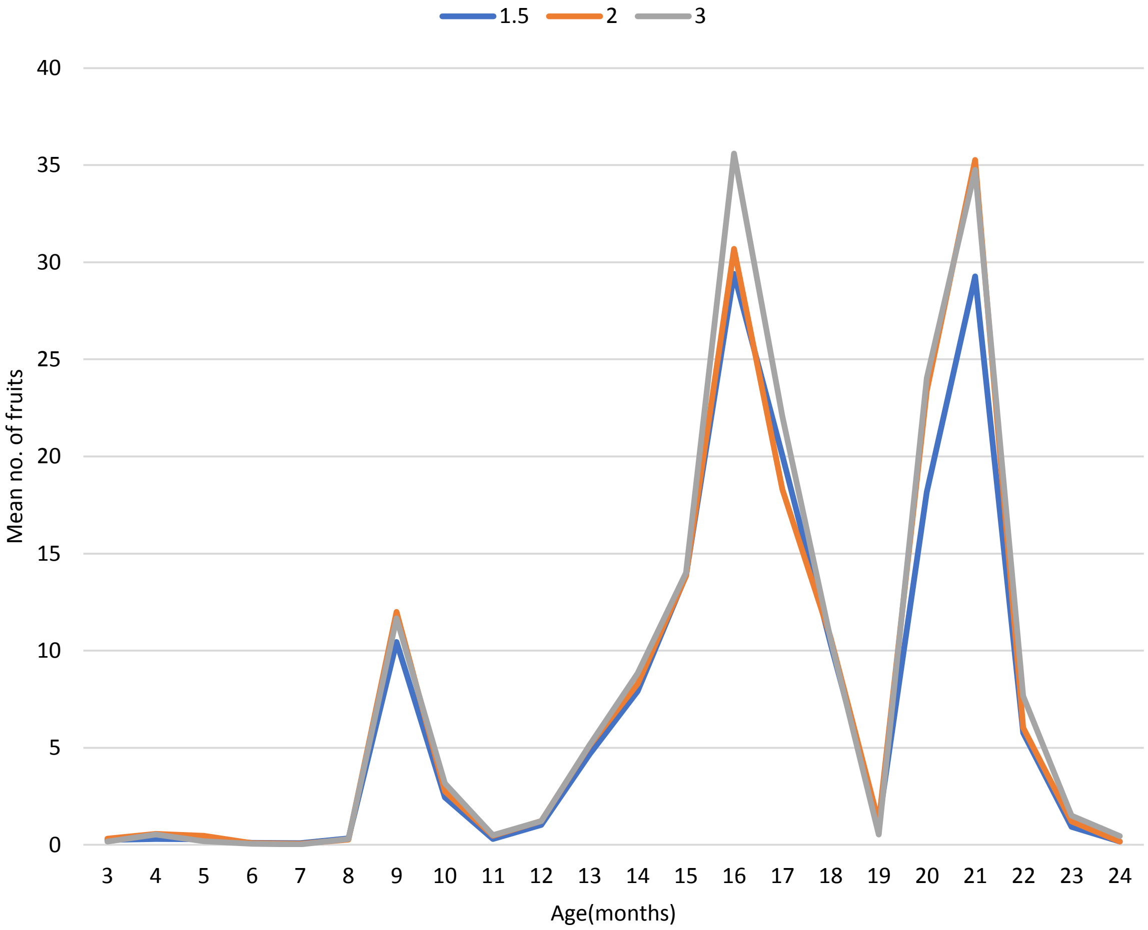

Figure 4.19: Fruiting phenophases by spacing levels

When One-way ANOVA was used to test existence of significant differences in fruit production by the three provenances under the three spacing levels, only 3m*3m showed significant differences ($p<0.05$) in fruit production among the three provenances. Tharaka provenance produced slightly higher number of fruits under the three spacing levels followed by Kibwezi then Baringo (Figure 4.20).

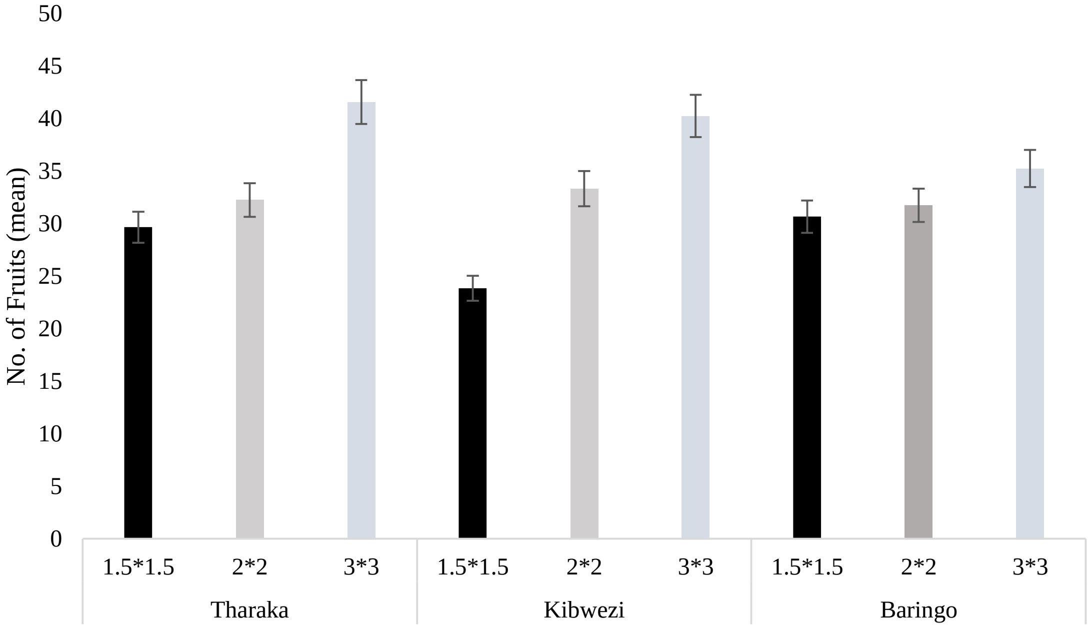

Figure 4.20: Number of fruits by provenances and spacing levels

4.4 Wool production by the three provenances of *C. procera* under different spacing

In terms of wool production, Tharaka had the highest mean production followed by Kibwezi and Baringo under the three spacing levels (Figure 4.21). 1.5m by 1.5m spacing had the highest mean production per hactare for the two year monitoring period followed by 2m by 2m then 3m by 3m spacing levels (Figure 4.21).

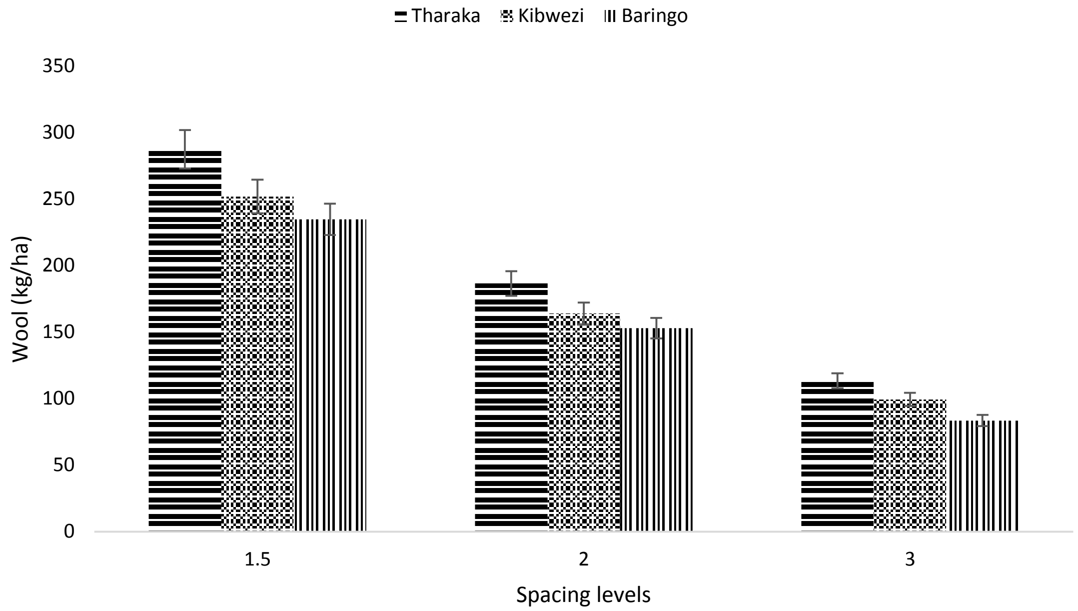

Figure 4.21: Wool production by provenances and spacing levels

Seasonal wool productivity was very low in the first season for all the *C. procera* provenances under the three spacing levels (Figure 4.22). The productivity peaked in season 3 and dropped marginally in season 4 (Figure 4.22). In each of the four seasons, 1.5m by 1.5m spacing recorded the highest wool productivity when the production was quantified into per hactare basis (Tharaka, 600.7kg. ha^{-1}; Kibwezi, 526.89 kg. ha^{-1} and Baringo = 488.81 kg. ha^{-1}). 2m by 2m ranked second in wool production followed by 3m by 3m spacing level (Figure 4.22). When seasonal wool productivity under the three spacing levels was subjected to DMRT, statistically significant differences ($p<0.05$) were obtained. Spearman correlation analysis showed a very strong positive correlation (Spearman corr, $r_s = 0.964$, $p<0.05$) between wool productivity and age of *C. procera* plants.

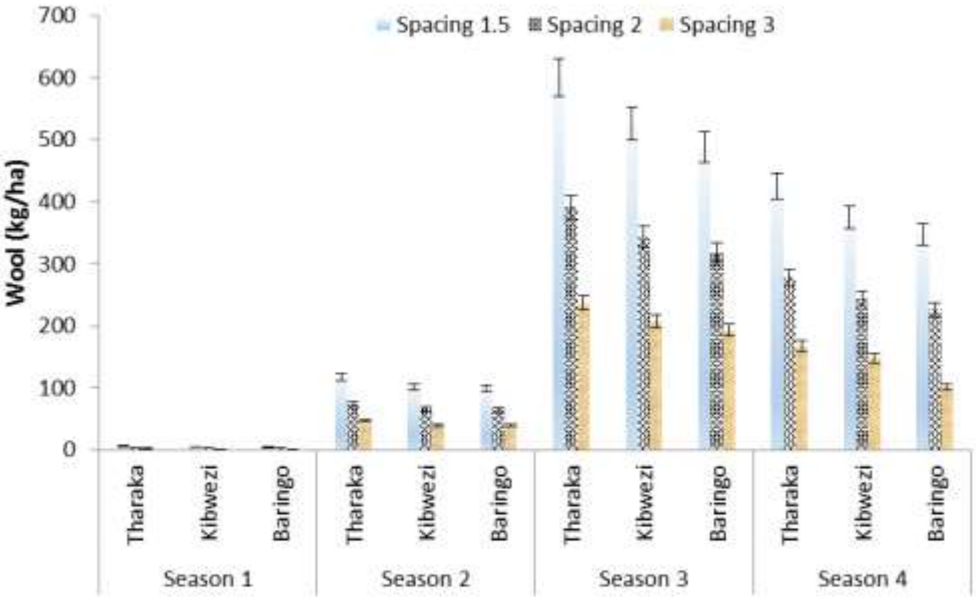

Figure 4.22: Seasonal wool production by provenances and spacing levels

Test of homogeneity of variances showed significant differences ($p<0.05$) in mean wool weight per fruit under the three spacing levels. Under the 1.5m by 1.5m spacing, the average wool weight per fruit was 1.71g while 2m by 2m spacing was 1.98g. The 3m by 3m spacing had the highest mean wool weight of 2.7g/fruit. Larger fruits had a maximum fruit length of between 7.5-10 cm and a diameter of 8-10 cm. However, the mean wool weight per fruit did not differ significantly across the three *C. procera* provenances.

4.5 Wool quality of *C. procera* provenances

Three grades of wool were obtained for the three provenances of *C. procera* based on clarity of wool. Grade one had the highest clarity while grade two and three had varying degrees of wool discoloration (Plate 4.16). The three provenances did not differ significantly ($p<0.05$) in terms of wool grades and spacing levels had no profound effects on wool grades.

Plate 4.16: Grades 1, 2 & 3 of *C. procera* wool

(*Source: Plate by Mutiso, 2017*)

The timing of fruit harvesting for wool extraction mainly determined the final grade of the wool. When fruits were harvested immediately they burst open or showed signs of opening at the fruit’s ventral suture (Plate 4.17), grade one wool was most often obtained. However, when fruits were harvested and it took 2-3 days for them to burst open, grade two or three wool was obtained. Once the fruits showed signs of opening at the ventral suture, it took a maximum of two days for seed dispersal to occur leading to a total loss of the wool. The pappus/wool acts as wings during seed dispersal. When pressure was applied on mature fruits to open, the fruit bursts open at the ventral suture releasing a gas and pop sound. The gas ensures pressure build-up for the ripe fruit to burst open naturally.

