ECO-PHYSIOLOGICAL FACTORS AFFECTING GROWTH AND DEVELOPMENT OF *Calotropis procera* IN THE SEMI-ARID REGIONS OF THARAKA AND MAKUENI, KENYA

BY

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DECLARATION

Declaration by the Candidate

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DEDICATION

This study is dedicated to my family members and people in semi-arid regions of Kenya.

ABSTRACT

Textile industry faces fibre supply deficit that can be filled by fibre from *C. procera*. However, current calotrope fibre supply is unsustainable because it is collected from the wild with inadequate information on its growth conditions. Therefore, this study investigated proximate eco-physiological factors affecting *C. procera's* growth in its natural habitats for better site matching and domestication. Specifically, the study determined; 1) edaphic and weather conditions in Tharaka and Makueni, 2) morphology, 3) size distribution, 4) phenology and 5) dieback condition of *C. procera* in Tharaka and Makueni at different time points. Repeated measure and factorial research designs were used. Purposive and simple random sampling techniques were used in selecting blocks with naturally growing *C. procera* and marking (20 x 20) m permanent plots respectively. Edaphic factors were assessed using soil chemical analysis while weather conditions were obtained from National Aeronautics and Space Administration satellite. Morphology was assessed using leaf surface area, leaf colour and fruit volume. Size distribution entailed measuring shrub's height, crown and root collar diameters. Phenology entailed estimating activity indices, number of flowers and fruits and phenophase intensities. Dieback condition was assessed through prevalence, severity and causative agents. Data was analyzed using factorial analysis of variance (ANOVA), mixed repeated ANOVA, Kruskal Wallis, Friedman, ordinal regression and generalized estimation equation. Results indicated that soil phosphorus in Tharaka and Makueni were 4.84 ppm and 10.76 ppm respectively at (20-40) cm soil depth. Average monthly rainfall and temperatures were (45.27 - 160.37) mm and (24.92 - 28.78) °C respectively. The volume of between 58.05% and 76.4% of fruits was < 100 cm^3. Relative frequency of *C. procera* stems in (1.5-<3) m height class in Tharaka and Makueni were 44.98% and 69.91% in (June-August) 2018 respectively. The lowest fruiting activity index of 42.71% and 43.64% for Tharaka and Makueni respectively were reported in (September-November) 2019. The highest dieback prevalence of 76.59% and 80.53%, and severity index of 3.56 and 3.42 were reported in Tharaka and Makueni in (September-November) 2019 respectively. *Fusarium* Fungi was the dominant dieback causative agent with 32.29% – 43.38% dominance. There were significant differences in fruit volume class distribution, size class distribution, activity index, dieback prevalence and severity between research time points ($P < 0.001$). There were significant associations between *C. procera's* growth with soil nitrogen, phosphorus, potassium, average monthly rainfall and temperature. In conclusion, eco-physiological conditions of Tharaka and Makueni favour growth and development of *C. procera*.

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ABBREVIATIONS AND ACRONYMS

°C:	Degree Celsius
AAS:	Atomic Absorption Spectrometer
ABA:	Abscisic Acid
AFR 100:	African Forest Landscape Restoration Initiative
ANOVA:	Analysis of Variance
ASALs:	Arid and Semi-Arid Lands
asl:	above sea level
DBH:	Diameter at Breast Height
FEM:	Finite Element Method
GEE:	Generalized Estimation Equation
GLM:	Generalized Linear Model
GME:	Geospatial Modelling Environment
GPS:	Global Positioning System
GRF5:	Growth-Regulating Factor 5
ICRAF:	International Centre for Research in Agroforestry
KEFRI:	Kenya Forest Research Institute
NACOSTI:	National Commission for Science, Technology and Innovation
NASA:	National Aeronautics and Space Administration
NGOs:	Non-Governmental Organizations
PLUM:	Polytomous Universal Mode
QGIS:	Quantum Geographic Information System
SDGs:	Sustainable Development Goals
SPSS:	Package for the Social Sciences
Usp:	Universal stress protein
WDM:	Water Displacement Method

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CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Globally, the textile industry is facing a deficit of over 3 million metric tons of both natural and synthetic fibre supply (Ramkumar, 2019). This may be as a result of overreliance and preference on natural cotton fiber that provides over 30% of textile fiber on the market despite the presence of synthetic fibres like polyester (Krifa & Stevens, 2016). Due to expected annual growth of textile fibre demand by 3.9% as a result of increasing human population and improved household income, fibre supply deficit is expected to increase in the near future (Krifa & Stevens, 2016; Kallio, 2021). Improved household income enhances the household's purchasing power of not only basic textile products like cloths, but also luxurious materials like napkins, wipes and non-woven construction materials because of rised living standards.

Calotropis procera W.T. Aiton, an evergreen shrub belonging to Asclepiadaceae family has been recommended for natural plant fibre production to counter the expected increase in textile fibre deficit (Borders & lee-Mader, 2014; Jianchu, 2016). This is because its seeds and fruits produce high quality calotrope fibre that compares well with cotton and silk in terms of characteristics. For instance, calotrope fibre has good fibre faireness with micronaire value of 2.09, stable lengths of 42.0 mm, fibre strengths of 29.5g/tex and fibre uniformity index of 81.6% compared to cotton and silk that exhibit micronaire value of 4.5 - 4.9, fibre length of 28-32 mm, fibre strength of 28-32g/tex and uniformity index of 80-82% (Cheema *et al*., 2010; Bajwa *et al*., 2013; Akhtar *et al*., 2014: Delhom *et al*., 2017).

In terms of growth, *C. procera* is more advantageous as it can grow in drought and saline conditions occurring in arid and semi-arid lands (ASALs) with 150 - 1000 mm annual precipitation and temperature range of 20 - 30 °C without irrigation (Yassin *et al*., 2016; Coêlho *et al*., 2019). It has also been naturalized in other warm climatic conditions with over 2000 mm annual precipitation, particularly in parts of North America, South America and Australia (Payal & Sharma, 2015).

However, the growth and regeneration of *C. procera* has been reported to be having undesirable characteristics like invasiveness in some eco-physiological conditions (Menge *et al*., 2017; Mbambala & Collinson, 2017). This is because some climatic and edaphic conditions favour its phenological plasticity that enables it to establish quickly and grow faster than native species (Payal & Sharma, 2015; Moustafa & Sarah, 2017). This has been reported especially in Australia, some parts of the United States, India, Angola and Ethiopia (Aravindhan & Rajendran, 2014; Mandal & Joshi, 2015; Rejmanek *et al*., 2016; Bufebo *et al*., 2016; Menge *et al*., 2017; Abeysinghe, 2018).

Contrary, in some eco-physiological conditions like those prevailing in Egypt and other parts of Northern Africa, *C. procera* has experienced low seed germination and slow growth rates as evidenced by dominance of smaller sized stems (Moustafa & Sarah, 2017; Coêlho *et al*., 2019). This indicates that its phenology and growth in terms of population distribution differ between regions based on prevailing eco-physiological conditions. It is therefore important to determine ecophysiological conditions affecting growth of *C. procera* in its natural habitat because phenology, regeneration and growth of *C. procera* is expected to be affected by changing climate and soils in a direction that research is yet to reveal (Frosi *et al*., 2013). Therefore, it is not clear how the impacts of climate change like increased frequency of prolonged

drought from one-in-twenty years to once after every 5 years and increased temperatures by 4.6 ± 0.4°C by 2080 above pre-industrial levels (Mullan *et al*., 2005; Cervigni & Morris, 2016; Girvetz *et al*., 2019; Squires & Gaur, 2020) will affect *C. procera's* growth.

In Kenya, *C. procera* grows naturally in the arid and semi-arid regions of Turkana, Kajiado, Baringo, Tharaka, Makueni and Kitui among others (Jianchu, 2016; Muchugi *et al*., 2017). According to Mutiso *et al*. (2017), communities in Kenyan ASALs mainly in Makueni and Tharaka have taken part in calotrope fibre collection pilot projects, but they have been collecting from the wild. As a result, Non-Governmental Organizations (NGOs) like World vision and World Agroforestry (ICRAF) partnerd and set pilot domestication programmes of the shrub in Tharaka and Makueni to maximize fibre quantity and quality to meet the demands of expanding textile industry (Jianchu, 2016). However, dieback condition is one of the noticeable challenges being faced in these demonstration plots, yet no study has been conducted to identify abiotic and biotic causative agents.

Therefore, if proper site matching for the species is done to promote growth, flowering and fruiting while minimizing invasiveness and dieback conditions, calotrope fibre from the shrub can provide communities in ASALs with alternative source of income while providing requisite material for textile industry. Increased income will be important to communities living in ASALs where crop failure, low income, inadequate livestock forage and high livestock mortality are frequent (Njoka, 2016; Muchugi *et al*., 2017). Providing alternative source of textile fibre will only enhance manufacturing as one of its big four agenda, but also meet agenda 8 and 9 of Sustainable Development Goals (SDGs) by ensuring decent work and economic growth, and industrial innovation and infrastructure development respectively.

Therefore, investigation on eco-physiological factors influencing growth of the species is required to ensure its proper management in the wild, and upscale on-farm cultivation to sustainably supply calotrope fibre (Muriira *et al*., 2015; Jianchu, 2016).

1.2. Statement of the Problem

Although *C. procera* has the potential to provide calotrope fibre to counter the increasing textile fibre deficit, calotrope fibre supply in Kenya is currently very little, unreliable and unsustainable as it is being collected from the wild with no proper management (Mutiso *et al*., 2017). The quantity, quality, reliability and sustainability of this fibre can be enhanced through on-farm cultivation/domestication as domestication improves productivity function through proper management and application of breeding technologies that stabilizes yield supply (Dawson *et al*., 2012; Ofori *et al*., 2014). However, domestication reguires proper understanding of eco-physiological factors that affect growth and establishment of the species to ensure proper site matching and dieback control, an area that *C. procera* has received limited research attention (Boutraa, 2010; Frosi *et al*., 2013; Yassin *et al*., 2016; Moustafa &Sarah, 2017). This is because most studies on *C. procera* have focused on pharmacological, medicinal and application of the shrub's genes in breeding and biotechnology mainly in greenhouses (El-Tantawy, 2000; Tezara *et al*., 2011; Sobrinho *et al*., 2013).

Lack of adequate information regarding the effects of ecophysiological factors on this species makes it difficult to conclusively predict how it will behave in different and ever changing ecophysiological conditions when domesticated (Moore &Lauenroth, 2017). Without conclusive prediction, it may lead to poor site matching of the species during domestication; leading to various challenges including high invasiveness, high

dieback condition or slow growth rates (Gaertner *et al*., 2014; Menge *et al*., 2016; Kumar & Khurana, 2017). Therefore, identifying areas with eco-physiological factors that favours optimal growth of *C. procera* will enhance its domestication and productivity due to proper site matching of species (Tezara *et al*., 2011; Muriira *et al*., 2015; Jianchu, 2016; Mutiso *et al*., 2017).

1.3. Justification

Understanding regeneration and growth of a species in their natural habitat before its domestication to improve people's livelihood by enhancing its productivity and service provision is crucial (Jamnadass *et al*., 2019). Such information helps in predicting potential challenges and opportunities that may exist in domesticating the species. On this basis, studies identifying ecophysiological factors affecting growth and regeneration of *C. procera* are encouraged because the shrub is important in improving people's livelihood economically, socially and culturally (Galal *et al*., 2015).

Therefore, this study provides fundamental information that can be used to guide the management of this important species under on-farm cultivation to optimize its productivity for developing calotrope-fibre-based textile industry. Successful establishment of calotrope-fibre-based textile industry will enable Kenya attain its desire of increasing manufacturing, which is one of the government's big four agenda. Increased manufacturing will provide descent employment opportunities (SDG 8) as well as industrial, innovation and infrastructure development (SDG 9 and vision 2030) especially in rural areas.

Enhanced cultivation of *C. procera* on-farms will increase household income among farmers and their casual workers; a condition that will reduce poverty (SDG1) and

hunger (SDG 2). Enhanced cultivation of *C. procera* will also boost the country (Kenya) achieve its desire of having 10% of its tree cover among other global commitments like African Forest Landscape Restoration Initiative (AFR 100). This will be important in enhancing carbon sequestration to mitigate climate change among other ecological benefits accrued from trees and shrubs.

1.4. Research Objectives

1.4.1. General objective

This study aimed at investigating proximate eco-physiological factors affecting growth and development of *C. procera* in its natural habitats in the semi-arid regions of Tharaka and Makueni in Kenya.

1.4.2. Specific objectives

i. To evaluate ecophysiological factors in terms of edaphic and weather conditions in the semi-arid regions of Tharaka and Makueni at different time points.
ii. To evaluate morphological characteristics of *C. procera* at different time points and ecophysiological factors affecting them in Tharaka and Makueni.
iii. To determine the population distribution of *C. procera* at different time points and ecophysiological factors related to them in Tharaka and Makueni.
iv. To determine phenology of *C. procera* at different time points and ecophysiological factors affecting them in Tharaka and Makueni.
v. To assess dieback condition on *C. procera* at different time points and ecophysiological factors associated with them in Tharaka and Makueni.

1.5. Hypothesis

i. There are no statistically significant differences in edaphic and weather conditions between the semi-arid regions of Tharaka and Makueni at different time points.

ii. Morphological characteristics of *C. procera* in the semi-arid regions of Tharaka and Makueni at different time points are not significantly different and are not influenced by edaphic and weather conditions.

iii. The population distribution of *C. procera* in terms of size classification at different time points in Tharaka and Makueni are neither significantly different nor affected by edaphic and weather conditions.

iv. Phenology of *C. procera* at different time points in Tharaka and Makueni are neither significantly different nor significantly influenced by edaphic and weather conditions.

v. Dieback condition on *C. procera* at different time points in Tharaka and Makueni are neither significantly different nor related to edaphic and weather conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1. Edaphic and Weather Conditions in Semi-Arid Regions

2.1.1. Edaphic conditions in semi-arid regions

Variability of soil physical, chemical and mineralogical properties in a landscape is as a result of complex interactions between biotic and abiotic factors, mineralogy of parent rocks, land use activities and formation processes (Queiroz *et al*., 2018; Dinesh *et al*., 2019). Land use activities like quarrying, poor farming practices, deforestation and overgrazing have detrimental impacts on soil properties in a landscape (Rodríguez-Seijo & Andrade-Couce, 2017; Belay *et al*., 2020).

Semi-arid regions experience harsh biophysics and socioeconomic conditions that leads to loss of soils, reduction in soil fertility and vegetation cover, compaction, acidification and salination over time (Vásquez-Méndez *et al*., 2011; Bünemann *et al*., 2018). Acidification and salination of soils builds up overtime as a result of high soil surface evaporation and transpiration, weathering of native rocks and low precipitation (Hussain *et al*., 2019). Vásquez-Méndez *et al*. (2011) and Ullah *et al*. (2019) attribute this degradation to increasing soil erosion threats, leaching, overgrazing and other poor farming methods. This degradation has led to deficiency in one or more soil nutrients, poor soil structure and texture (Saygin, 2017; Garcia-Franco *et al*., 2018).

Soil physical properties are determined based on soil texture, soil structure, soil bulky density and colour of the soil among others which are influenced by land use types (Mganga *et al*., 2011). Soil texture refers to the relative proportion of three major types of soils made up of sand, silt and clay as well as soil particles larger than sand

(Tueche, 2014; Stirling *et al.*, 2016). The surface layer of soils to a depth of about 25 cm is a portion of soil that is mostly used by most plants and crops (Rathinasamy & Saliha, 2014). Soil texture determines soil water holding capacity, soil structure, soil chemical properties, relative stabilization of soil organic matter, infiltration, erodibility, porosity, water movement, and aeration (Tueche, 2014; Stirling *et al*., 2016). Based on the European classification system, soil texture can be classified as clay, silt, very fine sand, fine sand, medium sand, coarse sand and very coarse sand (Rathinasamy & Saliha, 2014).

Soil structure determines the soil's pore sizes, through which roots grow (Passioura, 2002). Plants growing in soils with smaller pores grow better than plants growing in soils with larger pores that exceed root diameter (Beemster & Masle, 1996). In soils with larger pores, plant leaves are about 30% smaller than leaves of plants growing in fines soils (Beemster & Masle, 1996; Passioura, 2002). The reason behind this phenomenon is that large pores hinder the ability of roots to absorb water and nutrients in soils since roots are not in direct contact with soils (Passioura, 2002). Moreover, in case roots are clumped together in macrospores, the clumping may lead to wide spacing in soils that normally available water may be poorly accessible (Passioura, 1991). Poor soil structure especially hard soils may inhibit extension of plant roots deep in soils, a phenomenon that may result to inability of roots to supply adequate water and nutrients to leaves; resulting to reduced plant growth rate (Passioura, 1991).

Semi arid soils according to Karuma *et al*. (2015), a study conducted on the three horizons showed sandy loam soils in the upper horizon, sandy clay loam in the middle and sandy clay in the lowest soil horizon with averarage texture of sandy clay loam of 72.4%, 25.2% and 2.4% respectively in Mwala district. Therefore, improved soil

structure and texture ensures improved infiltration, air circulation and drainage thus enhancing root growth by enabling the plant to access greater amount of water and nutrients for their growth (Tueche, 2014; Jarvis *et al*., 2013).

Generally, Marx *et al*. (1999), Okalebo *et al*. (2002) and Horneck *et al.* (2011) provide critical levels of soil properties for adequate plant growth. Such properties are summarized in Table 2.1.

Table 2.1: Soil Nutrient Adequacy Levels

Parameter	**Adequate levels**
Soil pH(H_2O)	6.5-7.0
Soil Conductivity(mS/cm)	<0.15
Soil Nitrogen content (%)	0.12-0.25
Soil organic carbon content (%)	1.5-3.0
Available Phosphorus (ppm)	20-40
Exchangeable Potassium (ppm)	175-300
Exchangeable Magnesium (ppm)	80-180
Exchangeable Calcium (ppm)	1000-1600
Exchangeable Manganese (ppm)	10-50
Exchangeable Sodium (ppm)	<100

(Source: Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011)

In their review, Koala *et al.* (1988) states that 65.1% of soil samples from semi-arid regions in the tropics are phosphorus (P) and nitrogen (N) deficient. Al-Maliki *et al.* (2018) also established that soils in semi-arid lands have low organic carbon (OC) content as a result of low organic matter, poor vegetation cover and high temperatures. Soil organic matter correlates strongly with available P sorption which is an indicator that an increase in accumulation of organic carbon may lead to an increase in availability of P in surface soils (Hou *et al*., 2013; Yang *et al*., 2019). Low levels of some nutrients like P and N may also be attributed to poor soil texture, and low moisture content that influences soil organic matter accumulation and microbial activities (Suñer & Galantini, 2015; Bhat *et al*., 2017). However, there is hope as most

communities in ASALs embrace soil and water conservation practices to boost soil fertility and improve yields (Bhat *et al*., 2017; Meena *et al*., 2019).

In East Africa, soil properties including soil structure, pH, N and P vary within and between semi-arid landscapes depending on vegetation cover type and conservation measures in place (Egeru *et al*., 2019). In Kenyan semi-arid regions, various conservation measures like contour farming, ridging, agroforestry, intercropping, terracing and increasing soil surface cover among others have been undertaken to reduce erosion and improve soil fertility at different soil horizons (Karuku, 2018; Nadir *et al*., 2018).

2.1.2. Weather conditions in semi-arid regions

Hot semi-arid regions are fragile ecosystems that experience unreliable and varied rains, strong winds and high temperatures (Saygin, 2017; Mutua *et al*., 2020). Although semi-arid regions have adequate moisture at some periods of the year to produce livestock forage and crops, they are mostly affected by prolonged droughts and frequent intra and inter -annual periods of below-average rains (Lane & Nichols, 1999). Scholes (2020) attributes this high inter and intra -annual variations to intrinsic features of global atmospheric circulation and geomorphology as ultimately due to absence of glaciations and intermediate pace of pedogenesis during Pleistocene. Biasutti (2019) adds that inter-annual rainfall variability is explained by changes in ocean warming that causes structural and position of regional shallow circulations and allows intensive convective systems.

Hot semi-arid regions especially those in Africa experience high temperatures ranging from 18 °C to about 48 °C (Behera & France, 2016; Scholes, 2020). Apart from climate change and global warming, there are other natural causes of high

temperatures in arid and semi-arid regions (Rajaud & Noblet-Ducoudré, 2017). Such factors include high solar radiations especially at the equator and low cloud cover (Rajaud & Noblet-Ducoudré, 2017; Scholes, 2020). Therefore, temperature differences within and between semi-arid regions may arise as a result of their proximity to the equator, and cloud cover. According to Betts *et al*. (2013), while maximum temperature increases with decreasing cloud cover; minimum temperatures are influenced by earth's revolution which dictates proximate distance of the earth from the sun. Therefore, at the equator, minimum temperatures are almost equal at all times because of proximate equal distances from the sun at all times.

Hot semi-arid regions experience strong and dry winds that strongly affect evapotranspiration in already water stressed environments (Kousari *et al*., 2013). Wind speed according to Wooten (2011) depends on the level of pressure gradient between two regions, which is highly dependent on the average temperature. In this regard, regions with low and high temperatures have low and high pressure respectively, meaning that wind blows from regions of high temperature to regions of low temperature. Wind speed increases with increasing pressure gradient (Sun & Lenschow, 2012). Monahan and McFarlane (2013) also established that wind speed is affected by cloud cover. In their modelling, Monahan and McFarlane (2013) found that the probability of high wind speed is high in the presence of low clouds.

The relationship between low relative humidity and high temperatures in the semi-arid regions has been debatable with literature indicating contradicting results. According to Bui *et al*. (2019), high temperatures in semi-arid regions accompanied by low rains leads to low relative humidity. On the other hand, Rokonuzzaman and Rahman (2017) argue that relative humidity is mostly affected by air moisture content that is affected by evaporation rates from water bodies like ocean. Therefore, high

temperature increases air moisture content that eventually increase relative humidity. In this regard, temperature of large water bodies like ocean plays a bigger role in determining atmospheric relative humidity. Hardwick *et al*. (2010) on the other hand states that a decline in relative humidity during summer is as a result of high temperatures on land surface compared to ocean temperatures.

2.2. Description of *C. procera*

2.2.1. Morphological characteristics of *C. procera*

Calotropis procera is a xerophytic perennial and evergreen shrub in the Asclepiadaceae family that can grow to a height ranging from 2.6 m to 6 m (Orwa *et al*., 2009; Galal *et al*., 2016; Jianchu, 2016). The Shrub's stem is woody at the base, covered with a grayish, crooked, soft, thick and corky bark (Plate 2.1a). When young, *C. procera* forms a number of light gray succulent branches at the base (Plate 2.1b), but as the shrub become tree like, it remains with few airy crown twisted branches. The plant exudes milky and sticky sap (latex) when cut at any point of its part (Csurhes, 2016; Brown, 2013).

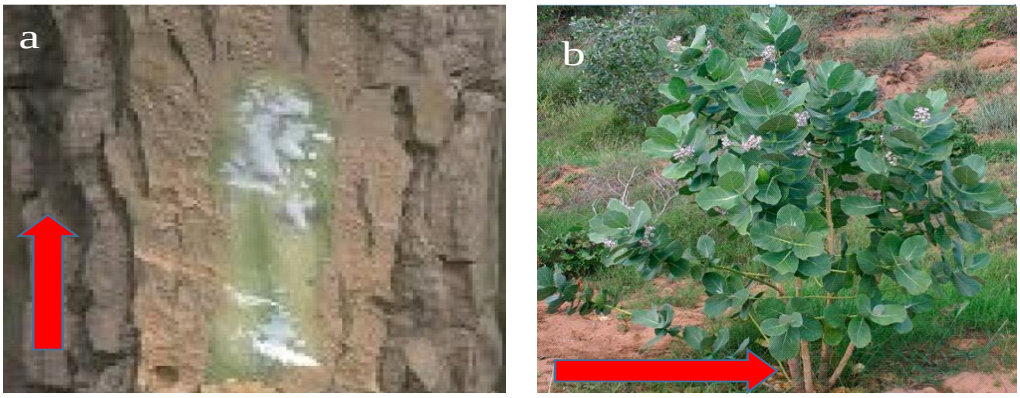

Plate 2.1: The Fissured Bark (a) and Young Branched *C. procera* (b)
(Sources: Orwa *et al*., 2009; Csurhes, 2016)

The succulent and oblong-obovate leaves of *C. procera* measuring (5 – 30 x 2.5 – 15.5) cm are simple and grow opposite each other on a stem with a short petiole

(Orwa *et al*., 2009; Brown, 2013; Bairagi *et al*., 2018). The apex ranges from short pointed to blunt in nature and clasping heart-shaped base. The main vein is conspicuously light yellowish, and blades are light to dark-green on top and whitish green beneath (Brown, 2013; Hassan *et al*., 2015).

The shrub produces many umbrella-like dense flowers arising from the nodes and appearing either axillary or terminal (Orwa *et al*., 2009). The pedicles are about 2.5 cm long, about five sepals that are approximately 0.6 cm long and the flower is approximately 2.0 cm in diameter (Brown, 2013). The corolla is succulent and consists of about 5 showy erect petals that are approximately 2.0 cm long, whitish and tinged purple at the apex (Brown, 2013).

Calotropis procera produce green kidney-shaped fruits ranging from 8 - 12.0 cm long and between 5 - 6.5 cm with curved and inflated follicles (Orwa *et al*., 2009; Brown, 2013; Bairagi *et al*., 2018**)**.

2.2.2. Ecology and biology of *C. procera*

The shrub is native to the tropical and sub-tropical Western Asia, Northern Africa, Eastern Africa, Central Africa, West-Africa, Arabian Peninsula, and Indian sub-continent (Payal & Sharma, 2015; Muriira *et al*., 2015; Yassin *et al*., 2016). However, recent studies have indicated that the species has been naturalized in other warm areas of North America, South America and Australia, but the plant is very rare in cold areas (Payal & Sharma, 2015; Yassin *et al*., 2016; Menge *et al*., 2016). The species has been reported to be dominant in abandoned cultivation areas with disturbed sandy soils, low annual rainfalls ranging from 150 to 1000 mm, warm climates with temperatures ranging from 20 - 30 °C , altitude of up-to 1,300 m above sea level (asl) and saline soils (Hassan *et al.*, 2015; Payal & Sharma, 2015). In Kenya, *C. procera*

grow in the dry lands, especially in severely overgrazed regions of Kitui, Makueni, Tharaka Nithi, Lodwar and Baringo (Jianchu, 2016; Muchugi *et al*., 2017).

The shrub reaches maturity and starts producing thousands of seeds per annum after 2 years (Sobrinho *et al*., 2013). The shrub mainly reproduces through seeds, but in case of damages like fire burn or cut, *C. procera* may sprout through suckers produced from its long tap root ranging from 3-4 m deep and lateral roots (Hassan *et al*., 2015; Vitelli *et al*., 2008). After flowering, the pollen grains are cross-pollinated by non-specialized pollinators including insects like monarch butterflies, large wasps and bee species (Orwa *et al*., 2009; Menge *et al*., 2017). The ability to reproduce through sexual and assexual process is an indicator of invasive species that though they mainly reproduce through seeds, they can sprout vegetatively (Gao *et al*., 2018).

At maturity, fruits burst to release seeds that have high units of non-specialized dispersal agents that enable the plant to quickly invade and colonize new site (Csurhes, 2016; Moustafa & Sarah, 2017; Menge *et al*., 2017). Since fruits are eaten by some animals like goats and elephants (Orwa *et al*., 2009; Jianchu, 2016); there are possibilities that seeds can be dispersed by animals especially when they remain undigested and excreted in dung (Hassan *et al*., 2015). However, most seeds are short-lived, reducing germination rate over time after sowing or falling on the ground (Csurhes, 2016). Over 89% of seeds germinate at the onset of wet season especially in the tropics, but only a few survive after the first dry season (Csurhes, 2016; Vitelli *et al*., 2008).

2.2.3. Uses of *C. procera*

Calotropis procera has many uses ranging from traditional to biotechnological applications. Traditionally, its uses include making ropes, carpets, sewing threads,

fishing nets, and use of its latex as poison in making arrows and spear (Kipkore *et al*., 2014; Chandrawat & Sharma, 2015). The stem bark, root bark and leaves are ground into powder, water added and taken to cure diseases such as diarrhoea, stomach-ache among others (Maroyi, 2012 & Al Sulaibi *et al*., 2020).

Various domestic modern uses of *C. procera* include: ornamental as its flowers attract monarch butterflies; use of young pods, leaves and flowers as fodder for goats and sheep; its ability to produce termite proof timber and a source of green manure that can improve soil fertility (Orwa *et al*., 2009; Sobrinho *et al*., 2013; Moustafa &Sarah, 2017). Currently, through phytochemical screening of various parts of the plant, medicinal products have been produced and sold over-the counter using the brand 'herbal medicine' (Borders &Lee-Mader, 2014). This is because the extracts from leaves of the plant showed antihelmintic effects while a combination of roots and leaves showed antibacterial, antifungal and anticancer effect (Al-Snafi, 2015).

At the industrial level, high-density fluids extracted from *C. procera* are rich in hydrocarbons in biodiesel production feedstock (Quazi *et al*., 2013; Phoo *et al*., 2014). The shrub has a high growth rate and can produce between 2 and 40 tons of dry matter per hectare per year; providing feedstock for industrial charcoal production (Brown, 2013; Quazi *et al*., 2013).

In the previous decade, studies by D'Souza *et al*. (2010) looked at the effectiveness of *C. procera* to remediate heavy metals in contaminated lands and found that the highest uptake of lead and cadmium metals was observed from sites with industrial activities. Other on-going research includes application of *C. procera* to produce high quality fibre that can be used in the textile industry and as a thermal insulating material (Cheema *et al*., 2010; Akhtar *et al.*, 2014; Gardetti, 2016). In South America,

pilot projects on fibre production by the shrub showed over 500 kg/ha per year based on a spacing of between 1 and 1.5 m (Kumar *et al*., 2011). In Kenya, well-known Non-Governmental Organizations (NGOs) like World Vision are working with partners like World Agroforestry (ICRAF) to maximize fibre quantity and quality to meet the demands of expanding textile industry (Jianchu, 2016). Although substantial progress has been achieved in using gene modification of cotton using *C. procera'*s gene to improve fibre strength (Bajwa *et al*., 2013), there is still little understanding on the application of *C. procera* genes as information on the possible occurrence of universal stress protein (Usp)-like genes is not available (Shokry *et al*., 2014; Girdhar *et al*., 2016; Moustafa & Sarah, 2017). Further research is being conducted by biotechnologists to test the ability of the shrub's excellent genes to enhance positive response to drought and salt tolerance among other plants (Shokry *et al*., 2014). Exploring this area will play an important role in increasing crop adaptation to climate change especially in relation to prolonged drought and increased atmospheric temperatures.

2.3. Variations in Morphological Characteristics of Plants

Plant morphology refers to the study of both physical form and external structures of plants in their environment (Kaplan, 2001). Studies that have looked at morphological traits of plants like Santos *et al*. (2012) emphasize on the use of both quantitative and qualitative traits in characterizing morphological variations of plants in a stand. This is because studying quantitative and qualitative morphological traits simultaneously brings out conclusive evidence on heterogeneity within plants that are traditionally classified in the same species; hence contributing to the development and conservation of biodiversity of plants especially in the changing climate (Frosi *et al*., 2013; Okereke *et al*., 2015; Houédjissin *et al*., 2015; Ha *et al*., 2016).

Nicotra *et al*. (2011) and Houédjissin *et al*. (2015) argues that qualitative and quantitative morphological differences within and between plant species located either in the same or different geographical locations may be as a result of developmental stage, that is young or old, and at different seasons of the year. This is supported by Xu *et al*. (2009) and Gichimu and Omondi (2010) that morphological traits like fruit size, leaf shape and colour may be affected by abiotic factors like environmental conditions and biotic factors like human intervention. For instance, light and water variability affects leaf size since leaf area correlates with water, temperature and light intensity; as leaf area reduces when plants are subjected to low light intensity and little water (Xu *et al*., 2009; Giuliani *et al*., 2013). Other leaf variables that positively correlate with water and light availability include leaf petiole length, leaf width, leaf length, leaf elongation, leaf length to petiole length ratios among others (Xu *et al*., 2009).

Reduction in leaf size under stressful environment is based on leaf boundary-layer conductance for gaseous and heat transport (Niinemets *et al*., 2007; Giuliani *at al*., 2013). In this regard, Xu *et al*. (2009) and Giuliani *et al*. (2013) established that variation in leaf morphology along climatic gradient is as a result of evaporative demands of different leaf sizes especially larger leaves because of enhanced thickness of boundary layer for gaseous and energy exchange.

According to Dolkar *et al.* (2018), the influence of climatic and soil factors on fruit growth, size, quality and yield is undoubtedly complex as it is not easy to single out one factor influencing fruits morphological traits. However, ecological factors like light exposure duration, air humidity and rainfall correlate with both quantitative morphology of fruits in terms of length and width significantly (Barrett, 2007; Houédjissin *et al*., 2015; Woźnicka *et al*., 2015). For example, fruit length, fruit width

and number of seeds per fruit of *Pentadesma butyracea* increases with an increase in water availability and soil nutrient level (Shamshir *et al*., 2012; Houédjissin *et al*., 2015). This concurs with Dolkar *et al.* (2018) and Bradfield and Guttridge (1984) that high rainfalls enhances soil moisture to an extent that plants are able to transport enough water to fruits which constitutes over 80% of immature fruit volume and mass. This also concurs with Junior *et al*. (2010) that adequate availability of plant nutrients enhances expansion of morphological traits.

Plant morphological features may be influenced by genetic composition and health condition of individual plant (Beckman & Muller-Landau, 2011; Konglerd *et al*., 2017; Balduzzi *et al*., 2017). Plant genes vary within and between species partly as a result of adaptation to external stimuli like light, gravity, altitude and temperatures among other biotic and abiotic factors (Nicotra *et al*., 2011; Guo *et al*., 2015). Within a species, gene modification may be initiated by external stimuli that make the plant to alter its growth properties in terms of inhibiting or promoting expansion (Balduzzi *et al*., 2017). For instance, expansion constraints on a cell wall limits the level at which the plant tissues expand (Gallien *et al*., 2016). In addition, plants in good health condition produce quality fruits in terms of size and nutrient content compared to plants of similar genes but under attack by diseases (Beckman & Muller-Landau, 2011).