A sign of a fruit dehiscence at the pericarp of the ventral suture

Opened fruit exposing the wool

Plate 4.17: ***C. procera*** **fruits ventral suture at different stages of opening**

(*Source: Plate by Mutiso, 2017*)

The mean fibre/wool length was 3.4cm. Mean fibre/wool length did not differ significantly across the three provenances. Similarly, differences in spacing levels did not affect the mean fibre/wool length. However, analysis of variances gave significant differences ($p<0.05$) in mean fibre/wool length depending on the trichome point of attachment within the fruit. The fibres/wool are botanically single celled seed trichomes (Plate 4.18). Fibre/wool at the head of the fruit tended to be significantly longer averaging 4.8cm compared to the ones attached at the tail-end of the fruit which averaged 2.3cm (Plate 4.18 and Table 4.18). Since the fibres are single celled trichomes attached to a seed, analysis of the number of seeds based on their location within the fruiting body indicated that few seeds and similarly short and few fibres occurred at the tail-end of the fruits. From this analysis, it was evident that most of the fibres within the fruiting body of *C. procera* fall under the category of staple length. When the fibres were taken into a laboratory for further quality analysis, efforts to undertake mechanical spinning of the fibre failed since the fibres failed to separate and some were stuck to the spinning machine.

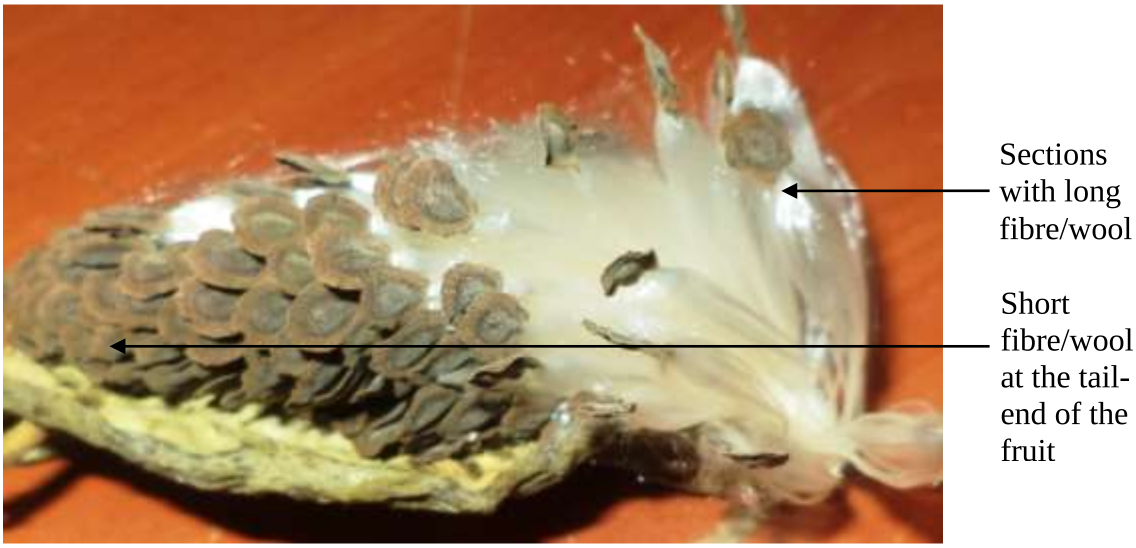

Plate 4.18: Different lengths of fibre/wool within the fruiting body

(*Source: Plate by Mutiso, 2017*)

Table 4.18: Wool length at different trichome attachment within the fruiting body

Provenance	Point of trichome attachment within the fruiting body		
	Head	***Middle***	***Tail-end***
Kibwezi	4.4	3.7	2.6
	5.1	3.1	2.4
	4.7	2.9	1.9
	4.5	3.1	2.3
	4.5	2.8	2
	4.9	3	2.4
Tharaka	5	3.9	2.7
	5.1	3.5	1.8
	4.6	2.8	2.4
	4.5	2.9	1.9
	5	3.1	2.8
	4.9	3.2	2.4
Baringo	4.7	2.9	2
	4.8	2.8	2.6
	5.1	3.2	1.8
	4.9	3	2.7
	4.5	3.2	2.3
	4.6	2.7	2.4
Mean length (cm)	**4.766667**	**3.1**	**2.3**

4.6 Soil properties at the trial plot and the natural stand of *C. procera*

The chemical properties of soil samples from the study site and the natural stand of *C. procera* were analysed. The pH averaged at 6.3 in the *C. procera* field trial plot. When pH data for subplots was separated by both space and provenance and subjected to Duncan Multiple Range Test (DMTR), no statistically significant differences ($P<0.05$) were observed (Table 4.19). Similarly, no significant differences were obtained when the data were separated by space (Table 4.20). Analysis of soil pH in the naturally growing stand of *C. procera* gave an average of 6.23, which was slightly below the field trial plot average. Other soil chemical properties analysed included soil total N (%), total P (ppm) and total K (ppm).

Table 4.19: Means separation by both space and provenance

pH_water			***Total_p_ppm***			***Total_N%***			***Total_K_ppm***		
Baringo	6.54	a	2 Baringo	716.3	a	**2 Baringo**	0.2667	a	1.5 Baringo	1624	a
3 Tharaka	6.44	ab	3 Baringo	658.8	a	**3 Kibwezi**	0.2267	ab	3 Tharaka	1547	ab
1.5 Kibwezi	6.41	ab	1.5 Tharaka	596	a	**3 Baringo**	0.2033	ab	2 Baringo	1508	ab
1.5 Baringo	6.41	ab	3 Kibwezi	563.9	a	**1.5 Kibwezi**	0.1867	ab	1.5 Kibwezi	1466	ab
3 Kibwezi	6.39	ab	1.5 Baringo	558.6	a	**2 Tharaka**	0.1867	ab	1.5 Tharaka	1446	ab
2 Baringo	6.38	ab	2 Kibwezi	498.4	a	**2 Kibwezi**	0.1867	ab	3 Kibwezi	1444	ab
1.5 Tharaka	6.34	ab	3 Tharaka	455.7	a	**3 Tharaka**	0.1667	ab	3 Baringo	1437	ab
2 Kibwezi	6.21	ab	2 Tharaka	427.6	a	**1.5 Tharaka**	0.1633	ab	2 Tharaka	1426	ab
2 Tharaka	6.18	b	1.5 Kibwezi	422.3	a	**1.5 Baringo**	0.1433	b	2 Kibwezi	1181	b
p value	***0.542***		***p value***	***0.68***		***p value***	***0.426***		***p value***	***0.646***	

**Means bearing the same letter in a column are not significantly different*

Table 4.20: Means separation by space

1_5Total_K_ppm			***1_5Total_N%***			***1_5Total_p_ppm***			***1_5pH_water***			***2Total_K_ppm***		
Baringo	1624	a	Kibwezi	0.1867	a	Tharaka	596	a	Kibwezi	6.413	a	Baringo	1508	a
Kibwezi	1466	a	Tharaka	0.1633	a	Baringo	558.6	a	Baringo	6.407	a	Tharaka	1426	a
Tharaka	1446	a	Baringo	0.1433	a	Kibwezi	422.3	a	Tharaka	6.34	a	Kibwezi	1181	a
p value	***0.232***		***p value***	***0.526***		***p value***	***0.723***		***p value***	***0.896***		***p value***	***0.488***	

Table 4.20: Continued…..

2Total_N%			***2Total_p_ppm***			***2pH (water)***			***3Total_K_ppm***			***3Total_N%***		
Baringo	0.2667	a	Baringo	716.3	a	Baringo	6.383	a	**Tharaka**	1547	a	Kibwezi	0.2267	a
Kibwezi	0.1867	a	Kibwezi	498.4	a	Kibwezi	6.213	a	**Kibwezi**	1444	a	Baringo	0.2033	a
Tharaka	0.1867	a	Tharaka	427.6	a	Tharaka	6.18	a	**Baringo**	1437	a	Tharaka	0.1667	a
p value	***0.394***		***p value***	***0.212***		***p value***	***0.214***		***p value***	***0.807***		***p value***	***0.504***	

Table 4.20: Continued…..

3Total_p_ppm			***3pH_water***		
Baringo	658.8	a	Baringo	6.537	a
Kibwezi	563.9	a	Tharaka	6.443	a
Tharaka	455.7	a	Kibwezi	6.39	a
p value	***0.379***		***p value***	***0.776***	

**Means bearing the same letter in a column are not significantly different*

A comparative soil chemical properties (pH (water), EC (ms/c), C (%), $NH^{3-}N$ (ppm), N (%), P (ppm), K (ppm), Mn (ppm), Zn (ppm), Fe (ppm) and Cu (ppm) between the study site and the natural stand of *C. procera* was done. The comparative soil chemical properties (rhizosphere) only captured significant differences ($P< 0.05$) for K and Fe with the study site capturing relatively higher concentrations of the two nutrients compared to the *C. procera* natural stand. A comparative analysis of soil physical properties (rhizosphere) between the study site and the *C. procera* natural stand showed higher moisture content (2.03) in the natural stand compared to 1.58 in the study site. The two sites recorded almost similar bulk densities (g/cm^3) with the natural stand recording a mean of 1.08 compared to 1.1 for the study site. Correlation analysis showed a strong positive spatial relationship (Pearson, $P<0.01$, $r_s = 0.734$) in soil chemical properties between the study site and the natural stand of *C. procera.*

Analysis of *C. procera* leafy tissues showed a tendency by *C. procera* to bioaccumulate heavy metals mainly micronutrients such as Zn, Mn and Fe. Pearson correlation analysis showed a very strong relationship (Pearson, $P<0.01$, $r_s = 0.966$) in terms of phytoextraction/phytoaccumulation of heavy metals (Zn, Mn, Cu and Fe) between the artificial and natural stands of *C. procera*. For instance, mean bioaccumulation of Zn was 216.04 (ppm) which was slightly higher than the recommended concentrations (Table 4.21). Mn had a mean bioaccumulation of 151.62 (ppm) and 119.29 (ppm) in the artificial stand and in the natural stand respectively. Fe had a mean bioaccumulation of 502.86(ppm) which was within the toxic levels for plants. However, Cu had mean concentrations of 2.25 (ppm) which was within the safe levels for plant concentrations.

Table 4.21: Mean concentration of different heavy metals by *C. procera*

	Mn (ppm)	Zn (ppm)	Fe (ppm)	Cu (ppm)
Natural stand of *C. procera*	119.29	202.12	524.24	1.31
Artificial stand	151.62	216.04	502.86	2.25
Normal (safe) concentrations for plants	50-500	10-200	50-250	<20

CHAPTER FIVE

5.0 Discussion

5.1 Seed germination and seedlings early growth

5.1.1 Germination energy, energy period, germination rate and germination value

The short time taken by all provenances to germinate was in consistence with Khaef *et al*. (2011) who documented short germination period and Leal *et al.* (2013) who observed similar high germination in 5 days. The quick germination is very critical in drylands where moisture is a limiting factor. Probably, germination media, seed viability and attack by pre-emergence damping off were responsible for the few seeds that failed to germinate. Germination media could have played a key role given that only 2 seeds failed to germinate when sandy soil was used as a germination media.

Typically, river washed sand provides a good germination media for tree seedbeds (Dickens, 2011; Anber & Hassanein, 2010). Sand offers good environmental conditions for germination such as good drainage, low organic matter, high moisture amongst others. Damping off in seedbeds occurs when environmental conditions for attack are conducive. Many of the damping off fungi are relatively weak pathogens that will only attack when environmental conditions are conducive. Typically, sand as a germination media does not provide conducive environment for attack by damping off while black cotton soil and nursery soil, due to their properties, provide conducive environment for attack. For instance, damping off caused by *Pythium spp* and *Phytophthora plurivora* (Weiland, 2012, Balci *et al*., 2007) and *Rhizoctonia solani* and *Fusarium spp* (Ajayi & Bradley, 2018; James, 2012b, Lazreg *et al*., 2014) cause attack when the growing conditions are characterized by poor drainage, high moisture, alkaline soils, fine textured soil, high humus, compacted soils, high temperatures amongst others.