Human interventions like placing plants in greenhouses and plant breeding to increase plant growth rate and yield also affect plant tissues by regulating expansion of plant tissues that eventually affect plant morphology (Marcelis & Pascale, 2009; Gray & Brady, 2016). These human interventions together with environmental factors leads to down-regulation or over-expression of genes like Growth-regulating factor 5 (GRF5)

that eventually increases or reduces size of organs produced by plants (Gonzalez *et al*., 2010).

Calotropis procera is characterized by morphological plasticity that enables it to strive in drought, saline and water logging conditions (Moustafa & Sarah, 2017). The shrub's ability to tolerate drought condition may be attributed to its latex content. According to Wang *et al*. (2016) and Sah *et al*. (2016), plants in ASALs have higher latex content which controlls abscisic acid (ABA) that modulates root structure and stomatal regulation through promotion of partial or total closure of stomata to reduce water loss during droughts. The shrub has shown to have an ever-green leafing pattern with long tap root system that enables the plant to reach water and nutrients deep in the soils (Bairagi *et al*., 2018). Although Leal *et al*. (2013) found no significant difference in seed size of *C. procera* planted in different regions of Brazil, the number of seeds per fruit in some regions like Caatinga were 11.85% higher than those in Restinga. This is because Caatinga experiences average temperature of 26 ^{o}C and annual rainfall of about 803 mm with that are highly saline thus more seeds are produced so as to increase chances of viability (Leal *et al*., 2013).

In general, literature has extensively outlined the effects of edaphic, climatic and genetic variations on plant morphology in terms of leaves and fruits. However, research on morphological variation of *C. procera* in different ecophysiological conditions remains seldom though important. This information on morphological plasticity of *C. procera* may help in genetic improvement, conservation and domestication programs of the species in aid of rural communities especially in ASALs.

2.4. Leaf Surface Area and Fruit Volume Traits

2.4.1. Leaf surface area

Leaf surface area refers to the area of the upper surface of the leaf measured on a plant and or immediately after plucking before shrinking or rolling (Nobel & Long, 1985). Understanding leaf surface area is essential in plant physiology as it determines photosynthetic rates by affecting carbon, water and light interception processes (Fascella *et al*., 2013; Wang *et al*., 2019). Both past and recent studies have confirmed that leaf surface area affects flower and fruit development as it influences photosynthesis. Halleb and Magness (1933) established that the number and quality of flowers and fruits in apples, pears and tomatoes depends on photosynthates and water supplied to plants by leaves. After monitoring fruit kinetics and photosynthetic rates of apples, Baïram *et al*. (2019) concluded that fruit growth rate was a function of photosynthetic rates and amount of carbon transferred to fruits from leaves. Therefore, leaf surface area plays an important role in determining flowering and fruiting processes.

Due to the importance of leaf surface area on plant physiology, various destructive and non-destructive methods have been developed to estimate leaf surface area. Such methods include grid count, photo-electric imagery, allometric equations, gravimetric and planimeter (Gerbera *et al*., 1994; Chaudhary *et al*., 2012).Grid count also called graph paper method entails plucking the leaf, placing it on a grid, tracing the leaf outline and the resultant leaf area estimated by counting grids covered by the leaf outline (Pandey & Singh, 2011). Although this method is accurate, it can only be applied on small samples as it is laborious and time consuming (Pandey & Singh, 2011; Chaudhary *et al*., 2012).

Gravimetric method entails plucking the leaf, placing it on a white paper, cutting the paper according to the leaf shape and then comparing the weight of the cut-paper to the weight of paper with known area (Chaudhary *et al*., 2012). This method is also time consuming, labour intensive and suffers from low accuracy because of variations in paper weight. Planimeter method entails using a planimeter device also called platometer to measure the leaf area. Though this method is less laborious, the equipment is expensive and experience less precision especially on small leaves (Chaudhary *et al*., 2012).

Photo-electric imagery technique is the most advanced, accurate and less laborious method of leaf area measurement that entails leaf image acquisition, processing, leaf region segmentation filling and area calculation (Chaudhary *et al*., 2012). For leaf region segmentation, researchers like Feng and Chun (2010) used contour extraction while others like Patil and Bodhe (2011) used threshold based segmentation. The accuracy and precision of photo-electric imagery technique depends on shape, size and capture resolutions (Bradshaw *et al*., 2007).

Use of allometric equations in estimating leaf surface area is the widely used technique. The method entail measuring leaf parameters like length, weight, and width and placing them in already existing allometric equations to establish leaf surface area. However, this approach according to Chaudhary *et al*. (2012) is erroneous because equation parameters especially coefficients differ between and within species depending on prevailing conditions. Therefore, it is appropriate that researchers develop species and site specific models to increase precision and accuracy (Kebede & Soromessa, 2018).

Various allometric equations ranging from simple linear to complex non-linear equations have been developed to estimate leaf surface area of different species in different regions as summarized in Table 2.2. Most common parameters used in estimating leaf surface area (Y) are leaf length (L) and leaf width (W) with better estimates observed in models having a product of L and W (L×W) (Demirsoy & Demirsoy, 2003; Santana *et al*., 2018). However, Santana *et al*. (2018) developed an allometric equation for predicting leaf surface area of *Dolichos lablab* species using length only because leaves were round in shape.

Table 2.2: Summary of Allometric Equations for Leaf Surface Area Prediction

Allometric Equation	**Species**	**Authors**
$Y = \beta_0 + \beta_1 L + \beta_2 W + \beta_3 L^2 + \beta_4 W^2 + \beta_5 (L \times W)$	*Crotalaria juncea, Canavalia ensiformis, Cajanus cajan, Dolichos lablab, Mucuna cinereum, Mucuna aterrima*	Santana *et al*., (2018)
$Y = \beta_0 + \beta_1 L + \beta_2 W\ (L \times W)$	*Crotalaria juncea*	
$Y = \beta_0 + \beta_1 \log L + \beta_2 \log W$	*Crotalaria juncea, Canavalia ensiformis, Cajanus cajan, Dolichos lablab, Mucuna cinereum, Mucuna aterrima*	
$Y = \beta_0 + \beta_1 L^2 + \beta_2\ W^2 + \beta_3 (L \times W)$	*Canavalia ensiformis*	Santana *et al*., (2018)
$Y = \beta_0 + \beta_1 L^2$	*Dolichos lablab*	
$Y = \beta_0 + \beta_1 (L \times W)$	*Rosa sempervirens, Rose hybrida*	Fascella *et al*., 2013

Table 2.2: Summary of Allometric Equations for Leaf Surface Area Prediction (continued)

$Y = \beta_0 + \beta_1 L + \beta_2 L^2 + \beta_3 WL^2 + \beta_4 (L \times W)$	Cherry cultivars in Turkey	Demirsoy & Demirsoy (2003)
$Y = \beta_0 + \beta_1 (L \times W)$	*Corylus avellana*	Cristofori *et al.* (2007)
$Y = \beta_0 + \beta_1 W$	Wheat species	Sastre-Vázquez *et al.* (2009)
$Y = \beta_0 + \beta_1 L$	Wheat species	

Key: Yis the leaf surface area**;** $\beta_0, \ldots \ldots, \beta_5$ are regression coefficients; W and L are leaf width and leaf lengths respectively.

2.4.2. Fruit volume

Biometric characteristics of fruits like weight, average diameter, length and volume are important in evaluating and selecting quality fruits (Costa *et al*., 2016). In fibre producing plants like cotton, fruit volume determines fibre yield because fibre economizes on resources by filling the volume of the fruit (Oosterhuis *et al*., 1994; Szewcyk *et al*., 2016).

Estimating fruit volume is a challenging and complex process because of existing fruits with irregular shapes (Szewcyk *et al*., 2016; Li & Han, 2018). Destructive and non-destructive methods including water displacement method (WDM)/ xylometric, finite element method (FEM), optical digital-image processing, and allometric equations have been used to measure volumes of fruits with irregular shapes. WDM through submersion of fruits in water and fruit volume estimated using displaced water has been used by studies like Fu *et al*. (2016) and Costa *et al*. (2016) as one of the methods in estimating the volume of Kiwi fruits. FEM involves preparing a two- or three-dimensional grid depicting fruit shape, sectioning the fruit along the selected axis and then section measurements used to estimate fruit volume. This method has been used by Goni *et al*. (2007) to estimate the volume of apple fruits. Optical digital-

image processing technique involves use of computer applications, digital cameras and scanners to reconstruct a geometrical representation of the fruit through lofting technique to establish fruit volume (Goni *et al*., 2007; Concha-Meyer *et al*., 2018).

Due to extensive time, labour and costs involved in other methods of estimating fruit volume, developing allometric equations has been considered as the most effective means of volume estimation especially when samples are large (Demirsoy & Demirsoy, 2007). Developing allometric equations entails estimating the volume of a small sample of fruits using WDM, xylometric or optical digital-image processing methods and then regressing against easily measurable fruit parameters like fruit length, diameter and weight (Bozokalfa & Kilic, 2010). Table 2.3 summarizes allometric equations that have been developed to predict fruit volume of different species using fruit traits like length, width, height and weight.

Table 2.3: Allometric Equations for Estimating Fruit Volume

Equation	Species	Authors
$Y = \beta_0 \times L \times D$, = $Y = \beta_0 \times L \times D^2 = LogY = log\beta_0 + log\beta_1 L + LogD^2$	*Solanum melongena*	Barbieri & Sifola (1990)
$Y = \beta_0 + \beta_1(L + D)$		
$Y = \beta_0 + \beta_1 D + \beta_2 L + \beta_3 W + \beta_4 H + \beta_5 D^2 + \beta_6 L^2 + \beta_7(D \times L) + \beta_8(D \times L \times H) + \beta_9(H \times D)/L + \beta_9 Cv$	Peach fruits	Demirsoy & Demirsoy (2007)
$Y = \beta_0 + \beta_1(L^2 + D^2) + \beta_2 D + \beta_3 L$		
$Y = \beta_0 + \beta_1 D + \beta_2 L + \beta_3 W$	*Capsicum annuum*	Bozokalfa & Kilic (2010)
$Y = \beta_0 + \beta_1 W$	*Acrocomia aculeata*	Costa *et al*. (2016)

Key: Y is the fruit volume**;** $\beta_0, \ldots\ldots, \beta_n$ are regression coefficients; D, L, W, Cv are fruit width, fruit length, fruit weight and cultivar respectively.

According to Rad *et al.* (2017) and Concha-Meyer *et al*. (2018), relationships between fruit volume and individual traits may not be significant in all situations, meaning that more analysis should be conducted by researchers to establish trait combinations that provide more accurate and precise results. Accuracy and precision of predicted results can be enhanced by selecting models with higher correlation coefficient (R), coefficient of determination (R^2), adjusted coefficient of determination (adj R^2) and low model standard error (Rajchal & Meilby, 2013; Labbafi *et al*., 2019).

2.5. Plant Species Population Demography

Plant population demography is a description of changes in certain plant traits over time and helps in monitoring and managing plant species that are either becoming invasive or extinct (Tarsi &Tuff, 2012; Galal *et al*., 2016). In a wild population, trees develop a natural size hierarchy comprising of small, medium and/or large trees even though they are of same species or age (Rocky & Mligo, 2012; Peck *et al*., 2014). Such differences may be attributed to variations in growth rates resulting from age differences, genetic variations, herbivory, competition and heterogeneity in eco-physiological factors affecting tree growth like availability of nutrients (Beckage & Clark, 2003; Galal, 2011; Rocky & Mligo, 2012; Ehrlen & Morris, 2015). However, Muriira *et al*. (2018) found that though Calotropis species experience genetic diversity between species, genetic variation is insignificantlydifferent within species. This implies that natural size hierarchy among *C. procera* stands may not be attributed to genetic variations.

Plants compete for a number of shared limited resources including light, nutrients and water, and competition may lead to a reduction in one or more fitness components either at the individual or population level (Gioria & Osborne, 2014). Mutiso *et al*.

(2017) adds that adequate spacing enhances tree growth rates by reducing competition to ensure availability of necessary nutrients per plant.

There are a number of parameters that have been used in determining size variation. The most common ones include total shrub height, average crown diameter, size index, diameter at breast height (DBH) and tree volume (Okereke *et al*., 2015; Galal *et al*., 2016; Mosallam *et al*., 2017). For instance, Galal *et al*. (2016) and Shaltout *et al.* (2015) used total shrub height and average crown diameter to determine the size structures, volume and establish the size index of *C. procera* in Egypt.

Establishing total height and stem diameter helps in assessing evolution and conservation implication. According to Galal *et al*. (2016), larger shrubs have higher survival rates: translating to higher chances of producing offspring for the next generation compared to smaller shrubs. On the other hand, a forest stand with over 50% of trees classified as small represents a rapidly growing population with high reproductive ability and high juvenile mortality as few stems reach larger sizes (Galal *et al*., 2016). *Calotropis procera* in many parts of the world including Libya and Egypt have shown this characteristic, where many stems are smaller in height and crown diameter (El-Beheiry & Shaltout, 2011; Galal *et al*., 2016).

Total height to stem diameter ratio helps in categorizing plants as either having higher vertical or horizontal elongation rates (Galal, 2011). Using this parameter, Shaltout *et al*. (2015) found that most plants adapted to ASAL conditions have high rate of horizontal expansion compared to vertical expansion as a strategy to ensure higher survival rates of young ones. High horizontal expansion enhances creation of safe sights for self-regeneration through shade that reduces severe heating and increase soil moisture (Mosallam *et al*., 2017).

High rates of horizontal expansion among *C. procera* is also important as it increases the chances of producing more flowers and fruits, which eventually enhances the chances of reproduction through seeds (Sobrinho *et al*., 2013; Mutiso *et al*. 2017). This is because larger stems hold larger crowns without breaking. Mutiso *et al*. (2017) also found that *C. procera* with larger diameters were less susceptible to cutworm attacks. Therefore, horizontal elongation is vital among *C. procera* stems.

According to Galal *et al*. (2016), size variables including total plant height, DBH, root collar diameter and crown diameter may have varied average values at different times of the year. For instance, plant height and diameter growth rates may be lower during winter and at the beginning of spring. This is because such seasons are characterized by low air temperatures which according to Hatfield and Prueger (2015) lowers growth rate of plants. This concur with Galal *et al*. (2015) that average total height, crown diameter and height to diameter ratio of a *C. procera* stand vary depending on season throughout the year, with low values reported during winter. Farahat *et al*. (2016) adds that perennial plants experience low growth rates during winter as a result of low temperatures. The implication is that *C. procera* reduces its growth rate during winter. However, over 67% of shrubs in *C. procera* stand is always less than 1.5 m in height in all seasons (Galal *et al*., 2015).

Although plant size-frequency distribution of different tree species both in ASALs and high potential areas have been researched on, size frequency distribution of *C. procera* is not well documented in literature (Galal *et al*., 2016; Ehrlen *et al*., 2015). This may lead to unclear understanding of size distribution of *C. procera*: resulting to challenges in controlling regeneration, mortality and growth as suggested by Alessandrini *et al*. (2011).

2.6. Plant Phenological Variations

Phenology refers to studying seasonal appearances of recurrent biological life-cycle events as a result of organisms' response to seasonal and climatic changes (Subrahmanyam & Murthy, 2005; Aparna, 2014). Phenology helps in describing the hypothesis of plant adaptation to annual seasonal cycle in terms of atmospheric changes that affect cyclical recurrent events like pollination, fertilization, appearance of buds, leaves, flowers and fruiting (Subrahmanyam & Murthy, 2005). Therefore, understanding phenological traits of plants is critical in understanding reproduction and survival of plants. Important parameters that have been used in studying phenological traits of a plant include: leaf sprouting, flowering and fruiting (Subrahmanyam & Murthy, 2005; Sobrinho *et al*., 2013).

Fundamental factors influencing plant phenology include water availability, temperature, altitude and soil nutrient concentration (Wan *et al*., 2007; Taffo *et al*., 2019). Temperature and rainfall are fundamental factors in plant development stages as high temperatures and low rainfall speed up plant development and leads to earlier switching of the plants to the next stage of development (Wan *et al*., 2007; Aparna, 2014). Since flower induction entails transformation of leaf buds to flower buds, most plants initiate leaf bud to flower bud transformation during low photosynthetic periods, or after periods of high reserve accumulation rates (Wan *et al*., 2007; Aparna, 2014).

In the tropics, some plants have consistent flowering patterns under a wide range of environmental conditions, but most species in general have inconsistent patterns in different conditions (Sobrinho *et al*., 2013). Variations in species phenology in different environments reflect the interaction between plants and the environment

(Houédjissin *et al*., 2015). For instance, in Southern Brazil, over 35 tree species in Araucaria forest showed that flushing and flowering correlate strongly with rainfall amounts, day-length and temperatures of preceding months, implying that plants receive phenological signal before their phenological response (Marques *et al*., 2004). In their study, Warrington *et al*. (1999) established that the number and size of apple fruits correlate positively with temperature as more and larger fruits were obtained at temperature above 22 °C in greenhouses.

In Atlantic Forest, plants experience seasonal flowering depending on the weather conditions like amount of rainfall, temperature and light intensity, with fruit development peaking during high humidity seasons, but ripening during low humidity seasons (Liuth *et al*., 2013). However, some plant species like Rubiaceae flower during winter but fruiting and leaf flushing takes place all year long (Marques *et al*., 2004; Liuth *et al*., 2013). This may be because Araucaria and Atlantic forests are located in areas with plenty of water all year long, a resource highly required in fruit formation stages as it helps in transporting necessary nutrients for fruit formation (Liuth *et al*., 2013; Loka *et al*., 2015). On the issue of soil nutrients, Aparna, (2014) established that plants require high levels of phosphorus compared to carbon and or nitrogen during flowering and fruiting. This is because phosphorus plays an important role in flower and seed production.

There are plants like litchi (*Litchi chinensis*) that water stress and high temperature induces fruiting (Shen *et al*., 2016). In such plants, high moisture and low temperatures prior to floral initiation suppresses flowering but promotes fruiting and vice versa (Carr & Menzel, 2014). This is because in those plants, genes that promote flowering get suppressed by high moisture and low temperatures and vice versa (Shen *et al*., 2016). However, the exact physiological metabolic processes responsible for

high temperature and water stresses promoting flowering but suppressing fruiting is not well understood in literature (Loka *et al*., 2015). In mild water deficit conditions after flowering, plants allocate resources to fruit formation, but severe droughts reduce fruit and yield quality (Carr & Menzel, 2014).

In Australia, *C. procera* were found to be experiencing long flowering season as opposed to fruiting season which only occur during warm months of the year when pollinators are active (Menge *et al*., 2017). In Saudi Arabia, *C. procera* starts flowering in early spring when temperatures are still low lasting for about 4 months and stops about 3 weeks before temperatures peak at 50 °C (El-Ghani, 1997). Farahat *et al*. (2016) adds that flowering and fruiting of *C. procera* in Egypt remained active throughout the year with flowering peak of 42.9% in May and fruiting peaking in July after flowering peak. However, Hassan *et al*. (2015) states that *C. procera* experiences continuous flowering for about 2-6 months each year.

The species flowering and fruiting correlate positively with temperature, but negatively with precipitation (Farahat *et al*., 2016). In Brazil where *C. procera* was introduced for ornamental purposes along roadways, has consistently indicated evergreen features with over 76.5% flowering and fruiting activity indices and intensities throughout the year (Sobrinho *et al*., 2013). El-Tantawy (2000) reported that *C. procera* has a unique characteristics exhibited by few plants in ASALs as it bears an average of over 959 flowers and 22 fruits. This indicates that *C. procera* has high phenological plasticity with continuous flowering and fruiting that enables the plant to reproduce successfully in arid and semi-arid regions (Orwa *et al*., 2009; Brown, 2013; Hassan *et al*., 2015; Moustafa & Sarah, 2017). However, with such high number of flowers but only 22 fruits means that the shrub according to Almeida *et al*. (2019) and Wyatt and Broyles (2012) has high levels of infertility, floral

abortion and or dropping, which is a common characteristic in the Asclepiadaceae family.

Phenology of plants may not only be affected by weather and edaphic factors but other factors like altitude play an important role in enhancing or inhibiting flowering and fruiting in plants (Hamann, 2004; Taffo *et al*., 2019). Bustamante and Búrquez (2008) add that plant characteristics including crown diameter may influence phenological traits of plants. For instance, plants with larger crown diameter tend to bear more fruits and flowers than smaller crowned plants regardless of age, genes and environmental condition.

Understanding plant phenology is important because the information plays a critical role in understanding reproduction and survival of plants. However, studies on the phenology of invasive species including *C. procera* in their natural habitat are scarce, most having been conducted in greenhouses (Sobrinho *et al*., 2013). In Kenya, where fibre from *C. procera* is expected to provide quality fibre to meet the demands of expanding textile industry, such information is needed to understand phenological plasticity in different environment and seasons to enhance domestication and conservation.

2.7. Dieback Condition in Plants

2.7.1. Definition and symptoms of dieback

Dieback is a condition that is experienced by trees and shrubs showing progressive death of branches and twigs from their tips towards the trunk as a result of plant diseases and or unfavourable environmental conditions (Jurskis & Turner, 2002; Bergdahl & Hill, 2016). The condition is mainly caused by severe stressing factors

including high temperatures, low rainfall and biotic factors (Horton *et al*., 2011; Ahmad *et al*., 2019).

General symptoms of dieback condition include thinning out of crowns of infected trees, limited growth of terminal branches and dying of branches beginning from the top. Other symptoms include crown defoliation, crown dieback, discoloration of leaves and shoot wilting, bark and root necrosis, elongated cankerous external and internal lesions on stems that are easily identified with the disease (Wangungu *et al*., 2011a; Enderle *et al*., 2013; Rolshausen *et al*., 2014). These symptoms are mostly observed on plant leaves and stems because the two plant tissues are great reservoirs of dieback causing fungi (Suradkar *et al*., 2013).

2.7.2. Prevalence and severity of dieback condition on plants

Prevalence of a disease refers to the proportion of diseased plants in a given population and can be determined through observation using naked eyes (Handiso & Alemu, 2017). Disease severity on the other hand refers to a measure of symptomatic areas of plant tissue (Campell & Benson, 1994).

A number of studies have been conducted to establish the prevalence of dieback condition in terms of their prevalence and severity. For instance, in Nigeria, dieback phenomenon was observed on citrus species of sweet Orange, Tangelo, Grape and Lemon species with a prevalence of 60%, 65%, 55% and 40% respectively (Ezeibekwe, 2011). The variation in dieback condition between species may be explained by interactions between climatic, edaphic and genetic factors (Robin-Abbott & Pardo, 2017; Kang *et al.,* 2016). Site conditions and seasonal changes contribute significantly on disease prevalence and severity of chili anthracnose respectively (Handiso & Alemu, 2017). Seasonal changes according to Kozlowski and

Pallardy (1997) results to changes in environmental conditions some of which are more stressful to plants like droughts and high temperatures. Harsh environmental conditions like high temperature and low moisture affects plants' effector-triggered and pattern-triggered immunities negatively, a condition that render plants susceptible to disease and other pathogenic organisms (Couto & Zipfel, 2016; Velásquez *et al*., 2018). Mukhtar *et al*. (2014) adds that variations in dieback disease prevalence and severity in different agro-ecological zones are as a result of variations in physical environment in these regions.

Temperature and moisture are important factors that influence the activity of pathogens, insects and viruses that causes dieback (Onyeka *et al*., 2008; Mukhtar *et al*., 2014). Soil pH and texture dictates the prevalence and severity of dieback conditions as more alkaline soils with loosely and heavily textured and poorly drained soils have higher (over 85%) prevalence of dieback conditions (Mukhtar *et al*., 2014). This is supported by Turczański *et al*. (2020) and Rousk *et al*. (2009) that high prevalence and severity of dieback conditions is common in soils with pH ranging from 4.5 to 8.3 because such conditions encourages fungal and bacterial growth.

Higher prevalence (75-80%) of dieback in Shisham trees were also experienced along river canals, meaning that high soil moisture and water are causes of high dieback prevalence and severity (Bajwa & Javaid, 2011).

In Kenya, most notable dieback causing fungi among citrus fruits include *Fusarium spp*., *Colletotrichum passiflorae, Alternaria passiflorae* and *Glomerella cingulata* (Amata *et al*., 2009). The presence of these fungi differs from one region to the other depending on the prevailing ecological conditions (Amata *et al*., 2009). However, ecological regions with similar prevailing climatic and edaphic factors are expected to

experience similar dieback incidences and severity. This is supported by Zarafi and Abdulkadir (2013) that the incidences of dieback disease caused by *Fusarium* fungi species on Jatropha did not vary among review months in Samaru. The *Fusarium* fungi were soil borne fungi that invaded roots of Jatropha plants; causing root rot and root necrosis (Zarafi & Abdulkadir, 2013).

In *C. procera,* leaf spot disease caused by *Alternaria altenata* and *Passalora calotropidis* has been proved to be prevalent during the months of January and February with more than 90% disease incidence in India (Mukhtar *et al*., 2013; Kumar & Khurana, 2017). Understanding ecophysiological factors affecting dieback conditions among *C. procera* plants helps in improving its management especially in the changing climate and global warming situation (Tezara *et al*., 2011).

2.7.3. Causes of dieback condition

a) Fungal infection

Fungi causing dieback can be grouped into root-degrading, vascular wilt, stem and branch canker and foliage (Haque, 2015). Due to this diversity of dieback causing fungi on plants, they can survive in different conditions and plant stages. It is on this basis that McKinney *et al*. (2014) concluded that dieback conditions exist at all time of the year even among young stems that may be infected by mature stems in the stand.

Root-degrading fungi are normally soil-borne that upon infection may cause root rot, root necrosis and phloem invasion; hence reducing water uptake ability of the plant that eventually leads to dieback (Davison, 2014). Root decaying fungi may either cause white rot which entails removal of all wood components simultaneously or lignin preferentially in early stages, or brown rot which entail breaking and removal

of cellulose and hemicellulose chains with lignin remaining intact (Allen *et al*., 2010a; Fackler & Schwanninger, 2012). Commonly known root-degrading fungal species include; *Pythium* (*oomycetes*), *Fusarium* (*sordoriomycetes*), *Phytophthora* (*oomycete*), *Armillaria* (*agaricomycetes*) and *Macrophomia* (*Dothideomycete*) (Wangungu *et al*., 2011b; Zarafi & Abdulkadir, 2013; Souli *et al*., 2014).

Vascular wilts are soil borne pathogens that infect woody plants through roots as they enter xylem where they proliferate and block water and mineral transportation (Heimann & Worf, 1999; Yadeta *et al*., 2013). This blockage ends up leaving leaves to wilt and eventually die (Agrios, 2005; Yadeta *et al*., 2013). The symptoms of vascular wilt include drooping leaves and branches, fading of leaves to yellow then brown before dying in case of severe infestation usually in spring (Allen *et al.,* 2010a). Most common genera within this group are *Fusarium ceratocystis* and *verticilium* all belonging to sordariomycete class that have been found to cause vegetation decline and mortality (Bal *et al*., 2013; Triki *et al*., 2011). Though vascular wilt in *C. procera* is yet to be determined, its incidence may be low because the plant has high extracts that significantly reduce wilt incidences by inhibiting fungal growth (Mukhtar, 2007).

Branch and stem canker pathogens like *Apiosporina morbosa* and members of Botryosphaeriaceae family are known to form distinctive black galls on stems and branches by encircling stems and eventually killing all living portions of plant phloem (Edwards, 2001; Mehl *et al*., 2013). In *C. procera*, *Puccinia oblique*, *Puccinia concrescens* and *Passalora calotropidis* causes lesions that may lead to the formation of large witches' brooms often causing gross distortions of infected branches (Barreto *et al*., 1999; Mukhtar *et al*., 2013). However, the presence of *Puccinia oblique, Puccinia concrescens* and *Passalora calotropidis* fungi are more prevalent in humid

conditions compared to dry conditions; as increase in aridity index reduces the prevalence of the fungi leading to invasive problem of Calotropis in pasture lands (Barreto *et al*., 1999; Mukhtar *et al*., 2013).

Foliage fungi include: *Phomopsis, Alternaria, Ascochyta, Blumeriella*, *Cercospora, Colletotrichum, Entomosporium*, *Guignardia, Septoria*, *Mycosphaerella, Venturia, Phyllosticta, Tubakia* and *Gnomoni* (Douglas, 2012; Janis, 2015). The fungi cause abnormal bunching and discoloration of foliage thus resulting to dieback, stunted growth and in severe condition death especially in spring when new growth is still wet (Mahadevakumar & Janardhana, 2016; Janis, 2015). In *C. procera,* leaf spot and necrotic lesion conditions caused by *Alternaria altenata, Passolora calotropidis* and *Collectotrichum* has been proved to be prevalent in wasteland with disease incidence of more than 90% (Gautam, 2014; Kumar & Khurana, 2017). *Uncinula necator*, *Phaeoramularia calotropidis, Phaeoramularia* sp, *Ascochyta tripolitana, Phoma calotropidis, Cladosporium calotropidis, Leveillula taurica,* and *Mycosphaerella calotropidis* are also known to cause dieback on *C. procera* through powdery mildew disease that causes leaf distortion mainly during rainy season (Barreto *et al*., 1999; Talgo *et al*., 2011; Korekar & Chavan, 2015).

b) Insect infestation

Insect infestation significantly affects tree mortality when subjected to severe conditions like frost, drought, and poor soils among others (Zeleznik *et al*., 2005; Perrette *et al*., 2014). Insects causing dieback can be classified based on the mode through which the insect damages the plant, including: sucking plant sap, tunnelling plant bark and wood, defoliation and vector transmission (Allen *et al*., 2010a).

Sap-sucking insects feed by sucking sugary sap produced by plants in foliage and transported to other plant parts through soft phloem tissues beneath plant bark (Allen *et al*., 2010a). Through piercing and sucking, insects may affect plant hormones leading to distinctive foliage and deformation (Rongai & Cerato, 1996; Nguyen *et al*., 2016). Despite the toxic latex within *C. procera* sap, the shrub is susceptible to insects in order Hemiptera (true bugs) and Homoptera (aphids) that damages its leaves causing them to fallout prematurely (Orwa *et al*., 2009; Allen *et al*., 2010a). They are also known to colonize plants at high densities such as over 100 individuals per leaf, hence weakening plants and impacting negatively on flowering and seed production (Borders & Lee-Mader, 2014).

Insects that tunnel barks and woods like Ash/lilac borer (*Podosesia syringae*), bark beetles and Bronze birch borer (*Agrilus anxius*) feed beneath the bark by making tunnels; hence damaging the food and water transporting tissues (Zeleznik *et al*., 2005). Defoliating insects like blister beetles **(***Epicauta* spp.), leaf beetles, cankerworm (*Paleacrita vernata* and *Alsophila pometaria*) and caterpillars on the other hand feed on plant leaves, causing defoliation of plants and other stress that render the plant susceptible to secondary attack by other insects or lowering the tree's ability to respire and photosynthesize (Baughman *et al*., 2009; Montecchio & Faccoli, 2014; Stursova *et al*., 2014). Boxelder twig borer (*Proteoteras* sp.) especially in the larvae stage skeletonizes the leaf as they bore into shoot, a condition that may lead to death of branches or entire plant (Zeleznik *et al*., 2005).

Vector transmission insects transmit disease causing vectors over long distances as they move from one infected plant carrying disease causing vectors like pitch canker to uninfected plant that they feed on (Allen *et al*., 2010a). In calotropis, aphids like *Aphis gossypii* are important vectors of both persistent and non-persistent viruses that

cause plant diseases like cucumber mosaic among other viral diseases (Borders & Lee-Mader, 2014). The honeydew excreted by aphids on *C. procera* also encourages the growth of sooty mould fungus, whose accumulation on leaves, stems or branches interfere with plant growth as it hinders light absorption for photosynthesis (Borders & Lee-Mader, 2014).

c) Abiotic factors

Dieback conditions may be caused by extreme abiotic factors like drought and high temperatures that interfere with normal functioning of the plant (Kennelly *et al*., 2012). Drought refers to a prolonged period of dryness without rainfall leading to extensive damage to plants (Funari *et al*., 2012). Plants experience hydraulic failure during severe droughts with high temperatures, low humidity and low moisture content; making them to lose more water through transpiration (Sevanto *et al*., 2014; Vose *et al*., 2016). This condition creates a high xylem water tension that progressively results to cavitation and conductivity loss of the xylem: restricting water uptake to the canopy, a condition that may lead to leaf wilting, scorching or marginal leaf necrosis and premature fall of leaves (Kennelly *et al*., 2012; Brunner *et al*., 2015).

Drought also induces carbon starvation due to hydraulic failure that affects stomatal closure (Sevanto *et al*., 2014; Vose *et al*., 2016). Coupling carbon starvation and hydraulic failure causes water stress, a factor that inhibits sugar transportation in phloem and hindering carbohydrate utilization (Sevanto *et al*., 2014; Brunner *et al*., 2015). This condition weaken plants to a level that they start dying from the crown, or renders the plant weak and susceptible to attack by insects and fungi among other pathogen (McDowell *et al*., 2008).

High temperatures experienced during drought conditions may lead to dieback and mortality symptoms (Brouwers *et al*., 2013). The common symptoms associated with high temperature stress include foliage scorch, shoot tip dieback and bark scorch that are also linked with water deficit due to high temperatures (Marer, 2006; Haque, 2015; Allen *et al*., 2010b).

Although *C. procera* grows profusely and survives well under drought conditions (Ibrahim, 2013), severe drought conditions leads to water deficit that makes *C. procera* to reduce photosynthetic apparatus through leaf shedding to minimize water loss through transpiration (Moustafa & Sarah, 2017). Shedding of leaves may affect flowering and fruiting of plants. According to Singh and Kushwaha (2006) and Omondi *et al*. (2016), plant phenological features like flowering and fruiting correlate positively with leafing.

2.8. Factors Affecting Plant Growth and Development

Plant growth and development is affected by abiotic, biotic, and edaphic factors (Jureková & Dražić, 2011).