Black cotton soil has fine textured particles, poor drainage, compacted and poor aeration (Nyakach *et al.,* 2018) as well as alkaline (Chavan, 2014; Shaikh *et al*., 2013) thus promoting attack of seedlings by damping off.). Normal nursery soil is usually high in organic matter and nutrients and these factors form conducive environment for seedlings attack by the damping off fungi. However, normal nursery soil is widely used in many nurseries due to its ability to support good seedlings early growth as observed in this study. Generally, black cotton soil and normal nursery soil provide conducive environmental conditions for attack by damping off fungi compared to sandy soil. However, further tests are usually required to determine whether the seeds failed to germinate because of damping off fungi or seed viability. The generally high germination percent observed in all the three provenances is an indication of high seed viability. The high germination percent observed in this study is consistent with observations by other researhers, for example, Kalita and Saikia (2001) who recorded similar high germination (98%, 96, 94, 88 and 86%) for five provenances of *C. procera* while Yakubu *et al.* (2009) obtained lower percentages (68.50 %, 61.25 % and 54.50 %) for three provenances under different germination conditions. The high germination energy and short energy period is an indication of seeds free of environmental or genetic germination inhibitors. In this study, the germination experiment took place during the dry period and watering took place thus providing conducive conditions for germination. Previous studies have identified several germination inhibitors for *C. procera* such as salinity, light, water and temperature (Zhang, 2012; Donohue *et al.*, 2010; Baskin and Baskin, 2001 and Menge *et al*., 2016)

The observed high germination values are very critical in raising nursery stock. Germination value is an index of combining speed and completeness of seed germination while germination energy is an indicator of the ability of seed to germinate. The different germination values obtained by Czabator and Djavanshir and Pourbeik methods can be attributed by a number of factors such as Czabator methods is mostly suitable when you are dealing with pine species, Czabator method considers speed and totality of germination while Djavanshir and Pourbeik method consider peak germination as the point where germination can be terminated (Djavanshir & Pourbeik, 1976). Geographical location of the seed source contributed to the slightly higher germination attributes observed in Tharaka provenance. The provenance, being nearer to the study site compared to the other provenances, probably enjoyed the near home-site advantages critical in seed transfers. According to Wani and Singh (2016), the seed sources with higher seed germination attributes have higher seedling vigour and thus can be important in selection criteria for breeding and improvement of the species.

Strong positive correlations amongst germination parameters are a good attribute for a seed lot. Patil *et al*. (2011) and Zdzisław *et al*. (2016) reported similar correlations among germination parameters. Elsewhere, Xu *et al.* (2016), in a study on germination and early growth of *Pinus densata* provenances, obtained a correlation of over 0.9. This study obtained a correlation of 0.976, which was higher than the 0.901 recorded by Wani and Singh (2016). Elsewhere, Simla *et al*. (2009) obtained similar strong positive correlation of 0.93. It is important to note that significant correlation among various seed germination parameters such as germination rate, germination value and germination speed can prove to be important criteria in selection of geographic seed sources (Wani & Singh, 2016).

Analysis of soil pH in a naturally growing stand of *C. procera* at Kwa Vonza (about 8km from the study site) showed a slightly acidic soil (pH - 6.23) while analysis of soil pH at the study site showed an almost similar slightly acidic soil (pH - 6.3). The findings of this study are in agreement with Frosi *et al*. (2012) who in a study of ecophysiological performance of *C. procera* in Brazilian semi-arid areas recorded a pH of 6.4 in a naturally growing stand of *C. procera*. Though site conditions differ, based on the findings of this study as well as previous studies, it is likely that *C. procera* prefers slightly acidic soils.

Germination test for *C. procera* at the study area occurred during dry season thus providing conducive temperature for germination. According to Pauw *et al*. (2008), the research site experiences high average temperatures throughout the year, which range from 16^0 C to 34^0 C. Similarly, Khaef *et al*. (2011) and Menge *et al*. (2016) recorded that germination of *C. procera* seeds was negatively affected by temperature of >30 and <20^{o}C. According to Pauw *et al.* (2008), the mean annual rainfall in the study area ranges between 500-1050 mm with 40% reliability. This is within the range for *C. procera* survival as observed by Santos *et al*. (2011), Fabricante *et al*. (2013) and Leal *et al.* (2013) documented mean annual rainfall range of 240-900 mm.

In a different germination experiment in Australia, Menge *et al.* (2016) documented absence of *C. procera* seeds dormancy and attributed this to the tendency of dryland plant species to lack dormancy driven by low and unpredictable rainfall regimes. In contrast, Baskin and Baskin (1998) and Ten *et al*. (2013) documented existence of dormancy of *C. procera* seeds by stating that the seeds are quiescent and quiescence is an important survival mechanism for regeneration of dryland species. Further, Kos and Poschlod (2007) stated that such survival mechanism might help in absorption of temporal environmental shocks until conditions for survival become conducive. Similarly, Finch-Savage and Bassel (2016) recognized the existence of a group of species that have naturally ‘very fast germination’ and tended to inhabit high-stress environments. Such species rapidly exploit favourable conditions for germination. Fast germination allows the root to grow into the soil surface as it dries and ensures seedling establishment before conditions become unfavourable.

The high germination percent, germination energy, energy period and germination value observed in sandy soil can be attributed to the generally good soil characteristics of sand as a germination media. Sandy soil has good aeration, porosity, drainage amongst others. The findings are in consistent with Mariappan *et al*. (2014), Dickens (2011) and Anber and Hassanein (2010) who found out that river sand provides best germination medium for *Jatropa carcus, Irvingia wombolu and Bauhinia variegata* and *Delonix regia* respectively. However, in a different study using sawdust, top soil and coarse sand as germination media, Omokhua *et al*. (2015) reported sawdust as the best germination media. Elsewhere, Okunomo (2010), recorded a higher germination percentage in topsoil with *Parkia bicolor* compared to other germination media.

The delayed germination and the few seeds that failed to germinate in the black cotton soil attributed to the soil characteristics such as poor aeration, porosity, drainage amongst others. Nyakach *et al*. (2018), Malavath *et al*. (2014) and Chavan (2014) reported poor drainage, aeration and permeability and salinity of black cotton soil. However, the black cotton soils physical characteristics can be improved to make it light weight with low bulk density, thus improving its aeration, permeability and nutrient status (Nyakach *et al*., 2017). It is important to note that *C. procera* performs better in slightly acidic soils. In a different study in India, Shaikh *et al*. (2013) found out that black cotton soil had toxic effects that affected seed germination and root development.

Apart from the influence of germination media on the observed germination energy and germination values, this study could not rule out the likely influence of *C. procera* seed genetic make up. Typically, germinative energy is a measure of the speed of germination and hence it is assumed to be a measure of seed vigour and the vigour of the seedling which it produces. Egli *et al*. (2010), defined seed vigor as the seed properties that determine the potential for rapid, uniform emergence and development of seedlings under a wide range of field conditions. Further, seed vigor refers to the total capability of seeds during initial growth. It deals with the ability of seeds to germinate, grow rapidly and uniformly under unfavorable conditions (Yoshitaka & Kazunobu, 2012). Germination uniformity, as noted in this study, is related to seed vigor (Egli *et al*., 2010). Seeds with high germinative energy germinate fast and are endowed with vigour. Such rapid germination and vigour ensures successful field establishment of the seedlings where competition for resources is usually stiff. In this study, black cotton soil showed a certain degree of delayed germination. It is important to note that seed vigour influences not only field performance, but also storage potential. According to Finch-Savage and Bassel (2016), the differences in field performance are caused by differences in seed vigour.

The observed extended germination period in black cotton soil was largely attributed to the soil properties. In plantation forestry, seeds that will show uniform germination in a relatively short time are given preference compared to those that show delayed germination. Excessively delayed germinants are usually out-compteted by vigorously growing seedlings through competition for above and below ground resources. At times, such delayed germinants may not make economic sense in plantation establishment especially if transplanting and beating up have already been done. Delayed germination can distort planting calendar especially transplanting and beating up activities.

Rate of germination entails the number of days required to attain 50% of germination capacity and is very critical in raising nursey stock. For instance, in this study, sandy soil attained 53% on the 7th day after sowing (i.e three days after germination started). The shorter the period, the greater the germination energy and uniformity of seedlings. Yakubu *et al*. (2009) recorded germination rates for three provenances of *C. procera* (68.50 %, 61.25 % and 54.50 %) which were very low compared to what was recorded in this study. However, according to Khaef *et al*. (2011), seeds of *C. procera* have poor germination rate under field conditions. This is probably due to environmental stresses common under field conditions.

Speed of germination is critical especially when seedlings are being raised for plantation purposes since it ensures uniformity of plantation crop. High germination rates within a short period ensures that nursery operations such as pricking out and transplanting schedules are adhered to. For instance, in many tropical species, pricking out is done after 21 days after germination. As such, delayed germination will result to different schedules for pricking out and transplanting for the same seeds sown at the same time. Such differences distort nursery and field calendars thus making management of plantation crops difficult. For instance, nursery management practices will be affected if seeds achieve a germination rate of, for example, 89% 64 days since sowing as documented by Manikandan and Arumugam (2010). Since this study is geared towards domestication of *C. procera* for wool production, a shorter germination rate and uniformity in germination will be key in adoption of the species as a plantation crop by farmers. Poor germination rates and non-uniformity of nursery stock not only distorts the plantation crop calendar but also increases plantation investment capital outlays.

5.1.2 Seedlings mortality

It is highly likely that mortality of seedlings was caused by insect pests and pathogenic attack. The clean cut at the root collar observed in some seedlings was a clear indication of insect pest attack especially by biting and chewing insect pest guilds. According to Mutiso *et al*. (2017), attack by cutworms does occur in seedlings of *C. procera.* Elsewhere, Dhafer *et al*. (2012) reported several insect pests such as the *Aphis nerii* (Boyer de Fonscolombe), *Semitocossus johannes* (Staudinger) and *Contigaspis zilla* (Hall) attacking *C. procera*. Mutiso *et al*. (2017), however, noted heavy infestation by *Aphis nerii* at a later stage in *C. procera* but not at the nursery stage. Dowdl and Lagrimini (2006) and Floate (2017) documented similar attacks by cutworms especially the dingy cutworm (*Feltia ducens*) in nurseries. A number of cutworms such as the *Feltia ducens*, *Agrotis segetum*, *Agrotis ipsilon* are known to cause damage to nursery stock especially when the seedlings are succulent and juvenile.

It is also important to note that attack of nursery stock by insect pests is usually severe at the early stages of seedling growth when the stems are juvenile and succulent. In many cases, attack by cutworms reduces as the root collar becomes harder with seedling age. This explains the observed seedling mortality in the first two weeks after germination and the observed correlation between seedling mortality and age. Further, insect pests, especially the biting and chewing guilds prefer seedlings exhibiting luxuriant growth. Such luxuriant growth was evident in seedlings grown in normal nursery soil and probably this explains the relatively high loss of seedlings in the normal nursery soil compared to the other soil media.

To authoritatively attribute mortality to pathogenic attack, isolation and identification of the causative pathogenic agent is usually done. However, symptoms and signs can be relied upon to identify disease causing agents in tree nurseries and in the forest. Rotting/decaying of a seedling at the root collar and falling off on the ground is a classical symptom of post emergence damping off. It is highly likely that seedlings that exhibited these classical symptoms were attacked by the damping off fungi. The exhibited symptoms are in agreement with observations by Lamichhane *et al*. (2017) and Alcala *et al*. (2016). However, Dowdl & Lagrimini (2006) and Floate (2017) cautioned that the dingy cutworm (*Feltia ducens*), occasionally clips seedlings at the groundline leaving the tops lying on the soil surface; a symptom that may be confused with damping off.

Typically, post emergence damping off fungi attack seedlings when they are young and tend to stop as the seedling root collar hardens with age. This probably explains why mortality of seedlings occurred in the first two weeks. The two soil media (normal nursery soil and black cotton soil), which had the highest seedlings mortality, are also known to provide conducive environment for attack by the damping off fungi. For instance, normal nursery soil contains high organic matter and nutrients while black cotton soil is characterized by poor drainage, poor aeration and alkalinity. All these soil properties favour attack by the post emergence damping off fungi. You *et al*. (2017) and Shankar (2016) documented environmental factors as key determinants of severity of damping off fungal attack. According to Njuguna (2011), succulent seedlings are predisposed to attack by stem canker caused by soil inhabiting fungi. According to Lamichhane *et al*. (2017), damping off fungi can cause a loss of between 5-80% of total seedlings in a nursery. Since the total seedling mortality in this study was 1.9% of the total nursery stock, this loss is very low to cause economic losses that may necessitate application of control measures.