2.8.1. Abiotic factors

Abiotic factors are environmental or non-living factors that influence growth and regeneration of plants (Jureková & Dražić, 2011). They include:

a) Temperature

Environmental temperature is a primary factor influencing plant growth and development as it affects all important growth processes including sprouting, photosynthesis, respiration, transpiration and blossoming (Hasanuzzaman *et al*., 2013; Holding, & Streich, 2013; Hatfield & Prueger, 2015). Different plant species have specific temperature range that best suits its survival and any deviation may

negatively affect plant's growth and development especially at early growth stages (Hatfield & Prueger, 2015). Temperature stress has a wide range of effects on plants in terms of physiology, biochemistry and gene regulations (Bita & Gerata, 2013).

High temperatures leads to high loss of cell water content, which ultimately reduce cell size and eventually cell growth. Morphological systems of high cell water loss in plants include: scorching of leaves and stems, fruit damage, root and shoot growth inhibition, leaf abscission and leaf shedding that eventually causes decrease in plant productivity (Bita & Gerats, 2013; Hasanuzzaman *et al*., 2013; Tomoki *et al*., 2018).

Extreme temperatures limit plant productivity in terms of fruit production due to disruption of pollination process though its magnitude varies among species (Bita & Gerata, 2013). Paradiso and Pascale (2014) found that temperature beyond 26 °C inhibits flowering and fruiting of *Phalaenopsis* spp. but promotes vegetative growth, implying that lower temperatures induces flowering even in immature plants. Lower temperatures on the other hand reduce length of flowers and number of flowers among Phalaenopisis plants (Paradiso & De Pascale, 2014). However, the devastating impacts of high temperatures are mostly felt during droughts, when rainfall and soil moisture are very low (Raza *et al.*, 2019). This concurs with Moore and Lauenroth (2017) that an interaction between precipitation and temperature shift the flowering and fruiting dates of over 21 shortgrass steppe species. Extreme conditions delay flowering and fruiting while favourable conditions were found to be shortening temporal variations in flowering and fruiting. Therefore, plants phenology requires optimal temperature and moisture (Moore *et al*., 2015)

Photosynthetic abilities of plants are greatly influenced by temperature stresses through alteration of enzyme activities, electron transport and leaf temperature which

affect conductance of stomata (Amedie, 2013; Hasanuzzaman *et al*., 2013). Temperatures also affect the closure and opening of stomata that eventually affects photosynthesis (Hasanuzzaman *et al*., 2013). This is supported by Kepova *et al*. (2005) that photosynthetic rates reduce by 60% in *Vitis vinifera* leaves when temperature increase from 25 °C to 45 °C due to reduction in stomatal closure by 15% to 30%. Lower temperatures increases plant injuries as it provide favourable environment for invasion of diseases and insects that may lead to high mortality rates (Haferkamp, 1988; Work & Mills, 2015).

Although *C. procera* is adapted to ASAL conditions, it strives well in average annual temperatures ranging from 20°C to 30°C but not tolerant to frost (Hassan *et al*., 2015). The growth rate increases with temperature to an optimum level of about 30 °C, but flowering starts early in Summer under mild temperature and stops before the arrival of highest temperatures of about 50 °C in countries like Saudi Arabia (Sobrinho *et al*., 2013; Yassin *et al*., 2016). Therefore, establishing optimal temperature that favours flowering and fruiting is crucial as temperatures affect ovule and pollen viability, pollinator visitation, and mediates flower and fruit development (Kooi *et al*., 2019). Therefore, understanding thermal ecology of species' phenology is very crucial.

b) Rainfall

Rainfall provides water, an important compound that all living organisms including plants require for growth (Haferkamp, 1988; Podlesny & Podlesna, 2011). Different plant species respond differently to water stresses a condition that occurs when water supply to the roots is insufficient as a result of drought and increased levels of soil salinity (Seyed *et al*., 2012; Knox County Master Gardeners, 2014). Most functions of plant growth depend on water such that water deficit leads to damage of the plant

cells that later on affects its growth, causing wilting, leaf scorch and eventually root damage, leaf drop and death (Haferkamp, 1988; Schutzki & Cregg, 2007). Severe water stresses reduces leaf area and causes stomatal closure that reduces the rate of photosynthesis and ability of plants to produce sugars necessary for plant growth; hence reducing their growth rates (Schutzki & Cregg, 2007; Basu *et al*., 2016).

In some species like *Salix* spp., water deficit lowers the ability of the plant to resist diseases, pests or weeds (Jureková & Dražić, 2011). Prolonged droughts also lead to hydraulic failure due to closure of stomata, leading to carbon starvation and eventually high mortality rates and low survival rates especially among seedling (McDowell *et al*., 2008). On the other hand, excess water reduces the availability of oxygen in the soil causing root damage thus making the plant susceptible to fungal disease (Paranjape *et al*., 2015). Therefore, plants require optimal amounts of water to survive.

According to Podlesny and Podlesna (2011), the amount of rainfall and its distribution had strong impact on development of morphological characteristics on Apple and Quince Rootstocks. For instance, severe water stress decreases shoot length, diameter, reduction in budding, and changes in leaf colour and size (Podlesny & Podlesna, 2011; Bolat *et al*., 2014). During dry seasons, plants indicate little growth with very few flowering and seed production compared to wet seasons that plants experience indeterminate growth with large amounts of seedlings (Basu *et al*., 2016). This may be explained by reduced energy production necessary for flowering and seedling formation (Schutzki & Cregg, 2007; Basu *et al*., 2016).

Calotropis procera grows well in desert conditions with rapid adjustments to water availability and loss, making it to have an exceptional ability to adapt and reproduce

within such unfavourable arid conditions (Ramadan *et al*., 2014). The species belong to a C_3 metabolism plant and according to Rivas *et al*. (2017) and Rivas *et al*. (2020) *Calotropis procera* indicated decreased CO_2 assimilation during the day in rainy seasons while on the other hand photosynthetic performance under prolonged drought was supported by high CO_2 mesophilic conductance. The plant uses the products of light reactions of photosynthesis, Adenosine triphosphate (ATP) and Nicotinamide adenine dinucleotide phosphate (NADPH) in fixing of atmospheric CO_2 into carbon compounds that are used by other plant metabolic activities (Ranes, 2011). Research carried out under controlled environment showed that *C. procera* survived under water deficit conditions causing more depletion of soil moisture content to 0.98%, reduction in total dry mass of the plant, increased root/shoot ratio about 3-fold, increased leaf shedding by 250%, and reduced chlorophyll content (Ibrahim, 2013). However, the shrub's metabolomics has quick response to water availability (Ramadan *et al.*, 2014).

Excess rainfall results to waterlogging; a condition which occurs when plant roots become saturated as a result of either rising groundwater or surface water that continuously inundates (Ahmed *et al*., 2013). Trees and shrubs respond differently to waterlogging conditions depending on the species, health and site (Baughman, 2012). During growing seasons some trees and shrubs can withstand short periods of flooding, but continuous saturation of soils with water leads to root decay and inhibit the ability of roots to absorb oxygen and nutrients such as iron, potassium and nitrogen (Davison, 2014; Kreuzwieser & Rennenberg, 2014). Inadequate nutrients cause leaf spotting, discoloration and dropping (Marer, 2006).

Flooding increases and reduces the pH of acid and alkaline soils respectively, which affects the normal functioning of the tree or shrub in general (Parolin & Wittmann,

2010; Baughman, 2012). This is because the plant functions normally in a specific range of soil and water pH, below or beyond the range the plant stops functioning, leading to death (Baughman, 2012).

Flood stressed trees and shrubs exhibit a number of symptoms including leaf chlorosis and defoliation, premature coloration and shading of leaves and dying of branches; a condition that can be regarded to as crown dieback (Baughman, 2012). Waterlogging conditions also creates favourable conditions for fungi growth, making the plant more susceptible to dieback conditions resulting from fungal diseases (Marer, 2006). The dieback symptoms may progress gradually and result to plant death over a long period of time, or may recover from the stress if conditions change (Nishiuchi *et al*., 2012; Baughman, 2012).

In a research conducted in a greenhouse, waterlogging conditions induce leaf shading in *C. procera* as a result of hormonal disorder and limited energy resulting from soil oxygen deprivation (Tezara *et al*., 2011; Ibrahim, 2013).

c) Wind speed and intensity

Wind tends to have both negative and positive impacts on plant reproductive development (Saúco, 1993; Young *et al*., 2018). This is because wind affects plant growth, reproduction, distribution, death and evolution of plants as it carries particles such as pollen, plant propagules, disease causing organisms and gas molecules like CO_2 and pollutants from one place to the other (Nobel, 1981; Onoda & Anten, 2011). High wind results to thinner layer of air boundary making the leaf to get closer to air temperature; a phenomenon that influence convection of sensible heat and latent heat loss through leaves (Anten *et al*., 2010). High wind speed and intensity hinders flowering and fruiting on branches which are constantly exposed to their action due to

scorching and sudden drop of flowers and fruits (Saúco, 1993). Strong winds also lowers the chances of flower fertilization by making flowers unattractive to potential pollinators through desiccation of flowers (Young *et al*., 2018).

Spatial patterns of litter dispersal are also influenced by wind making them to accumulate in wind protected regions or at the base of shrubs in desert ecosystem making such sites favourable for seedling establishment (Nobel, 1981). Pollination and seed dispersal are factors that have been influenced by wind to ensure regeneration and growth of plants in different ecosystems (Nobel, 1981; Knox County Master Gardeners, 2014).

Other effects include leaf tearing and removal, leaf folding, lodging, shorter vegetation with more xeromorphic leaves and wind-throw as a result of increased transpiration and water stress (Smith & Ennos, 2003). High turbulence resulting from high wind speed creates transpiration and vapour deficit on leaves and increases fruit fall (Bock & Graham, 2010; Burgess *et al*., 2016). This condition leads to low turgor pressure in leave cells, leading to reduced leaf size and eventually reduction in photosynthesis rates.

Leaf morphology and anatomy are also affected by wind speed during their growth and development stages. Wind speed at 15 ms^{-1} showed lower stomatal conductance on maize leaves as well as 10% decrease in leaf length (DLangre, 2008; Onoda & Anten, 2011). Moreover, branches, stems and trunks of trees have also been observed swept to the direction of wind whereby the plant secondary cell wall is entrained in a particular wind direction forming stem curvature that results from single meristem (Cleugh *et al.,* 1998). In *C. procera*, Hassan *et al*. (2015) established that wind plays an important role in seed dispersal.

d) Relative humidity

Relative humidity refers to the ratio of the actual amount of water vapour content to the amount of water vapour content saturated at a given temperature and pressure and is always high around the equatorial regions that experience high evaporation (Hardwick *et al*., 2015: Lonagre & Patil, 2017).

Relative humidity has direct influence on plant growth in terms of water relations and indirectly influences leaf growth, food manufacture, pollination, disease occurrence and eventually economic yield (Lonagre & Patil, 2017). Since leaf growth occurs upon a physical process of cell enlargement as a result of turgor pressure developed within cells, high relative humidity result to high turgor pressure due to low transpiration thus causing increase in leaf enlargement. Low relative humidity on the other hand affect photosynthesis process by increasing transpiration that leads to water deficit causing stomata to close partially or fully and increase mesophyll resistance that blocks carbon dioxide entry (Chater *et al*., 2014). In high relative humidity, pollen from the anthers may not be dispersed, insect pests (aphids) and disease incidence (blight disease) is high since high relative humidity favours germination of fungal spores on plant leaves (Shemahonge, 2013).

2.8.2. Biotic factors

Biotic factors refer to both macro and micro-organisms that are living in nature affecting growth and development of plants (Orcutt & Nilsen, 2000).

a) Micro-organisms

Micro-organisms like bacteria stimulate plant growth through different forms such as nutrient solubilization and mobilization in soils, production of plant growth regulators, protection against phytopathogens, soil structure improvement and

recovery of polluted soils (Ahemad, 2012; Maheshwari *et al*., 2013). Bacterial species including *Rhizobacteria*, *Rhizobium*, *Bradyrhizobium*, *Mesorhizobium* and non-symbiotic bacteria like *Pseudomonas*, *Bacillus*, *Azotobacter*, and *Azospirillum* play an important role in nutrient cycling in soils and soil fertility (Orcutt & Nilsen, 2000; Hakeem *et al*., 2016). However, bacteria like *Pseudomonas* and *Xanthomonas* cause plant infections like leaf spot, wilts, scabs, cankers and blights among others that may slow plant growth, cause dieback or death in severe occasions (Orcutt & Nilsen, 2000; Pandey *et al*., 2017). Leaf spot appear on leaves blossoms, fruits and stems that may cause necrosis. Canker infections appear on stems, trunks, twigs and branches as canker, gum exudation or sour odour (Schultz, 2006).

Fungi are other group of important decomposers and are particularly prevalent in most soils especially those characterized by low soil pH (Orcutt & Nilsen, 2000). Mycorrhizal fungi form a network of fine filaments around rooting system of plants so as to increase surface area for water and nutrient uptake by plants and releasing enzymes that allows break down and penetration of substrates (Bongard, 2012; Kaur *et al*., 2014). Non-pathogenic fungi have a symbiotic relation with vascular plants that provide carbohydrates and organic substances like vitamins that sustain fungi; fungi on the other hand increases absorption abilities of plant roots by aiding in acquisition of nutrients and water (Orcutt & Nilsen, 2000). This benefit enhances plant regeneration and survival, improved drought tolerance, enhance flowering and fruiting, increased tolerance to salinity and reduced occurrence of diseases (Mohammadi *et al*., 2011; Bongard, 2012). However, mycorrhizal under saline conditions inhibit transfer of sodium ions and chlorine ions to the shoots (Mohammadi *et al*., 2011). Pathogenic fungi on the other hand causes general or localized infections like leaf spot, dieback, anthracnose, canker, damping off, and

scab among others (Mahadevakumar & Janardhana, 2016; Janis, 2015). Most distinctive features of fungal infections include hyphae, mycelia, pores and fruiting bodies (Schultz, 2006).

Some other microorganisms affecting plant growth and regeneration include actinomycetes and nematodes (Orcutt & Nilsen, 2000). Actinomycetes are free-living saprophytes mostly found in arid and semi-arid environments where soil pH is high and low soil water content (Orcutt & Nilsen, 2000; Jiao *et al*., 2016). Some like *Grampus griseus* actinomycetes have antifungal properties that protect their hosts from fungal diseases, while others like *Frankia* spp. contribute to the nitrogen fixing (Orcutt & Nilsen, 2000). Nematodes are wormlike micro-organisms that can be found in almost all habitats with some species like *Steinernema* spp. being beneficial in the decomposition of organic matter and attacking insects among other disease causing pathogens (Ladner *et al*., 2008). Nematodes as soil living micro-organisms lead to plant production biomass increase of +9%, net nitrogen of +25% and net phosphorus of +23% available which is a clear indicator that nematodes connect below and above ground processes through increasing nutrient availability (Gebremikael *et al*., 2016; Groenigen *et al*., 2014).

On *C. procera*, studies like Barreto *et al*. (1999), Talgo *et al*. (2011) and Korekar and Chavan (2015) and Mukhtar (2007) have identified that fungi attack *C. procera*, causing diseases that affect their growth and regeneration. On the other hand, Elmurugan *et al*. (2012) and Begum and Pandey (2017) have established that *C. procera* contains antibacterial, antifungal and antiviral characteristics.

b) Macro-organisms

Insects, birds and animals have both negative and positive impacts to the growth and regeneration of plants by improving soil fertility, acting as pollinators and dispersers, and through herbivory (Orcutt & Nilsen, 2000; Amsberry, 2003; Carson & Schnitzer, 2008). These macro-organisms decompose when dead, contributing significantly to soil fertility and improved soil structure, aeration and water infiltration (Culliney, 2013). Through locomotion, mites and earthworms have been observed to carry saprophytic fungi that enhance soils for plant growth and regeneration (Adriaanse *et al*., 2017).

In terms of herbivores, low level herbivory improves plants' fitness by stimulating compensatory growth, but intense herbivory removes foliage or entire shoot leading to stunted growth, reduce the probability of flowering, number of flowers and leaves on plants and possibly death (Orcutt & Nilsen, 2000; Lehndal & Ågren, 2016). This is because herbivory reduces photosynthetic pigments like leaves and apical parts of stems, rendering less energy for plant growth and regeneration (Goldstein & Santiago, 2016). Herbivores also weaken plant tissues by promoting pathogenic attack, a condition that may inhibit plant growth and reproduction (Orcutt & Nilsen, 2000; Jones, 2014).

Macro-organisms also influence seed dispersal in arid and semi-arid regions, which affect plant distribution (Sekercioglu, 2010; Rotllan-Puig & Traveset, 2015). Dispersion reduces the presence of stems in sub-optimal areas, which may be the determinant for their survival (Rotllan-Puig & Traveset, 2015). Macro-organisms also act as pollinators, shaping the patterns of plant reproduction by either increasing or

decreasing effective pollination that determine the likelihood of fruit and seed formation (Willcox *et al*., 2017).

Plants also pose intra and inter species competition as they share limited resources including light, nutrients and water; leading to a reduction in one or more fitness components either at the individual or population level (Gioria & Osborne, 2014).

2.8.3. Edaphic factors influencing plant growth

a) Soil moisture content

Soil moisture can be improved by increasing soil organic matter, though in small quantities but can sustain growth during periods of low or short rainfall of about 5-10 days (Emerson, 1995). Under severe and prolonged exposure to low soil moisture, plants wilts and die as they can't obtain enough water from soils to meet their demands (Tueche, 2014). Although plants reduce their growth rate under limited soil moisture in general, shoot growth is hit hard compared to root growth (Haferkamp, 1988). Morphologically, high soil moisture content causes major increase in plant height, plant diameter, leaf size, leaf number and flowering (Yáñez-Chávez *et al*., 2014).

Contrary, high soil moisture leads to short supply of oxygen in soils that eventually disturb normal exchange of gasses from roots to soil; hence affecting plant growth and plant survival (Haferkamp, 1988; White & Edwards, 2007). However, plants growing in ASALs have deeper roots, experience seasonal leaf shedding, smaller photosynthetic leaf area, low osmotic potential, and high water utilization efficiency due to limited soil moisture (Tezara *et al*., 2011). Deeper roots enable plants to draw water from deeper soils. However, shallow soils with hard pan hinder deep rooting systems to access soil nutrients and moisture deeper (Leeuwen, 2010; Moustafa &

Sarah, 2017). In *C. procera*, lowest plant density in Brazil were reported in the month of February that experience low temperature and low soil moisture as the two factors constrain the growth of the species (Galal *et al*., 2016).

b) Soil salinity

Soil salinity refers to accumulation of salts in soils to a level that affects plant growth and infrastructure negatively (Hardie & Doyle, 2012). Soil salinity can be measured by evaporating soil water extracts to determine total soluble salts or by determining the electrical conductivity (EC) of distilled water: soil dilution ratio (1:5) or a saturated paste extract (Hardie & Doyle, 2012). Saline soils are those with EC of the saturation extract in the root zone exceeding $4dSm^{-1}$, approximately 40 mM NaCl at 25 °C and have an exchangeable sodium of 15% (Shrivastava & Kumar, 2015).

Arid and semi-arid soils are prone to salinity as aresult of high soil surface evaporation and transpiration, weathering of native rocks and low precipitation (Hussain *et al*., 2019). Soil salinity limits plant growth in arid and semi-arid regions where high soil salinity creates osmotic and nutritional imbalance by reducing the process of nutrient cycling thus limiting growth of plants (Dmuchowski *et al*., 2011; Zhang *et al*., 2017). It also causes water stresses in the root zone as water molecules get held tightly by salt ions (Gould, 2013; Parnes, 2013; Hussain *et al*., 2019). This condition makes it difficult for plant roots to absorb adequate water for normal plant functioning thus affecting plant growth (Parnes, 2013). Soil degradation has been realised as a result of high salinity in soil since high concentration of sodium ions attaches themselves to soil particles displacing other soil elements like potassium and phosphorus (Gould, 2013). This situation leads to leaf burn, leaf shed and twig die-back among other symptoms thus inhibiting plant growth (Gould, 2013; Gupta &

Huang, 2014). The effects of soil salinity on plants vary within and between species. For instance, *C. procera* is tolerant to high saline conditions (Yassin *et al*., 2016; Moustafa & Sarah, 2017), and has been considered to use avoidance and tolerance mechanism as ways of response to salinity stress (Ibrahim, 2013).

c) Soil chemical properties

For plant growth, roots obtain nutrients from soil chemical elements and compounds like calcium (Ca), potassium (K), magnesium (Mg), nitrogen (N), sulphur (S), phosphorus (P), organic carbon (OC) sodium (Na), chlorine (Cl) among others at optimal soil pH (Kieran, 2006; Stirling *et al*., 2016). These soil properties vary within and between regions and even at different soil horizons depending on prevailing parent rocks, land use, leaching levels and nutrient management practices (Rani *et al*., 2015; Nadir *et al*., 2018). Dinesh *et al*. (2019) and Rani *et al*. (2015) established that nature of parent rocks, topography and land use were significantly contributing to spatial variations in soil pH, OC, N, P, K, boron (B) zinc (Zn) and EC in ASALs.

Soil pH refers to the acidic and alkalinity properties of the soil ranging from 0-14, where values less than 7, equal to 7 and greater than 7 depicts acidic, neutral and alkaline soils respectively (Kieran, 2006). pH values that are in decreasing order increases solubility of plant micro-nutrients such as iron (Fe), copper (Cu), manganese (Mn) aluminium (Al) and zinc (Zn) that leads to deficiency of nutrients such as Ca, Mg, P and K (Long *et al*., 2009; Villalobos & Fereres, 2016). Such antagonistic reactions and interactions may lead to stunted growth, dieback conditions and poor reproduction (Bal *et al*., 2014).

Deficiencies of K and N in plants causes scorching of leaf margins and chlorosis especially on older leaves, slow growth rates due to slowed photosynthesis, lower

resistance to diseases and smaller seeds and fruits (Hopkins & Huner, 2009; Heidari & Mohammad, 2012). Potassium helps in maintaining ion homeostasis, osmotic pressure and enhances antioxidants defence in plants; hence inducing plants abiotic stress tolerance (Hasanuzzaman *et al*., 2018). According to Teixeira *et al*. (2011), application of potassium fertilizer improves fruits sizes and yield in pineapples in environmentally stressed conditions.

Adequate K and N absorption also helps in synthesizing sugars and other compounds that act as food to disease causing pathogens, hence increasing disease resistance (Heidari & Mohammad, 2012; Marschner, 2012; Cruz *et al*., 2017). In their study, Vose *et al*. (1994) established that pine plantations in soils deficient in N and OC have smaller leaf area index compared to pines in N and OC rich environment. This is because optimal provision of N, OC and P enhance development of active photosynthetic pigments by increasing stromal, thylakoid proteins in chloroplast; which enhances leaf development (Razaq *et al*., 2017). Availability of N and K increases photosynthesis rates which ensure availability of energy and carbohydrates for growth, development and quality reproduction in terms of fruit sizes and fertility (Bustan *et al*., 2011; Fischer *et al*., 2012; Guo *et al*., 2019). Deficiency in Ca, Mg, N and K may lead to slow growth rates of plant shoot and leaves, loss of colour between leaf veins shrivelled or aborted fruits, and crop stunting due to low rates of photosynthesis (Hopkins & Huner, 2009).

At pH values less than 5.5, Mn, Zn and Al nutrient solubility increases and becomes toxic in excess to a level that they may affect some plants negatively by impairing root growth thus reducing the ability of roots to grow through acidic subsurface soil (Villalobos & Fereres, 2016; Stirling *et al*., 2016). An increase in soil pH may also be as a result of increased exchangeable basic cations like K and Ca; hence affecting the

soil's EC (Mucheru-Muna *et al*., 2007; Iwuagwu *et al*., 2019). However, a decrease in pH reduces availability of available P as it becomes insoluble Fe and Al minerals that can either be toxic to plants or cannot be absorbed by plants (Weil & Brad, 2017). Erel *et al.* (2016) established that deficiency in available P reduces the fertility of plant's male and female reproductive organs, leading to aborted flowers and fruits in olive trees.

In addition, microbial activities in soils decrease as a result of extreme pH values affecting processes such as organic matter decomposition, biological N fixation and nitrification (Villalobos & Fereres, 2016). Soil pH also affects physical properties of soils. According to Villalobos and Fereres (2016), soils that are considered to be acidic normally have poor physical properties like poor soil structure or poor permeability. Based on various reactions and interactions of soil physical, mechanical and chemical properties, understanding the effects of soil properties on crops and plants requires a holistic approach that encompasses all properties (Szili-Kovács *et al*., 2011).

Although Galal *et al*. (2016) determined chemical properties in areas occupied by *C. procera* in Brazil; authors did not determine how such properties were affecting growth and regeneration of the species. Unavailability of this information makes it difficult to determine which chemical soil elements may enhance growth and regeneration of *C. procera* if cultivated on farms.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Study Sites

The study was conducted in the semi-arid regions of Tharaka and Makueni in the Eastern part of Kenya as shown in figure 3.1 and figure 3.2 respectively. The two regions lie in the agro-climatic and eco-climatic zone V, which is characterized by low and unreliable rainfall, dispersed population, marginal agricultural lands and infertile soils (Pratt & Gwynne, 1977). The two study sites were proposed by ICRAF due to availability of collaborating partners.

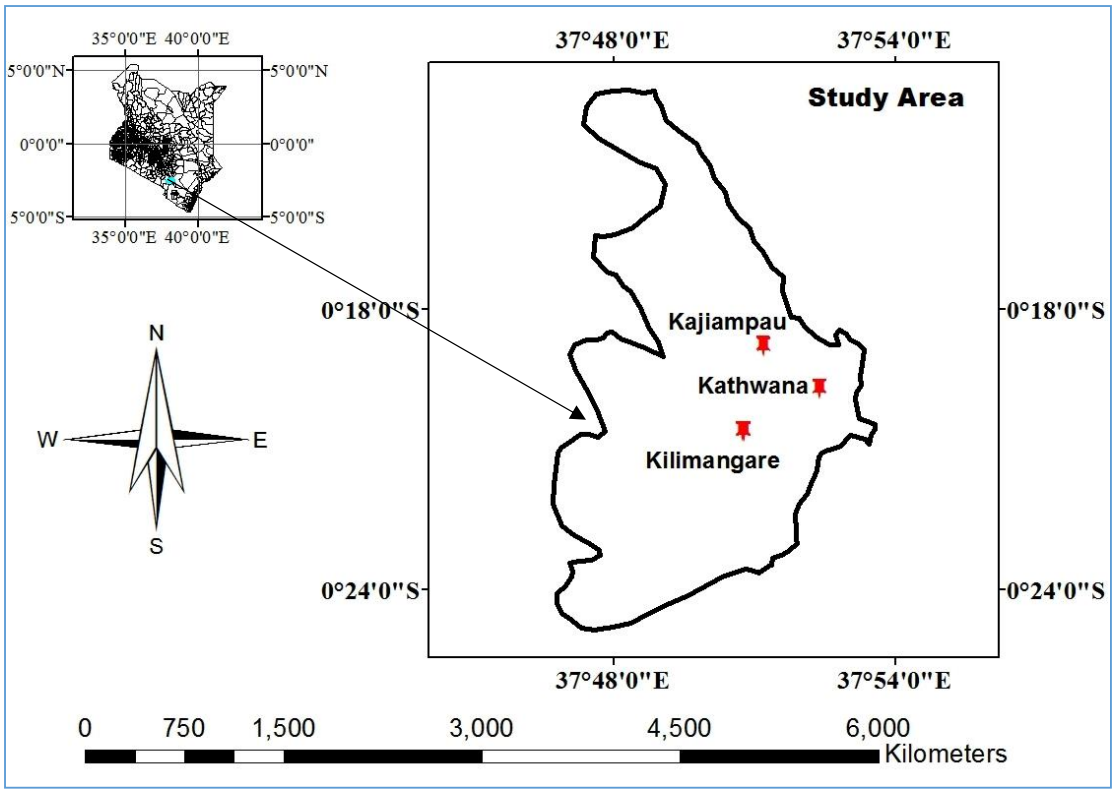

Figure 3.1: The Map Showing Study Sites in Tharaka Region

(Source: Author, 2018)

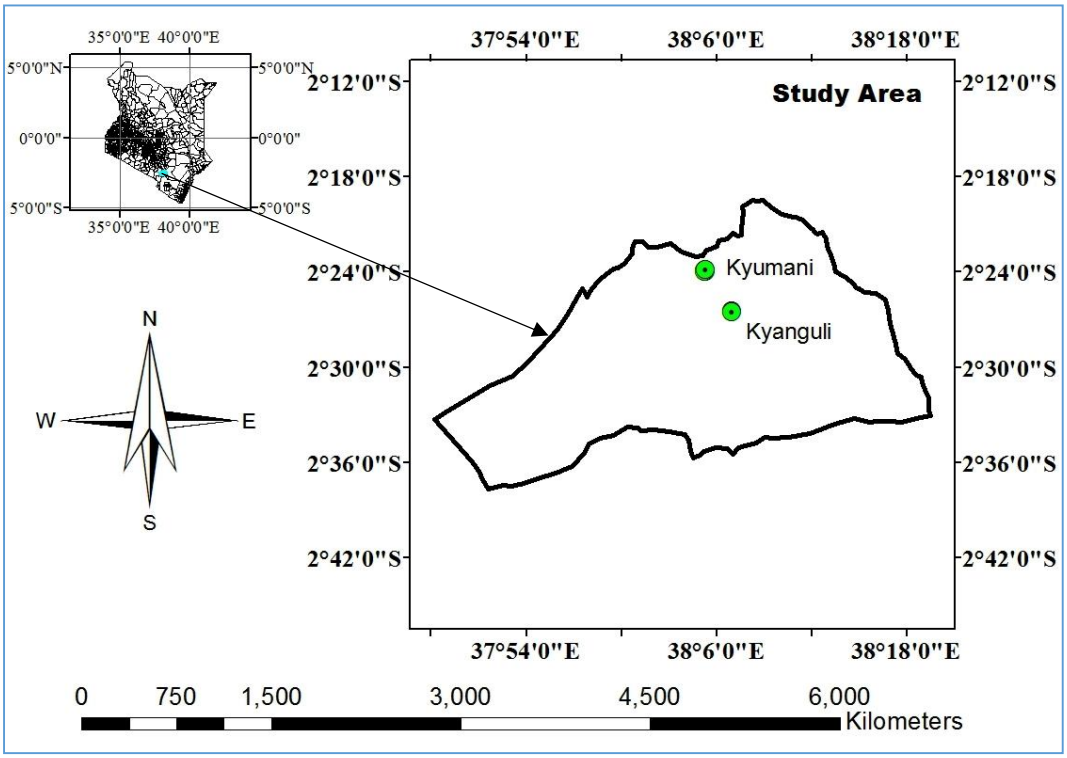

Figure 3.2: The Map showing Study Sites in Makueni Region

(Source: Author, 2018)

3.1.1. Semi-arid region of Tharaka

According to the Ministry of Agriculture, Livestock and Fisheries (MoALF) (2017), the semi-arid region of Tharaka covers about 2,662.1 km^2 and is located between latitudes 00° 07' and 00° 26' South and Longitudes 37° 19' and 37° 46' East. The region's altitude ranges from 5,000 m asl in Chuka and Maara to as low as 600 m asl in the eastern parts. Mt. Kenya forest covering about 360 km^2 in Tharaka is the main physical feature (Tharaka Nithi County Government, 2018).

The region has five major hills including Munuguni, Njuguni, Ntugi, Kijege and Kiera with high soil erosion due to hilly terrains (Tharaka Nithi County, 2012). The topography of Tharaka is highly influenced by Mt. Kenya volcanic activities, which have created V-shaped valleys that form the origin of River Tana tributaries like Thuci, Naka and Mara among others. Other rivers that transverse the region include Mutonga, Kathika and Ura among others. Such rivers provide water for irrigation

especially in lowlands with moderate forest cover (Tharaka Nithi County, 2013). The region has varied vegetation cover as a result of altitude variation. The vegetation in high elevated areas comprises of deciduous montane forest trees like "Croton-Brachylaena, Calodendrum, mixed *Podocarpus latifolius*, Newtonia and Croton-Premna forests" (Kathambi, 2020). The low land areas on the other hand have dry forest vegetation characterized by shrubs and trees like Combretum, Acacia, Commiphora and Sanseviera (Wisner, 1977).

The study was specifically conducted in the lower parts of Tharaka, mainly Kathwana, Kilimangare and Kajiampau located between latitudes (0.32869S, 37.87315E; 0.34344S, 37.84633E and 0.31355S, 37.85316E) respectively. These low lands experience varied, unreliable and poorly distributed bimodal rains of about 500 mm annually with longer rains in April to June and shorter rains in October to December (MoALF, 2017; Tharaka Nithi County Government, 2012). The low lands of Tharaka experience high temperatures ranging from 22 °C to 39 °C with some days experiencing over 40 °C (Tharaka Nithi County Government, 2013).

Low land areas are sparsely populated with a population density of 150 persons/km^2, low population growth rate of 1.8% and over 13.6% of the population aged below 5 years compared to 5.2% aged above 64 years. The region's poverty level is over 40%, majority of them depending on livestock farming, honey production, cassava, millet and sorghum farming (Tharaka Nithi County Government, 2018).

3.1.2. Semi-arid region of Makueni

The semi-arid region of Makueni covers approximately 8,034.7 km^2 and lies on Latitude 1° 35' and 3° 00' South, and Longitudes 37° 10' and 38° 30' East (Makueni County, 2013). The region's major physical features include hills like Chyulu,

Mbooni, Kilungu and Iuani hills. Apart from hilly areas, the rest of the region's terrain is generally low-lying at an altitude of 600 m asl. Athi River is the main perennial river fed by seven tributaries, namely Kaiti, Kambu, Thwake, Kikuu, Kiboko, Muuoni and Mtito Andei that provide opportunities for small- and large-scale irrigation (Government of Makueni County, 2018). Tsavo national park located on the eastern part of Makueni provides greater opportunity for tourism in the region (Makueni County, 2013).

The region's vegetation cover is influenced by altitude, climate and soil pattern variations. In uplands, the presence of moderate rains and sandy loam volcanic soils have led to the presence of vibrant vegetation cover compared to lowland areas with poor soils and depressed rains that allow stunted growth vegetation. The natural vegetation in the low land regions consist of vast stretches of indigeneous savanna grasslands, scattered acacia and other shrubbery (County Government of Makueni, 2018). The main species in the lowland regions include: Themeda, Balanites, Acacia, Commiphora and Sanseviera trees and shrubs (Rotich *et al*., 2018).

The study was conducted in the low lands of Makueni in Kyumani and Kyanguli that lies between latitudes (2.39901S, 38.08776E and 2.44212S, 38.11551E) respectively. The two regions have an elevation of of aproximatly 600 m asl and receive bimodal rainfall ranging from 250 mm to 400 mm annually in April to June and from October to December (Mengich *et al*., 2013; MoALF, 2016). The low lands also experience high temperatures of up-to 35.8 °C (MoALF, 2016; Government of Makueni County, 2018). Anthropogenic activities like cultivation on riparian, overgrazing, charcoal production and encroachment have made the situation worse (Makueni County, 2013).

Low land regions of Makueni experience a human population growth rate of 1.4% with about 14.3% of the population aged below 5 years compared to 1.8% above 80 years. The population is sparsely distributed with a population density of 115 persons per km^2. The region's high poverty level of about 60.6% is as a result of low income, high levels of unemployment, and low agricultural productivity (Makueni County, 2016).

3.2. Research Design

The study used a mixture of mixed repeated measure and factorial research designs. Mixed repeated measure research design entails multiple measurements of dependent variables on the same subjects or objects or matched subjects or objects under different conditions or over a period of time (Kraska, 2010). In this regard, repeated measures were taken on the same *C. procera* stems in the semi-arid regions of Tharaka and Makueni four times from June 2018 to April 2020. This was considered appropriate because it enabled assessment of dependent variables at different weather seasons over time.

Factorial research design entails establishing the main and interaction effects between more than two independent variables with each variable measured at more than two levels and a continuous response variable. For example, in this case, the three independent variables were: regions (Tharaka and Makueni), soil depth [at (0-20) and (20-40)] cm and research time point [(Jun-Aug) 2018, (Mar-May) 2019, (Nov-Sept) 2019, and (Feb-April) 2020.

3.3. Sampling Techniques and Sample Size Determination

3.3.1. Selection of study sites

The study entailed an inventory of farms with naturally growing *C. procera* in the semi-arid regions of Tharaka and Makueni in Eastern Kenya. Tharaka and Makueni were selected using purposive sampling technique based on availability of prospective ICRAF collaborating partners. In each region, purposive sampling technique was used in choosing farms (blocks) containing naturally growing *C. procera*. This is because the selected farms were only those whose owners voluntarily accepted research to be conducted in their farms. Using this criterion, three blocks (Kathwana, Kilimangare and Kajiampau) were selected in Tharaka and three blocks (Kyumani, Kabiyani and Kyanguli) were selected in Makueni. However, during the second phase of data collection in Makueni, researchers were denied entry to Kabiyani block (farm), the farm was therefore dropped.

3.3.2. Selection, number and development of main- and sub- plots

Simple random sampling technique was used in marking (20 x 20) m permanent main plots in each block using blue galvanized iron pipes. This entailed creating polygons of selected farms by digitizing their boundaries using Google map. The polygons were then opened using QGIS software to give files geographical correction projection and convert the farm's polygons to shape files, and then relevant attributes like name of the farm were added. Shapefiles were opened on Geospatial Modelling Environment (GME) software, which enabled addition of information to the layout like the number of random points required and through command; the software generated random numbers in the boundaries of the shapefiles. The new shape file with random points was again opened using QGIS software to identify the coordinates

of the points, and additional unique identifiers to randomly generated points like point 1 (P1), point 2 (P2) and point 3 (P3) all the way to the last point (Figure 3.3 and Figure 3.4). The points were then transferred from the computer to Global Positioning System (GPS) using DNR software.

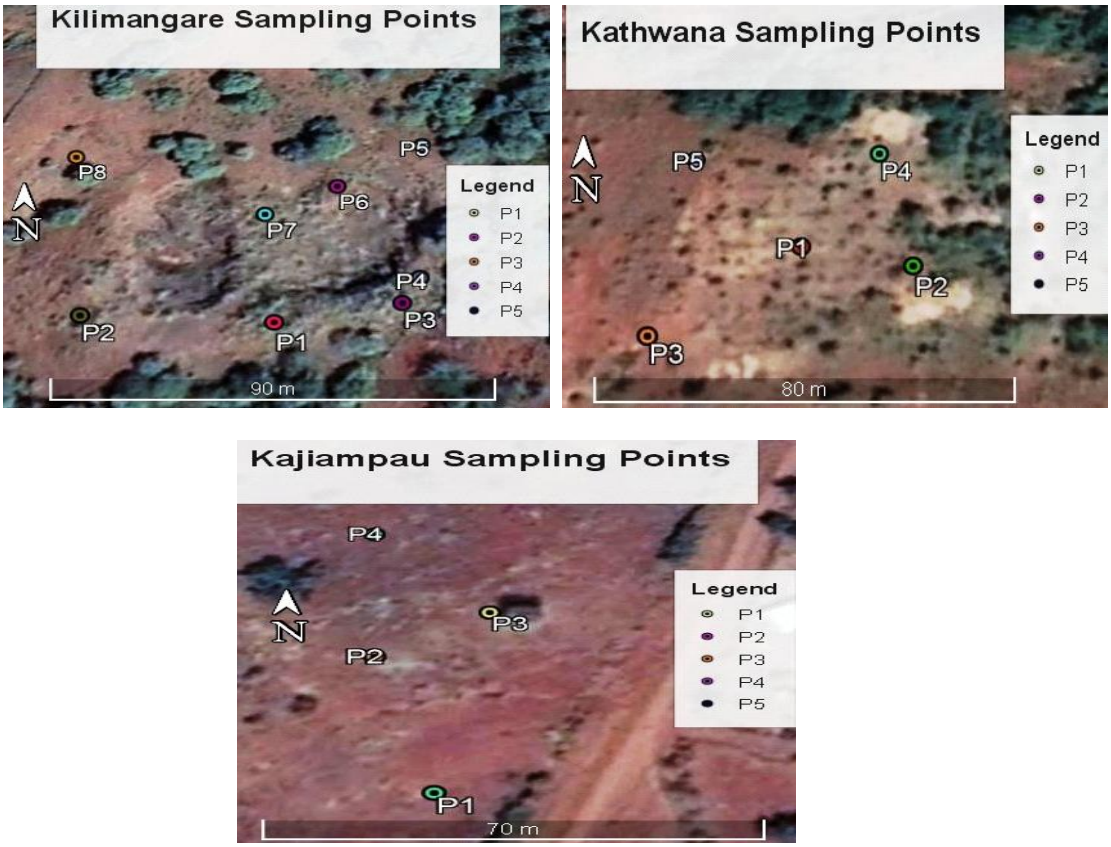

Figure 3.3: Randomly Generated Centre Points in Tharaka

(Source: Author, 2018)

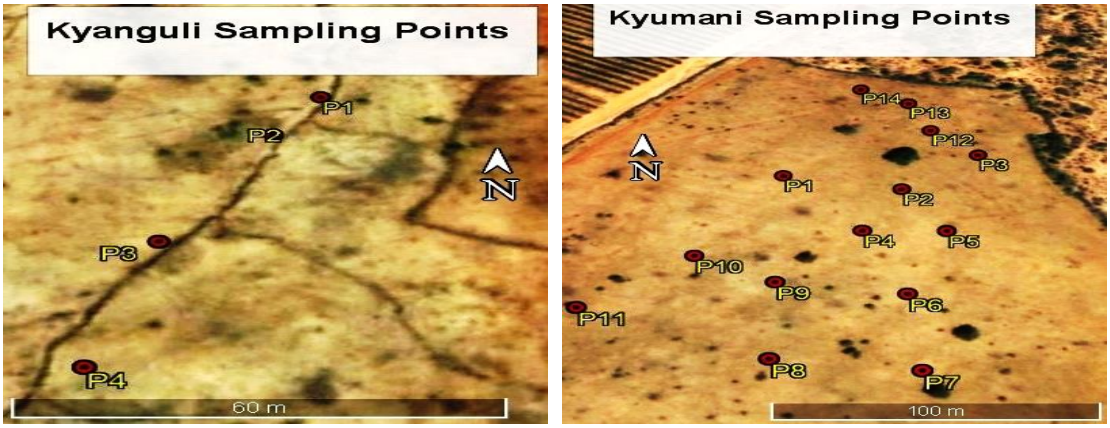

Figure 3.4: Randomly Generated Centre Points in Makueni

(Source: Author, 2018)

The GPS was used to identify each point in the field with coordinates used as the centre of the main plots. Square plots were used because they are easy to set up using a tape, easy to set corners and boarders (Curtis & Marshall, 2015). A total of 14, 4, 5, 8 and 4 permanent main plots were marked in Kyumani, kyanguli, Kathwana, Kilimangare and Kajiampau respectively. For subsequent data collection, plots were identified using coordinates in GPS gadget.

In each main permanent plot, permanent sub-plots measuring (5 x 5) m were marked using white painted galvanized iron pipes. Systematic random sampling technique was used in selecting sub-plots to be included in the study; where every third sub-plot was included in the sample. The total number of permanent sub-plots included in the study was calculated using equation 3.1 (Ralph *et al*., 2002).

$$\boldsymbol{n = \log\alpha / \log p \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}}$$

Where

n = Sample size

α = permitted error (0.05 correspond with 95% confidence level)

p = proportion of subplots estimated as having a particular characteristics, in this cases *C. procera*. Since it was not known, it was estimated at 50% (0.5) as recommended by Ralph *et al*. (2002).

As a result, the number of sub-plots in each plot was computed as:

$$\boldsymbol{n = \log 0.05 / \log 0.5}$$

$$= 4.32 \text{ plots} \approx 5 \text{ plots}$$

Calotropis procera stems present in each main plot at the initial stage of data collection (June-August) 2018 were identified, marked with a number and included in the sample. Marking was important as successive measurements were to be taken on

the same stems. Since *C. procera* were growing on stumps, guidelines set by Muchiri *et al.* (2016) were used to differentiate stems and branches. In this case, stems were individuals sprouting below 15 cm on a stump from the ground. Therefore, sprouts above 15 cm from the ground were considered as branches on a stem. After developing main plots and selecting sub-plots, sampling techniques and sample sizes varied between and within objective as follows.

3.3.3. Sampling technique for edaphic conditions in Tharaka and Makueni

Systematic random sampling technique was used in selecting one point where a pit was dug in each of the selected sub-plot at every research time point. In the first phase, a point was randomly selected; the point was them marked to avoid picking the same point in the successive phases. In the subsequent research phases, a pit was dug after every 2 m from the preceding point in each of the selected sub-plots. Soil samples from all sub-plots in the main plot were then mixed to form plot's composite soil. From each composite soil one sample was picked for soil chemical analysis.

3.3.4. Sampling technique for morphological characteristics of *C. procera*

a). Sampling of leaves and fruits for modelling leaf surface area and fruit volume

In developing leaf surface area and fruit volume allometric equations, 5 stumps were selected in each block (Nizinski & Saugier, 1988; Blanco & Folegatti, 2003). Systematic random sampling technique was used to select every 5^{th} stump in each block. In case there were less than 5 stumps in the block, all stumps in the block were included in the sample. For leaf surface area modeling, 10 leaves of different sizes without distortions as advised by Morris *et al*. (1996) were randomly selected and plucked from each of the selected stump.

For fruit volume modeling, 5 fruits of different sizes (Arellano-Durán *et al*., 2018) were randomly selected from each stump. In case there were less than five fruits on a stump, then all fruits were harvested.

b). Sampling of leaves and fruits for surface area and volume estimation

After developing allometric equations, individual parameters to predict leaf surface area fruit volume were assessed in selected sub-plots (5 x 5) m. In measuring leaf length and width, leaves were sampled according to Xu *et al*. (2009), where 15 leaves were selected based on simple random sampling technique from each shrub. In case the shrub had less than 15 leaves, then all leaves on the stem were selected.

Sampling of fruits was done according to Houédjissin *et al.* (2015), where 10 fruits from each fruiting stem in the selected sub-plots were sampled based on simple random sampling. In case the stem had less than 10 fruits, then all fruits were selected.

3.3.5. Sampling for population distribution and phenology of *C. procera*

a) Population distribution of *C. procera*

All *C. procera* stems that were present in each main plot and were marked during plot development were included in the sample for population distribution.

b) Phenology of *C. procera*

All *C. procera* stems in selected sub-plots were included in the sample.

3.3.6. Dieback condition

All *C. procera* stems in selected sub-plots were included in the sample to determine the dieback prevalence and severity.

In establishing the dieback causative agents, the sample size of infected cuttings from infected stems in each main plot was estimated based on Ralph *et al*. (2002) (Equation 3.2) expressed as:

$$\boldsymbol{n = \log\alpha/\log p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(3.2)}$$

Where n, α and p remains as defined in equation 1.

Therefore, the sample size was: $\boldsymbol{n = \log 0.05/\log 0.5}$ = 4.32 ≈ 5 cuttings per main plot.

The cuttings were made on stems indicating dieback condition based on systematic random sampling technique where every 4th stem was included in the sample to ensure a larger representation. In case there were less than four stems, then all the stems in the plot indicating dieback conditions were included in the sample. The cutting samples selected per plot were based on equation 3.2. In the event that the cuttings per plot were less than 5, then all cuttings were selected. Samples from all plots in a block were mixed to form a composite sample. From each composite, a sample, whose size was calculated according to Daniel (1999) (equation 3.3) was selected.

$$\boldsymbol{n = \frac{Z^2 P(1-P)}{d^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(3.3)}$$

Where:

n = sample size,

Z = Z statistic for the level of confidence, in this the Z statistic was 1.96, corresponding to 95% level of confidence,

P = expected prevalence of the condition under investigation, in this case dieback. Since it was unknown, Ralph *et al*. (2002) proposes 0.5,

d = precision, which according to Naing *et al*. (2006) is P/2, in this case d= 0.5/2 = 0.25.

Therefore, the total number of cuttings that were taken to the lab for analysis from each block's composite sample was:

$$n = \frac{1.96^2 \times 0.5 \times (1-0.5)}{0.25^2} = 15.37 \approx 16 \text{ cuttings from each block}$$

In case the composite comprised less than 16 cuttings, then all cuttings from that block were taken to the laboratory. In selecting the 16 cuttings, all the cuttings were laid on the ground and every 2nd cutting selected.

3.4. Field and Laboratory Data Collection Procedures

Data was collected four times in (June-August) 2018, (March – May) 2019, (September – November) 2019 and (February – April) 2020. This was based on temporal replicates to determine the behaviour of *C. procera* at different time points.

3.4.1. Edaphic characteristics in Tharaka and Makueni

Soil pits were dug at selected points to collect soil samples at (0-20) cm and (20-40) cm depth. The composite samples were then packed in sampling bags of about 2000g. The sample bags were clearly labelled i.e. sampling date, depth and block for sample identification purposes and taken to KEFRI laboratory for analysis. Soil samples were air- dried, ground and passed through a 2 mm sieve to obtain fine soil sample for soil chemical analysis. Sample preparation and analysis of soil pH, EC, N, OC, Mg, P, Na, Ca and K were conducted according to Okalebo *et al*. (2002) and the procedures were as follows.

a). Soil pH and EC determination

A soil sample of 20g from soil composite from the field was weighed and transferred to 300 ml sample plastic shaking bottle. Distilled water measuring 50 ml was added and the mixture stirred on mechanical shaker for 30 minutes to disperse the hydrogen

ions from the soil colloids. It was then removed and allowed to settle for 10 minutes and pH of the soil suspension was potentiometrically measured using pH meter. For EC measurement, the mixture was allowed to settle for 15 minutes and reading made using conductivity meter. The procedure was repeated for other soil samples.

b). Total nitrogen

A sample of 0.3 g of oven dried (70 ^{o}C) soil sieved through (< 0.25 mm, 60 mesh) was weighed and transferred into labelled, dry and clean digestion tubes into which 4.4 ml of digestion mixture comprising of 14 g of lithium sulphate and 0.42 g of selenium powder was added to each tube and the reagent blanks for each batch of samples. The samples were then subjected to heat in digestion block at 330 ^{o}C for 2 hours until colourless solution and remaining sand white was achieved. The content was allowed to cool for digestion process. About 25 ml of distilled water was added and the contents mixed well until no more sediment dissolves. The mixture was further allowed to cool and the solution made up to 50 ml with distilled water. The sample digest was then subjected to further quantitative analysis.

A sample of 1 ml of set N standard series and sample digest was pippeted and transferred into clean well labelled test tubes. Into each test tube, 9 ml of distilled water was added to make an aliquot solution of 10 ml from which 0.2 of the aliquot solution was pipetted and transferred into another set of clean and well labelled test tube. Starting with standards, 5 ml of reagent N1 followed by 5 ml of reagent N2 were added in each sample plus the blanks respectively and the solution vortexed. The contents were allowed to stand for 2 hours until a stable green colour was formed. Total nitrogen was calorimetrically determined using the UV spectrophotometer at a

wavelength of 450 nm. The calibration curve for the standards was obtained for calculation of unknown concentration of N in the samples.

The concentration of N in the fresh soil sample expressed in percent (%) was calculated according to (equation 3.4).

$$\% \text{ N in soil} = \frac{(a-b)\times 0.1\times v\times 100}{1000\times w\times al} \quad \text{.....(3.4)}$$

where a = Absorbance for sample; b = absorbance for the blank; v = final volume of the digestion; w = fresh weight of the sample taken; al = aliquot of the solution taken for analysis.

c). Soil ogarnic carbon

This was determined based on Walkely Black method. A sample of 0.1 to 0.4 g of ground (60 mesh) soil sample was weighed and transferred into 400 ml conical flask. Potassium dichromate measuring 10 ml was added to the soil sample and the blank samples followed by 20 ml of conc. H_2SO_4. The mixture was then swirled carefully under a fumed hood and the content left to stand for 2 hours for complete oxidation after which 5 ml of 5 M orthophospheric acid was added. The mixture was then placed on a mechanical stirrer where 10 ml of carbon indicator was added and the mixture (unused potassium dichromate) was titrated against ferrous ammonium sulphate. The volume of Ferous solution used at the end point (colour change from brown to jungle green) of titration was then recorded. Soil organic carbon was calculated according to (equation 3.5).

Organic carbon (%) = $\frac{T \times 0.2 \times 10/AvBlk}{Wt}$ **.....(3.5)**

Where:

T = Titre value (Vb-Vs)

0.2 = Average amount of organic carbon in the soil

10 = Volume of potassium dichromate added

AvBlk = Average volume of the titter value of blank sample

Wt = Weight of the soil sample taken

Vb = Volume of the blank after titration,

Vs = Volume of $[FeSO_4(NH_4)2].2\ H_2O$ used for sample titration.

d). Soil exchangeable Mg, Ca, K and Na determination procedure

A sample of 5 g of air dry soil (< 2 mm) was weighed and transferred into plastic bottle with a stopper. Ammonium acetate solution (pH 7) measuring 100 ml of 1 M (NH_4OAc) was added. The content was shaken for 1 hour and filtered through Whatman paper No. 42. This formed the soil extract A that was used for Na, K, Ca and Mg determination. The procedure was repeated for other soil samples. Soil solution A measuring 5 ml was pippeted into a 50 ml volumetric flask into which 1 ml of 26.8 % lanthanum chloride solution was added with a set of standard series and the solution was diluted up to the mark by addition of 1 M NH_4OAc (Ammonium acetate) extraction solution. The solution was sprayed into the flame of Atomic absorption spectrometer (AAS 5000 series) and atomised for determination of Na, Ca and K measurement.

Soil extract A was diluted 25 times for magnesium determination. To make this dilution, 2 ml of the soil extract solution A was pipetted into a 50 ml volumetric flask

into which 5 ml of 5000 ppm Sr as $SrCl_2$ (strontium chloride) was added to the solution plus a series of standards and the solution diluted up to the mark filled up with 1 M NH_4OAc (Ammonium acetate) extracting solution. The solution was sprayed into the flame of the atomic absorption spectrophotometer at absorbance equivalent to Mg and concentration recorded in parts per million (ppm).

e). Available phosphorus

This was determined based on Olsen method (Olsen & Sommers, 1982). A sample of 2.5 g of air-dry (2 mm) soil was weighed and transferred into 250 ml polythene shaking bottle and 50 ml of the Olsen's extracting solution (0.5 M 42 $NaHCO_3$, pH 8.5) added to each bottle. The bottles were tightly closed using a stopper and placed on a mechanical shaker for 30 minutes. The suspension solution was then filtered after shaking through the Whatman No. 42. This filtrate was used for the colorimetric P measurement.

A set of P starndard solution series and 10 ml of the sample filtrates and 2 reagent blank were pipetted into 50 ml volumetric flasks into which 5 ml of 0.8 M boric acid was added to each flask. Beginning with the standards and blanks, 10 ml of the ascorbic acid reagent was added to each flask. The solution was filled to the 50 ml mark with distilled water. The content was closed using a stopper, well shaken and left to stand for 1 hour after which the absorbance/transmittance of the solution at a wavelength setting of 880 nm was quantified using UV spectrophotometer. The calibration curve of P standards was also obtained for calculation of unknown concentration of P in the samples. Concentration of P (ppm) was calculated according to (equation 3.6).

$$\textbf{P (ppm) in soil} = \frac{(a-b)\times v\times f\times 1000}{1000\times w} \quad \textbf{(3.6)}$$

where a = concentration of P in the sample; b = concentration P in the blank; v = volume of the extracting solution; f = dilution factor; w = weight of the soil sample.

The results obtained were recorded in data collection sheet 1 (Appendix 1).

3.4.2. Weather conditions in Tharaka and Makueni

Data on weather conditions including average monthly rainfall (mm/month), temperatures (^{o}C/month), wind speed (m/s) and relative humidity (%) were obtained from National Aeronautics and Space Administration (NASA) satellite (NASA, 2019; NASA, 2020) using geographical coordinates of study sites and data recorded in data collection sheet 2 (Appendix I).

Data on weather conditions was collected in the periods preceding field data collection, that is in (January – June) 2018 preceding (June – August), (July 2018– March 2019) preceding (March – May) 2019, (April - September) 2019 preceding (September – November) 2019 and (October 2019 – February 2020) preceding (February – April) 2020.

3.4.3. Morphological characteristics of *C. procera*

Morphological features of *C. procera* were determined by estimating and observing leaf surface area, leaf colour and fruit volume. For developing allometric equations, destructive method was used to pluck selected leaves whose length and width was measured and surface area was determined using graph paper method (Pandey & Singh, 2011).

Leaf length was measured from the petiole (B) to the tip (A) while the breadth was measured at the largest point of the leaf's width (F to G) (Figure 3.5), using a Vanier

calliper. Leaf surface area was estimated using allometric equations developed. This information was recorded in data collection sheet 3 (Appendix I) where leaf surface area was categorized into 5 classes [<50, (50-<100), (100-<150), (150-<200) and ≥ 200] cm^2.

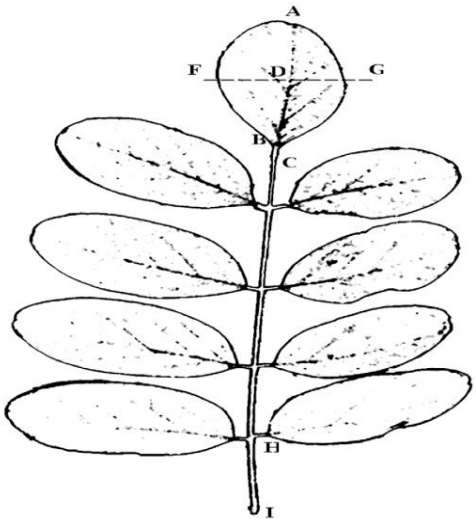

Figure 3.5: Illustrated Diagram of Leaf Measurement
(Source: Xu *et al*., 2009)

For developing fruit volume allometric equations, destructive method was used to pluck selected fruits whose length and average diameter was measured using a Vanier calliper. Fruit volume was estimated using WDM. Fruit length was measured from the stalk to the stamen. Average fruit diameter was the average of perpendicular and diagonal fruit diameters taken at the largest point of a fruit. Data was recorded in data collection sheet 4 (Appendix I) and fruit volume established using allometric equation. The volumes were categorized into 4 classes [<100, (100-<200), (200-<300) and ≥ 300] cm^3.

3.4.4. Population distribution of *C. procera* in terms of size distribution

Size classification was determined using shrubs'total height, average crown diameter and root collar diameters as described by Galal *et al*. (2016) and Okereke *et al*. (2015)

as fundamental parameters of tree size classification. Total height of *C. procera* stems was mainly measured using graduated pole. However, in case of taller stems, the suunto was used. The information was recorded in data collection sheet 5 (Appendix I) and categorized in 4 classes of [<1.5, (1.5-<3), (3-<4.5) and ≥4.5] m.

The average crown diameter of *C. procera* stems were calculated using two measurements from two paerpendicular points in a single stem using a steel tape. The steel tape was used to avoid stretching as advised by Powell (2005). The measurements of crown diameter were done from perpendicular points like East-West (EW) and North-South (NS) directions through the centre of the shrub pole as described by Popescu *et al*. (2003). The crown diameter (CD) was therefore calculated as in equation 3.7.

$$\mathbf{CD} = \frac{(\boldsymbol{EW}+\boldsymbol{NS})}{\mathbf{2}} \quad \textbf{..... (3.7)}$$

The information was recorded in data collection sheet 4 (Appendix I) and results classified into four size classes of [<40, (40-<80), (80-<120) and ≥ 120] cm.

Diameter tape was used to measure the root collar diameter (2 cm from the ground) of *C. procera* stems and data recorded in data collection sheet 5 (Appendix I). The results were classified into 3 diameter size classes of [<4, (4-<8), and ≥] 8 cm.

3.4.5. Phenology of *C. procera* in Tharaka and Makueni

Phenology of *C. procera* was estimated using activity index, number of flowers and fruits, and phenophase intensity. Flower and fruit activity index entailed recording total number of stems in a sub-plot, counting the number of stems with either flowers or fruits and recording them in data collection sheet 6 (Appendix I). Flower and fruit

activity indices (AIs) were estimated as indicated in equations 3.8 and 3.9 respectively.

$$\textbf{Flower AI} = \frac{\textbf{nfl}}{N} \text{ ..... (3.8)}$$

$$\textbf{Fruit AI} = \frac{\textbf{nfr}}{N} \text{ ..... (3.9)}$$

Where: nfl, nfr and N mean total number of *Calotropis procera* stems with flowers in a subplot, total number of *Calotropis procera* stems with fruits in a sub-plot and total number of *Calotropis procera* in sub-plot respectively.

Number of flowers and fruits (ripe or green) entailed physical counting of flowers and fruits on each flowering and or fruiting *C. procera* stems respectively in each sub-plot. The information was recorded in data collection sheet 7 (Appendix I).

Flowering and fruiting phenophase intensity entailed counting and recording the total number of branches on a flowering and or fruiting stem, and the total number of branches with flowers or fruits and recorded in data collection sheet 7 (Appendix I). Phenophase intensity (Pi) were determined by dividing number of branches with flowers (bf_l) or fruits (bf_r) with total number of branches on an individual stem (b) (equations 3.10 and 3.11) (Sobrinho *et al*., 2013).

$$Pi_{fl} = (\frac{bf_l}{b}) * 100 \text{ ..... (3.10)}$$

$$Pi_{fr} = (\frac{bf_r}{b}) \text{ x } 100 \text{ ..... (3.11)}$$

Where:

Pi_{fr} and Pi_{fl} - phenophase intensity for fruits and flowers respectively

b_{fl} and b_{fr} - the number of branches on an individual tree with fruits and flowers respectively

b: total number of branches on a tree

3.4.6. Dieback conditions on *C. procera* in Tharaka and Makueni

a) Prevalence and severity of dieback disease on *C. procera*

The prevalence of dieback was determined according to Ezeibekwe (2011). This entailed complete enumeration of *C. procera* stems in selected sub-plots and those exhibiting symptoms and signs of dieback (shoots, branches or leaf margins) counted and recorded in data collection sheet 8 (Appendix I). Prevalence was calculated using equation 3.12.

$$P = \frac{I}{N} \times 100\% \text{ ..... (3.12)}$$

Where: P = prevalence, I= the total number of infected stems of *Calotropis procera* in each sub-plot, and N = total number of stems in each sub-plot.

Dieback severity was determined based on 0-5 severity scale as explained by Ezeibekwe (2011) and Wangungu *et al*. (2011a). The scale was based on symptoms of the disease as observed, where; 0 = healthy shrub and no symptoms of the disease, 1 = 5% of the shrub showing dieback of shoots, 2 = 25% of the crown showing dieback, 3 = 50% of the shrub showing dieback of bigger branches, 4 = 65% of the shrub

showing severe shoot dieback, 5 = >65% shows very severe shoot dieback. Every marked *C. procera* stem in a sub-plot was evaluated to determine the percentage of the affected part and data recorded in data collection sheet 9 (Appendix I). The number of shrubs in each scale were counted using the percentages and used to calculate sub-plot severity index (Equation 3.13) expressed as;

$$\boldsymbol{SPsi} = \frac{(\mathbf{0}*\mathbf{a})+(\mathbf{1}*\mathbf{b})+(\mathbf{2}*\mathbf{c})+(\mathbf{3}*\mathbf{d})+(\mathbf{4}*\mathbf{e})+(\mathbf{5}*\mathbf{f})}{\mathbf{N}} \quad \textbf{..... (3.13)}$$

Where:

SPsi = sub-plot severity index; Numbers 0, 1, 2, 3, 4 and 5 = scales of severity; Alphabets a, b, c, d, e; and f = number of stems examined in each category of severity; N = total number of *Calotropis procera* stems assessed in a sub-plot.

b) Causative agent of dieback diseases in *C. procera*

The selected cuttings were taken to KEFRI pathology laboratory to establish dieback causing agents as explained by von Arx (1981) and Agrios (2005). A nutrient media (Malt Extract Agar at 2%) was prepared in six conical flasks. Malt extract weighing 25 g and 5 g of agar were put in each flask. Distilled water was added to 500 Ml in each flask. The flasks were corked using cotton wool and autoclaved at 121 °C for 20 minutes. It was then allowed to cool to 81 °C and the autoclave opened to remove the media. In each flask, 25 drops of streptomycin was added to prevent against bacteria. The media was transferred to the sterilized Petri dishes and allowed to cool.

On each cutting from the field, twelve pieces of *C. procera* were chopped from sections of the samples across living and dead tissues and sterilized using hydrogen peroxide for a period of 1 minute. Samples were rinsed three times using distilled water to remove excess hydrogen peroxide and then transferred to the filter paper

using forceps for the purpose of blotting dry. Samples were then taken to the isolation hood for drying after which plating was done such that each sample had 3 plates with 4 replicates in each plate.

Incubation was done at 23 $^{\circ}$C and after 3 days, part of the fruiting body developing on the nutrient media were sub-cultured and taken back to the incubator for further growth. After 14 days, spores had formed. The sporulated areas were scratched with clean inoculating needle and placed on a slide for observation under a dissecting microscope to identify the dieback causative agent and data recorded in data collection sheet 10 (Appendix I). The causative agents were identified based on their morphology using taxonomic keys for ascomycetes and imperfect fungi and reproductive structures of the isolates (von Arx, 1981; Agrios, 2005; Barnett & Hunter, 2006).

The dominance of each dieback causative agent per sample collected from the field was calculated using equation 3.14.

$$\mathbf{Y = \left(\frac{n}{N}\right) * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.14)}$$

Where: Y – the dominance of an identified dieback causative agent, n – Frequency of the agent counted on all plates whose specimen was chopped from a sample, N – Total frequency of agents identified on that sample.

3.5. Data Presentation and Analysis

Data were presented as tables, line and bar graphs using Microsoft Excel windows 07 and analysed using Statistical Package for the Social Sciences (SPSS) version 25.

3.5.1. Edaphic and weather conditions in Tharaka and Makueni

Data on edaphic and weather conditions were presented in tables and analyzed using factorial analysis technique. Shapiro-Wilk and Levene's tests were used to test for normality of dependent variable and homogeneity assumptions respectively at α = 0.05 and data sets with $p \geq 0.05$ were reckoned as having met assumptions of normality (O'Neill & Mathews, 2002; Verma, 2015).

A 4*2*2 factorial analysis according to Soni (2003), was used to determine significant differences and interactions in soil chemical properties (soil pH, EC, N, OC, P, K, Mg, Ca and Na) between research time points [(June – August) 2018, (March – May) 2019, (September – November – 2019) and (February – April) 2020] at two soil depths [(0-20) cm and (20-40) cm] between the two semi-arid regions (Tharaka and Makueni). In case of significant differences in soil properties between any variables with more than two factor levels; post-hoc analysis was conducted using Turkey's HSD technique (Salkind, 2010). Correlation analysis was also conducted to establish if there were significant correlations between different soil chemical properties.

A two-way ANOVA was used to determine if there were significant differences in weather conditions (Average monthly rainfall, temperature, wind speed and relative humidity) within the four research time points and between the two semi-arid regions.

3.5.2. Morphological characteristics of *C. procera* in Tharaka and Makueni

Regression analysis was used in developing allometric equations to predict leaf surface area and fruit volume. Model selection was based on Rajchal and Meilby (2013) and Labbafi *et al*. (2019) recommendations that best models have high R, R^2, adj R^2 and low model standard error.

Kruskal Wallis test according to Baïram *et al*. (2019) was used to test statistically significant differences in leaf surface area and fruit volume classes within the research time points. In case of significant difference, pair-wise analysis between each of the time points was conducted using Mann-Whitney *U* test which entails comparing two ordinal or continuous independent variables with normally distributed data (Hazra & Gogtay, 2016). Mann-Whitney *U* test was also used to test significant differences in leaf surface area and fruit volume classes between the semi-arid regions.