The observed canker was mainly lower stem canker caused by soil inhabiting fungi associated with a number of other seedling diseases. Slippers and Wingfield (2007) documented such associations and noted that co-occurrence of pathogens increased the capability of pathogens to overcome the host plant resistance to attack especially when conditions are not conducive. Co-occurrence is also a common strategy employed by weak saprophytic fungi to overcome the host defense and initiate infection. Such weak saprophytic fungi are unable to put an aggressive invasion of the the host and as such depend on co-occurrence for successful inoculation and infection. According to Njuguna (2011) such fungi are also present on healthy seedlings.

Seedlings recovery from the stem canker can be greatly attributed to defense mechanism. Typically, diseased plants are known to put up strong physical and chemical defense against invading pathogens. In resistant varieties, infected plants are known to produce chemical defense inform of phytotoxins, which are phenolic compounds associated with defense mechanism. Chemical defense entails expenditure of a lot of energy and the affected plant is forced to increase the rate of respiration as well as activate the pentose pathway and fermentation to supply the required energy for mobilization of defense mechanism. In a different study (Njuguna, 2011) noted similar wound healing, as observed in this study, on seedlings of *Melia volkensii* and *Azaratchta indica* following infection by canker. This was attributed to the host's active defense mechanism and virulence of the pathogen. The resprouting of the seedling after attack by the stem canker, as noted in this study, can be attributed to the strong coppicing ability of *C. procera*. Singh (2010), documented excellent resprouting ability of *C. procera* after cutting or burning.

5.1.3 Seedlings early growth

This study attributed the observed good performance in seedlings' early growth of Tharaka provenance to seed source distance. Tharaka provenance, being the nearest seed source to the study site compared to Kibwezi and Baringo, probably enjoyed minimal disturbances common when provenances are tranferred over long distances from their native homeland. According to Matias *et al*. (2016), the higher growth in the early-life stages may grant the provenance a competitive advantage and the differences in growth may be even higher in later stages. Further, Fredrick *et al*. (2015) in a different provenances study reported that growth during seedlings' initial stages can be used as an indicator of future growth.

However, in the current study, it is highly likely that the geographical sources of the provenances could have played a key role in the observed differences. Short seed transfer distances minimize pronounced changes in elevation/altitude, latitude and climatic conditions. In a different study on two provenances of silver fir, Matias *et al*. (2016) observed that seedlings of one provenance performed better in terms of growth and this was attributed to the differences in biogeographical lineages. Though the three seed sources are ASALs, their levels of aridity differ with Baringo being the driest followed by Kibwezi then Tharaka.

Typically, a species or provenance will perform better in its native homeland where it is adapted and is able to continue with normal evolutionary processes. It is likely that Tharaka provenance had the least geographical and climatic alterations given that the seed source is near to the study site compared with the other seed sources. These minimal disturbances might have given it an upper hand compared to the other provenances hence better seedlings growth performance. It is highly likely that the home site advantage played a critical role in the observed differences. This is in consistence with Matias *et al*. (2016) who observed that changes in climatic conditions altered growth and survival of seedlings of two provenances of silver fir.

In a different study, Moya *et al.* (2017) reported similar differences in seedlings growth of two provenances of *Nothofagus glauca*. According to their findings, provenance and site had significant effects on most of the provenance traits under study. The differences were attributed to the high intra-provenance variability indicating provenance high potential to adapt to climate variability. Similarly, in a study by Lukkarinen *et al.* (2009) to investigate the growth performance of seedlings of *Larix sibirica* and *Larix gmelinii* larch provenances, noted clear and statistically significant differences in growth parameters under study. The differences were attributed to differences in geographical attributes such as latitude and temperature. The study also reported strong positive correlation between growth parameters as also noted in this current study.

The observed significant differences in growth performance of different provenances agreed with Aigbe *et al*. (2016) who reported significant differences in seedlings growth parameters for different seed sources. According to the study, such information is important when selecting seed sources and ensures that provenances with poorly adapted genotypes are avoided. Elsewhere, in an experiment using six provenances of *Zanthoxylum rhetsa*, Patil *et al.* (2016) found significant differences in seedlings growth parameters which were mainly attributed to geographical variations. Further, Calvo *et al.* (2016), in a study using *Pinus pinaster* provenances, stated that it is crucial to select the best seed source that will be well adapted to the planting site principally to ensure seedling good performance.

Similar significant differences obtained in this study are in line with Bischoff *et al.* (2008) who noted that seedlings of local provenances performed significantly better in terms of growth compared with exotic provenances. Further, Azad *et al.* (2014), in a study using *Tamarindus indica* provenances, found significant differences in seedling growth parameters caused by genetic and environmental influence. The results of this study are in consistence with Fredrick *et al.* (2015) who, in a study using five provenances of *Faidherbia albida*, reported significant differences in seedlings early growth parameters and concluded that such variations can be important in selecting best adapted provenance as well as provenance site matching.

The observed differences in seedlings early growth in different soil media can be attributed to the differences in soil physical and chemical properties. For instance, sand soil is known to have coarse particles and thus unable to hold enough water for proper seedlings growth and it also gets too hot in strong sun. Sandy soil also lacks important nutrients critical for seedlings growth. Black cotton soil is known to have fine particles that make water permeability into the soil very slow. This poor drainage in turn affects soil aeration and consequently seedling growth. Normal nursery soil provides the correct mixture of sand, clay and organic matter which improves soil physical and chemical properties and consequently plant growth. The results of this study agree with Nyakach *et al*. (2018) who reported that crops planted using topsoil performed better than the black cotton soil and coarse sand due to improved drainage, nutrient flow and aeration conditions. The results are also consistent with Anber (2010) who in an experiment using *Bauhinia variegata* and *Denolix regia* obtained better performance in seedlings grown in topsoil compared to other soil media. However, Okunomo (2010), in a different study using *P. bicolor*, recorded best leaf production in seedlings grown in poultry droppings compared to other growth media.

It is important to note that the normal nursery soil offers the best growth media for raising nursery stock since it is widely available and offers a mixture of fine and coarse particles. Further, solid grains provide the framework for good and stable soil pores and anchorage for proper plant growth. The large pores allow for necessary aeration within the soil media while the small pores provide adequate water holding capacity. According to Gama *et al*. (2015), soil media affects seedling early growth parameter such as leaf production and height growth hence it is important to ensure the soil media is well aerated and has a good water holding capacity. Similarly, Tian *et al*. (2017) reported significant influence of growth medium on seedlings growth parameters.

The observed significant differences in seedlings growth performance can also be attributed to differences in nutrients across the three soil media. Typically, normal nursery soil is known to be rich in nutrients. According to Gama *et al*. (2015), the growth medium should provide growing space and nutrients necessary for plant growth. The observed stunted growth, yellowing and shedding of leaves by seedlings grown in sand soil can be attributed to poor soil nutrient status. In a nursery experiment using *Eucalyptus tereticornis*, Murugesan *et al.* (2016) attributed vigorous and fast growth of seedlings to growth media fertility and vice versa. Rahman *et al.* (2007) made similar observation of vigorous and fast growth of seedlings influenced by soil media. Other soil chemical properties such as pH probably contributed to the observed seedlings poor performance especially in black cotton soil. *C. procera* requires slightly acidic soils for good performance. Black cotton soil is usually alkaline and this probably affected the seedlings growth. These findings are in consistence with Chavan (2014) who reported incidences of soil salinity in black cotton soil. Further, in a different study in India, Shaikh *et al*. (2013) reported toxicity in black cotton soil that affected seedling growth performance.

5.2 Field establishment of *C. procera*

5.2.1 Field seedlings survival

The observed high field survival of the three provenances can be attributed to the fact that the study site represented a typical arid and semi-arid land hence favouring the species. Good species site matching translates to better field survival and establishment. The study site is a typical semi-arid area and thus offered a conducive environment for survival and growth for *C. procera* which is even known to survive in arid and desert environments. At the early stages of field establishment, space was not limiting and as such, spacing could not have caused significant influences on field survival of *C. procera*. Different studies have shown *C. procera* to be a drought resistant species characterized by hardness, xerophytic, high water use efficiency and high photosynthetic rate during dry spells (Galal *et al*., 2015b; Ramadan *et al*. 2014; Boutraa, 2010; Frosi *et al*., 2012; Kumar *et al*., 2013 and Tureza *et al*., 2013)

5.2.2 Growth performance of the three *C. procera* provenances

5.2.2.1 Production of branches

The multiple branches observed in the three provenances is a typical growth characteristic of *C. procera.* The heavy branching is important during the reproduction phase since most of these branches become floral in the reproductive stage. Similar relationship of branching and reproduction phase is documented by Sobrinho *et al*. (2013) who recorded multi-branching characterized by phenophases of leaf flush, flowering and fruiting. Several studies have reported the multi-stemmed nature of *C. procera* (Yogi *et al*., 2016; Sharma *et al*., 2011 and Hassan *et al*., 2015).

Other studies have documented that *C. procera* is single stemmed or few branches (Al-Snafi, 2015 and Orwa *et al.*, 2009). Elsewhere, Galal *et al.* (2015c), in a study on the demography and size structure of the giant milkweed shrub *C. procera* (Aiton) reported maximum mean branches of 26 compared to the maximum of at least 40 obtained in this study. Probably, the difference can be attributed to the fact that Galal's branching study was done on *C. procera* growing in the wild while the current study was done in a farm setting. Typically, plants in a farm will always have an added advantage of growing space compared to those growing in the wild.

While the multi-stemmed growth nature of *C. procera* observed in this study may be typical to the species, the study established that damage induced by pests and diseases acted as a stimulus for excessive branching. Sprouting of new branches after loss of apical dominance is a mechanism of recovery from damage of the apex of the leader stem.

Damage induced branching as observed in this study is likely to have been hormone mediated. In many instances, such branching is controlled by auxin which is a hormone released after loss of apical dominance to end dormancy of axillary buds and trigger development of new shoots. Thus, the loss of apical dominance due to attack by pests and diseases as observed in some plants in this study is likely to have triggered the release of the hormone which in turn ended dormancy of axillary buds leading to heavy branching. Levelling off of branch production is an indication of plant maturity. Typically, as a plant matures, there is a tendency of reduced active growth hence levelling of increment in branches, height and diameter.

The observed sprouting after loss of apical dominance is in consistence with Müller and Leyser (2011) who documented that loss of apical dominance activates the release of dormant axillary buds to form new branches. It is worthwhile to note that apical dominance ensures that resources are channeled to the leader stem while activation of dormant buds allows for recovery after damage of the apex of the leader stem. Weng *et al*. (2016) and Cline and Harrington (2007) reported that the growth of axillary buds is usually inhibited by the apex-derived auxin but upon loss of apical dominance, domarcy of axillary buds end. Though branching after damage helps in recovery, Dun *et al*. (2006) cautioned that excessive branching may be costly and hence it is modulated in response to environmental factors. Similarly, Dong *et al.* (2015) reported that excessive branching leads to shading of some of the branches and this decreases the growth especially in shaded branches.

5.2.2.2 Horizontal (DBH) growth of *C. procera* provenances

The lack of significant differences in diameter growth in the first nine months of field establishment is likely to have been caused by homegeneity in resources allocation in the initial stages of field establishment. However, as the stems grow, competition for resources such as light, water amongst others is expected to start. In the presence of competition, the adaptive capability of a provenance to the local conditions will determine its growth. Provenance performance based on environmental conditions such as light, moisture an d temperature has been documented by Azad *et al*. (2014) and Rweyongeza *et al*. (2011). Lack of levelling off of diameter size by the end of the two year monitoring period is a clear indication that none of the three provenances had reached full maturity. It is a clear indication that *C. procera* can achieve a higher DBH than the mean DBH obtained

(Tharaka -5.74cm, Kibwezi - 5.49 and Baringo - 5.23). Elsewhere, Hassan *et al*. (2015) documented that *C. procera* can have a diameter of 25cm. Hassan's diameter is in consistence with a similar one noted in a *C. procera* stems growing in the wild in the course of this study. In a different study, Kumar *et al*. (2013) came up with six diameter classes (<0.5, 0.5–1, 1–1.5, 1.5–2.5, 2.5–3.5, >3.5) in a study on the effects of urban habitat heterogeneity on functional traits plasticity of the invasive species *C. procera*. The different diameter classes in Kumar's study are a reflection of heterogeneity in DBH growth as observed in this study.

The observed slow increment in DBH as the plants approached two years of age can be attributed to reduced meristematic activities at the cambium as the plants age. Similar dependence of cambial activities to tree age has been documented by Rossi *et al*. (2008a). Similarly, Rathgeber *et al*. (2011) noted similar relationship of cambial activities and tree age in a mature silver-fir plantation. This study could not authoritatively explain the observed huge diameter ranges for individual stems across the three provenances but provenance genetic heterogeneity was suscepected to have been involved. In a typical plantation, individual stems for each provenance should fall in one or two diameter classes and show homogeneity in terms of diameter distributions. However, the influence of soil fertility on the observed differences was ruled out since analysis of soil micro and macro nutrients in the study site didn't capture statistically significant differences.

Though the differences in mean DBH across the three provenances was not high, the low mean DBH in Baringo provenance is likely to have been caused by seed transfer distance. From a geographical location of the seed sources for the three provenances, Baringo was the furthest from the research site followed by Kibwezi then Tharaka. The results of this study support what many researchers have reported that local provenances are better and the further a provenance is moved from its native homeland, the higher the chances of poor performance. Lisa *et al*. (2018) and Rweyongeza *et al*. (2011) tried to answer the question of how far plant material can be moved from home sites and remain ecologically appropriate in a restoration setting. The study concluded that subjecting a plant material to long distance transfers can result in phenological mismatches between plants and pollinators. However, it is important to note that management of the local micro-site will also play a critical role in determining the performance of a provenance in a new environment.

In a study using pine provenances, Lisa *et al*. (2018) tried to explore the home-site advantages in seed transfer distance during restoration programs. Typically, when a provenance is grown within its native homeland, it will have the advantage of continuing with co-evolutionary processes in the ever-changing environment thus giving it the home-site advantage. However, when a provenance is moved away from its homeland, such co-evolutionary processes are interfered with in the new environment. According to Boshier *et al*. (2015) concerns exist over the actual scale of adaptation in trees and the relative dangers of incorrect seed source. Lu *et al*. (2014), in a study using 245 white spruce provenances, observed similar differences in provenance performances caused by climatic differences. Similarly, Liebing *et al*. (2013), in a study using six *P. tecunumanii* provenances noted similar differences in growth performance.

The results of this study can act as a guideline in future *C. procera* seed collection for maximum growth. Based on DBH performance in this study, Tharaka was the optimum seed source. Typically, an optimum seed source is a geographical locality which can act as a seed source for provenances with the highest growth potential. Based on this concept, it is highly likely that better DBH growth could have been achieved if seeds originated from *C. procera* natural stands near the research site. In a study using 16 provenances, Kristina *et al*. (2016) reported local provenance as the threshold at which geographic distance corresponds to statistically significant genetic distance. The seed transfer distance affects latitude and elevation (Rweyongeza *et al*., 2011***)*** which in turn determines climatic conditions. The three provenances (seed sources) were derived from areas with different elevations and this could have played a role in influencing climatic conditions. Viherä-Aarnio (2009), in a study on field performance of silver birch provenances in different latitudes, observed that a longer transfer led to decreased yield and the proportion of trees with stem defect increased.

Increase in the number of branches increases the number of leaf area and possibly leads to increased rate of photosynthesis. Increased photosynthesis increases the amount of energy generated and allocated for plant growth. This, probably, explains the observed positive relationship between branching and DBH growth. Farahat *et al*. (2015), in a study on effects of urban habitat heterogeneity on functional traits plasticity of *C. procera*, observed similar relationship between branching and DBH growth. Contrary, Planck and MacFarlane (2014), in a modelling study using hardwoods, reported a weak negative correlation between the number of branches and DBH (Pearsons, $r_s = -0.29$).

5.2.2.3 Vertical (height) growth of *C. procera* provenances

The observed relatively low and good performance in mean height by Baringo and Tharaka provenances is likely to have been caused by seed transfer distances. Tharaka provenance seed source being nearer to the research site compared to Baringo probably had a better home-site advantage over Baringo. The seed transfer distance is used in development of seed transfer guidelines in many countries. Such guidelines give local provenances priority and ensure that seeds from a given provenance are not moved over long distances that can lead to pronounced changes in elevation and latitude. It is worth to note that the elevation and latitude are key determinants of climate of a given locality through their influence on temperature.

Influence of latitude on performance of different provenances from different seed sources have been reported by Barzdajn *et al.* (2016), Viherä-Aarnio (2009) and Rweyongeza *et al*. (2011). Planck and MacFarlane (2014) documented the effects of seed origin on the timing of height growth cessation and field performance of *Betula pendula* from different latitudes. The influence of home-site advantages on provenance performance primarily due to local climatic and environmental conditions have been documented by Kundu (2000), Weber and Montes (2007), Pengxin *et al*. (2014), Leibing *et al*. (2013), Eilmann *et al*. (2014), Lisa *et al*. (2018) and Boshier *et al*. (2015). Based on this, the current study proposes that *C. procera* seed collection should strive to minimize the seed transfer distances for optimum performance. Similar assertions on observation of provenance seed transfer distances during restoration activities have been documented by Rweyongeza *et al*. (2011), Boshier *et al*. (2015) and Kristina *et al*. (2016).

This study could not authoritatively establish the causes of individual plants variations in stem heights in the even aged *C. procera* domestication trial plots but probably genetic make-up of the individual provenances played a role. However, micro-site influences primarily due to soil properties was ruled out since analysis of the soil macro and micro nutrients for the different sub-plots did not yield significant statistical differences (P<0.05). Elsewhere, Nieto *et al*. (2016) attributed microsite homogeneity to lack of significant differences in provenance performance. Similar microsite homogeneity was recorded in this study.

It is, however, important to note that similar variations in stem heights in even aged stands have been documented. For instance, Silva *et al*. (2002) analyzed individual tree growth pattern in an even aged stand and reported significant variation in individual tree growth pattern in terms of stem height and DBH. Similarly, Wilson and Leslie (2008) documented similar height variations in an even aged stand and asserted that by giving priority to allocating resources to height growth over diameter growth, a tree ensures that it maintains its position in the forest canopy, survives and reaches maturity. However, *C. procera* is classified as a small tree and may not compare well with high canopy tree species.

The failure of height growth curves for the three *C. procera* provenances to level off by the end of the two year monitoring period is a clear indication that the plants had not reached their maximum height at maturity and that the obtained maximum height of 4.49m is not the maximum height at maturity. It is evident that given more time, the plant heights will keep on increasing. Therefore, there is need for further monitoring to ascertain the point in time at which the height growth curves will level off at the maximum height and maturity. The mean heights obtained in this study are relatively high compared with Galal *et al*. (2015c) who reported the highest of individual plants to be 1.6m. However, the findings are consistent with Orwa *et al*. (2009) who suggested that *C. procera* is a shrub or small tree that grows up to a maximum of 6m in height.

Other documented heights of *C. procera* include 2-6m (Hassan *et al*., 2015 & Ara *et al*., 2017), maximum of 5.5m (Sharma *et al*., 2010), Maximum of 5.4m (Yogi *et al*., 2016), and 2-6m (Vitelli *et al*. 2008). A different species; *Calotropis gigantea* has been described by Kumar *et al.* (2013) as a shrub or a small tree with a height of between 2.5-6m. Generally, from the findings of this study and what other researchers have reported, it is highly likely that the maximum height of *C. procera* at maturity is at least 6m.

The reported strong positive correlation in the number of branches, DBH and height in the three provenances can largely be attributed to allometric growth pattern common in many forest shrub and tree species. Allometric growth ensures systematic growth of DBH and height hence the observed positive correlations. Other different studies using different species in different environments and under different management have reported allometric growth patterns. For instance, Mahmut (2004) and Rais *et al.* (2014), in a study on the relationships between height-diameter at breast height (DBH), crown diameter-DBH and crown diameter-height of *Pinus brutia* of Baskonus Mountain, Kahramanmaras, found the strongest relationship to be that of height-DBH relationship. Similarly, Wang *et al*. (2017), in a tree height-diameter relationships comparative study between alpine treeline ecotone and closed forests in Changbai Mountain, Northeastern China, reported similar allometric growth pattern. Elsewhere, Fulton (1999) observed similar relationship between DBH and height growth for selected tree species and sites in Eastern Texas.

According to Vanclay (2009), the height and diameter relationship does not imply a constant relationship between height and diameter of individual trees. In a study on height-DBH relationship, Sumida *et al*. (2013) and Sumida (2015) found out that while the trajectories of the most vigorously growing trees had an almost linear height-DBH relationship, trees with a declining DBH growth rate exhibited an asymptotic tendency towards height growth. According to Mugasha *et al*. (2013), height-DBH relationship is important in describing forest stands and the parameters are key variables in developing volume and biomass models. Further, tree diameter and height are important variables in forest inventory and management and carbon-stock estimation (Li *et al.*, 2015). This study found a linear height-DBH relationship since by the end of the two year monitoring period, both height and DBH curves had not levelled-off.

5.2.2.4 Flowering of the three provenances of *C. procera*

The observed flowering at a tender age of 4 months is likely to have been triggered by attainment of physiological maturity of the *C. procera* plants. The 4 months coincided with the month of October when flowering of *C. procera* peaked at the onset of short rains. Occurrence of flowering during the short and long rains is an indicator of bimodal phenological event. The observed syschronization of the peak flowering with the rain season is consistent with observations by Sobrinho *et al*. (2013), who documented that most of the native woody species flowered during the rainy season. Fandohan *et al*. (2015) reported similar synchronizing of flowering and rain season in a study on *Tamarindus indica* in Sahel and Sudan.

El-Tantawy (2000) reported that most of the desert species flowered during or after rainy season. Further, Omondi *et al*. (2016), in a study using *Senegalia senegal* reported that the species had two peak flowering and fruiting phenophases which were synchronized to coincide with short and long rainy seasons. However, Dejene *et al*. *(*2016) reported a different scenario where flowering of *Sterculia setigera* in Ethiopia coincided with the dry seasons. According to Borchert *et al*. (2004) seasonal variation in rainfall and moisture availability are the main causes of flowering periodicity. Since *C. procera* is a dryland species, synchronization of the peak flowering with the onset of the rains is critical to the survival of the species since it ensures that the species flowers, fruits and seeds at a time when critical resources such as water is not limiting. The 15-30 flowers per cluster obtained in this study is relatively higher than what has been documented. For instance, Hassan *et al*. (2015) noted that each flower cluster contains 3-15 flowers. The higher number of flowers per cluster in this study may be attributed to the fact that the *C. procera* were growing in a typical farm setting compared to those growing in the wild where competition for resources is usually high.

The significantly good performance in flower production by Tharaka provenance can probably be attributed to the influence of seed transfer distances. Tharaka being the nearest seed source to the study site compared to Kibwezi and Baringo probably made the provenance to enjoy near home-site advantages. The furthest moved provenance such as Baringo is usually disadvantaged due to changes in environmental and climatic conditions probably resulting to poor performance. Flowering of *C. procera* throughout the year with seasonal peaks seems to be a typical characteristic of the species. Previous studies, Silvia *et al*. (2009), Leal *et al*. (2013) and Mellissa *et al*. (2013) have documented continuous flowering with annual peaks. Hassan *et al.* (2015) reported flowering of *C. procera* throughout the year. According to Lloret *et al*. *(*2005), Godoy *et al*. *(*2009) and Mellissa *et al*. *(*2013), long flowering periods is an important attribute for invasive species. Elsewhere, El-Tantawy (2000) in a study on the flowering and fruiting eco-physiology of *C. procera* observed that the *C. procera* flowers nearly throughout the year.

Sharma *et al.* (2010) reported flowering of *C. procera* from March to October. In temperate regions, flowering of *C. procera* begins in winter (Csurhes & Edwards, 1998; Parsons & Cuthbertson, 1992). In Israel, flowering of *C. procera* has been reported to occur for six months during the spring and summer (Eisikowitch, 1986) while in Saudi Arabia, flowering was found to start early in the spring and to last for four months (El-Ghani, 1997). The massive flowering noted during peak flowering seasons is a typical characteristic of *C. procera.* The average of about 1000 flowers per plant is very close to what was obtained by El-Tantawy (2000) who obtained an average of 959 flowers per plant at the end of the rain season. His study documented very low transition from flowers to fruits as noted in this current study. El-Tantawy (2000) attributed this low transition to probably lack of enough pollinators resulting in a similar massive failure in fertilization. Massive flowering is also a character typical of species of low fecundity since it ensures that out of the many flowers, a handful make to the fruiting stage thus ensuring continuity of the species.

In this study, mass flower loss was partly attributed to attack by *Aphis nerii, which* was controlled by application of pesticides. The *A. nerii* is a sap sucker which extracts sap from the flowers leading to premature death of flowers. Attack of *C. procera* by *Aphis nerii* (oleander aphids) has been documented by Marugan *et al*. (2000), Dhafer *et al*. (2012) and Salau and Nasiru (2015). According to Mckone *et al*. (1998), many mass flowering trees are attacked by specialist flower and seed feeding insects that are satisfied in mast years. Since the *Aphis nerii* were found to attack leaves, flowers and fruits of *C. procera* at the study site, it is likely that the pest is more of a generalist than a specialist.