3.5.3. Population distribution of *C. procera* based on size classification

Data on size distribution was presented using bar graphs. Friedman test according to Hazra and Gogtay (2016) was used in establishing significant differences in the ordinal repeated measure data of total height, average crown diameter and root collar diameter within the research time points. In case of statistically significant difference ($p<0.05$) Wilcoxon signed-rank test which entails comparison of two independent variables with data that has violated independence and normalcy assumptions (Derrick & White, 2017), was conducted for pair-wise comparison. Wilcoxon signed-rank test as explained by (Hazra & Gogtay, 2016; Derrick & White, 2017) was also used to test significant differences in size distribution classes between the semi-arid regions of Tharaka and Makueni.

3.5.4. Phenology, dieback prevalence and dieback severity

Phenology, dieback prevalence and severity data were presented using line graphs. The assumptions of sphericity and homogeneity of variance were tested using Mauchly's test of sphericity and Levene's test of equality of error variances respectively (Verma, 2015). A two way mixed repeated measure analysis of variance (ANOVA) was used to analyze continuous and repeated phenology (flowering and

fruiting activity indices, number of flowers and fruits, and flowering and fruiting phenophase intensities), dieback prevalence and severity data within the four research time points and between the two semi-arid regions. Research time point was considered as a within-subject variable while semi-arid region was a between-subject variable. Bonferroni test according to Lee and Lee (2018) was used for post-hoc analysis to establish time points with significant differences in phenology, dieback prevalence and severity.

3.5.5. Dieback causative agents

Data on dieback causing agents and their dominance were presented in tables. A 6*4*2 factorial analysis was used to determine significant differences and interactions of 6 levels of dieback causative agents within the four research time points between the 2 semi-arid regions. Despite data on dominance of causative agent meeting homogeneity test and violating normality test, factorial analysis was still interpreted based on F statistics. According to Gotelli and Ellison (2004) as quoted by Kozak (2009), the assumption of normality may be violated in case of a large sample with unequal sample sizes, meaning that it is not restrictive in such cases. In this case, there were 1416 cases that were analyzed and there were evidences of unequal sample sizes in terms of cuttings from the field from time to time as this was affected by number of infected stems in each main plot. In case of significant differences in dominance of dieback causative agents within or between any of the independent variables with more than 2 factor levels; post-hoc analysis was conducted using Turkey's HSD technique (Salkind, 2010).

3.5.6. Edaphic and weather conditions affecting morphological characteristics of *C. procera*

Ordinal regression analysis based on polytomous universal mode (PLUM) as explained by Kavade (2009), was used to establish if associations between ordinal measures of leaf surface area and fruit volume classes with continuous edaphic and weather conditions were significant. Ordinal response variables were leaf surface area and fruit volume classes while edaphic and weather condition variables were covariate response variables. Variables that were not significantly contributing to the model based on effects' test were eliminated from the model list wise until only significant variables remained in the model (Kavade, 2009). This implies that all covariate variables were included in the model during the first instance (level 1) of analysis. In case some covariate variables were not contributing to the model in level 1 analysis, the second level (level 2) analysis was conducted by eliminating such variables list wise. This process of eliminating variables continued until all variables remaining in the model were significantly contributing to the model. The results were interpreted in terms of how a unit increase in predictor was associated with the odds of an ordinal response variable being in a higher class.

3.5.7. Edaphic and weather conditions affecting size distribution of *C. procera*

Ordinal logistic regression based on generalized estimation equation (GEE) as explained by Ballinger (2004), was used to establish relationships between ordinal repeated measures of height, average crown and root collar diameter classes with continuous edaphic and weather conditions. Ordinal logistic regression based on GEE technique was used because of its ability to establish relationships between ordinal repeated measures as response variable and continuous data with unknown

covariance. Stem identity number, block and plot were subject variables while research time point was a within subject variable in the two regions. Response variables were height, average crown and root collar diameter while soil chemical characteristics and weather conditions were covariate predictor variable. The results were interpreted based on how a unit increase or decrease in edaphic and weather variables were associated with the odds of total height, average crown and root collar diameter classes being in a higher class at a given confidence interval based on exponentiated values as explained by Ballinger (2004).

3.5.8. Edaphic and weather conditions affecting activity indices, phenophase intensities, dieback prevalence and severity

Linear regression based on GEE according to Schober and Vetter (2018), was used to establish if there were significant associations between continuous repeated measures of activity indices, phenophase intensities, dieback prevalence and dieback severity with edaphic and weather variables. Linear regression based on GEE was appropriate because dependent variable was measured repeatedly on the same subject, hence failing the independence of observations. For activity index, dieback prevalence and dieback severity, sub-plot, plot and block were between subject variables in the two regions. However, stem number, block and plot were between subject variables when analyzing phenophase intensities. Research time point was within subject variable in all the analysis while covariate predictor variables were edaphic and weather variables. The results were interpreted based on how many times a response variable will increase or decrease as a result of a unit increase or decrease in predictor variables under a given confidence interval using exponentiated values.

3.5.9. Edaphic and weather conditions affecting number of flowers and fruits

Poisson regression based on GEE as explained by Laerd Statistics (2018) was used to establish if there were significant relationships between count repeated measures of number of flowers and fruits on *C. procera* stems with continuous edaphic and weather variables. Research blocks, plot and stem number were between subject variables while research time point was within-subject variables. Number of flowers and fruits were response variables while edaphic and weather variables were predictor variables. Results were interpreted in terms of how many times the response variables will be higher or lower with a unit increase in predictor variable within a given confidence interval based on exponentiated values.

3.5.10. Edaphic and weather conditions affecting dominance of dieback causative agents

Linear regression based on generalized linear model (GLM) was used to establish if there were significant associations between dominance of dieback causing agents with edaphic and weather variables. GLM was used because of its ability to operationalize non-normal data without jeopardizing satisfactory approximation for response distribution (Molenaar & Bolsinova, 2017). Dominance of dieback causative agents was the response variable while edaphic and weather conditions were predictor variables. The results were interpreted in terms of how many times the response variable will increase or reduce per unit increase in predictor variable at a given confidence level.

CHAPTER FOUR

RESULTS

4.1. Edaphic and Weather Conditions in Tharaka and Makueni

4.1.1. Edaphic factors in the semi-arid regions of Tharaka and Makueni

Soil OC content and exchangeable Na at (0-20) cm soil horizon were 3.0% and 112.5 ppm in Tharaka and 3.08% and 75 ppm in Makueni respectively, compared to 2.92% and 85 ppm in Tharaka and 2.63% and 74 ppm in Makueni respectively at (20-40) cm soil depth (Table 4.1). However, soil pH at (0-20) cm and (20-40) cm soil recorded equal values of 7.3 in Tharaka and 6.8 in Makueni (Table 4.1). Soils from Tharaka recorded higher average soil EC and Na than Makueni at both (0-20) cm and (20-40) cm depth. On the other hand, soils from Makueni recorded higher values of N, P, K, Mg, and Ca at both (0-20) cm and (20-40) cm than soils from Tharaka (Table 4.1). On available P, both soils from Tharaka and Makueni recorded higher values at (0-20) cm and (20-40) cm respectively. On soil depth, soil EC, N, K, Mg and Ca in both Tharaka and Makueni recorded higher values at (20-40) cm than (0-20) cm (Table 4.1).

Shapiro-Wilk and Levene's tests demonstrated that data on soil nutrients from Tharaka and Makueni met the normality and homogeneity assumptions (Appendix IIa and b). Factorial analysis (Appendix IIc) indicated that soil pH ($F_{(1,264)} = 9.269$, $p = 0.003$, $\eta p^2 = 0.034$), EC ($F_{(1,264)} = 5.504$, $p = 0.020$, $\eta p^2 = 0.020$), total N ($F_{(1,264)} = 242.066$, $p < 0.001$, $\eta p^2 = 0.478$), OC content ($F_{(1,264)} = 153.544$, $p<0.001$, $\eta p^2 = 368$), available P ($F_{(1,264)} = 286.703$, $p < 0.001$, $\eta p^2 = 0.521$), exchangeable K ($F_{(1,264)} = 70.473$, $p < 0.001$, $\eta p^2 = 0.211$), exchangeable Mg ($F_{(1,264)} = 27.529$, $p < 0.001$, $\eta p^2 = 0.094$), exchangeable Ca ($F_{(1,264)} = 26.363$, $p < 0.001$, $\eta p^2 = 0.091$) and exchangeable Na ($F_{(1,264)} = 21.271$, $p < 0.001$, $\eta p^2 = 0.076$) were significantly different between the two semi-arid regions of Tharaka and Makueni.

In addition, soil EC ($F_{(1, 264)} = 3.914$, $p = 0.049$, $\eta p^2 = 0.015$), total N ($F_{(1, 264)} = 3.987$, $p=0.047$, $\eta p^2 = 0.015$), exchangeable K ($F_{(1, 264)} = 5.489$, $p = 0.020$, $\eta p^2 = 0.020$), exchangeable Mg ($F_{(1, 264)} = 3.980$, $p = 0.047$, $\eta p^2 = 0.015$) and exchangeable Na ($F_{(1, 264)} = 21.271$, $p < 0.001$, $\eta p^2 = 0.076$) were significantly different between the two soil depths of (0-20) cm and (20-40) cm soil (Appendix IIc).

Table 4.1: Edaphic Conditions in the Semi-arid Regions of Tharaka and Makueni

Soil Property	Soil Depth (cm)	Tharaka					Makueni				
		(Jun-Aug) 2018	(Mar-May) 2019	(Nov-Sept) 2019	(Feb-Apr) 2020	Mean	(Jun-Aug) 2018	(Mar-May)2019	(Nov-Sep) 2019	(Feb-Apr) 2020	Mean
Soil pH	(0-20)	7.2	7.3	7.2	7.3	**7.3**	6.7	6.8	6.8	6.8	**6.8**
	(20-40)	7.2	7.3	7.2	7.4	**7.3**	6.6	6.9	6.7	6.9	**6.8**
Soil conductivity (mS/cm)	(0-20)	0.15	0.11	0.11	0.12	**0.12**	0.09	0.08	0.09	0.09	**0.09**
	(20-40)	0.15	0.14	0.13	0.15	**0.14**	0.11	0.11	0.11	0.12	**0.11**
Nitrogen content (%)	<(0-20)	0.14	0.13	0.15	0.16	**0.15**	0.23	0.26	0.23	0.21	**0.23**
	(20-40)	0.17	0.18	0.17	0.20	**0.18**	0.24	0.28	0.25	0.24	**0.25**
Organic carbon (%)	(0-20)	2.75	3.01	3.24	2.98	**3.00**	3.29	3.25	3.35	2.38	**3.08**
	(20-40)	2.83	2.91	3.12	2.80	**2.92**	3.37	2.29	2.42	2.43	**2.63**
Phosphorus (ppm)	(0-20)	4.53	4.79	4.90	4.90	**4.78**	10.58	10.50	10.71	10.77	**10.64**
	(20-40)	4.66	4.68	5.01	5.02	**4.84**	10.75	10.58	10.84	10.87	**10.76**
Potassium (ppm)	(0-20)	103.56	104.26	122.24	128.73	**118.18**	225.36	212.04	204.16	204.19	**211.44**
	(20-40)	143.08	150.86	134.87	161.12	**147.48**	231.74	225.47	227.01	228.58	**228.20**
Magnesium (ppm)	(0-20)	79.59	81.06	76.35	74.76	**77.76**	105.22	109.17	94.67	105.39	**103.61**
	(20-40)	93.12	89.41	81.88	87.06	**87.87**	115.06	114.72	105.5	116.72	**113.00**
Calcium (ppm)	(0-20)	1014	1084	1042	1018	**1040**	1333	1443	1220	1369	**1341**
	(20-40)	1198	1178	1040	1102	**1130**	1535	1502	1329	1527	**1473**
Sodium (ppm)	(0-20)	116	114	108	112	**112.5**	77	75	76	77	**75**
	(20-40)	88	87	86	85	**85**	70	72	69	85	**74**

Soil properties tested did not vary significantly within research time points with $p > 0.05$ (Appendix IIc). There were also no significant interactions between research time points with semi-arid region; research time points with soil depth; semi-arid region with soil depth and research time points with semi-arid region and soil depth for all tested nutrients with $p > 0.05$ (Appendix IIc).

Correlation analysis of soil properties (Appendix IId) and outputs summarized in Table 4.2 indicates that there were significant correlations between different soil properties.

There were also evidences of *C. procera* growing in degraded lands with rocks and quarrying that had been done in Tharaka and farmland soil conditions without rocks in Makueni (Plate 4.1).

Plate 4.1: Soil Conditions (a-Evidence of rocks and quarrying in Tharaka, b-Farmland soil conditions in Makueni)
(Source: Author, 2019)

Table 4.2: Summarized Correlation Analysis Output of Soil Properties

	EC At (0-20) cm	N at (0-20) cm	OC at (0-20) cm	P at (0-20) cm	K at (0-20) cm	Mg at (0-20) cm	Ca at (0-20) cm	Na at (0-20) cm	pH at (20-40) cm	EC at (20-40) cm	Nat (20-40) cm	OC at (20-40) cm	P at (20-40) cm	K at (20-40) cm	Mg at (20-40) cm	Ca at (20-40) cm	Na at (20-40) cm
pH at (0-20) cm	*	*	*	n.c	*	*	*	*	*	*	*	n.c	*	*	*	n.c	n.c
EC at (0-20) cm		*	*	*	*	*	*	*	*	*	*	*	*	*	n.c	*	*
N at (0-20) cm			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
OC at (0-20) cm				*	*	*	*	*	*	*	*	*	*	*	*	*	*
P at (0-20) cm					*	*	*	*	*	n.c	*	*	*	*	*	*	*
K at (0-20) cm						*	*	*	n.c	*	*	*	*	*	*	*	*
Mg at (0-20) cm							*	*	*	*	*	n.c	*	n.c	*	*	*
Ca at (0-20) cm								*	*	*	*	*	*	*	*	*	*
Na at (0-20) cm									*	*	*	*	*	*	*	*	*
pH at (20-40) cm										*	*	*	*	*	n.c	n.c	n.c
EC at (20-40) cm											n.c	*	*	*	*	*	n.c
N at (20-40) cm												*	*	*	*	*	*
C at (20-40) cm													*	*	*	*	*
P at (20-40) cm														*	*	*	*
K at (20-40) cm															*	*	n.c
Mg at (20-40) cm																*	*
Ca at (20-40) cm																	*

* = significant correlation, n.c = no significant correlation at 5% probability level

4.1.2. Weather conditions in the semi-arid regions of Tharaka and Makueni

Figure 4.1 indicates that between (January to June) 2018 and (April to September) 2019, average monthly rainfall decreased from 135.44 mm to 45.27 mm in Tharaka and 138.44 mm to 52.55 mm in Makueni respectively. However, there was an increase in average monthly rainfall between (April to September) 2019 and (October 2019 to February 2020) from 45.27 mm to 143.83 mm in Tharaka and 160.37 mm in Makueni.

Contrary to average monthly rainfall trend, average monthly temperature raised from 25.78 °C to 28.15 °C in Tharaka and 24.92 °C to 28.74 °C in Makuni between (January to June) 2018 and (April to September) 2019. There was a slight decline in average monthly temperature from 28.15 °C to 25.58 °C in Tharaka and from 28.74 °C to 26.07 °C) in Makueni between (April to September) 2019 and (October 2019 to February 2020) (Figure 4.1)

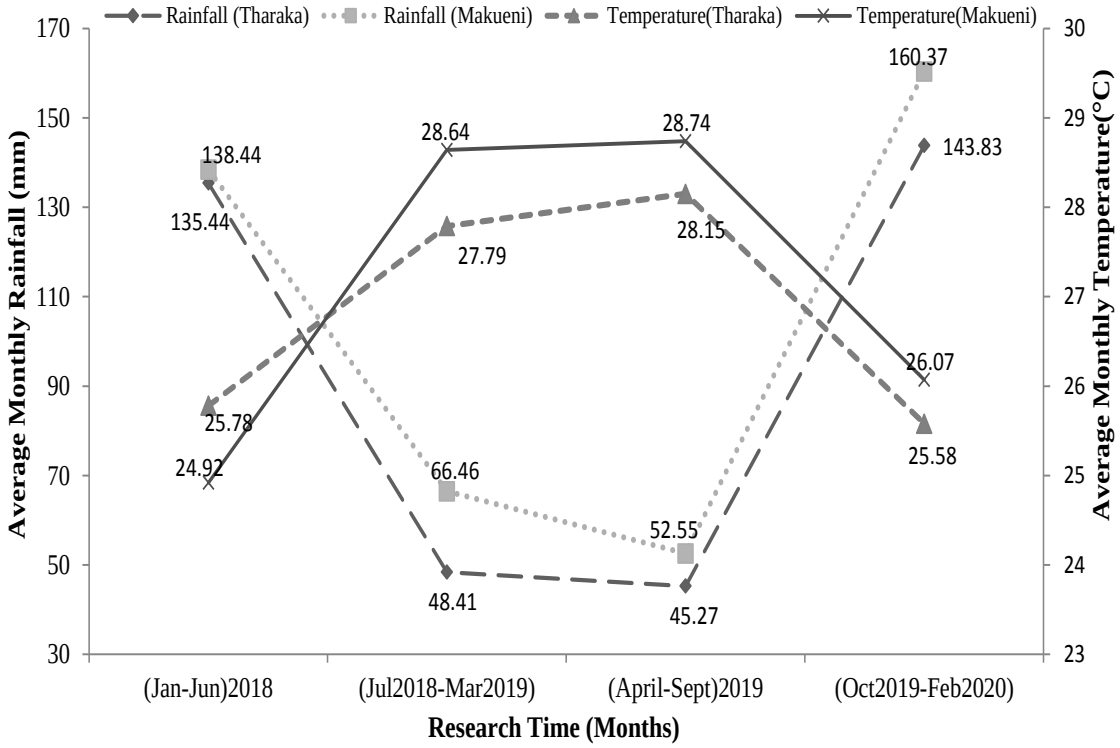

Figure 4.1: Average Monthly Rainfall and Temperature in Tharaka and Makueni

Figure 4.2 indicates that average monthly relative humidity decreased from 69.07% to 60.42% in Tharaka and from 66.89% to 61.52% in Makueni from (Junaury to June) 2018 to (April to September) 2019). Over the same period, wind speed increased from 2.9 m/s to 3.6 m/s in Tharaka and 2.12 m/s to 3.07 m/s in Makueni. However, there was an increase in average monthly relative humidity from 60.42% to 76.11% in Tharaka and from 61.52% to 70.18% in Makueni between (April to September) 2019 and (October 2019 to February 2019). Over the same time, average monthly wind speed decreased from 3.6 m/s to 2.86 m/s in Tharaka and 3.07 m/s to 2.23 m/s in Makueni.

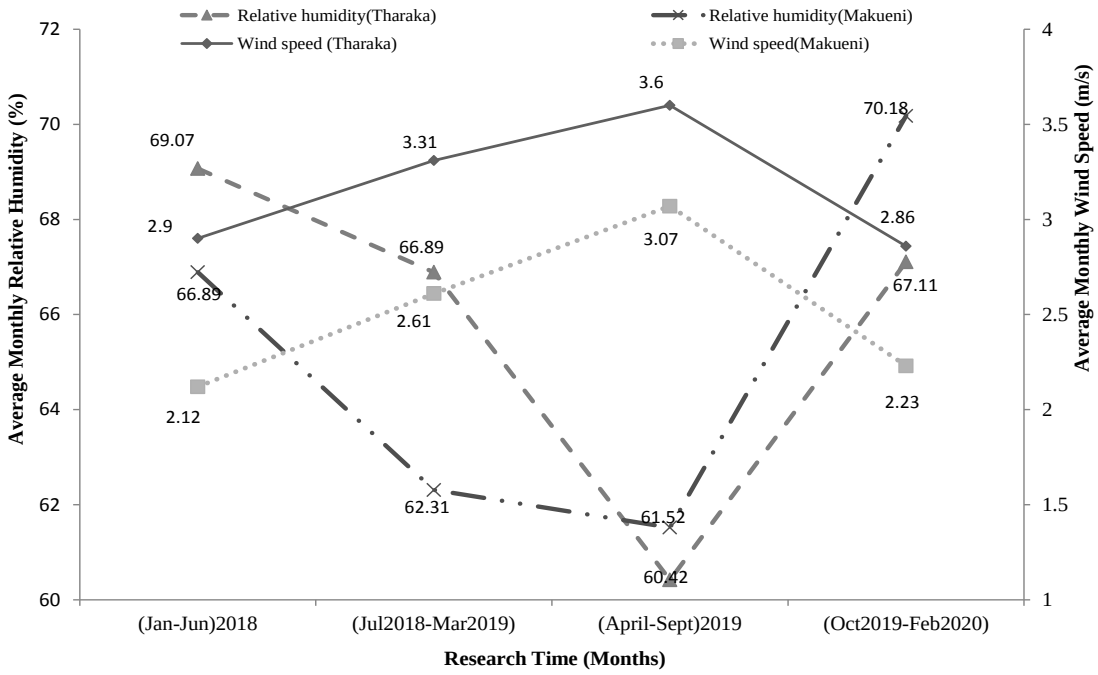

Figure 4.2: Monthly Relative Humidity and Wind Speed in Tharaka and Makueni

Synchrony of figure 4.1 and figure 4.2 indicates that at the time average monthly wind speed and temperatures were increasing between [(January – June) 2018 and (April – September) 2019], average monthly rainfall and relative humidity were decreasing. On the other hand, when average monthly rainfall and relative humidity were increasing between [(April – September) 2019 and (October 2019- February 2020), average monthly wind speed and temperature were decreasing. The results therefore

indicate that average monthly rainfall and relative humidity have an inverse relationship with wind speed and temperatures.

Weather data from Tharaka and Makueni met normality and homogeneity assumptions with $p>0.05$ (Appendix IIIa and b). A two-way ANOVA (Appendix IIIc) indicates that the mean monthly average rainfall ($F_{(3,44)} = 35.589$, $p < 0.001$, $\eta p^2 = 0.708$), temperature ($F_{(3,44)} = 19.069$, $p < 0.001$, $\eta p^2 = 0.565$) and wind speed ($F_{(3,44)} = 5.361$, $p < 0.001$, $\eta p^2 = 0.268$) varied significantly within research time points. However, the means of monthly average relative humidity were statistically the same at all four research time points ($F_{(3,44)} = 1.155$, $p= 0.338$, $\eta p^2 = 0.073$). In addition, average monthly wind speed was the only weather variable with mean significantly varying between the two semi-arid regions of Tharaka and Makueni ($F_{(3,44)} = 1.155$, $p=0.338$, $\eta p^2 = 0.001$).

Post-hoc analysis (Appendix IIId) indicates that average monthly rains in (July 2018 to March 2019) and (April to September) 2019 in Tharaka and Makueni were significantly lower than in (January to June) 2018 and (October 2019 to February 2020). Average monthly temperatures and average wind speed in (October 2018 to March 2019) were significantly higher than in (January to June) 2018 and (October 2019 to February 2020) in both Tharaka and Makueni (Appendix IIId).

Correlation analysis of weather conditions was carried out (Appendix IIIe) and outputs summarized in Table 4.3 indicating that average monthly rainfall was significantly correlated with temperature, wind speed and relative humidity.

Table 4.3: Summarized Correlation Analysis of Weather Conditions in Tharaka and Makueni

	Average monthly temperature	Average monthly wind speed	Average Monthly relative humidity
Corelation analysis in Tharaka			
Average monthly rainfall	$p < 0.001$	$p < 0.001$	$p = 0.002$
Average monthly temperature		$p = 0.003$	$p = 0.001$
Average monthly wind speed			$p = 0.427$
Corelation analysis in Makueni			
Average monthly rainfall	p<0.001	p< 0.001	p< 0.001
Average monthly temperature		p = 0.017	p< 0.001
Average monthly wind speed			*p = 0.419*

4.2. Morphological Characteristics of *C. procera* in Tharaka and Makueni

4.2.1. *Calotropis procera'*s leaf colour

Table 4.4 indicates that in Tharaka, the colour of 88.1%, 85.3%, 86.0% and 85.5% of *C. procera's* leaves was green in (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020, compared to 2.4%, 1.5%, 2.7% and 3.0% of leaves that had turned yellow over the same time. In Makueni, the trend of *C. procera's* leaf colour is similar to Tharaka as 94.2%, 93.0%, 87.0% and 92.9% of the leaves were green in (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020, compared to 1.2%, 1.6%, 1.6% and 0.4% that were appearing yellow (Table 4.4). However, there were stems that were totally without leaves due to leaf shedding (evidenced in plate 4.2), mainly in (September – November) 2019 as a result of harsh weather conditions experienced in the preceeding months between April and September 2019.

However, there were significant differences within leaves colour as the relative frequency of leaves with green colour had the highest frequencies in both Tharaka ($\chi^2_{(2)} = 5.673$, p< 0.001) and Makueni ($\chi^2_{(2)} = 5.673$, p< 0.001).

Table 4.4: Proportion (%) of *C. procera* Stems Having Green or Yellowish Leaves

Region	Research Time	Green(%)	Beginning to be Yellow(%)	Yellow(%)	No leaves(%)
Tharaka	(June – August) 2018	88.1	6.8	2.4	2.7
	(March – May) 2019	85.3	10.2	1.5	3
	(September – November) 2019	86	7.3	2.7	4
	(February – April) 2020	85.5	8.5	3	3
Makueni	(June – August) 2018	94.2	2.7	1.2	1.9
	(March – May) 2019	93	3.1	1.6	2.3
	(September – November) 2019	87	7.1	1.6	4.3
	(February – April) 2020	92.9	4.7	0.4	2

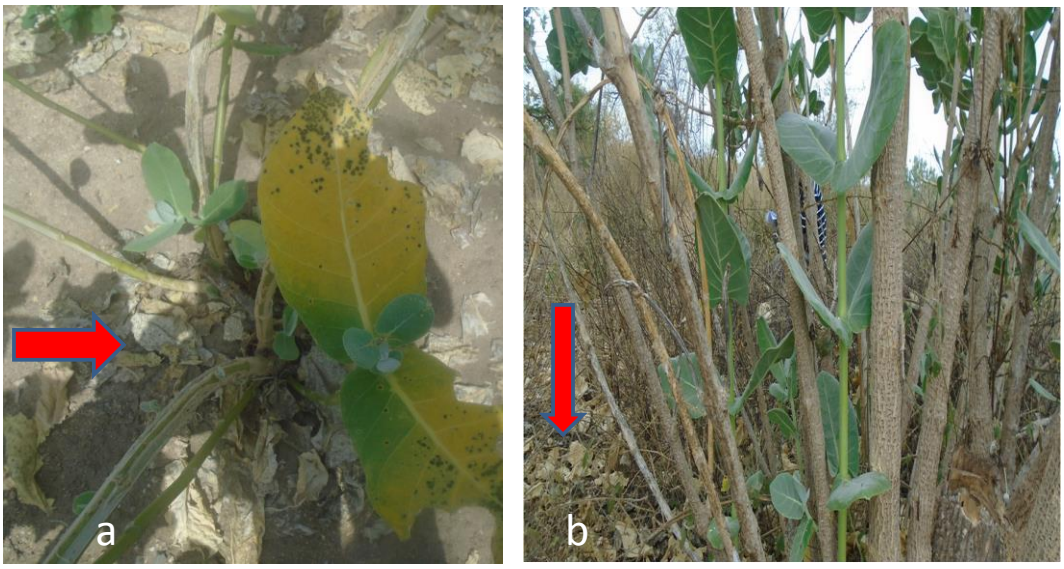

Plate 4.2: Evidence of *C. procera*'s Leaf Shedding in (September - November) 2019 (a- Tharaka and b- Makueni)

(Source: Author, 2019)

Pearson chi-square test of association indicated that there were no statistically significant associations between leaf colour with research time point ($\chi^2_{(9)} = 6.386$, $p = 0.701$) and with semi-arid region ($\chi^2_{(3)} = 20.998$, $p = 0.061$).

4.2.2. Models predicting leaf surface area of *C. procera* in Tharaka and Makueni

Among models that were tested using leaf surface area as response variable (Y), the model with high R (0.991), R^2 (0.982), adj R^2 (0.982) and low model standard error

(8.00137) was one having the product of leaf length (L) and width (W) as predictor variable (Table 4.5). Therefore, leaf surface area of *C. procera* was predicted using equation 4.1.

$$\mathbf{Y = 6.709 + 0.712(L \times W)cm} \text{..... (4.1)}$$

Table 4.5: Models Predicting *C. procera*'s Leaf Surface Area

Equation	R	R^2	Adj R^2	Model S.E	Model *p*	Coef	Coef S.E	Coef *p*
$Y= b_0 +b_1L$	0.971	0.942	0.941	14.451	<0.001	b_0 = -128.14	9.509	<0.001
						b_1 = 15.02	0.536	<0.001
$Y= b_0 +b_1W$	0.983	0.966	0.966	11.057	<0.001	b_0 = -83.33	6.016	<0.001
						b_1 = 22.39	0.604	<0.001
$Y= b_0 +b_1(L\times W)$	0.991	0.982	0.982	8.001	<0.001	b_0 = 6.709	2.677	<0.016
						b_1 = .71	0.014	<0.001
$Y= b_0 +b_1(L) + b_2(H)$	0.987	0.974	0.973	9.776	<0.001	b_0 = -115.66	6.045	<0.001
						b_1 = 9.19	0.218	<0.001
						b_2= 4.95	1.999	<0.001

4.2.3. Leaf surface area of *C. procera* in Tharaka and Makueni

Figure 4.3 indicates that the relative frequency (%) of *C. procera's* leaves with surface area ≥ 200 cm^2 in (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020 was 12.9% ,5.9%, 2.8%, 5.1% in Tharaka and 12%, 3.8%, 3.0%, 7.9% in Makueni respectively. This class of *C. procera's* leaf surface area contained the least relative frequencies compared to other leaf surface area classes of <50 cm^2, (50-<100) cm^2, (100-<150) cm^2 and (150-<200) cm^2 at all research time points and in the two study sites.

Pairwise analysis of between leaf surface area classes at different time points indicates that, the highest relative frequencies (%) of *C. procera's* leaf surface area were measuring (100-<150) cm^2 in (June to August) 2018, (50-<100) cm^2 in (March to May) 2019, (50-<100) cm^2 in (September to November) 2019 and (50-<100) cm^2 in (February to April) 2020 in both Tharaka and Makueni (Table 4.6 part a and b).

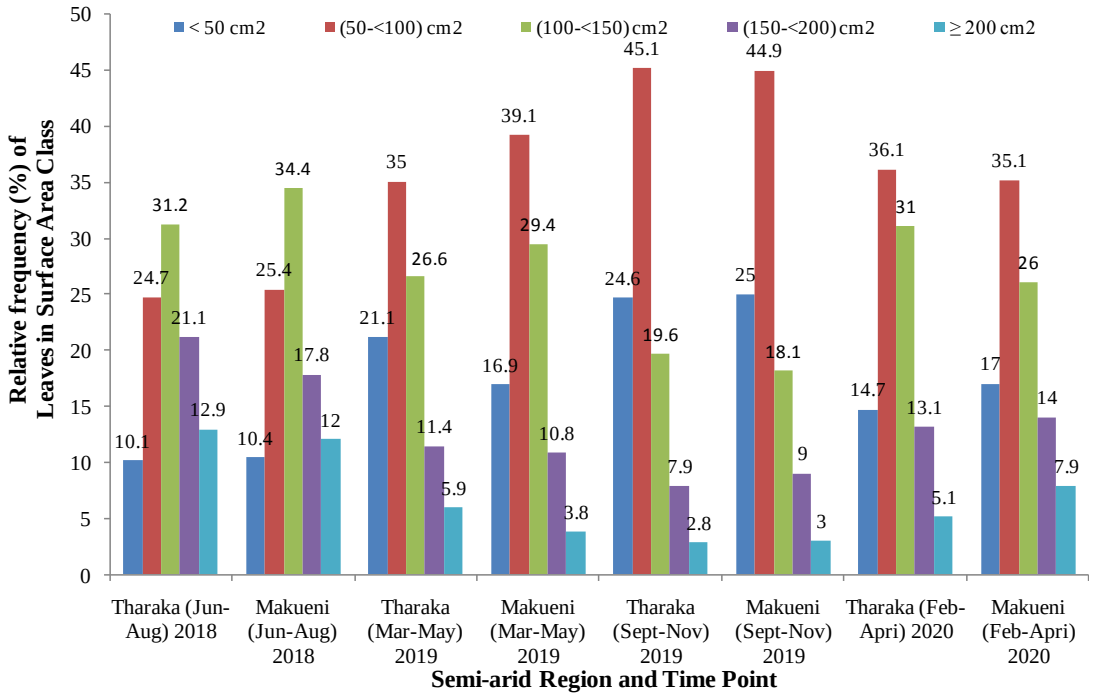

Figure 4.3: Relative Frequency (%) of *C. procera*'s Leaf Surface Area Class Distribution

Kruskal Wallis test indicates that there was a statistically significant difference in *C. procera*'s leaf surface area class distribution between different research time points (*Kruskal-Wallis H* $_{(3)}$ = 719.245, p < 0.001), with leaf surface area mean-ranks of 6625.58 for (June to August) 2018, 5218.88 for (March to May) 2019, 4452.09 for (September to November) 2019 and 5561.74 for (February to April) 2019.

Mann-Whitney *U*'s pair-wise comparison (Table 4.7) indicates that the leaf surface area class distribution in (June to August) 2018 had higher mean-rank than the rest of research time points.