The observed flower abortion was also attributed to poor pollination largely caused by the ant-pollinator conflicts. Flowers of *C. procera* had high visitations by ants not only to get nectar from flower but also sugarly dew produced by the *Aphis nerii*. It is most likely that the ants, in the process of protecting the aphids from natural enemies such as the ladybird beetle, kept potential pollinators away and this resulted to ant-pollinator conflict. This probably, reduced the pollination and fertilization level and subsequently led to the observed massive flower abortion. The findings of this study agree with Nora *et al*. (2019) who documented similar protective services by ants which can inturn hindered pollination and kept away pollinators. In their study, they proposed the ‘Distraction Hypothesis’, whereby extrafloral nectaries located close to flowers could be used to attract the ants and, in the process, keep them away from the reproductive structures and consequently reduce ant-pollinator conflicts especially during pollination period. In a study using *Taramarindus indica*, Fandohan *et al*. (2015) reported excessive flower abortion after massive flowering. Diallo *et al*. (2008) attributed abortion in *Tamarindus indica* to sterility, selfing and low floral visits by pollinators. According to Joseph and John (2018), to deal with chronic pollen limitations some plant species have long-lived flowers with long periods of stigmatic receptivity.

The hermaphroditic character of *C. procera* might have contributed to the observed massive flowering and a very low flower to fruit ratio since many hermaphroditic plants are known to produce many flowers but few transits to fruiting stage. El-Tantawy (2000), Orwa *et al*. (2009), Sobrinho *et al*. (2013) and Ranjan *et al*. (2017) have all reported hermaphrodite flowers in *C. procera.* Most hermaphroditic species exhibit some degree of self-fertilization. Typically, hermaphroditic flowering plants commonly produce more flowers than fruits. According to Morgan (1993), hermaphroditic flowering plants will always produce many flowers but only few fruits will reach maturity. It is likely that the hermaphroditic character of *C. procera* contributed to the observed low flower to fruit transition of 2.5-10.5%. It is, however, important to note that flowers were attacked by *Aphis nerii* and the pest formed a mutualistic relationship with ants. As such, the study could not rule out the contribution of ant-pollinator conflicts in the observed low flower to fruit transition.

5.2.2.5 Fruiting of the three provenances of *C. procera*

The occurrence of fruiting phenophases in the month of April and November was an indication that fruiting peaked shortly after peak flowering in the month of March and October when adequate moisture was available. Sychronization of fruiting phenological event with the rainy season is important to allow for fruit growth and maturation since this stage requires a lot of photosynthates. The synchronization of fruiting and rain seasons are in consistence with Fandohan *et al*. (2015) who in a study in the Sahel and Sudan noted that synchrony is an adaptation strategy developed against water scarcity. Khan (1999) who reported that flowering and fruiting activities may be synchronized to concide with favourable weather condition for optimum performance further supports the findings of this study. Further, Omondi *et al*. (2016) reported synchronization of fruiting of *Senegalia senegal* to peak rain season. In a different study, Okullo *et al*. (2004) noted a positive relationship between phenology timing and atmospheric relative humidity.

Lack of fruits in the first season and during off seasons despite flowering taking place is an indication that it is only during mass flowering episodes that some flowers will make it to the fruiting stage. At tender age and off seasons, the number of flowers is small hence minimal chances of survival. The number of flowers increased with increase in chronological age thus increasing the number of fruits and hence the observed positive correlation between *C. procera* chronological age and the number of fruits. Similar relationship between tree size/age and number of fruits has been noted elsewhere. For instance, according to David and Richard (2019), fruit production is a function of tree size, nutrient availability and and spacing with larger trees tending to produce more fruits.

The generally high number of fruits produced by Tharaka provenance can be attributed to the high number of flowers produced by the provenance as well as seed source transfer distance. Attack of fruits by *aphis nerii* coupled with premature fall of juvinile fruits contributed greatly to the observed reduction in harvestable fruits in each of the fruiting seasons. Fruits that formed towards the end of rain seasons (end of April for long rains and end of December for short rains) mostly failed to reach harvestable stage probably due to reduced water availability. Such fruits, which are supposed to mature by May and January respectively fall prematurely due to hot conditions during the two months. The observed 1-3 fruits per flower cluster noted in this study has also been documented elsewhere. For example, Hafiza *et al*. (2010) reported that the number of fruits of *C. procera* varied from 1-3 per inflorecent.

The 25-105 fruits per plant obtained in this study was relatively high compared to Hafiza *et al*. (2010) average of 23 fruits per plant. El-Tantawy (2000), in a study on flowering and fruiting eco-physiology of *C. procera* in Suez area, in the Eastern Desert of Egypt, reported an even lower number of ripened fruits that ranged between 4-18 fruits/plant. Probably, the high number of fruits obtained in this study is because the *C. procera* were grown in a typical farm setting where human agromanagement practices influenced the overall productivity. When ripe fruits are not closely monitored, they can dehisce and release the wool. The 30-40 days required for *C. procera* fruits to mature as obtained in this study compares relatively well with the 30-35 days documented by Hafiza *et al*. (2010). The recorded fruit diameter and length at maturity in this current study is in agreement with what has been documented in previous studies. For instance, Orwa *et al*. (2009) and Upadhyay (2014) documented that the fruit of *C. procera* can be ≥10cm in diameter. Similarly, Kiew (2001) and Heuzé *et al*. (2016) reported that the length of *C. procera* fruit varied from one to another averaging between 9-13.1 cm and a mean of 11.7 ± 1.4.

The low number of fruits obtained in this study can, also, be attributed to the hermaphroditic nature of *C. procera*. In this study, a maximum of 10.5% of flowers per plant managed to transit to the fruiting stage. This percentage is relatively high compared to 1% obtained in other hermaphroditic species such as *Persia americana* where more than 99% of the flowers produced at anthesis are not able to form fruits (Alcaraz & Hormaza, 2019). It is important to note that hermaphroditic plants are characterized by selfing and some plants will give preference in resource allocation to fruits with a higher proportion of outcrossed seeds while the selfed seeds are aborted leading to selective fruit abortion linked to pollen origin.

5.3 Effects of spacing on growth and Phenology of *C. procera* provenances

5.3.1 Effects of spacing on branching of the three *C. procera* provenances

Lack of significant differences in branching in the early growth stages of *C. procera* provenances under different spacing levels can be attributed to the fact that at this stage, space was adequate and no intra-specific competition had started. However, as the plants grew bigger, it is likely that the closely spaced plants started experiencing space limitation compared to wider spaced plants hence the observed differences in number of branches. The findings are in agreement with Kirongo *et al.* (2013) who in a study at the coast, Kenya reported Intra-specific competition for closely spaced plants. Levelling of branching curves towards the end of the test period is an indication that spacing was becoming limiting for all plants under the different spacing levels leaving minimal room for additional branch production. The observed weak correlation between age and branching rate at the juvenile stages of *C. procera* can be attributed to the fact that at tender age, the plants tend to be single stemmed hence few branches. However, as the plants grow older, they tend to become multi-stemmed thus increasing the branching rate hence the observed strong positive correlation. It was also evident that as the plants aged, some were attacked by stem canker that led to loss of apical dominance that may have triggered massive branching.

The findings of this study that wider spacing generally promotes branching are supported by other studies. For instance, Campo *et al*. (2017) documented that closer spacing reduces branching in trees. Further, Henskens *et al*. (2001) found out that widely spaced trees have a tendency of retaining most of the lower branches. In addition, Caron *et al*. (2015) observed that in closely spaced plantations, there is stagnation of growth in young stems while in widely spaced plantations stagnation occurs later when the stems are old. The obtained significant differences on the effects of spacing on branch production in this study were also observed elsewhere by Eloy *et al*. (2017). According to Hebert *et al*. (2016), low stocking level resulted to a higher branch retention and growth. Sibomana *et al*. (1997), in a study on the effects of spacing on growth of teak reported increased number of branches with increased spacing level. Nichols *et al*. (2012) and Glencross *et al*. (2012) reported similar correlation between spacing and number of branches as obtained in this study.

5.3.2 Effects of spacing on vertical growth of the three *C. procera* provenances

When plantation species are young, spacing level does not affect growth parameters since at this juvenile stage, space is not a limiting factor. However, as the plants increase in size, crowding starts occurring and competition for space sets in. In a typical plantation, space limitation will trigger aggressive growth in height as plants compete to occupy the upper canopy primarily to access key resources such as light. Generally, plants under high spacing levels (closely spaced) fall casualty of space limitation early than those under wider spacing. This, most probably, explains the observed trends in vertical growth during the test period as well as the observed correlations between plant height growth and spacing over time.

Different heights of *C. procera* have been reported by different researchers. For instance, 6m (Orwa *et al*., 2009; Hassan *et al*., 2015; Ara *et al*., 2017) and 5.5m (Sharma *et al*., 2010). The findings of this study agree with Liziniewicz (2014) who obtained significant differences in height growth under different spacing. According to his study, trees under 2*2m spacing were tallest compared to those under 3*3m spacing which were significantly shorter. Similarly, Clara *et al.* (2011), in a study on the effects of initial spacing on height growth of loblolly pine, reported an early advantage in height growth in closely spaced stands. Elsewhere, Brar *et al.* (2013), in a study using *Psidium guajava* under different spacing, reported reduction in height growth as the spacing levels increases.

5.3.3 Effects of spacing on horizontal (DBH) growth of the three *C. procera* provenances

Spacing generally determines the amount of below and above ground resources such as light, nutrient, water among others available per plant per unit area (Kirongo *et al*., 2013). According to Brar *et al*. (2013), increasing plant spacing affects canopy temperature and relative humidity. A wider spacing, therefore, translates to availability of more resources such as water, nutrient, light among others. This, inturn promotes plant growth in terms of diameter increment. This explains the observed relatively high diameter sizes in wider spacing level and the positive correlation between diameter growth and spacing level of *C. procera.* It is also important to note that high spacing results to high stocking which subsequently increases competition for below and above ground resources hence affecting diameter increment negatively. The results of this study are in agreement with several studies that have found increasing diameter with increment in spacing levels (Hébert *et al*., 2016; Liziniewicz., 2014; Forrester *et al*., 2013; Zahabu *et al*., 2015; Mehari & Habte, 2006; Kumar *et al*., 2014 and Brar *et al.*, 2013).

5.3.4 Effects of spacing on flowering of *C. procera*

It is likely that branching promoted increment in flowering. The flower clusters of *C. procera* are usually produced at internodes where some auxilliary buds develop. The number of internodes is influenced by age and number of branches (Christine *et al.*, 2003). Similarly, the number of branches is positively correlated to spacing hence the wider the spacing, the more the branches. This explains the observed lack of differences in the number of flower clusters for all provenances under the three spacing levels in the first two flowering seasons but significant flowering for plants under the 3m*3m in the last two flowering seasons. The findings in this study are consistent with Campo *et al*. (2017) who observed that the number of flowers increased at the same rate in the initial years but in later years, increment was ristricted to plants under wider spacing. In their study, they also noted that closer spacing lowered the number of branches per plant. Such reduction affects the total number of flowers produced as observed in this study. Previous studies using different species have documented increment in flower numbers with increased in spacing levels (Prabhakar *et al*., 2016; Williams *et al*., 2006; Prakash, 2015 and Sarrwy *et al*., 2012).

5.3.5 Effects of spacing on fruiting of *C. procera*

The chronological age which was 4 months was largely attributed to the few fruits produced in the first season. Further, at this juvenile age, space was not a limiting factor hence the observed lack of significant differences in fruiting under different spacing. As the plants mature, spacing becomes limiting and only widely spaced plants have the ability to produce more branches and consequently more flowers and fruits in the long run. This, largely, explains the observed significantly high fruit production under the 3m*3m spacing in the final two flowering and fruiting seasons as well as the observed positive correlation between flowering and fruiting. The recorded relatively high production of fruits by Tharaka provenance was likely caused by the relatively short seed source transfer distance compared to the other two provenances. The findings of this study are consistent with previous studies using different species that documented increment in number of fruits with increment in spacing levels (Brar *et al*., 2013; Prabhakar *et al*., 2016 and Campo *et al*., 2017). Other studies have reported increased fruit number, size and quality with increased spacing levels (Malhotra & Deshmukh, 2017; Minor & Richard, 2019 and Kumawat *et al*., 2014).