Table 4.6: Mann-Whitney *U* Analysis of Bewteen Leaf Surface Area Classes at Different Time Points in Tharaka and Makueni

		(June to August) 2018				(March to May)2019				(September to November) 2019				(February to April) 2020			
Part a: Analysis of between leaf surface area classes at different time points in Tharaka																	
		(50-<100) cm^2	**(100-<150)** cm^2	**(150-<200)** cm^2	**≥ 200** cm^2	**(50-<100)** cm^2	**(100-<150)** cm^2	**(150-<200)** cm^2	**≥ 200** cm^2	**(50-<100)** cm^2	**(100-<150)** cm^2	**(150-<200)** cm^2	**≥ 200** cm^2	**(50-<100)** cm^2	**(100-<150)** cm^2	**(150-<200)** cm^2	**≥ 200** cm^2
<50 cm^2	Z	-21.71	-16.23	-15.41	-1.21	-14.08	-20.53	-3.22	-24.76	-69.41	-2.54	-14.24	-13.10	-25.21	-12.19	-2.19	-13.03
	Sig.	<0.001	<0.001	0.006	0.740	0.019	0.017	0.641	0.012	<0.001	0.672	0.041	0.045	0.012	0.037	0.710	0.031
(50-<100) cm^2	Z		-22.26	-4.48	-8.31		-12.43	-33.98	-52.15		-33.41	-37.65	-39.29		-18.09	-0.97	-33.11
	Sig.		<0.001	0.403	0.039		0.041	<0.001	<0.001		<0.001	<0.001	<0.001		0.001	0.657	0.015
(100-<150) cm^2	Z			-15.41	-41.21			-16.68	-22.15			-11.25	-17.12			-22.26	-35.21
	Sig.			0.021	<0.001			0.010	0.002			0.014	0.011			0.007	0.022
(150-<200) cm^2	Z				-6.21				-2.15				-0.92				-0.25
	Sig.				0.609				0.079				0.114				0.802
Part b: Analysis of between leaf surface area classes at different time points in Makueni																	
<50 cm^2	Z	-32.70	-52.48	-18.18	-0.99	-12.42	-24.74	-4.63	-26.42	-59.42	-1.22	-17.41	-16.24	-31.44	-14.81	-4.01	-14.05
	Sig.	<0.001	0.001	0.012	0.610	0.031	0.09	0.241	<0.001	<0.001	0.891	0.029	0.030	0.004	0.021	0.602	0.038
(50-<100) cm^2	Z		-24.10	-3.21	-9.90		-15.78	-41.91	68.32		-34.12	-65.81	-61.43		-20.20	-.531	-38.58
	Sig.		<0.001	0.403	0.039		0.041	<0.001	<0.001		<0.001	<0.001	<0.001		0.001	0.657	0.015
(100-<150) cm^2	Z			-25.76	-29.47			-21.53	-33.82			-43.92	-16.54			-28.42	-34.32
	Sig.			0.002	<0.001			0.021	<0.001			<0.001	0.032			<0.001	<0.001
(150-<200) cm^2	Z				-3.86				-0.65				-1.45				-0.61
	Sig.				0.706				0.892				0.281				0.602

Table 4.7: Mann-Whitney *U*'s Pair-wise Comparison of Leaf Surface Area Class Distribution WithinTime Points in Tharaka and Makueni

	(Jun-Aug) 2018 & (Mar-May) 2019	(Jun-Aug) 2018 & (Sept-Nov) 2019	(Jun-Aug) 2018 & (Feb-April) 2020	(Mar-May) 2019 & (Sept-Nov) 2019	(Mar-May) 2019 & (Feb-April) 2020	(Sept-Nov) 2019 & (Feb-April) 2020
Part a: Comparison of leaf surface area classes in Tharaka						
Z	-17.172	-25.834	-13.260	-9.561	-4.256	-13.833
	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Part b: Comparison of leaf surface area classes in Makueni						
Z	-16.981	-27.849	-12.003	-9.000	-6.814	-12.956
	<0.001	<0.001	0.001	<0.001	<0.001	<0.001

Mann-Whitney *U* test also indicates that there was no statistically significant difference in leaf surface area class distribution of *C. procera* between the semi-arid regions of Tharaka and Makueni (Mann Whitney $U = 14741296.00$, $p = 0.554$),with mean-ranks of 5459.61 and 5484.99 respectively.

4.2.4. Edaphic factors affecting *C. procera*'s leaf surface area class distribution

The model fitting information based on ordinal regression analysis indicates that models with independent variables in Tharaka and Makueni were significantly different from the intercept only models ($p < 0.001$) (Table 4.8 part a and b).

Table 4.8: Model Fitting Test for Edaphic Factors Affecting *C. procera's* Leaf Surface Area Class Distribution

Model	-2 Log Likelihood	Chi-Square	df	*P*
Part a: Model Testing for Tharaka				
Intercept Only	3163.380			
Final	2780.352	383.028	18	< 0.001
Link function: Logit				
Part b: Model Testing for Makueni				
Intercept Only	2485.183			
Final	2112.188	372.996	16	< 0 .001
Link function: Logit				

In Tharaka soil available P ($p = 0.001$) at (0-20) cm, soil available P ($p < 0.001$) at (20-40) cm and soil OC content ($p = 0.021$) at (20-40) cm were significantly associated

with leaf surface area distribution in the semi-arid regions of Tharaka (Table 4.9 part a). On the other hand, soil pH, EC, total N, exchangeable K, exchangeable Mg, exchangeable Ca and exchangeable Na at both (0-20) cm and (20-40) cm as well as soil OC content at (0-20) cm were not significantly associated with leaf surface area class distribution in Tharaka (Table 4.9 part a).

In Makueni, soil total N, available P and exchangeable K all at (20-40) cm with (p = 0.001), (p = 0.042) and (p = 0.010) respectively were significantly associated with leaf surface area class distribution (Table 4.9 part b). However, soil pH, EC, OC content, exchangeable Mg, exchangeable Ca and exchangeable Na at both (0-20) cm and (20-40) cm were not significantly associated with leaf surface area class distribution in Makueni. In addition, soil total N, available P and exchangeable K at (0-20) cm were not significantly associated with leaf surface area class distribution in Makueni (Table 4.9 part b).

Table 4.9: Effect Test of Edaphic Factors Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni

Parameter					95% Confidence Interval	
	Estimate	Wald	df	*p*	Lower Bound	Upper Bound
Part a. Edaphic factors affecting leaf surface area class distribution in Tharaka						
pH at (0-20)cm	-1.398±0.364	14.763	1	0.472	-2.110	-0.685
EC at (0-20)cm	0.350±0.363	0.931	1	0.070	-0.361	1.062
N at (0-20)cm	1.714±0.364	22.187	1	0.052	1.001	2.428
OC at (0-20)cm	3.018±0.367	67.725	1	0.057	2.300	3.737
P at (0-20)cm	-0.074±0.021	12.882	1	0.041	-0.115	-0.034
K at (0-20)cm	-1.537±0.519	8.764	1	0.173	-2.554	-0.519
Mg at (0-20)cm	-1.036±0.273	14.433	1	0.491	-1.571	-0.502
Ca at (0-20)cm	-0.108±0.024	19.883	1	0.090	-0.155	-0.060
Na at (0-20)cm	0.011±0.017	0.415	1	0.048	-0.022	0.043
pH at (20-40)cm	-0.003±0.001	34.864	1	0.230	-0.004	-0.002
EC at (20-40)cm	0.011±0.002	49.192	1	0.061	0.008	0.014
N at (20-40)cm	0.000±0.000	33.319	1	0.061	0.000	0.000
OC at (20-40)cm	0.002±0.001	11.791	1	0.021	0.001	0.003
P at (20-40)cm	0.079±0.043	3.283	1	<0.001	-0.006	0.163
K at (20-40)cm	-0.784±0.267	8.625	1	0.063	-1.306	-0.261
Mg at (20-40)cm	-1.163±0.188	38.092	1	0.418	-1.532	-0.793
Ca at (20-40)cm	-0.066±0.025	7.168	1	0.061	-0.115	-0.018
Na at (20-40)cm	0.161±0.016	97.293	1	0.333	0.129	0.193

Table 4.9: Effect Test of Edaphic Factors Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni (Continued)

Parameter					95% Confidence Interval	
	Estimate	Wald	df	*p*	Lower Bound	Upper Bound
Part b. Edaphic factors affecting leaf surface area class distribution in Makueni						
pH at (0-20)cm	0.142±0.024	35.556	1	0.264	0.095	0.188
EC at (0-20)cm	-1.803±0.322	31.383	1	0.185	-2.434	-1.172
N at (0-20)cm	0.625±0.310	4.055	1	0.064	0.017	1.232
OC at (0-20)cm	-0.142±0.033	18.668	1	0.490	-0207	-0.078
P at (0-20)cm	0.031±0.023	1.810	1	0.179	-0.014	0.077
K at (0-20)cm	0.001±0.000	13.228	1	0.751	0.000	0.002
Mg at (0-20)cm	0.049±0.005	114.782	1	0.093	0.040	0.059
Ca at (0-20)cm	-0.004±0.000	106.363	1	0.051	-0.004	-0.003
Na at (0-20)cm	-0.001±0.001	1.144	1	0.285	-0.003	0.001
pH at (20-40)cm	-0.081±0.020	16.456	1	0.050	-0.120	-0.042
EC at (20-40)cm	1.575±0.284	30.727	1	0.182	1.018	2.131
N at (20-40)cm	-0.734±0.211	12.073	1	0.001	-1.148	-0.320
OC at (20-40)cm	0.031±0.023	1.810	1	0.179	-0.014	0.077
P at (20-40)cm	-0.034±0.004	91.706	1	0.042	-0.042	-0.027
K at (20-40)cm	0.001±0.000	3.557	1	0.010	-0.042	-0.027
Mg at (20-40)cm	-0.034±0.004	91.706	1	0.059	-2.189	0.001
Ca at (20-40)cm	0.003±0.000	87.669	1	0.078	0.002	0.003
Na at (20-40)cm	0.000±0.001	1.315	1	0.252	-0.002	0.001

Conducting the second level analysis by eliminating variables that were statistically insignificant in the first level analysis indicates that soil available P ($p < 0.001$) at (0-20) cm and soil available P ($p < 0.001$) at (20-40) cm were significantly associated with *C. procera*'s leaf surface area class distribution in Tharaka (Table 4.10 part a). On the other hand, soil OC ($p = 0.082$) at (0-20) was not significantly associated with *C. procera*'s leaf surface area class distribution (Table 4.10 part a).

In Makueni, soil available P ($p = 0.032$) at (20-40) cm was significantly associated with leaf surface area class distribution (Table 4.10 part b). On the other hand, soil total N ($p = 0.299$) and exchangeable K ($p = 0.057$) at (20-40) cm were not significantly associated with leaf surface area class distribution in Makueni (Table 4.10 part b).

Table 4.10: 2nd Level Test of Edaphic Factors Affecting *C. procera*'s Leaf Surface Area Class Distributionin Tharaka and Makueni

Parameter					95% Confidence Interval	
	Estimate	Wald	df	*p*	Lower Bound	Upper Bound
Part a. Edaphic factors affecting leaf surface area class distribution in Tharaka						
P at (0-20) cm	-0.044±0.011	8.150	1	0.263	-0.065	-0.023
OC at (20-40)cm	0.292±.0.074	15.492	1	0.082	0.147	0.238
P at (20-40) cm	0.077±0.009	22.380	1	<0.001	0.060	0.094
Part b. Edaphic factors affecting leaf surface area class distribution in Makueni						
N at (20-40) cm	-0.981±0.166	34.730	1	0.299	1.000	0.584
P at (20-40) cm	0.045±0.009	25.848	1	0.032	0.028	0.062
K at (20-40) cm	0.000±0.000	3.613	1	0.057	0.000	1.497E-5

Third level analysis indicates that: soil available P at (0-20) and soil available P at (20-40) cm were significantly associated with with leaf surface area class distribution in the semi-arid regions of Tharaka with $p < 0.001$ (Table 4.11 part a). On the other hand, soil available P ($p = 0.021$) at (20-40) cm was significantly associated with leaf surface area class distribution in Makueni (Table 4.11 part b).

Table 4.11: 3rd Level Test of Edaphic Factors Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni

Parameters					95% Confidence Interval	
	Estimate	Wald	Df	*p*	Lower Bound	Upper Bound
Part a. Edaphic factors affecting leaf surface area class distribution in Tharaka						
P at (20-40) cm	-1.161±0.055	46.218	1	< 0.001	-1.269	-1.053
P at (20-40) cm	0.076±.009	77.969	1	<0.001	0.059	0.093
Part b. Edaphic factors affecting leaf surface area class distribution in Tharaka						
P at (20-40) cm	0.008±0.007	1.549	1	0.021	-0.005	0.021

Parameter estimate indicates that: in Tharaka, a unit increase in soil available P at (0-20) cm and (20-40) cm were significantly associated with an increase in the odds of *C. procera*'s leaf surface area in Tharaka to be in ≥ 200 cm^2 class with odd ratios of 1.028 (95% CI, 1.067 to 1.086), Wald $\chi^2_{(1)} = 46.218$, $p < 0.001$ and 1.025 (95% CI, 1.042 to 1. 188), Wald $\chi^2_{(1)} = 77.969$, $p < 0.001$ respectively (Appendix IVa part a). On the other hand, a unit increase in soil available P at (20-40) cm in Makueni was significantly associated with an increase in the odds of *C. procera*'s leaf surface area

to be in ≥ 200 cm^2 class with odd ratios of 1.059 (95% CI, 0.002 to 1.00), Wald $\chi^2_{(1)}$ = 1.549, p = 0.021 (Appendix IVa part b).

4.2.5. Weather conditions affecting *C. procera*'s leaf surface area class distribution in Tharaka and Makueni

The model fitting information (Table 4.12 parts a and b) indicate that models with independent variables were significantly different from the intercept only models in both Tharaka and Makueni ($p < 0.001$).

Table 4.12: Model Fitting Test for Edaphic Factors Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni

Model	-2 Log Likelihood	Chi-Square	df	*p*
Part a: Model Testing for Tharaka				
Intercept Only	586.486			
Final	148.772	437.714	4	< 0.001
Part b: Model Testing for Makueni				
Intercept Only	457.146			
Final	150.735	306.412	3	< 0.001
Link function: Logit.				

In Tharaka, average monthly rainfall ($p < 0.001$), temperature ($p < 0.001$), wind speed ($p = 0.010$) and relative humidity ($p < 0.001$) were significantly associated with *C. procera*'s leaf surface area class distribution (Table 4.13 part a). In Makueni also, average monthly rainfall ($p < 0.001$), temperature ($p<0.001$), wind speed ($p = 0.036$) and relative humidity ($p = 0.041$) were significantly associated with the distribution of *C. procera*'s leaf surface area class (Table 4.13 part b).

Table 4.13: 1st Level Test of Weather Conditions Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni

Parameter					95% Confidence Interval	
	Estimate	Wald	df	*p*	Lower Bound	Upper Bound
Part a. Weather conditions affecting leaf surface area class distribution in Tharaka						
Rainfall (mm)	0.012±0.003	17.221	1	< 0.001	0.006	0.017
Temperature (°C)	2.592±0.309	70.420	1	< 0.001	1.987	3.197
Wind speed (m/s)	-4.823±0.368	171.398	1	0.010	-5.545	-4.101
Relative humidity (%)	5.447±6.883	3.714	1	< 0.001	36.956	63.937

Table 4.13: 1st Level Test of Weather Conditions Affecting *C. procera*'s Leaf Surface Area Class Distribution in Tharaka and Makueni (Continued)

Parameter	Estimate	Wald	df	*p*	95% Confidence Interval	
					Lower Bound	Upper Bound
Part a. Weather conditions affecting leaf surface area class distribution in Makueni						
Rainfall (mm)	-0.018±.003	41.724	1	< 0.001	0.006	0.017
Temperature (°C)	-1.337±0.252	28.031	1	< 0.001	1.987	3.197
Wind speed (m/s)	-0.106±0.343	0.095	1	0.036	-5.545	-4.101
Relative humidity (%)	-0.028±0.033	42.324	1	0.041	36.956	63.937

Parameter estimate (Appendix IVb part a) indicates that: a unit increase in preceding months' average rainfall and relative humidity were significantly associated with an increase in odds of *C. procera'*s leaf surface area to be in ≥ 200 cm^2 class with odd ratios of 1.007 (95% CI, 1.014 to 1.020), Wald $\chi^2_{(1)} = 17.22$, $p < 0.001$ and 1.005 (95% CI, 1.007 to 1.049, Wald $\chi^2_{(1)} = 3.714$, $p <$ 0.001 respectively in Tharaka. On the other hand, a unit increase in preceding months' average temperature and wind speed were significantly associated with a decrease in odds of *C. procera'*s leaf surface area to be in ≥ 200 cm^2 class with odd ratios of 0.649 (95% CI, 0.614 to 0.713), Wald $\chi^2_{(1)} = 70.720$, $p < 0.001$ and 0.987 (95% CI, 0.323 to 0.471), Wald $\chi^2_{(1)} = 171.398$, $p = 0.010$ in Tharaka respectively.

In Makueni, a unit increase in preceding months' average rainfall and relative humidity were also significantly associated with increasing the odds of *C. procera'*s leaf surface area to be in ≥ 200 cm^2 class with odd ratios of 1.012 (95% CI, 1.021 to 1.139), Wald $\chi^2_{(1)} = 41.724$, $p < 0.001$ and 1.005 (95% CI, 1.004 to 1.063, Wald $\chi^2_{(1)} =$ 41.724, $p <$ 0.001 respectively. A unit increase in preceding months' average temperature and wind speed in Makueni were significantly associated with decreasing the odds of *C. procera'*s leaf surface area to be in ≥ 200 cm^2 class with odd ratios of 0.610 (95% CI, 0.902 to 0.1.000), Wald $\chi^2_{(1)} = 28.031$, $p < 0.001$ and 0.891 (95% CI, 0.791 to 0.992), Wald $\chi^2_{(1)} = 95.00$, $p = 0.036$ in Makueni respectively.

4.2.6. Models predicting *C. procera*'s fruit volume

The model predicting fruit volume (Y) with highest R (0.994), R^2 (0.987), adj R^2 (0.987) and low model standard error (14.380) was one having the sum of fruit length (L) and average diameter (D)[(L+D)], average diameter (D) and length (L) as predictor variables (Table 4.14). Therefore, fruit volume (Y) was estimated using equation 4.2 expressed as:

$$Y= b_0 +b_1(L^2+D^2) + b_2 (D) + b_3 (L) .....(4.2)$$

Table 4.14: Models Predicting the Volume of *C. procera*'s Fruits

Equation	R	R^2	Adj R^2	Model S.E	Model *p*	Coef	Coef S.E	Coef *p*
Response Variable: Fruit Volume (cm^3)								
$Y= b_0 +b_1D$	0.915	0.838	0.836	51.18257	<0.001	b_0 = -157.60	12.605	<0.001
						b_1 = 43.104	1.868	<0.001
$Y= b_0 +b_1(L)$	0.896	0.802	0.800	56.58276	<0.001	b_0 = -142.71	13.528	0.001
						b_1 = 23.304	1.141	<0.001
$Y= b_0 +b_1(D\times L)$	0.980	0.961	0.960	25.26261	<0.001	b_0 = -44.040	3.935	0.278
						b_1 = 1.933	0.039	<0.001
$Y= b_0 +b_1(W+L)$	0.971	0.943	0.943	30.33366	<0.001	b_0 = -42.097	4.714	<0.001
						b_1 = 0.815	0.020	<0.001
$Y= b_0 +b_1(L^2+D^2) + b_2 (D) + b_3 (L)$	0.994	0.987	0.987	14.38018	<0.001	b_0 = 47.881	7.009	<0.001
						b_1 = 1.404	0.041	<0.001
						b_2 = 12.061	1.868	<0.001
						b_3= -25.356	1.349	<0.001

4.2.7. Volume of *C. procera*'s fruits

There was an increase in relative frequency (%) of fruits with volume (< 100) cm^3 between (June to August) 2018 and (September to November) 2019 from 58.05% to 76.4% in Tharaka and from 60.18% to 63.01% in Makueni, but the same reduced in (February to April) 2020 to 61.84% and 60.52% in the same order (Figure 4.4). On the othe hand, the relative frequency (%) of fruits with volume ≥ 300cm^3 remained the least in (June to August) 2018, (March to May) 2019, (September to November) 2019, and (February to April) 2020 with 10.3%, 0.55%, 0%, and 10.58% in Tharaka and 10.62%, 5.35%, 6.85% and 7.01% in Makuni respectively. The relative

frequency of fruits with volume (100 to <200) cm^3 remained fairly constant at all research time points with the highest frequency of 26.7% in Tharaka and 23.28% in Makueni recorded in March to May 2019.

Mann-Whitney *U* (Table 4.15) indicates that the relative frequency (%) of fruits with volume <100 cm^3 were significantly higher at all research time points in both Tharaka and Makueni (p<0.001). However, there were no significant differences in relative frequencies of fruits with volumes between (200 to <300) cm^3 and ≥300cm^3 in both Tharaka and Makueni at all research time points.

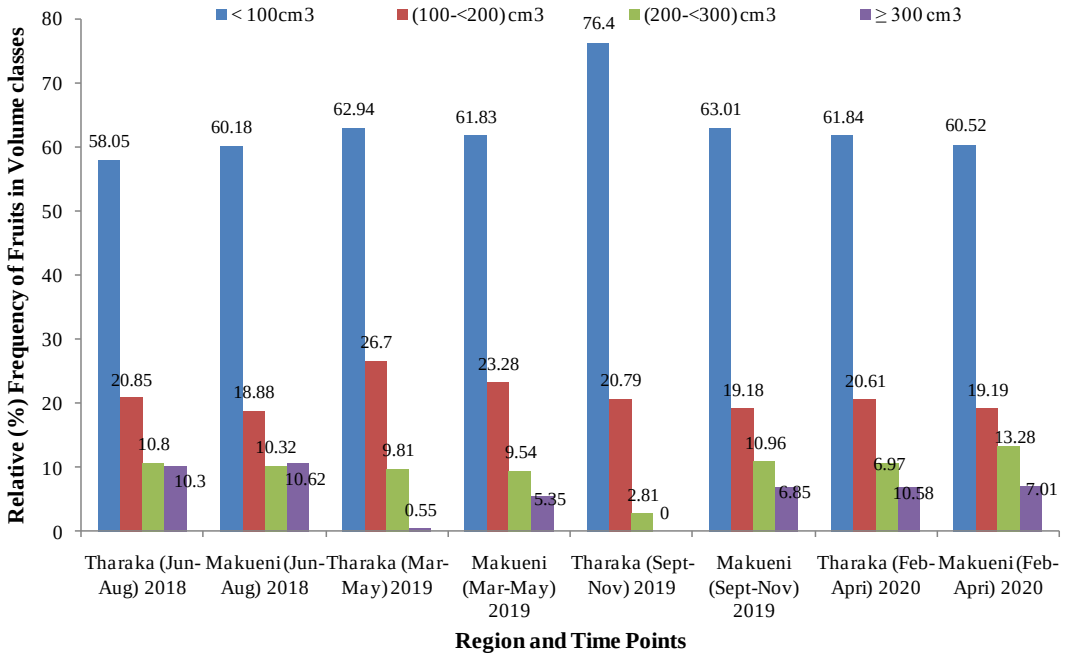

Figure 4.4: Relative Frequency (%) of *C. procera*'s Fruit Volume Class Distribution

Table 4.15: Mann-Whitney *U* Analysis of Bewteen Fruit Volume Classes at Different Time Points in Tharaka and Makueni

		(June to August) 2018			(March to May)2019			(September to November) 2019			(February to April) 2020		
Part a: Analysis of fruit volume classes at different time points in Tharaka													
		(100-<200) cm^3	**(200-<300)** cm^3	**≥300** cm^3	**(100-<200)** cm^3	**(200-<300)** cm^3	**≥300** cm^3	**(100-<200)** cm^3	**(200-<300)**	**≥300** cm^3	**(100-<200)** cm^3	**(200-<300)** cm^3	**≥300** cm^3
< 100 cm^3	Z	-26.68	-32.92	-41.66	-27.94	-38.43	-41.54	-48.35	-63.81	-65.24	-29.75	-31.19	-33.39
	p	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
(100-<200) cm^3	Z		-12.12	16.38		-18.02	-27.64		-25.95	-27.15		-16.51	-19.74
	p		0.016	<0.001		0.029	<0.001		<0.001	<0.001		0.017	0.020
(200-<300) cm^3	Z			-0.34			-2.92			-1.68			-4.25
	p			0.581			0.095			1.000			1.000
Part b: Analysis of fruit volume classes at different time points in Makueni													
< 100 cm^3	Z	-18.87	-21.09	-34.65	-22.05	-24.33	-33.89	-18.28	-25.95	-26.34	-21.67	-35.53	-42.13
	Sig.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
(100-<200) cm^3	Z		-19.18	-22.52		-18.82	-27.63		-13.81	-19.25		-10.11	-17.48
	p		0.001	<0.001		<0.001	<0.001		0.013	0.032		0.029	0.022
(200-<300) cm^3	Z			-9.18			-8.03			-1.86			-9.28
	p			0.144			0.078			0.566			0.411

Kruskal Wallis test indicates that there was a statistically significant difference in *C. procera*'s fruit volume class distribution within research time points (*Kruskal-Wallis* $H = 18.260$, $p < 0.001$), with fruit volume mean-ranks of 1253.83 for (June to August) 2018, 1170.61 for (March to May) 2019, 1103.34 for (September to November) 2019 and 1215.89 for (February to April) 2019.

Mann-Whitney *U'*s pair-wise comparison (Table 4.16) indicates that the fruit volume mean-ranks in (June to August) 2018 were significantly higher compared to fruit volume in (March to May) 2019 and (September to November) 2019.

Table 4.16: Mann-Whitney *U*'s Pair-wise Comparison of *C. procera*'s Fruit Volume Class Distribution Within Time Points

	(Jun-Aug) 2018 & (Mar-May) 2019	(Jun-Aug) 2018 & (Sept-Nov) 2019	(Jun-Aug) 2018 & (Feb-April) 2020	(Mar-May) 2019 & (Sept-Nov) 2019	(Mar-May) 2019 & (Feb-April) 2020	(Sept-Nov) 2019 & (Feb-April) 2020
Mann-Whitney *U*	215386.00	128253.00	224714.00	117376.00	190457.00	113394.00
Z	-2.581	-3.970	-1.163	-1.918	-1.374	-2.958
Asymp. Sig. (2-tailed)	0.010	< 0.001	0.245	0.055	0.169	0.003

Mann-Whitney *U* test also indicates that there was no statistically significant difference in *C. procera*'s fruit volume class distribution between the semi-arid regions of Tharaka and Makueni (Mann Whitney *U* test, $U = 687776.000$, $p = 0.123$), with mean-ranks of 1179.75 and 1217.59 respectively.

4.2.8. Edaphic factors affecting *C. procera*'s fruit volume class distribution

The model fitting test (Table 4.17 part a and b) indicates that the model with edaphic factors as independent variables was significantly different from the intercept only model ($p < 0.001$) in both Tharaka and Makueni.

Table 4.17: Model Fitting Test of Edaphic Factors Affecting *C. procera*'s Fruit Volume Class Distribution

Model	-2 Log Likelihood	Chi-Square	df	*p*
Part a: Model Testing for Tharaka				
Intercept Only	601.299			
Final	549.417	51.882	18	<0.001
Part b: Model Testing for Makueni				
Intercept Only	592.053			
Final	525.638	66.415	18	<0.001
Link function: Logit.				

Fixed effect test (Table 4.18 part a) indicates that soil total N ($p = 0.003$) and available P ($p = 0.033$) at (0-20) cm, and total N ($p = 0.014$), available P ($p = 0.039$) and exchangeable K ($p = 0.030$) at (20-40) cm soil depths were the only edaphic

factors significantly associated with *C. procera*'s fruit volume class distribution in Tharaka.

In Makueni, only available P (p =0.027) at (20-40) cm soil depth was significantly associated with *C. procera's* fruit volume class distribution (Table 4.18 part b).

Table 4.18: Fixed Effect Test of Edaphic Factors Affecting *C. procera*'s Fruit Volume Class Distribution in Tharaka and Makueni

Parameter	Estimate	Wald	df	*p*	95% Confidence Interval	
					Lower Bound	Upper Bound
Part a. Edaphic factors affecting *C. procera's* Fruit Volume class distribution in Tharaka						
pH at (0-20) cm	-0.006±0.046	0.018	1	0.893	-0.096	0.083
EC at (0-20) cm	-0.033±01.415	0.001	1	0.981	-2.807	2.740
N at (0-20) cm	-2.165±0.722	8.984	1	0.003	-3.581	-0.749
OC at (0-20) cm	-0.117±0.065	3.217	1	0.073	-0.245	0.011
P at (0-20) cm	0.037±0.040	4.827	1	0.033	-0.042	0.116
K at (0-20) cm	-0.001±0.002	0.470	1	0.493	-0.004	0.002
Mg at (0-20) cm	-0.004±0.005	0.750	1	0.387	-0.013	0.005
Ca at (0-20) cm	0.000±0.000	1.303	1	0.254	0.000	0.001
Na at (0-20) cm	0.001±0.001	0.317	1	0.573	-0.002	0.004
pH at (20-40) cm	-0.044±0.115	0.145	1	0.704	-0.268	0.181
EC at (20-40) cm	0.875±0.695	1.587	1	0.208	-0.487	2.237
Nat (20-40) cm	1.342±0.543	6.097	1	0.014	0.277	2.407
OC at (20-40) cm	-0.058±0.075	0.597	1	0.440	-0.205	0.089
P at (20-40) cm	0.093±0.045	4.281	1	0.039	0.005	0.180
K at (20-40) cm	-0.002±0.001	4.694	1	0.030	-0.004	0.000
Mg at (20-40) cm	-0.021±0.012	3.140	1	0.076	-0.044	0.002
Ca at (20-40) cm	0.001±0.001	2.209	1	0.137	0.000	0.003
Na at (20-40) cm	0.000±0.004	0.002	1	0.966	-0.007	0.007
Part b. Edaphic factors affecting *C. procera's* Fruit Volume class distribution in Makueni						
pH at (0-20) cm	0.261±0.730	0.128	1	0.721	-1.170	1.692
EC at (0-20) cm	1.507±0.732	4.240	1	0.039	0.073	2.941
N at (0-20) cm	2.876±0.741	15.069	1	<0.001	1.424	4.329
OC at (0-20) cm	-0.076±0.075	1.035	1	0.309	-0.223	0.071
P at (0-20) cm	-0.665±0.151	0.334	1	0.563	-2.921	1.591
K at (0-20) cm	-0.041±0.964	0.002	1	0.966	-1.931	1.849
Mg at (0-20) cm	-0.125±0.103	1.490	1	0.222	-0.326	0.076
Ca at (0-20) cm	0.017±0.058	0.092	1	0.762	-0.095	0.130
Na at (0-20) cm	0.001±0.001	3.357	1	0.067	-9.660E-5	0.003
pH at (20-40) cm	-0.007±0.006	1.267	1	0.260	-0.018	0.005
EC at (20-40) cm	0.000±0.000	0.991	1	0.320	0.000	0.001
Nat (20-40) cm	0.000±0.002	0.046	1	0.830	-0.005	0.004
OC at (20-40) cm	0.110±0.065	2.902	1	0.088	-0.017	0.236
P at (20-40) cm	-1.047±0.687	22.327	1	0.027	-2.393	0.298

Table 4.18: Fixed Effect Test of Edaphic Factors Affecting *C. procera*'s Fruit Volume Class Distribution in Tharaka and Makueni (Continued)

Parameter	Estimate	Wald	df	*p*	95% Confidence Interval	
					Lower Bound	Upper Bound
K at (20-40) cm	0.172±0.572	0.091	1	0.763	-0.949	1.293
Mg at (20-40) cm	0.151±0.158	0.912	1	0.340	-0.159	0.462
Ca at (20-40) cm	-0.034±0.080	0.185	1	0.667	-0.191	0.122
Na at (20-40) cm	-0.001±0.001	1.905	1	0.167	-0.003	0.000

Second level analysis through list-wise elimination of variables that were not statistically significant at first level analysis indicates that: soil total N ($p = 0.049$) and available P ($p = 0.028$) at (0-20) cm, and total N ($p < 0.001$), available P ($p < 0.001$) and exchangeable K ($p = 0.011$) at (20-40) cm soil depths were significantly associated with *C. procera*'s fruit volume class distribution in Tharaka (Appendix IVc part a).

In Makueni, available P ($p < 0.004$) at (20-40) cm soil depths was significantly associated with *C. procera*'s fruit volume class distribution (Appendix IVc part b).

Parameter estimates indicates that in Tharaka: an increase in soil total N at (0-20) cm, available P at (0-20) cm, soil total N at (20-40) cm, available P at (20-40) cm and exchangeable K at (20-40) were associated with an increase in odds of *C. procera*'s fruit volume to be in ≥ 300 cm^3 class with odd ratios of 1.093 (95% CI, 1.098 to 1.914), Wald $\chi^2_{(1)} = 21.453$, $p = 0.048$; 1.070 (95% CI, 1.024 to 1.830), Wald $\chi^2_{(1)} = 21.453$, $p = 0.028$; 1.003 (95% CI, 1.000 to 1.009), Wald $\chi^2_{(1)} = 17.439$, $p < 0.001$; 1.034 (95% CI, 1.000 to 1.535), Wald ($\chi^2_{(1)} = 12.876$, $p = 0.030$; and 1.097 (95% CI, 1.569 to 1.907), Wald $\chi^2_{(1)} = 16.435$, $p = 0.011$ respectively (Appendix IVc part a).

In Makueni, an increase in available P at (20-40) cm was associated with an increase in odds of *C. procera*'s fruit volume to be in ≥ 300 cm^3 class with odd ratios of 1.001(95% CI, 1.000 to 1.003), Wald $\chi^2_{(1)} = 18.316$, $p = 0.015$.

4.2.9. Weather conditions affecting *C. procera*'s fruit volume class distribution

The model fitting test (Table 4.19 part a and b) indicates that models with weather conditions as independent variables was significantly different from the intercept only model ($p < 0.001$).

Table 4.19: Model Fitting Test of Weather Conditions Affecting *C. procera*'s Fruit Volume Class Distribution

Model	-2 Log Likelihood	Chi-Square	df	*p*
Part a: Model Testing for Tharaka				
Intercept Only	140.005			
Final	111.279	28.725	3	<0.001
Part b: Model Testing for Makueni				
Intercept Only	93.435			
Final	90.872	2.563	3	<0.001
Link function: Logit.				

Fixed effect test indicates that in Tharaka, preceding months' average rainfall (p = 0.024), temperature (p = 0.027), wind speed (p= 0.008) and relative humidity (p= 0.049) were significantly associated with *C. procera*'s fruit volume class distribution (Appendix IVd part a).

In Makueni also, average rainfall (p = 0.0048), temperature (p = 0.032), wind speed (p= 0.024) and relative humidity (p= 0.037) were significantly associated with *C. procera*'s fruit volume class distribution (Appendix IVd part b).