5.4 Wool production by the three provenances of *C. procera* under different spacing

The relatively high wool production by Tharaka provenance can be attributed to the observed high number of fruits. It is highly likely that Tharaka provenance being the closest seed source to the study site benefited from the near home site advantages compared to the furthest seed source (Baringo provenance). Azad *et al*. (2014), Rweyongeza *et al*. (2011) and Lisa *et al*. (2018) have documented provenance performance based on environmental conditions associated with seed transfer distances. The high wool production per hactare under closer spacing (1.5m by 1.5m) can be associated with the overal stocking level. Under wider spacing, wool yield per plant is usually high (Prabhakar *et al*., 2016) but overal low stocking may compromise the yield per hactare. Thus from an economic perspective, 1.5m by 1.5m is the most appropriate spacing for wool production.

Fruit and consequently wool production is a function of the size of a plant. This explains why wool production was very low in the first season but peaked as the plants matured. It also explains the observed positive correlation between wool production and the age of *C. procera* plants. The findings of this study agree with David and Richard (2019) who asserted that fruit production is a function of tree size and larger trees were more likely to produce more fruits. The significant differences in wool weight per fruit under different spacing can be attributed to the observed variations in fruit sizes under different spacing levels. The generally larger fruits under wider spacing translated to a relatively high amount of wool per fruit. This is in consistence with Kumawat *et al*. (2014) who reported that trees under wider spacing levels produced better quality fruits than those under closer spacing levels.

5.5 Wool quality of *C. procera* provenances

The findings of this study indicated that the physical grading of wool based on clarity as it is done in the cotton (*Gossypium hirsutum*) industry can be applied for *C. procera* wool. Further, it is highly likely that the grade of *C. procera* wool and consequently the quality obtained in this study was greatly determined by the maturity of fruit at the time of wool harvesting. The observed dehiscence of the fruit at the central suture was a clear indicator of a ripe fruit hence grade 1 wool. As such, the grade of the wool from *C. procera* is mainly controlled by the maturity of the fruit but not factors such as provenance or spacing.

Dehiscence of the fruit at the central suture is driven by pressure build-up within the fruiting body. According to El-Tantawy (2000), it is believed that the accumulation of nitrogen and oxygen gases in the fruiting body plays a critical role in *C. procera* fruit dehiscence. At maturation, the gases, which occupy about 70%, expands with increased temperature and exert pressure on the fruit pericarp forcing it to split open at the ventral suture and as such exposing the seeds (Ibrahim *et al*., 2016). The dehiscence of the fruit exposes the wool to wind which is a key atmospheric factor that leads to total loss of wool in the process of seed dispersal. This also explains why wool harvesting in this study occurred shortly after the rainy season when temperatures were relatively high for pressure build-up in the fruiting body. The pop sound produced when mature fruits were hand pressed can be attributed to the presence of gases (O_2 and N_2) in the fruits.

The mean wool length (3.4cm) obtained in the current study compares relatively well with what has been reported in previous studies. For instance, 3.0-3.5cm by Abbas *et al.* (1992), 3.16 ± 0.4cm by El-Tantawy (2000), 0.95-3.0cm by Jiang *et al.* (2012) and Hassanzadeh and Hasani (2015), 3.2cm by Louis and Andrews (1995), about 2-3.5cm by Orwa *et al.* (2009) and Dietmar (2005), ≥3cm by Kumar *et al.* (2013) and Meena *et al.* (2011). Yuanhui *et al.* (2018) obtained relatively higher mean lengths for *Calotropis* species where *Calotropis gigantea* fibre averaged 3.86cm, *Ceiba pentandra* fibre 2.32cm and *Gossypium hirsutum* fibre 3.16cm.

The observed significant differences in wool length within the fruiting body can be attributed to the fact that wool length tends to decrease from the head of the fruit to the tail-end. Srinivas and Babu (2013) documented similar observations of different lengths of wool depending on their location in the fruiting body. The reason why most of the fibres within the fruiting body fall under the category of staple length (the most frequent length in a fibrous sample) is that the fruit of *C. procera* is usually wide at the head and tapers moderately towards the tail-end. The wide part of the fruit houses a relatively big number of seeds and consequently high number of fibres, which are usually long. Conversely, the tail-end of the fruit is characterized by fewer number of seeds and fewer and relatively short fibres. Since the staple length of *C. procera* fibres is long, this character gives the species a high potential for use in textile industry.

Azzouz *et al*. (2008) reported that staple length is one of the most important factors of fibre quality. The longer staples are the most preferred in textile industry since they are usually finer and stronger. The mean of 3.4cm fibre length obtained in this study compares relatively well with the common length staples for *Gossypium hirsutum*. Azzouz *et al*. (2008) came up with three categories of staple lengths for *Gossypium hirsutum* namely short staples ranging from 0.95cm-2.4cm, medium from 2.54cm-2.86cm and long staples from 3cm-6.35cm. Other researchers have also found other superior qualities of *C. procera* fibres. For instance, Abbas *et al.* (1992) reported that the fibre quality of *C. procera* is strong and can be woven into strong cloth. Further, Yuanhui *et al*. (2018) documented that the *C. procera* wool does not collapse upon drying like *Gossypium hirsutum* fibre and has higher breaking strength than *Ceiba pentandra* fibre. These characters make *C. procera* fibre an ideal material to replace some natural cellulose fibres such as *Ceiba pentandra* and *Gossypium hirsutum*.

According to Johar *et al*. (2012), *Calotropis* fibre is being given a lot of attention nowadays since it has similar qualities of renewability and diodegradability like those of *Gossypium hirsutum* and as such is an environmentally friendly source of fibre compared to petroleum-based sources. In a comparative study of cloth made from *Calotropis*, Kumar (2009) documented that the *Calotropis* cloth had high tensile and abrasion strength and more weight compared to cloth made from *Gossypium hirsutum* but there was need to improve the yarn's evenness and fineness. Maji *et al*. (2013) who reported similar properties of *Calotropis* cloth compared to *Gossypium hirsutum* expressed similar sentiments.

The challenge encountered in the laboratory when spinning *C. procera* wool during this study has been documented elsewhere. Varshney (1987) attributed the poor spinning ability of *Calotropis* fibre to the fibre brittleness. Further, Yuanhui *et al*. (2018) attributed the challenges of spinning the fibre into yarn to the smooth and straight fibre contour. Thangavel and Murugan (2013) attempted to spin *C. procera* fibres and reported similar challenges of spinning. Hassanzadeh and Hasani (2015) stressed on the importance of having knowledge on the spinning ability of *Calotropis* fibre. Using *Calotropis gigantae*, Tuntawiroon *et al*. (1984) and Jiang *et al*. (2012) reported similar spinning problems but recommended further research on its properties related to fabric wear ability.

It is important to note that genetic improvement to meet specific quality requirements forms final stages of a species domestication process. Domesticated species are subjected to selection initiatives involving genetic modifications to achieve specific characteristics. For instance, Akhtar *et al*. (2014) in a study using *Gossypium hirsutum* supported the idea of improving the species fibre length through genetic modification. While investigating the sweat releasing capability of *C. gigantea* fibre, Yuanhui *et al*. (2018) observed that the fibres had over 97% sweat transmissibility while cotton fibres transmited 50%. This made the researchers to conclude that *C. gigantea* wool had the best sweat absorption and transmitting capability and could make cloth with good comfortability. The cellulose content in *C. procera* fibres compares well with that of *Gossypium hirsutum* but is better than that of linen (Maji *et al*., 2013).

Despite the challenges of spinning *C. procera* fibres, it is important to note that in order to solve the challenges of environmental pollution, many designers and engineers in textile industry are focusing on natural sources of fibre as a solution to substitute polymer-based fibre sources. Polymer-based raw materials are non-renewable and non-biodegrable and their usage leads to environmental degradation. Hassanzadeh and Hasani (2015) documented *Calotropis* fibre as a substitute fibre due to its numerous unique properties. Further**,** Batello *et al*. (2004) and Yasin *et al*. (2012) documented that the fibre of *C. procera* is a potential substitute for silk.

C. procera has also been found to make good composites/blends. *C. procera* fibres have been mixed with cotton at a 1:1 ratio with results indicating enough potential in natural fibre-reinforced composites (Akhtar *et al*., 2014). According to Pratik *et al*. (2016), there is growing interest in industrial applications and research in natural fiber reinforced polymer composite materials. Natural reinforced polymer blends are known to be cheap, have good mechanical properties and are environmentally friendly and thus are seen as potential substitutes for traditional wool such as *Gossypium hirsutum*, *Ceiba pentandra*, linen among others. Different researchers have developed composites of *Gossipium hirsutum* and *Calotropis* with excellent mechanical properties (Srinivas & Babu, 2013), best sweat absorption and transmitting capability (Yuanhui *et al*., 2018) as well as good strength, fitness and evenness (Kumar, 2009). This study strongly supports investments in improving the fibre quality of *C. procera* through genetic modification. This will make its spinning and other processing easy and thereby increase its use in the textile industry and a potential replacer of synthetic polymers used in the textile industry. Replacement of some of the polymer-based fibre sources with natural sources will greatly reduce environmental pollution associated with polymers.

5.6 Soil properties at the trial site and the natural stand of *C. procera*

Lack of significant differences in soil chemical properties across the study site sub-plots is a clear indication that the microsites were homogenous and that the observed differences in performance of *C. procera* provenances cannot be attributed to the soil properties. With respect to pH, the study can authoritatively ascertain that the study site had a pH commonly found in natural habitats of *C. procera*. Comparison of soil pH in the study site and that of the natural stand of *C. procera* showed that the soils were slightly acidic (pH of 6.3 in the study site and 6.23 in the natural stand). The findings of this study are in agreement with Frosi *et al.* (2012) who in a study of ecophysiological performance of *C. procera* in Brazil recorded a pH of 6.4 in a naturally growing stand of *C. procera*. Other studies have shown that *C. procera* can do well in soils that are acidic, neutral and basic. This implies that the species has a wide pH range and generally, the level of pH may not have played a critical role in determining the observed growth performance of the three provenances of *C. procera* in the current study. In studies on survival of *C. procera* in different pH levels, Galal *et al*. (2015a) documented good performance in residential habitat with a pH of 7.7 and road side habitat with a pH of 7.8 while Farahat *et al*. (2015) documented good growth in railway habitat with pH of 8.3. High concentrations of heavy metals such as Zn, Cu, Pb, Cd, and Mn Galal *et al*. (2015a) as well as aluminium (Oliveira *et al*., 2009) have been reported in leafy tissues of *C. procera*.

The homogenous soil bulk densities in the study site and in the *C. procera* natural stand can be attributed to the location of the two sites. The natural stand is located at the outskirts of an urban area hence subject to occasional anthropogenic disturbances while the current study site had been previously subjected to slash and burn agriculture. *C. procera* is not selective in nutrients requirement and as such the insignificant differences in soil macronutrients in different sub-plots at the study site may not have influenced growth of the provenances. Generally, *C. procera* is well adapted to survive in a wide range of soil types ranging from poorly drained black cotton soils to well-drained but infertile sandy soils. The adaptive capacity of the species to a wide range of soil types in terms of texture, salinity, fertility and moisture has been documented by De Oliveira *et al*. (2009), Kumar *et al*. (2013) and Ara *et al*. (2017). *C. procera* is known to tolerate drought and soil salinity (Francis, 2002; Orwa *et al*., 2009; Galal *et al*., 2015b and El-Midany, 2014). Elsewhere, Lottermoser (2011), in a study on colonization of abandoned mines by *C. procera,* noted that the species can tolerate adverse climatic conditions, poor and polluted soils. According to Kumar *et al*. (2013), one of the key features of *C. procera* is its ability to survive in different soil types.

The observed high concentration of heavy metals (ZN, Cu, Mn and Fe) in plant tissues of *C. procera* in the study site and the natural stand is an indicator of the species' ability to undertake phytoremediation. Pyhtoextraction/pytoremediation is the ability of plant species to remove contaminants such as heavy metals from the soil and air and accumulate them in their tissues such as the leaves, stems and roots. This aids in the removal of pollutants in the environment. Several studies have demonstrated the ability of *C. procera* to bioaccumulate heavy metals as observed in this study. For instance, Alyemeni *et al*. (2011), detected higher mean Cd and Cu values in above ground tissues of *C. procera* though the levels were below the phytotoxic ranges of 5–700 mg kg-1 and 25–40 mg kg-1 for Cd and Cu respectively. D'Souza *et al*. (2010), in a study of soil contaminated with Pb and Cd in India, identified *C. procera* as an effective phyto-remediator of soils contaminated with heavy metals.

In this study, though *C. procera* accumulated copper within its foliage, the concentrations (2.25) were within safe levels for plant growth. However, Galal *et al*. (2015a) obtained mean concentration values of Cu of 24.2 mg kg-1 in *C. procera* growing in railways habitat and the levels were considered to be within the toxic concentrations. It is important to note that though Cu is a heavy metal, it is vital a vital plant nutrient and plays a critical role in various enzymatic activities. Further, Cu tends to bio-accumulate in roots and is rarely concentrated into aboveground plant tissues such as the leaves and stems. Copper can cause toxicity when aboveground tissues pyto-accumulate levels beyond 20 mg kg-1 (Galal *et al*., 2015a). Plants affected by heavy metal toxicities show a wide range of leaf symptoms. For instance, Cu toxicity often causes foliar interveinal chlorosis with increasing exposure (Reichman, 2002).

This study noted Zn bioaccumulation mean values of 216.04 mg kg-1 that were almost reaching toxic levels. According to Ghaderian and Ravandi (2012), Zn is a vital nutrient for plants and occurs in concentrations of between 10-200 mg kg-1 with toxic concentrations starting from 230 mg kg-1. Zinc toxicity is manifested by symptoms such as chlorosis and reddening of younger leaves (Reichman, 2002). In a different study, Galal *et al*. (2015a) obtained mean values of Zn phytoremediation of 58.5 mg kg-1 and 122.4 mg kg-1 in *C. procera* growing in railway and roadside habitats respectively. In a different study using *Sorghum bicolor*, Mirshekali *et al*. (2012) reported that the plants tolerated <900 mg kg-1 of zinc concentrations and as such recommended the plant as a phyto-remediator of zinc contaminated soils.

This study reported Mn bioaccumulation in leafy tissues of *C. procera* both in the artificial stand (151.62 mg kg-1) and the natural stand (119.29 mg kg-1). According to Galal *et al*. (2015a), manganese plays a critical role in photosynthetic reaction and is important in a number of enzymes that catalyze redox, decarboxylation, and hydrolytic reactions. However, concentrations of Mn above 50–500 mg kg-1 are considered toxic to plants. As such, the mean concentration values obtained from the study site (151.62 mg kg-1) and the natural stand of *C. procera* (119.29 mg kg-1) were within the normal range for plant growth.

Toxicity symptoms of Mn include chlorosis especially on older leaves and necrotic lessions on young foliage (Reichman, 2002). Elsewhere, Prajapati and Meravi (2013) found that *C. procera* is a phyto-remediator of soils contaminated with Mn owing to the species ability to bio-concentrate Mn in its above ground tissues. In a different study in Jeddah City-Kingdom of Saudi Arabia, Abdullatif *et al*. (2016) estimated the amount of heavy metals such as Aluminum, Chromium, Boron, Barium, Copper, Manganese, Iron, Lead and Zinc in the soil and plant tissues of *C. procera.* Results revealed that *C. procera* is capable of phytoextraction of the heavy metals and as such the species can be used as a phyto-remediator by absorbing the pollutants from the soil as well as atmosphere and concentrating the same in the above ground tissues.

Out of the heavy metals analyzed, only Fe had bioaccumulation levels (502.86 mg kg-1) that were within toxic concentrations for most plants. Similar accumulation of Fe to toxic concentrations were obtained by Galal *et al*. (2015a) who reported that Fe concentration in *C. procera* from residential and roadside habitats exceeded the normal concentration for plant survival. Out of the micronutrients required by plants, Fe is needed in high amounts with normal concentration for plant growth ranging between 50-250 mg kg-1. Iron is an essential micronutrient and plays critical role in DNA synthesis, enzymatically mediated processes, respiration and photosynthesis (Rout & Sahoo, 2015). Fe toxicity symptoms include yellowing and dieback of oldest leaves, necrotic lessions, growth retardation among others. It is important to note that the growth of *C. procera* in the artificial stand and the natural stand was characterized by occasional leaf yellowing followed by complete defoliation and dieback of aerial shoots. Given the observed levels of Fe and the effects of its excess bioaccumulation, it is likely that it played a critical role in the observed occasional loss of chlorophyll, defoliation and dieback of shoots.

Comparing the Fe normal ranges of 50 and 250 mg kg-1 and the mean values of 502.86 mg kg-1 obtained in this study, it is evident that *C. procera* can tolerate exceptionally high Fe levels. This observation is further supported by De Oliveira *et al*. (2009) who, in a study in Canga and Caatinga in Brazil, found out that *C. procera* had the capacity to tolerate high levels of iron which is characteristic of Canga soils. In Riyadh and Gazan, Saudi Arabia, Al-Yemni *et al.* (2011) noted significant concentrations of nutrient and heavy metals such as N, Ca, Cd and Fe in above ground tissues of *C. procera* and *Citrullus colocynthis* indicating that the two species have the potential for pollution monitoring of soils contaminated with such heavy metals. Elsewhere, in a study to monitor distribution of Nickel and Vanadium in Jeddah City, Saudi Arabia, Al-Dhaibani *et al*. (2018) noted concentrations of the two elements in the soil and *C. procera* tissues and recommended use of *C. procera* as a biological technique for monitoring the concentration of the two airbone heavy metals.

CHAPTER SIX

6.0 Conclusions and Recommendations

6.1 Conclusions

Sandy soil is the best germination media for *C. procera* seeds. However, growth of seedlings after germination was very poor in sand soil and was characterized by stunted growth and yellowing of leaves. Though seedlings in normal nursery soil performed slightly lower than sand soil in terms of germination attributes, they potrayed a very good early seedlings growth indicating that normal nursery soil was the best growth media.

Tharaka provenance performed significantly better in height and diameter growth, flowering and fruiting compared to Baringo and Kibwezi provenances. This was largely attributed to the fact when seeds are moved over long distances some environmental conditions such as elevation changes which inturn affects the temperature and rainfall regimes. Provenances that are far moved from their home-site find it difficulty to adapt the new environment and this is largely reflected in the growth and productivity of the provenance. Peak flowering & fruiting are synchronized with the rain seasons though flowering occurs throughout the year. This was mainly attributed to the fact that flowering and fruiting require a lot of resources especially water and as such dryland species are physiologically tuned to ensure the two processes concide with the rain seasons when water is not limiting.

The strongest impediment to growth, flowering and fruiting was periodic attack by *Aphis nerii* which led to loss of apical dominance and heavy flower and fruit abortions. This was mainly attributed to the fact that *Aphis nerii* is a generalist pest that feeds on leaves, flowers and fruits thereby affecting growth and productivity of the *C. procera* provenances. For good growth, flowering and fruiting, wider spacing (3m by 3m) performed best for the three provenances. Wider spacing provided a higher resource allocation per plant per unit area and this was probably reflected in terms of growth and productivity.

Peak flowering & fruiting are synchronized with the rain seasons though flowering occurs throughout the year. The strongest impediment to growth, flowering and fruiting was periodic attack by *Aphis nerii* which led to loss of apical dominance and heavy flower and fruit abortions.

Seasonal wool yield was significantly affected by spacing with closer spacing (1.5m by 1.5m) yielding higher amount of wool per hectare than the other spacing levels. Though 3m by 3m spacing gave the highest amount of wool per plant, it yielded the lowest per hectare. From an economic perspective, the 1.5m by 1.5m is the best spacing for adoption by farmers. Spacing and provenance type did not affect wool quality though timing of fruit harvesting affected the wool grade. When the fruits were harvested when they were not completely mature, discoloured wool was obtained thus reducing the wool grade.

There were no significant differences in soil chemical properties in the field subplots and as such, chemical soil properties did not influence the observed growth and phenological characteristics in the three provenances of *C. procera*. The subplots tended to be almost homogenous in terms of soil chemical properties. *C. procera* prefers a slightly acidic soil and has the ability to concentrate heavy metals (Zn, Cu, Mn and Fe) in the plant tissues indicating that the species has the ability to undertake phytoremediation/phytoextraction of soils contaminated with heavy metals

6.2 Recommendations

Though sand soil is the best germination media, this study recommends use of normal nursery soil due to its advantages in promoting early seedlings growth. Though sand soil gave the best germination, seedling early growth was poor characterized by stunted growth and yellowing of leaves. Nursery seedlings early growth acts as an indicator of performance in the plants in the later years in the field. Since seedling germination in the normal nursery soil was slightly lower that sand soil, it is more economical to accept a slightly lower germination but be assured of good seedlings early growth at the nursery and later years in the field.

In order to reduce the effects associated with long distance seed transfers and ensure the species benefits from home-site advantages as well as promote good growth, flowering, fruiting and wool production, *C. procera* seeds for raising nursery stock should be sourced from the nearest seed source possible. Though wider spacing (3m by 3m) gave the highest wool quantity per plant, in a farm setting, 1.5m by 1.5m spacing should be adopted for maximum wool production per hectare. For high grade wool, it is strongly recommended that harvesting of fruits should be done when fruit shows signs of dehiscence at the ventral suture of the pericarp. *C. procera* can be used as a heavy metal remediator especially in soils contaminated with ZN, Cu, Mn and Fe.

6.3 Areas for further research

The is need for further investigation on at what stage do the horizontal and vertical growth curves of *C. procera* completely levels off. Such information will give insight on the maximum height and diameter the species can achieve at the farm setting. Further studies are required on seed transfer distances for *C. procera* and the key environmental and climatic conditions responsible for the observed differences in field performance of *C. procera* provenances. Such information will aid in developing *C. procera* seed transfer guidelines.

There is need for further research on the most appropriate management measures for *C. procera* aphids (*Aphis nerii*). The effectiveness of the observed lady bird beetle (*Menochilus sexmaculatus*) as a natural enemy of the aphids needs to be investigated. Further, the interference on the effectiveness of natural enemies in the control of the *Aphis* *nerii* by the observed aphid (*Aphis nerii*)-ant (*Camponotus compressus*) symbiotic relationship needs to be clearly understood. There is need for further studies to establish if the observed periodic chlorosis followed by complete defoliation of *C. procera* stands is linked to bioaccumulation of heavy metals in the plant’s leafy tissues. There is need for further research on how to improve the spinning properties of *C. procera* wool. This will form basis for large scale textile industrial use of the wool.

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8.0 APPENDICES

Appendix 1: Treatment combination descriptions and codes

No.	Description/Treatment combinations	Code
1.	Kibwezi provenance, sand soil	T_{1S}
2.	Kibwezi provenance, black cotton soil	T_{1B}
3.	Kibwezi provenance, normal nursery soil	T_{1N}
4.	Tharaka Nithi provenance, sand soil	T_{2S}
5.	Tharaka Nithi provenance, black cotton soil	T_{2B}
6.	Tharaka Nithi provenance, normal nursery soil	T_{2N}
7.	Baringo provenance, sand soil	T_{3S}
8.	Baringo provenance, black cotton soil	T_{3B}
9.	Baringo provenance, normal nursery soil	T_{3N}

Appendix 2: Nursery Experiment Layout

T_{1S}	T_{3S}	T_{3B}	T_{1B}	T_{3B}	T_{2N}	T_{1B}	T_2	T_{3S}
T_{2S}	T_{1B}	T_{3N}	T_{2B}	T_{1S}	T_{2S}	T_{2S}	T_{1N}	T_2
T_{2B}	T_{2N}	T_{1N}	T_{3N}	T_{3S}	T_{1N}	T_3	T_{3N}	T_1

3 Provenances x 3 Replicates x 3 soil types

T – Treatment (Provenances)

S – Sand

B – Black cotton soil

N – Nursery soil

Appendix 3: Field treatment combination descriptions and codes

No.	**Description/Treatment combinations**	**Code**
1.	Kibwezi provenance, 1.5m by 1.5m spacing	$T1_{1.5}$
2.	Kibwezi provenance, 2m by 2m spacing	$T1_{2}$
3.	Kibwezi provenance, 3m by 3m spacing	$T1_{3}$
4.	Tharaka Nithi provenance, 1.5m by 1.5m spacing	$T2_{1.5}$
5.	Tharaka Nithi provenance, 2m by 2m spacing	$T2_{2}$
6.	Tharaka Nithi provenance, 3m by 3m spacing	$T2_{3}$
7.	Baringo provenance, 1.5m by 1.5m spacing	$T3_{1.5}$
8.	Baringo provenance, 2m by 2m spacing	$T3_{2}$
9.	Baringo provenance, 3m by 3m spacing	$T3_{3}$

Appendix 4: Field Experiment Layout

T_2	**T_1**	**T_2**	**T_3**	**T_1**	**T_1**	**T_2**	**T_3**	**T_1**
T_3	**T_2**	**T_3**	**T_1**	**T_2**	**T_3**	**T_2**	**T_3**	**T_2**
T_2	**T_1**	**T_3**	**T_1**	**T_3**	**T_2**	**T_3**	**T_1**	**T_1**

T_1 – Kibwezi

T_2 – Tharaka

T_3 – Baringo