The parameter estimates indicates that in Tharaka: an increase in preceding months' average rainfall and relative humidity were associated with an increase in odds of *C. procera*'s fruit volume to be in ≥ 300 cm^3 class with odd ratios of 1.002 (95% CI, 1.002 to 1.106), Wald $\chi^2_{(1)} = 11.612$, $p = 0.024$; and 1.039 (95% CI, 1.008 to 1.273), Wald $\chi^2_{(1)} = 12.950$, $p = 0.049$ respectively. An increase in preceding months' average temperature and wind speed were associated with a decrease in odds of *C. procera's* fruit volume to be in ≥ 300 cm^3 class with odd ratios of 0.914 (95% CI, 0.851 to

1.086), Wald $\chi^2_{(1)} = 17.008$, $p = 0.027$; and 0.810 (95% CI, 0.589 to 1.110), Wald $\chi^2_{(1)} = 17.111$, $p = 0.008$ respectively (Appendix IVd part a).

In Makueni, an increase in preceding months' average rainfall and relative humidity were associated with an increase in odds of *C. procera*'s fruit volume to be in ≥ 300 cm^3 class with odd ratios of 1.042 (95% CI, 1.031 to 1.139), Wald $\chi^2_{(1)} = 12.344$, $p = 0.048$; and 1.007 (95% CI, 1.006 to 1.041), Wald $\chi^2_{(1)} = 17.248$, $p = 0.037$ respectively. An increase in preceding months' average temperature and wind speed were associated with a decrease in odds of *C. procera's* fruit volume to be in ≥ 300 cm^3 class with odd ratios of 0.788 (95% CI, 0942 to 1.000), Wald $\chi^2_{(1)} = 17.337$, $p = 0.032$ and 0.929 (95% CI, 0.761 to 0.888), Wald $\chi^2_{(1)} = 21.000$, $p = 0.037$ respectively (Appendix IVd part b).

4.3. Population Distribution of *C. procera* in Terms of Size Classification

4.3.1. Height class distribution of *C. procera* in Tharaka and Makueni

Figure 4.5 indicates that the relative frequency (%) of *C. procera* stems with total height <1.5 m showed a reducing trend from 46.18% to 36.7% in Tharaka and 16.05% to 3.79% in Makueni between (June to August) 2018 and (February to April) 2020 (Figure 4.5). Over the same period, the general trend indicates that the relative frequency (%) of stems with total height (3 to 4.5) m increased from 1.11% to 12.7% in Tharaka and 10.3% to 27.44% in Makueni though with flactuations in (September to November) 2019 (Figure 4.5). A reduction in relative frequencies of stems with total height <1.5 m and an increase in relative frequencies of stems with (3 to <4.5) m is a sign of stem growth in terms of height.

Pairwise analysis of relative frequencies between total height classes based on Wilcoxon signed-rank tests indicates that relative frequencies (%) of 48.33%, 48.55%

and 48.45% in Tharaka and 58.33%, 60.82% and 65.3% in Makueni reported for *C. procera* stems with total height (1.5 to <3) m in (March to May) 2019, (September to November) 2019 and (February to April) 2020 respectively were significantly higher than the relative frequencies in other height classes of <1.5 m, (3-<4.5) m, and ≥4.5 m at all research time points in both Tharaka and Makueni ($p < 0.01$) (Table 4.20). on the other hand, the relative frequency of *C. procera* stems with total height ≥4.5 m were significantly lower at all research times in both Tharaka and Makueni.

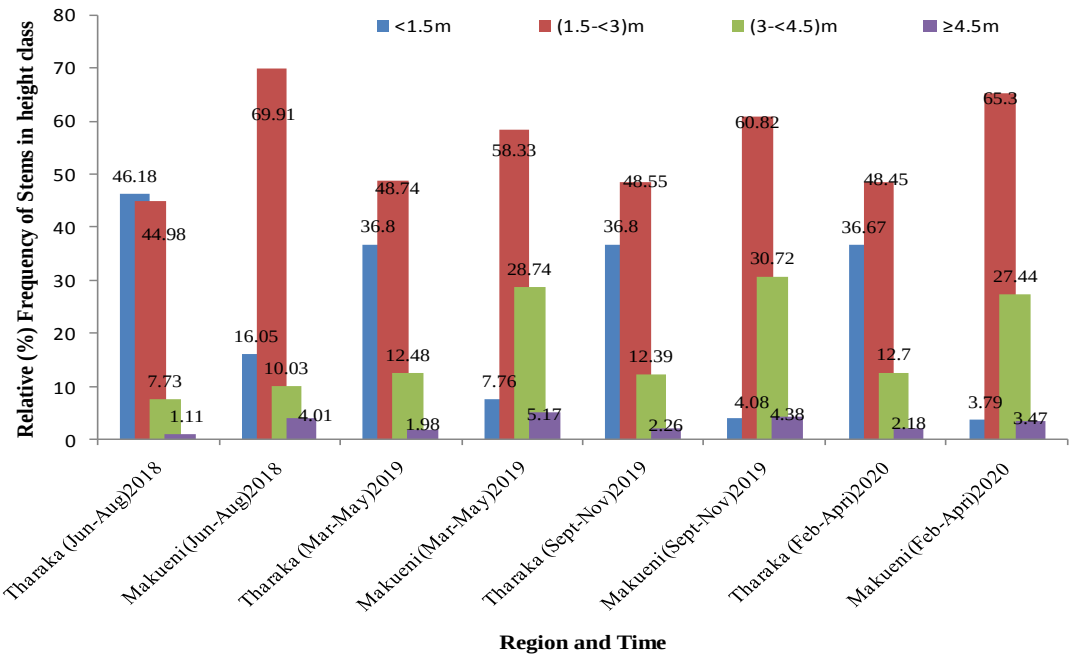

Figure 4.5: Relative Frequency (%) of *C. procera*'s Height Class Distribution

There were also evidence of human interference through cutting of *C. procera* stems in (September to November) to allow goats feed on leaves (Plate 4.3).

Plate 4.3: Human Interferences with Naturally Growing *C. procera* in Tharaka (September-November) 2019

(Source: Author, 2019)

Table 4.20: Wilcoxon signed-Rank Tests Analysis of Bewteen *C. procera*'s Total Height Classes at Different Time Points in Tharaka and Makueni

		(June to August) 2018			(March to May)2019			(September to November) 2019			(February to April) 2020		
Part a: analysis of total height classes at different time points in Tharaka													
		(1.5-< 3) m	**(3-< 4.5) m**	**≥4.5 m**	**(1.5-< 3) m**	**(3-< 4.5) m**	**≥4.5 m**	**(1.5-< 3) m**	**(3-< 4.5) m**	**≥4.5 m**	**(1.5-< 3) m**	**(3-< 4.5) m**	**≥4.5 m**
< 1.5 m	Z	-8.42	-16.98	-25.00	-14.13	-25.05	-23.71	-17.62	-23.79	-29.25	-15.94	-18.15	-23.76
	p	0.053	0.006	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
(1.5-< 3) m	Z		-11.91	-18.74		-14.75	-17.42		-14.63	-16.61		-17.0	-17.49
	p		0.043	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001
(3-< 4.5) m	Z			0.000			-3.97			-7.59			-6.65
	p			1.000			1.000			1.000			1.000
Part b: analysis of total height classes at different time points in Makueni													
< 1.5 m	Z	-27.13	-5.85	-13.63	-26.19	-18.41	-2.04	-26.96	-17.84	-.03	-27.00	-25.63	0.00
	p	< 0.001	0.652	0.014	< 0.001	< 0.001	1.000	< 0.001	< 0.001	1.000	0.001	< 0.001	1.000
(1.5-< 3) m	Z		-19.60	-27.89		-15.38	24.09		-12.06	-26.07		-18.83	24.41
	p		< 0.001	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001
(3-< 4.5) m	Z			-2.79			-9.11			-19.63			-16.04
	p			1.000			0.0931			< 0.001			0.004

Friedman test indicates that there was a statistically significant difference in height class distribution of *C. procera* stems within research time point ($\chi^2_{(3)}$ = 684.372, p <0.001), with height class distribution mean-ranks of 2.17, 2.58, 2.63 and 2.62 for (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020 respectively.

Post hoc analysis using Wilcoxon signed-rank tests (Table 4.21) indicates that mean-ranks of *C. procera*'s height class distribution in (June to August) 2018 was significantly lower than in (March to May) 2019, (September to November) 2019 and (February to April) 2020.

Table 4.21: Wilcoxon Signed-Rank's Post Hoc Analysis of *C. procera*'s Height Class Distribution within Time Points

	(Mar-May)2019 & (Jun-Aug) 2018	(Sep-Nov)2019& (Jun-Aug)2018	(Feb-April)2020 & (Jun-Aug)2018	(Sep-Nov)2019 & (Mar-May)2019	(Feb-April)2020 &(Mar-May)2019	(Feb-April)2020 & (Sep-Nov)2019
Z	-16.415	-17.652	-17.240	-1.578	-.721	-1.050
Asym. Sig. (2-tailed)	<0.001	< 0.001	< 0.001	0.115	0.471	0.294
Exact Sig. (2-tailed)	< 0.001	< 0.001	< 0.001	0.111	0.458	0.358

Mann-Whitney *U* test indicates that there was a statistically significant difference in height class distribution of *C. procera* stems between the semi-arid regions of Tharaka and Makueni (Mann Whitney U= 1906676.000, p < 0.001), with mean-ranks of 2668.93 and 3723.64 respectively. The mean-ranks depicts that *C. procera* in Makueni were taller than in Tharaka.

4.3.2. Edaphic factors affecting *C. procera*'s height class distribution

In Tharaka, soil available P (p = 0.015) at (0-20) cm, soil EC (p = 0.016) at (20-40) cm, soil total N (p <0.001) at (20-40) cm, soil available P (p = 0.022) at (20-40) cm and exchangeable K (p =0.016) at (20-40) cm were significantly associated with *C.*

procera's height class distribution (Table 4.22 part a). On the other hand, soil total N (p = 0.001) and available P (p = 0.002) at (20-40) cm were significantly associated with *C. procera*'s height class distribution in Makueni (Table 4.22 part b).

Table 4.22: Effect Test of Edaphic Factors Affecting *C. procera*'s Height Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a. Edaphic factors affecting *C. procera's* height class distribution in Tharaka			
pH at (0-20) cm	0.740	1	0.390
EC at (0-20) cm	1.950	1	0.095
N at (0-20) cm	2.449	1	0.055
OC at (0-20) cm	5.524	1	0.069
P at (0-20) cm	9.964	1	0.015
K at (0-20) cm	1.931	1	0.165
Mg at (0-20) cm	1.523	1	0.217
Ca at (0-20) cm	0.143	1	0.706
Na at (0-20) cm	8.111	1	0.064
pH at (20-40) cm	1.135	1	0.713
EC at (20-40) cm	1.970	1	0.016
N at (20-40) cm	13.775	1	<0.001
OC at (20-40) cm	0.527	1	0.468
P at (20-40) cm	15.275	1	0.022
K at (20-40) cm	11.912	1	0.016
Mg at (20-40) cm	1.575	1	0.175
Ca at (20-40) cm	1.591	1	0.381
Na at (20-40) cm	0.001	1	0.977
Part b. Edaphic factors affecting *C. procera's* height class distribution in Makueni			
pH at (0-20) cm	1.650	1	0.101
EC at (0-20) cm	1.751	1	0.186
N at (0-20) cm	1.183	1	0.171
OC at (0-20) cm	0.528	1	0.873
P at (0-20) cm	2.458	1	0.121
K at (0-20) cm	1.943	1	0.326
Mg at (0-20) cm	2.542	1	0.111
Ca at (0-20) cm	2.848	1	0.091
Na at (0-20) cm	1.396	1	0.237
pH at (20-40) cm	1.352	1	0.245
EC at (20-40) cm	1.452	1	0.204
N at (20-40) cm	12.078	1	0.001
OC at (20-40) cm	0.197	1	0.082
P at (20-40) cm	9.590	1	0.002
K at (20-40) cm	1.933	1	0.164
Mg at (20-40) cm	1.968	1	0.121
Ca at (20-40) cm	3.395	1	0.237
Na at (20-40) cm	0.224	1	0.636

The second level analysis by eliminating variables that were statistically insignificant in level 1 analysis indicates that: soil available P (p = 0.026) at (0-20) cm, EC (p = 0.001) at (20-40) cm, available P (p = 0.005) at (20-40) cm, exchangeable K (p = 0.008) at (20-40) cm and total N at (20-40) cm were significantly associated with *C. procera*'s height class distribution in Tharaka (Table 4.23 part a).

Table 4.23: 2nd Level Test of Edaphic Factors Affecting *C. procera*'s Height Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***P***
Part a. Edaphic factors affecting *C. procera's* height class distribution in Tharaka			
P at (0-20) cm	12.472	1	0.026
EC (20-40) cm	11.330	1	0.001
P at (20-40) cm	13.553	1	0.005
K at (20-40) cm	11.022	1	0.008
N at (20-40) cm	15.148	1	< 0.001
Part b. Edaphic factors affecting *C. procera's* height class distribution in Makueni			
N (20-40) cm	26.617	1	<0.001
P at (20-40) cm	16.553	1	0.016

The parameter estimate (Appendix Va part a) indicates that: a unit increase in soil available P at (0-20) cm, EC at (20-40) cm, available P at (20-40) cm, exchangeable K at (20-40) cm and total N at (20-40) cm were significantly associated with increasing the odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratios of 1.015 (95% CI, 1.066 to 1.524), Wald $\chi^2_{(1)}$ = 12.472, p = 0.026; 1.003 (95% CI, 1.676 to 7.074), Wald $\chi^2_{(1)}$ = 11.330, p = 0.001; 1.025 (95% CI, 0.949 to 1.001), Wald $\chi^2_{(1)}$ = 13.553, p<0.005; 1.030 (95% CI, 1.999 to 2.001), Wald $\chi^2_{(1)}$ = 11.022, p = 0.008; and 1.174 (95% CI, 1.470 to 3.215), Wald $\chi^2_{(1)}$ = 15.148, p < 0.001 respectively.

In Makueni, Appendix Va part b indicates that a unit increase in soil total N and available P at (20-40) cm were significantly associated with increasing the odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratios of 1.081 (95% CI, 2.293 to

3.338), Wald $\chi^2_{(1)} = 26.617$, $p < 0.001$and 1.001(95% CI, 1.997 to 2.032), Wald $\chi^2_{(1)} = 16.553$, $p = 0.016$ respectively.

4.3.3. Weather conditions affecting *C. procera*'s height class distribution

The effect test (Table 4.24 part a and b) indicates that preceding months'average monthly rainfall ($p < 0.001$), temperature ($p < 0.001$), wind speed ($p < 0.001$) and relative humidity ($p < 0.001$) were significantly associated with height class distribution of *C. procera* in Tharaka and Makueni respectively.

Table 4.24: Effect Test of Weather Conditions Affecting *C. procera's* Height Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a. Weather conditions affecting *C. procera's* height class distribution in Tharaka			
Total monthly rainfall (mm/month)	90.599	1	<0.001
Mean monthly temperature (°C/month)	30.112	1	<0.001
Mean monthly wind speed (m/s)	22.528	1	<0.001
Monthly relative humidity (%)	31.357	1	<0.001
Part b. Weather conditions affecting *C. procera's* height class distribution in Makueni			
Total monthly rainfall (mm/month)	20.557	1	<0.001
Mean monthly temperature (°C/month)	21.633	1	<0.001
Mean monthly wind speed (m/s)	32.098	1	<0.001
Monthly relative humidity (%)	14.655	1	<0.001

Parameter estimate (Appendix Vb) indicates that: a unit increase in average monthly rainfall was significantly associated with an increase in odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratio of 1.028 (95% CI, 1.980 to 2.985), Wald $\chi^2(_1) = 90.599$, $p < 0.001$. On the other hand, a unit increase in average monthly temperature, wind speed and relative humidity were associated with a decrease in odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratios of 0.867 (95% CI, 0.047 to 0.095), Wald $\chi^2_{(1)} = 30.112$, $p < 0.001$; 0.937 (95% CI, 0.671 to 0.941), Wald $\chi^2_{(1)} = 22.528$, $p < 0.001$ and 0.993 (95% CI, 0.021 to 0.471), Wald $\chi^2_{(1)} = 12.116$, $p < 0.001$ respectively.

In Makueni, parameter estimate (Appendix Vb part b) indicates that: a unit increase in average monthly rainfall was significantly associated with an increase in odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratio of 1.007 (95% CI, 1.005 to 1.010), Wald $\chi^2_{(1)} = 32.587$, $p < 0.001$. On the other hand, a unit increase in average monthly temperature, wind speed and relative humidity were associated with a decrease in odds of *C. procera*'s height to be in ≥ 4.5 m class with odd ratios of 0.859 (95% CI, 0.487 to 0.862), Wald $\chi^2_{(1)} = 21.644$, $p < 0.001$; 0.974 (95% CI, 0.183 to 0.354), Wald $\chi^2_{(1)} = 22.111$, $p < 0.001$ and 0.981(95% CI, 0.855 to 0.988), Wald $\chi^2_{(1)} = 15.765$, $p < 0.001$ respectively.

4.3.4. Crown diameter class distribution of *C. procera*

The relative frequency (%) of C. *procera'*s stems with crown diameter <40 cm showed a decreasing trend from 56.48% to 49.09% in Tharaka and 25.21% to 19.56% in Makueni from the initial time point (June toAugust) 2018 to the final time point (February to April) 2020 (Figure 4.6). On the other hand, the relative frequency of *C. procera* stems with crown diameter (80 to <120) cm and ≥120 cm showed an increasing trend from the initial time point to the final time point both in Tharaka and Makueni. This showed that *C. procera* has the ability to expand its crown diameter as it grows over time.

Pairwise analysis using Wilcoxon signed-rank tests between crown diameter classes indicates that the frequency of *C. procera* stems with crown diameter <40 cm recorded in (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020 as 56.48%, 49.82%, 49.28% and 49.09% respectively were significantly higher than relative frequencies in other crown diameter classes in all research time points in Tharaka (Table 4.25). However, in

Makueni, the relative frequency of *C. procera* stems with crown diameter ≥ 120cm were the ones significantly higher than relative frequency in other classes at all time points.

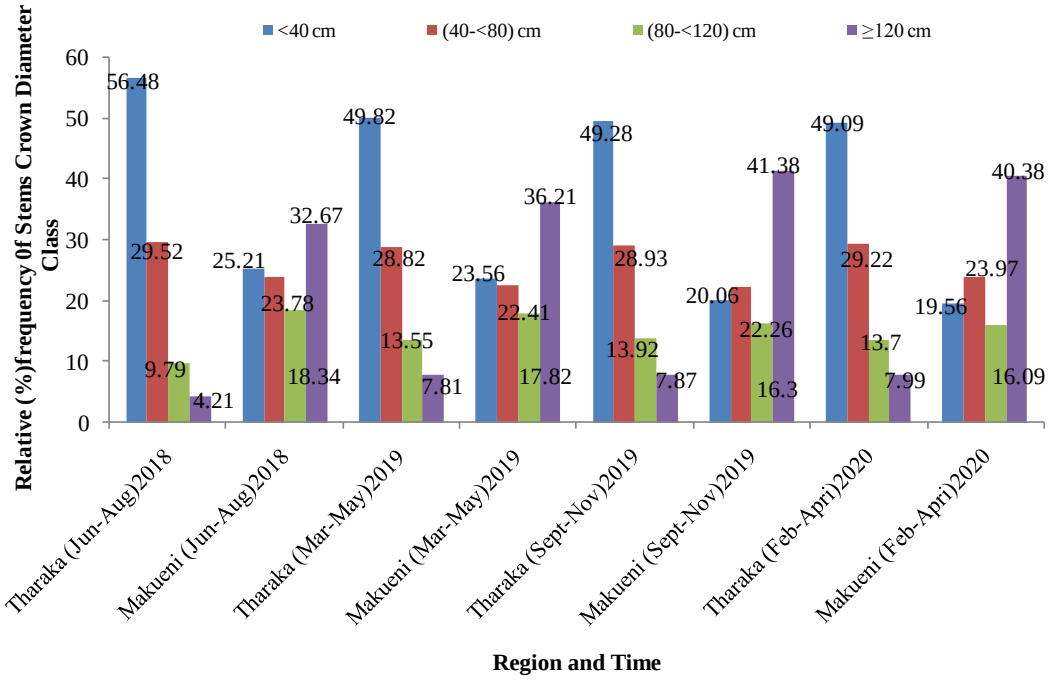

Figure 4.6: Relative Frequency (%) of *C. procera*'s Crown Diameter Class Distribution

Table 4.25: Wilcoxon Signed-Rank Tests Analysis Between Crown Diameter Classes at Different Time Points in Tharaka and Makueni

		(June to August) 2018			(March to May)2019			(September to November) 2019			(February to April) 2020		
Part a: Analysis of crown diameter classes at different time points in Tharaka													
		(40-<80)cm	**(80-<120)cm**	**≥120cm**	**(40-<80)cm**	**(80-<120)cm**	**≥120cm**	**(40-<80)cm**	**(80-<120)cm**	**≥120cm**	**(40-<80)cm**	**(80-<120)cm**	**≥120cm**
< 40 cm	Z	-13.48	-23.91	-32.57	-16.47	-21.82	-28.04	-15.61	-19.00	-24.83	-14.08	-20.93	-27.63
	p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
(40-<80) cm	Z		-17.84	-21.95		-14.56	-19.06		-15.44	-20.85		-13.96	-16.04
	p		<0.001	<0.001		<0.001	<0.001		<0.001	<0.001		<0.001	0.020
(80-<120) cm	Z			-0.052			-5.44			-3.12			-4.24
	p			1.000			1.000			1.000			1.000
Part b: Analysis of crown diameter classes at different time points in Makueni													
< 40 cm	Z	<0.001	<0.001	-10.19	<0.001	<0.001	-14.86	<0.001	<0.001	-13.74	<0.001	<0.001	-16.93
	p	1.000	1.000	0.048	1.000	1.000	0.039	1.000	1.000	0.031	1.000	1.000	0.020
(40-<80) cm	Z		<0.001	-11.74		<0.001	-11.94		<0.001	-15.62		-0.084	-17.67
	p		1.000	0.049		1.000	0.043		1.000	0.036		0.674	0.009
(80-<120) cm	Z			-14.53			-15.95			-21.11			-24.98
	p			<0.001			<0.001			<0.001			<0.001

Friedman test shows that there was a statistically significant difference in *C. procera*'s crown diameter class distribution within research time points ($\chi^2_{(3)}$ = 516.973, $p < 0.001$), with crown diameter class mean-ranks of 2.26, 2.57, 2.58 and 2.59 for (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020 time points respectively.

Wilcoxon signed-rank's pair-wise analysis (Table 4.26) shows that the mean-ranks of *C. procera*'s crown diameter class distributions in (June to August) 2018 was significantly lower than in (March to May) 2019, (September to November) 2019 and (February to April) 2020.

Table 4.26: Wilcoxon Signed-Rank's Post Hoc Analysis of *C. procera*'s Crown Diameter Class Distributions within Time Points

	(Mar-May)2019 & (Jun-Aug)2018	**(Sep-Nov)2019 & (Jun-Aug)2018**	**(Feb-April)2020 & (Jun-Aug)2018**	**(Sep-Nov)2019 & (Mar-May)2019**	**(Feb-April)2020 & (Mar-May)2019**	**(Feb-April)2020 & (Sep-Nov)2019**
Z	-13.885	-12.683	-13.871	-0.068	-1.744	-1.530
Asym. Sig. (2-tailed)	< 0.001	< 0.001	< 0.001	0.946	0.081	0.126
Exact Sig. (2-tailed)	< 0.001	< 0.001	< 0.001	0.950	0.096	0.116

Mann-Whitney *U* tests indicates that there was a statistically significant difference in *C. procera*'s crown diameter class distributions between the two semi-arid regions of Tharaka and Makueni (Mann Whitney $U = 1639758.000$, $p < 0.001$).

4.3.5. Edaphic factors affecting *C. procera*'s crown diameter class distributions

The effect test (Table 4.27 part a) indicates that: soil EC ($p = 0.031$), total N ($p = 0.001$), available P ($p < 0.001$), exchangeable K ($p = 0.022$) and exchangeable Mg ($p = 0.737$) at (20-40) cm were significantly associated with *C. procera'*s crown diameter class distributions in Tharaka.

In Makueni, soil EC ($p < 0.001$), OC content, ($p = 0.42$), available P ($p = 0.009$) and exchangeable Ca ($p < 0.002$) at (20-40) cm were significantly associated with *C. procera'*s crown diameter class distributions in Makueni (Table 4.27 part b).

Table 4.27: Effects Test of Edaphic Factors Affecting *C. procera*'s Crown Diameter Class Distributions in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a. Edaphic factors affecting crown diameter class distribution in Tharaka			
pH at (0-20) cm	1.482	1	0.223
EC at (0-20) cm	2.348	1	0.071
N at (0-20) cm	2.353	1	0.074
OC at (0-20) cm	1.262	1	0.261
P at (0-20) cm	1.386	1	0.239
K at (0-20) cm	1.118	1	0.078
Mg at (0-20) cm	1.303	1	0.254
Ca at (0-20) cm	2.113	1	0.121
Na at (0-20) cm	1.432	1	0.103
pH at (20-40) cm	1.721	1	0.095
EC at (20-40) cm	4.651	1	0.031
N at (20-40) cm	12.020	1	0.001
OC at (20-40) cm	1.871	1	0.094
P at (20-40) cm	15.083	1	<0.001
K at (20-40) cm	5.277	1	0.022
Mg at (20-40) cm	2.041	1	0.173
Ca at (20-40) cm	4.387	1	0.063
Na at (20-40) cm	1.668	1	0.096
Part b. Edaphic factors affecting crown diameter class distribution in Makueni			
pH at (0-20) cm	1.034	1	0.183
EC at (0-20) cm	1.951	1	0.162
N at (0-20) cm	0.922	1	0.337
OC at (0-20) cm	1.016	1	0.314
P at (0-20) cm	0.962	1	0.461
K at (0-20) cm	1.418	1	0.234
Mg at (0-20) cm	0.001	1	0.970
Ca at (0-20) cm	0.395	1	0.530
Na at (0-20) cm	1.467	1	0.198
pH at (20-40) cm	2.391	1	0.122
EC at (20-40) cm	8.764	1	<0.001
N at (20-40) cm	2.188	1	0.139
OC at (20-40) cm	4.138	1	0.042
P at (20-40) cm	6.880	1	0.009
K at (20-40) cm	3.932	1	0.062
Mg at (20-40) cm	1.554	1	0.212
Ca at (20-40) cm	9.192	1	0.002
Na at (20-40) cm	0.344	1	0.558

The second level analysis by eliminating variables that were not significantly associated with *C. procera*'s crown diameter class distributions in the first level analysis indicates that all remaining variables were significantly associated with *C. procera*'s crown diameter class distributions in Tharaka and Makueni (Table 4.28 part a and b).

Table 4.28: 2nd Level Test of Edaphic Factors Affecting *C. procera*'s Crown Diameter Class Distributions in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***P***
Part a. Edaphic factors affecting crown diameter class distribution in Tharaka			
EC at (20-40) cm	12.482	1	<0.001
N at (20-40) cm	4.046	1	0.044
P at (20-40) cm	4.602	1	0.047
K at (20-40) cm	5.500	1	0.019
Mg at (20-40) cm	11.073	1	<0.001
Part a. Edaphic factors affecting crown diameter class distribution in Makueni			
EC at (20-40) cm	7.493	1	0.006
OC at (20-40) cm	4.255	1	0.039
P at (20-40) cm	8.271	1	0.004
Ca at (20-40) cm	5.227	1	0.033

In Tharaka, the parameter estimate (Appendix Vc part a) indicates that: a unit increase in soil EC, total N, available P, exchangeable K and exchangeable Mg all at (20-40) cm were increasing the odds of crown diameter to be ≥ 120 cm class with odd ratios of 1.050 (95% CI, 2.733 to 11.271, Wald $\chi^2_{(1)} = 12.482$, $p < 0.001$; 1.048 (95% CI, 1.010 to 2.107, Wald $\chi^2_{(1)} = 4.046$, $p = 0.044$; 1.001 (95% CI, 1.998 to 3.000), Wald $\chi^2_{(1)} = 5.500$, $p = 0.019$; and 1.001 (95% CI, 1.748 to 2.831), Wald $\chi^2_{(1)} = 11.073$, $p < 0.001$ respectively.

In Makueni, (Appendix Vc part b) indicates that a unit increase in soil EC, OC content, available P and exchangeable Ca at (20-40) cm were associated with an increase in odds of crown diameter to be ≥ 120 cm class with odd ratios of 1.071 (95% CI, 1.452 to 9.504), Wald $\chi^2_{(1)} = 7.493$, $p = 0.006$; 1.056 (95% CI, 1.003 to

1.112), Wald $\chi^2_{(1)} = 4.255$, $p = 0.039$; 1.059 (95% CI, 8.352 to 16.276), Wald $\chi^2_{(1)} = 8.271$, $p = 0.004$ and 1.002 (95% CI, 1.000 to 1.034), Wald $\chi^2_{(1)} = 5.227$, $p = 0.033$ respectively. .

4.3.6. Weather conditions affecting *C. procera*'s crown diameter class distribution

Effect test indicates that preceding monthly's rainfall ($p < 0.001$), temperature ($p < 0.001$), wind speed ($p < 0.001$) and relative humidity ($p < 0.001$) were significantly associated with *C. procera*'s crown diameter class distribution (Table 4.29 part a and b).

Table 4.29: Effects Test of Weather Conditions Affecting *C. procera*'s Crown Diameter Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a. Weather conditions affecting crown diameter class distribution in Tharaka			
Total monthly rainfall (mm/month)	11.259	1	<0.001
Mean monthly temperature (°C/month)	41.852	1	<0.001
Mean monthly wind speed (m/s)	17.932	1	<0.001
Monthly relative humidity (%)	23.002	1	<0.001
Part b. Weather conditions affecting crown diameter class distribution in Makueni			
Total monthly rainfall (mm/month)	14.962	1	<0.001
Mean monthly temperature (°C/month)	32.398	1	<0.001
Mean monthly wind speed (m/s)	13.717	1	<0.001
Monthly relative humidity (%)	16.374	1	<0.001

In Tharaka, parameter estimate (Appendix Vd part a) indicates that: a unit increase in preceding months' average rainfall was associated with an increase in odds of crown diameter to be in $\geq$ 120 cm class with an odd ratio of 1.032 (95% CI, 1.023 to 1.198), Wald $\chi^2_{(1)} = 11.259$, $p < 0.001$. On the other hand, a unit increase in preceding monthly's average temperature, wind speed and relative humidity were associated with a decrease in odds of crown diameter to be in $\geq$ 120 cm class with odd ratios of 0.901 (95% CI, 0.641 to 0.983), Wald $\chi^2_{(1)} = 41.852$, $p < 0.001$; 0.967 (95% CI, 0.264

to 0.486), Wald $\chi^2_{(1)}$ = 17.932, p < 0.001 and 0.998 (95% CI, 0.782 to 0.831, Wald $\chi^2_{(1)}$ = 23.002, p < 0.001 respectively.

In Makueni, parameter estimate (Appendix Vd part b) indicates that: a unit increase in preceding months' average rainfall was associated with an increase in odds of crown diameter to be in ≥ 120 cm class with an odd ratio of 1.022 (95% CI, 2.182 to 5.842), Wald $\chi^2_{(1)}$ = 14.962, p < 0.001. A unit increase in preceding monthly's average temperature, wind speed and relative humidity were decreasing the odds of crown diameter to be in ≥ 120 cm class with odd ratios of 0.843 (95% CI, 0.056 to 0.174), Wald $\chi^2_{(1)}$ = 32.398, p < 0.001; 0.974 (95% CI, 0.462 to 0.641), Wald $\chi^2_{(1)}$ = 13.717, p < 0.001 and 0.988 (95% CI, 0.164 to 0.438, Wald $\chi^2_{(1)}$ = 16.374, p < 0.001 respectively.

4.3.7. Root collar diameter class distribution of *C. procera*

The relative frequency (%) of *C. procera* stems with root collar diameter <4 cm showed a reducing trend from 49.87% and 42.12 % in (June to August) 2018 to 36.33% and 28.71 % in (February to April) 2020 in Tharaka and Makueni respectively (Figure 4.7). On the other hand, the relative frequency of *C. procera* stems with root collar diameter (4-< 8) cm and ≥8 cm showed an increasing trend from 35.79% to 43.05% and 14.34% to 20.62% in Tharaka and 33.52% to 41.95% and 24.36% to 29.34% in Makueni from (June to August) 2018 to (February to April) 2020 (Figure 4.7). This shows that over time, *C. procera* grows by increasing its root collar diameter.

However, pairwise analysis between size classes at every time point (Table 4.30) indicates that the relative frequency of *C. procera* stems with root collar diameter ≥8 cm was significantly lower than the relative frequencies of *C. procera* stems at every

research time points in both Tharaka and Makueni. On the other hand, there were no significant differences in the relative frequencies.

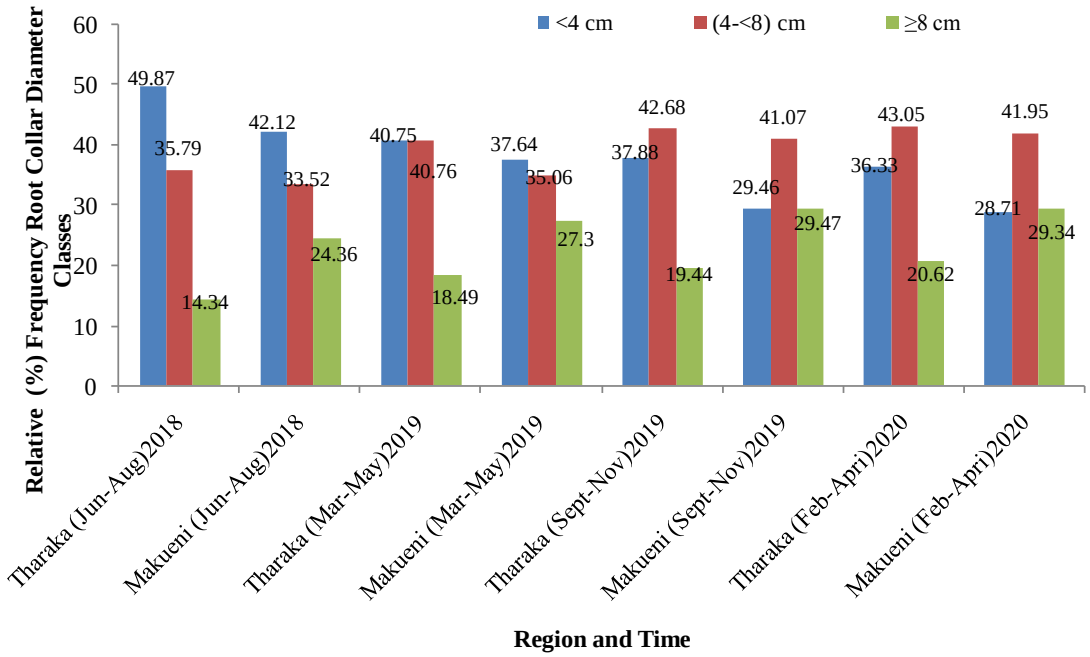

Figure 4.7: Relative Frequency (%) of *C. procera*'s Root Collar Diameter Class Distribution

Table 4.30: Wilcoxon Signed-Rank Tests Analysis of Bewteen *C. procera*'s Root Collar Diameter Classes at Different Time Points in Tharaka and Makueni

		(June to August) 2018		(March to May)2019		(September to November) 2019		(February to April) 2020	
Part A: analysis of root Collar Diameter classes at different time points in Tharaka									
		(4-<8) cm	**≥8 cm**	**(4-<8) cm**	**≥8 cm**	**(4-<8) cm**	**≥8 cm**	**(4-<8) cm**	**≥8 cm**
< 4 cm	Z	-4.27	-12.93	-1.46	-14.17	-5.04	-19.32	-1.36	-16.52
	p	0.061	0.013	0.063	0.023	0.070	<0.001	0.082	<0.001
(4-<8) cm	Z		-13.63		-14.75		-15.83		-19.64
	p		0.010		<0.001		<0.001		<0.001
Part b: analysis of root Collar Diameter classes at different time points in Makueni									
< 4 cm	Z	-2.26	-9.55	-2.98	-11.94	-3.14	-15.68	-2.00	-22.38
	p	0.098	0.044	0.078	0.044	1.000	<0.001	0.0801	<0.001
(4-<8) cm	Z		-12.68		-13.16		14.49		-19.95
	p		0.031		0.041		<0.001		<0.001

Friedman test shows that there was a statistically significant difference in root collar diameter class distribution within research time points ($\chi^2_{(3)} = 513.475$, $p < 0.001$),

with root collar diameter class mean-ranks of 2.27, 2.51, 2.58 and 2.64 for (June to August) 2018, (March to May) 2019, (September to November) 2019 and (February to April) 2020 respectively.

Pair-wise comparisons using Wilcoxon signed-rank tests (Table 4.31) indicates that the root collar diameter class distribution's mean-ranks in (February to April) 2020 was significantly higher than in (June to August) 2018, (March to May) 2019 and (September to November) 2019.

Table 4.31: Wilcoxon Signed-Ranks' Post Hoc Analysis of *C. procera*'s Root Collar Diameter Class Distribution Within Time Points

	(Mar-May) 2019 & (Jun-Aug) 2018	**(Sep-Nov) 2019 & (Jun-Aug) 2018**	**(Feb-April) 2020 & (Jun-Aug) 2018**	**(Sep-Nov) 2019 & (Mar-May) 2019**	**(Feb-April) 2020 & (Mar-May) 2019**	**(Feb-April) 2020 & (Sep-Nov)2019**
Z	-12.347	-14.390	-15.765	-4.833	-7.371	-5.864
Asym. Sig. (2-tailed)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Exact Sig. (2-tailed)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Mann-Whitney *U* tests showed a statistically significant difference in root collar diameter sizes between Tharaka and Makueni (Mann Whitney $U = 2664290.0$, $p < 0.001$).

4.3.8. Edaphic factors affecting *C. procera*'s root collar diameter class distribution

In Tharaka, the effect test (Table 4.32 part a) indicates that soil pH ($p < 0.001$) at (0-20) cm, cm, total N ($p = 0.014$) at (20-40) cm, and exchangeable Mg ($p = 0.028$) at (20-40) cm were significantly associated with *C. procera*'s root collar diameter class distribution.

In Makueni, soil EC ($p < 0.001$) and total N ($p < 0.001$) at (20-40) cm were the only edaphic factors significantly associated with *C. procera*'s root collar diameter class distribution (Table 4.32 part b).

Table 4.32: Effects Test of Edaphic Factors Affecting *C. procera*'s Root Collar Diameter Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Edaphic Factors Affecting Root Collar Diameter Class Distribution in Tharaka			
pH at (0-20) cm	36.151	1	<0.001
EC at (0-20) cm	1.049	1	0.306
N at (0-20) cm	1.164	1	0.233
OC at (0-20) cm	1.257	1	0.262
P at (0-20) cm	0.857	1	0.354
K at (0-20) cm	1.170	1	0.279
Mg at (0-20) cm	1.340	1	0.247
Ca at (0-20) cm	0.444	1	0.505
Na at (0-20) cm	1.131	1	0.288
pH at (20-40) cm	0.468	1	0.494
EC at (20-40) cm	3.898	1	0.048
N at (20-40) cm	6.094	1	0.014
OC at (20-40) cm	2.023	1	0.155
P at (20-40) cm	1.809	1	0.179
K at (20-40) cm	.085	1	0.771
Mg at (20-40) cm	4.842	1	0.028
Ca at (20-40) cm	1.975	1	0.061
Na at (20-40) cm	0.395	1	0.420
Part b: Edaphic Factors Affecting Root Collar Diameter Class Distribution in Makueni			
pH at (0-20) cm	2.492	1	0.114
EC at (0-20) cm	0.406	1	0.524
N at (0-20) cm	4.257	1	0.054
OC at (0-20) cm	0.879	1	0.199
P at (0-20) cm	0.665	1	0.231
K at (0-20) cm	4.428	1	0.055
Mg at (0-20) cm	4.826	1	0.058
Ca at (0-20) cm	3.835	1	0.052
Na at (0-20) cm	1.854	1	0.173
pH at (20-40) cm	2.823	1	0.076
EC at (20-40) cm	17.545	1	<0.001
N at (20-40) cm	18.415	1	<0.001
OC at (20-40) cm	0.569	1	0.411
P at (20-40) cm	0.440	1	0.741
K at (20-40) cm	0.768	1	0.381
Mg at (20-40) cm	0.840	1	0.648
Ca at (20-40) cm	2.280	1	0.074
Na at (20-40) cm	0.373	1	0.541

Second level analysis by eliminating variables that were not statistically significant in first level analysis indicates that soil pH ($p < 0.001$) at (20-40) cm , EC ($p = 0.034$) at (20-40) cm, total N ($p < 0.001$) at (20-40) cm and exchangeable Mg ($p < 0.001$) at (20-40) cm were significantly associated with root collar diameter class distribution in Tharaka (Table 4.33 part a).

In Makueni, soil EC ($p < 0.001$) at (20-40) cm and total N ($p < 0.001$) at (20-40) cm were significantly associated with root collar diameter class distribution (Table 4.33 part b).

Table 4.33: 2nd Level Test of Edaphic Factors Affecting *C. procera*'s Root Collar Diameter Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Edaphic Factors Affecting Root Collar Diameter Class Distribution in Tharaka			
pH at (0-20) cm	19.139	1	<0.001
EC at (20-40) cm	12.894	1	0.034
N at (20-40) cm	19.037	1	<0.001
Mg at (20-40) cm	24.690	1	<0.001
Part b: Edaphic Factors Affecting Root Collar Diameter Class Distribution in Makueni			
EC at (20-40) cm	12.247	1	<0.001
N at (20-40) cm	24.458	1	<0.001

In Tharaka,a unit increase in soil pH at (0-20) cm was associated with a decrease in the odds of root collar diameter to be in ≥ 8 cm class with odd ratios of 0.900 (95% CI, 0.858 to 0.943), Wald $\chi^2_{(1)} = 19.139$, $p < 0.001$. Contrary, a unit increase in soil EC, total N and exchangeable Mg at (20-40) cm were associated with an increase in the odds of root collar diameter to be in ≥ 8 cm class with odd ratios of 1.027 (95% CI, 1.383 to 2.398, Wald $\chi^2_{(1)} = 12.894$, p= 0.0034; 1.046 (95% CI, 1.334 to 2.659), Wald $\chi^2_{(1)} = 19.037$, $p < 0.004$; and 1.092 (95% CI, 3.995 to 5.998), Wald $\chi^2_{(1)} = 24.690$, $p < 0.001$ respectively (Appendix Ve part a).

In Makueni, a unit increase in soil pH at (0-20) cm, soil EC and total N at (20-40) cm were increasing the odds of root collar diameter to be in ≥ 8 cm class with odd ratios of 1.075 (95% CI, 2.159 to 15.316), Wald $\chi^2_{(1)} = 12.247$, $p < 0.001$; and 1.089 (95% CI, 1.865 to 4.229, Wald $\chi^2_{(1)} = 24.458$, $p < 0.001$ respectively (Appendix Ve part b.

4.3.9. Weather conditions affecting root collar diameter of *C. procera*

Effects test (Table 4.34) indicates that preceding months' average monthly rainfall ($p < 0.001$), temperature ($p < 0.001$) and relative humidity ($p < 0.001$) were significantly associated with root collar diameter class distribution of *C. procera* in Tharaka. On the other hand, only preceeding month's rainfall ($p < 0.001$) and temperature ($p < 0.001$) were significantly associated with *C. procera*'s root collar class distribution diameter in Makueni.

Table 4.34: Effects Test of Weather Conditions Affecting *C. procera*'s Root Collar Diameter Class Distribution

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Weather Conditions Affecting Root Collar Diameter Class Distribution in Tharaka			
Average monthly rainfall	112.717	1	<0.001
Mean monthly temperature	112.114	1	<0.001
Mean monthly wind speed	13.598	1	1.000
Mean monthly relative humidity	196.598	1	<0.001
Part b: Weather Conditions Affecting Root Collar Diameter Class Distribution in Makueni			
Average monthly rainfall	104.630	1	<0.001
Mean monthly temperature	98.993	1	<0.001
Mean monthly wind speed	10.715	1	1.000
Mean monthly relative humidity	13.194	1	1.000

The second level analysis by eliminating variables that were not statistically significant in the first level analysis indicates that: preceding months' average rainfall ($p< 0.001$), temperature ($p = 0.002$) and relative humidity ($p = 0.001$) were significantly associated with *C. procera*'s root collar diameter class distribution in Tharaka (Table

4.35 part a). On the other hand, preeceding month's rainfall ($p < 0.001$) and temperature ($p < 0.001$) were significantly associated with *C. procera*'s root collar diameter class distribution in Makueni (Table 4.35 part b).

Table 4.35: 2nd Level Test of Weather Conditions Affecting *C. procera*'s Root Collar Diameter Class Distribution in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Weather Conditions Affecting Root Collar Diameter Class Distribution in Tharaka			
Total monthly rainfall	179.687	1	<0.001
Mean monthly temperature	196.898	1	<0.001
Average monthly relative humidity	212.021	1	<0.001
Part b: Weather Conditions Affecting Root Collar Diameter Class Distribution in Makueni			
Total monthly rainfall	22.836	1	<0.001
Mean monthly temperature	30.329	1	<0.001
Average monthly relative humidity	22.836	1	<0.001

Parameter estimate (Appendix Vf part a) indicates that: a unit increase in average monthly rainfall and temperature were associated with an increase in odds of *C. procera*'s root collar diameter to be in ≥ 8 cm class with odd ratios of 1.136 (95% CI, 1.973 to 1.980), Wald $\chi^2_{(1)} = 179.687$, $p < 0.001$ and 1.114 (95% CI, 1.084 to 2.155), Wald $\chi^2_{(1)} = 196.898$, $p < 0.001$ respectively. On the other hand, a unit increase in relative humidity was associated with a decrease in odds of *C. procera*'s root collar diameter to be in ≥ 8 cm class with an odd ratio of 0.864 (95% CI, 0847 to 0.881), Wald $\chi^2_{(1)} = 212.021$, $p < 0.001$.

In Makueni, a unit increase in average monthly rainfall and temperature were associated with an increase in odds of *C. procera*'s root collar diameter to be in ≥ 8 cm class with odd ratios of 1.015 (95% CI, 1.009 to 1.021), Wald $\chi^2_{(1)} = 22.836$, $p < 0.001$ and 1.347 (95% CI, 1.732 to 3.179), Wald $\chi^2_{(1)} = 30.329$, $p < 0.001$ respectively (Appendix Vf part b).

4.4. Phenology of *C. procera* in the Semi-Arid Regions of Tharaka and Makueni

4.4.1. Flowering and fruiting activity indices of *C. procera*

Figure 4.8 indicates that from (June to August) 2018 to (September to November) 2019, flowering indices of naturally growing *C. procera* showed a reducing trend from 75.87% to 48.05% in Tharaka and from 83.06% to 50.48% in Makueni respectively. Over the same time, fruiting activity indices also reduced from 64.97% to 42.71% in Tharaka and 69.6% to 43.64% in Makueni respectively. However, there was an increase in flowering and fruiting activity indices from 48.05% to 61.66% and 42.71% to 52.39% in Tharaka and 50.48% to 65.54% and 43.64% to 47.62% in Makueni from (September to November) 2019 to (February to April) 2020 respectively.

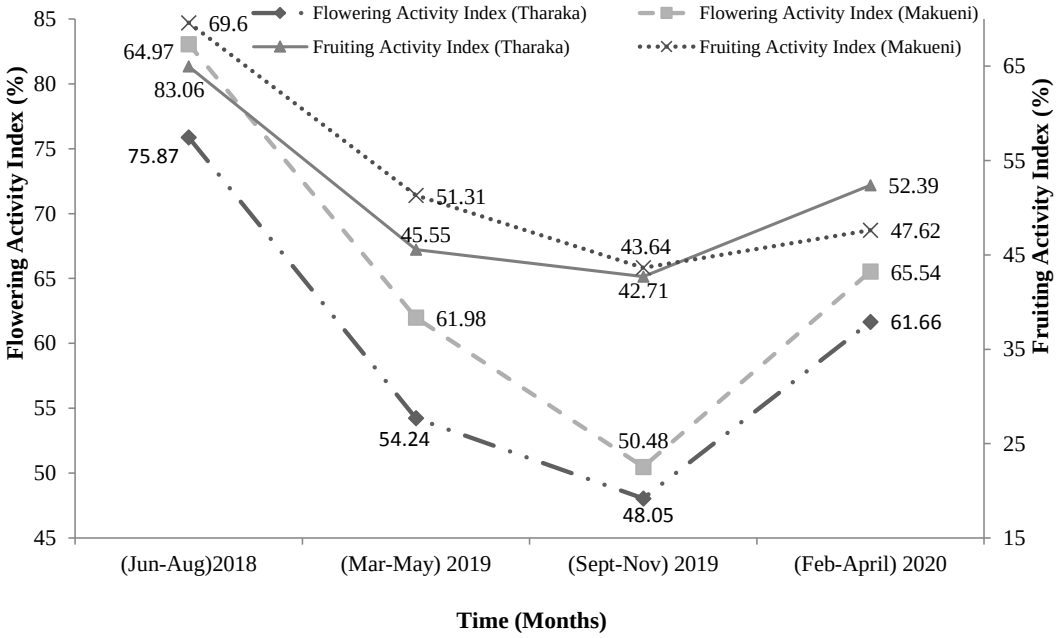

Figure 4.8: Flowering and Fruiting Activity Indices of *C. procera*

For analysis, the assumptions of sphericity and homogeneity of variance were met with Mauchly's test and Levene's test having $p > 0.05$ for flowering and fruiting activity index in both Tharaka and Makueni.

Between the regions, there was a statistically significant difference in mean flowering activity index between the semi-arid regions of Tharaka and Makueni ($F_{(1,89)} = 5.094$, $p = 0.026$, $\eta p^2 = 0.054$) but no significant difference in the mean fruiting activity index between the two semi-arid regions ($F_{(1,89)} = 0.262$, $p = 0.610$, $\eta p^2 = 0.003$) (Table 4.36 parts a and b). This imply that naturally growing *C. procera* in Makueni have higher flowering activity index than in Tharaka.

Table 4.36: Between-Subject Tests for *C. procera*'s Activity Indices

Source	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Part a: Between-Subjects' Test (Semi-Arid Regions) for Flowering Activity Index						
Region	2430.158	1	2430.158	5.094	0.026	0.054
Error	42462.217	89	477.104			
Part b: Between-Subjects' Test (Semi-Arid Regions) for Fruiting Activity Index						
Region	273.828	1	273.828	0.262	0.610	0.003
Error	92987.169	89	1044.800			

Mixed repeated measure ANOVA showed a statistically significant difference in the mean flowering ($F_{(3,165)} = 27.256$, $p < 0.001$, $\eta p^2 = 0.239$) and fruiting ($F_{(3,165)} = 10.064$, $p < 0.001$, $\eta p^2 = 0.155$) activity indices of *C. procera* in the semi-arid region of Tharaka within research time points (Table 4.37 part a and b).

In Makueni, there were also statistically significant differences in the mean flowering ($F_{(3,102)} = 10.948$, $p < 0.001$, $\eta p^2 = 0.244$) and fruiting ($F_{(3,102)} = 6.764$, $p < 0.001$, $\eta p^2 = 0.166$) activity indices of *C. procera* within research time points (Table 4.37 part c and d).

Table 4.37: Within-Subject's Effects for *C. procera*'s Activity Indices in Tharaka and Makueni

Source		Type III Sum of Squares	df	Mean Square	F	***P***	Partial Eta Squared
Part a: Tests Within-Subjects' Effects (Time) for Flowering Activity Index in Tharaka							
Time	Sphericity Assumed	24113.931	3	8037.977	17.256	<0.001	0.239
Error (Time)	Sphericity Assumed	76857.280	165	465.802			
Part b: Tests Within-Subjects' Effects (Time) for Fruiting Activity Index in Tharaka							
Time	Sphericity Assumed	17094.378	3	5698.126	10.064	<0.001	0.155
Error (Time)	Sphericity Assumed	93416.940	165	566.163			
Part c: Tests Within-Subjects' Effects (Time) for Flowering Activity Index in Makueni							
Time	Sphericity Assumed	19114.478	3	6371.493	10.948	<0.001	0.244
Error (Time)	Sphericity Assumed	59364.352	102	582.003			
Part d: Tests Within-Subjects' Effects (Time) for Fruiting Activity Index in Makueni							
Time	Sphericity Assumed	13828.927	3	4609.642	6.764	<0.001	0.166
Error (Time)	Sphericity Assumed	69512.425	102	681.494			

Bonferroni's pair-wise analysis (Appendix VIa) whose outputs summarized in Table 4.38 part a, b, c and d indicate that the mean flowering (75.87%) and fruiting (64.97%) in Tharaka and mean flowering (83.06%) and fruiting (69.6%) activity indices in (June to August) 2018 were significantly higher than in (March to May) 2019, (September to November) 2019 and (February to April) 2020.

Table 4.38: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s Activity Indices Within Time Points

	(March-April) 2019	**September–November) 2019**	**(February-April) 2020**
Part a: Pairwise Comparison of Flowering Activity Index in Tharaka			
(June-August) 2018	$p<0.001$	$p<0.001$	$p<0.001$
(March-April) 2019		$p = 0.129$	$p = 0.096$
(September–November) 2019			$P = 0.001$
Part b: Pairwise Comparison of Fruiting Activity Index in Tharaka			
(June-August) 2018	$P < 0.001$	$P < 0.001$	$P = 0.003$
(March-April) 2019		$p= 0.462$	$p= 0.103$
(September–November) 2019			$p= 0.046$

Table 4.38: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s Activity Indices Within Time Points (Continued)

	(March-April) 2019	September–November) 2019	(February-April) 2020
Part c: Pairwise Comparison of Flowering Activity Index in Makueni			
(June-August) 2018	*P* = 0.003	*p*< 0.001	*P* = 0.007
(March-April) 2019		*p*= 0.609	*P* = 1.000
(September–November) 2019			*P* = 0.072
Part d: Pairwise Comparison of Fruiting Activity Index in Makueni			
(June-August) 2018	*P* = 0.015	*P* = 0.001	*P* = 0.004
(March-April) 2019		*p*= 1.100	*p*= 1.000
(September–November) 2019			*p*= 1.000

4.4.2. Edaphic factors affecting *C. procera*'s activity indices

In Tharaka, soil OC content (p = 0.024) at (0-20) cm, available P (p = 0.022) at (0-20) cm, soil OC content (p = 0.021) at (20-40) cm available P (p = 0.002) at (20-40) cm and exchangeable Na (p =0.039) were significantly associated with flowering activity index (Table 4.39 part a). However, there were no significant association between all edaphic factors tested with fruiting activity index in Tharaka (Table 4.39 part b).

In Makueni, OC content (p = 0.001) at (0-20), available P (p = 0.002) at (0-20) cm, OC content (p = 0.029) at (20-40) cm and available P (p < 0.001) at (20-40) cm were significantly associated with flowering activity indices of C. *procera* (Table 4.39 part c). However, there were also no significant association between all tested edaphic factors at both (0-20) and (20-40) cm with *C. procera*'s fruiting activity indices (Table 4.39 part d).

Table 4.39: Effect Test of Edaphic Factors affecting *C. procera*'s Activity Indices

Source	Type III Wald Chi-Square	df	*p*
Part a: Edaphic Factors Affecting *C. procera's* Flowering Activity Index in Tharaka			
(Intercept)	21.840	1	<0.001
pH at (0-20) cm	1.514	1	0.541
EC (0-20) cm	2.233	1	0.782
N (0-20) cm	0.431	1	1.000
OC (0-20) cm	21.001	1	0.024

Table 4.39: Effect Test of Edaphic Factors affecting *C. procera*'s Activity Indices (Continued)

Source	Type III Wald Chi-Square	df	*p*
P (0-20) cm	25.353	1	0.022
K (0-20) cm	0.530	1	0.360
Mg (0-20) cm	0.054	1	1.000
Ca (0-20) cm	2.213	1	0.703
Na (0-20) cm	3.075	1	0.342
pH at (20-40) cm	2.785	1	0.734
EC at (20-40) cm	0.848	1	1.000
N at (20-40) cm	2.160	1	0.684
OC at (20-40) cm	22.017	1	0.021
P at (20-40) cm	27.399	1	0.002
K at (20-40) cm	4.704	1	0.298
Mg at (20-40) cm	2.520	1	0.961
Ca at (20-40) cm	8.939	1	0.237
Na at (20-40) cm	18.840	1	0.039
Part b: Edaphic Factors Affecting *C. procera's* Fruiting Activity Index in Tharaka			
(Intercept)	56.638	1	<0.001
pH at (0-20) cm	0.404	1	1.000
EC at (0-20) cm	6.170	1	0.458
N at (0-20) cm	3.423	1	0.672
OC at (0-20) cm	7.864	1	0.426
P at (0-20) cm	0.201	1	1.000
K at (0-20) cm	1.431	1	0.981
Mg at (0-20) cm	2.138	1	0.792
Ca at (0-20) cm	11.661	1	0.356
Na at (0-20) cm	7.199	1	0.457
pH at (20-40) cm	5.255	1	0.452
EC at (20-40) cm	4.777	1	0.456
N at (20-40) cm	6.579	1	0.328
OC at (20-40) cm	0.040	1	1.000
P at (20-40) cm	6.413	1	0.997
K at (20-40) cm	4.823	1	0.543
Mg at (20-40) cm	1.298	1	0.762
Ca at (20-40) cm	1.352	1	0.170
Na at (20-40) cm	0.029	1	0.800
Part c: Edaphic Factors Affecting *C. procera's* Flowering Activity Index in Makueni			
(Intercept)	23.133	1	<0.001
pH at (0-20) cm	0.587	1	0.443
EC (0-20) cm	0.105	1	0.745
N (0-20) cm	3.013	1	0.083
OC (0-20) cm	10.447	1	0.001
P (0-20) cm	9.759	1	0.002
K (0-20) cm	4.995	1	0.025
Mg (0-20) cm	1.099	1	0.294
Ca (0-20) cm	1.483	1	0.223
Na (0-20) cm	0.121	1	0.728
pH at (20-40) cm	1.280	1	0.258
EC at (20-40) cm	0.679	1	0.410
N at (20-40) cm	0.974	1	0.324
OC at (20-40) cm	15.396	1	0.029

Table 4.39: Effect Test of Edaphic Factors affecting *C. procera*'s Activity Indices (Continued)

Source	Type III Wald Chi-Square	df	*p*
P at (20-40) cm	25.501	1	<0.001
K at (20-40) cm	2.027	1	0.155
Mg at (20-40) cm	2.710	1	0.100
Ca at (20-40) cm	4.249	1	0.239
Na at (20-40) cm	0.061	1	0.805
Part d: Edaphic Factors Affecting *C. procera's* Fruiting Activity Index in Makueni			
(Intercept)	4.123	1	0.042
pH at (0-20) cm	0.051	1	0.821
EC at (0-20) cm	0.040	1	0.841
N at (0-20) cm	3.261	1	0.071
OC at (0-20) cm	3.450	1	0.063
P at (0-20) cm	3.094	1	0.079
K at (0-20) cm	0.426	1	0.514
Mg at (0-20) cm	0.012	1	0.913
Ca at (0-20) cm	0.005	1	0.941
Na at (0-20) cm	0.098	1	0.754
pH at (20-40) cm	0.485	1	0.486
EC at (20-40) cm	0.560	1	0.454
N at (20-40) cm	0.257	1	0.613
OC at (20-40) cm	2.174	1	0.140
P at (20-40) cm	2.521	1	0.112
K at (20-40) cm	0.155	1	0.693
Mg at (20-40) cm	1.609	1	0.205
Ca at (20-40) cm	2.528	1	0.112
Na at (20-40) cm	1.575	1	0.210

Second level analysis (Table 4.40 part a) after eliminating edaphic variables that were statistically insignificant in the first level: soil available P at (0-20) cm and at (20-40) cm was the only edaphic factors having significant association with flowering activity indices in Tharaka. On the other hand, only soil available P at (20-40) cm was significantly associated with flowering activity indices of *C. procera* in Makueni (Table 4.40 part b).

Table 4.40: 2nd Level Test of Edaphic Factors Affecting *C. procera*'s Flowering Activity Indices in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Edaphic Factors Affecting *C. procera*'s Flowering Activity Index in Tharaka			
(Intercept)	21.297	1	<0.001
OC at (0-20) cm	0.596	1	1.000
P at (0-20) cm	17.931	1	0.027
OC at (20-40) cm	3.093	1	0.275
P at (20-40) cm	14.976	1	0.032
Ca at (20-40) cm	2.083	1	0.073
Na at (20-40) cm	0.021	1	1.000
Part b: Edaphic Factors Affecting *C. procera*'s Flowering Activity Index in Makueni			
(Intercept)	14.093	1	<0.001
OC at (0-20) cm	1.962	1	0.099
P at (0-20) cm	0.927	1	0.247
OC at (20-40) cm	0.829	1	1.000
P at (20-40) cm	11.780	1	0.033

Third level analysis (Table 4.41 part a) by eliminating edaphic factors that were statistically insignificant in the second level analysis indicates that available P at (0-20) cm and (20-40) cm was significantly associated with *C. procera'*s flowering activity index in Tharaka.

In Makueni, third level analysis indicates that soil available P at (20-40) cm was significantly associated with *C. procera'*s flowering activity index in Makueni.

Table 4.41: 3rd Level Test of Edaphic Factors Affecting *C. procera*'s Flowering Activity Indices in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Edaphic Factors Affecting *C. procera*'s Flowering Activity Index in Tharaka			
(Intercept)	19.578	1	<0.001
P at (0- 20) cm	11.959	1	0.016
P at (20-40) cm	12.072	1	0.008
Part b: Edaphic Factors Affecting *C. procera*'s Flowering Activity Index in Makueni			
(Intercept)	17.181	1	<0.001
P at (20- 40) cm	15.521	1	0.047

In Tharaka, a unit increase in soil available P at (0-20) cm and (20-40) cm depth was significantly increasing *C. procera*'s flowering activity index by 1.128 (95% CI,

0.097 to 1.475), Wald $\chi^2_{(1)}$ = 11.959, p = 0.016 and 1.172 (95% CI, 0.367 to 3.738), Wald $\chi^2_{(1)}$ = 12.072, p = 0.008 times respectively (Appendix VIb part a).

In Makueni, a unit increase in soil available P at (20-40) was significantly increasing *C. procera*'s flowering activity index by 1.238 (95% CI, 1.238 to 2.941), Wald $\chi^2_{(1)}$ = 15.521, p = 0.047 times (Appendix VIb part b).

4.3.3. Weather conditions affecting flowering and fruiting activity indices

Linear regression based on GEE (Table 4.42 parts a, b, c and d) indicates that preceding monthly's rainfall, temperature and wind speed were significantly associated with flowering and fruiting activity indices of *C. procera* in the semi-arid regions of Tharaka and Makueni.

Table 4.42: Effect Test of Weather Conditions Affecting *C. procera*'s Activity Indices in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Weather conditions affecting flowering activity index in Tharaka			
(Intercept)	5.963	1	<0.001
Mean monthly rainfall (mm/month)	7.902	1	<0.001
Mean monthly temperature (°C/month)	6.952	1	<0.001
Mean monthly wind speed (m/s)	9.063	1	0.031
Monthly relative humidity (%)	0.791	1	0.862
Part b: Weather conditions affecting fruiting activity index in Tharaka			
(Intercept)	13.963	1	<0.001
Mean monthly rainfall (mm/month)	7.902	1	<0.001
Mean monthly temperature (°C/month)	6.936	1	<0.001
Mean monthly wind speed (m/s)	8.275	1	0.025
Monthly relative humidity (%)	1.903	1	0.362
Part c: Weather conditions affecting flowering activity index in Makueni			
(Intercept)	8.938	1	<0.001
Mean monthly rainfall (mm/month)	11.942	1	<0.001
Mean monthly temperature (°C/month)	7.964	1	0.002
Mean monthly wind speed (m/s)	10.743	1	<0.001
Monthly relative humidity (%)	1.834	1	0.785
Part d: Weather conditions affecting fruiting activity index in Makueni			
(Intercept)	16.942	1	<0.001
Mean monthly rainfall (mm/month)	16.036	1	<0.001
Mean monthly temperature (°C/month)	12.936	1	<0.001
Mean monthly wind speed (m/s)	11.528	1	<0.001
Monthly relative humidity (%)	1.165	1	0.319

Second level analysis (Table 4.43 parts a, b, c and d) by eliminating weather variables that were statistically insignificant in the first level analysis indicates that: preceding months' mean monthly rainfall, temperature and wind speed were significantly associated with flowering and fruiting activity indices of naturally growing *C. procera* in Tharaka and Makueni.

Table 4.43: 2nd Level Test of Weather Factors Affecting *C. procera*'s Activity Indices in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Weather Conditions Affecting *C. procera*'s Flowering Activity Index in Tharaka			
(Intercept)	8.043	1	0.005
Mean monthly rainfall	5.266	1	0.022
Mean monthly temperature	10.738	1	0.001
Mean monthly wind speed	14.790	1	<0.001
Part b: Weather Conditions Affecting *C. procera*'s Fruiting Activity Index in Tharaka			
(Intercept)	5.262	1	0.022
Mean monthly rainfall	6.733	1	0.033
Mean monthly temperature	7.170	1	0.007
Mean monthly wind speed	13.422	1	<0.001
Part c: Weather Conditions Affecting *C. procera*'s Flowering Activity Index in Makueni			
(Intercept)	7.851	1	0.005
Mean monthly rainfall	9.014	1	0.003
Mean monthly temperature	5.134	1	0.023
Mean monthly wind speed	6.024	1	0.037
Part d: Weather Conditions Affecting *C. procera*'s Fruiting Activity Index in Makueni			
(Intercept)	12.122	1	<0.001
Mean monthly rainfall	12.045	1	0.001
Mean monthly temperature	9.385	1	0.002
Mean monthly wind speed	7.753	1	0.036

In Tharaka, (Appendix VIc part a and b) indicates that: a unit increase in preceding months' average monthly rainfall was significantly increasing *C. procera*'s flowering and fruiting activity indices by 1.234 (95% CI, 1.054 to 2.951), Wald $\chi^2_{(1)} = 5.266$, $p = 0.022$ and 1.163 (95% CI, 0.995 to 2.153), Wald $\chi^2_{(1)} = 6.733$, $p = 0.033$ times respectively. However, a unit increase in preceding month's average monthly temperature was significantly reducing *C. procera*'s flowering and fruiting activity

indices by 0.941 (95% CI, 1.254 to 3.434) Wald $\chi^2_{(1)}$ = 10.738, p = 0.001 and 0.867 (95% CI, 1.360 to 2.400), Wald $\chi^2_{(1)}$ = 7.170, p = 0.007 times respectively. A unit increase in preceding months' average monthly wind speed was significantly reducing flowering and fruiting activity indices of *C. procera* by 0.992 (95% CI, 1.372 to 2.391), Wald $\chi^2_{(1)}$ = 14.790, $p < 0.001$ and 0.956 (95% CI, 0.1.304 to 9.533), Wald $\chi^2_{(1)}$ = 13.422, $p < 0.001$ times respectively.

In Makueni, (Appendix VIc part c and d) indicates that: a unit increase in preceding months' average monthly rainfall was significantly increasing *C. procera*'s flowering and fruiting activity indices by 1.158 (95% CI, 1.407 to 2.828), Wald $\chi^2_{(1)}$ = 9.014, p = 0.003 and 1.075 (95% CI, 0.312 to 0.723), Wald $\chi^2_{(1)}$ = 12.045, p = 0.001 times respectively. On the other hand, a unit increase in preceding month's average monthly temperature was significantly reducing *C. procera*'s flowering and fruiting activity indices by 0.974 (95% CI, 0.567 to 1.004) Wald $\chi^2_{(1)}$ = 5.134, p = 0.023 and 0.879 (95% CI, 1.1554 to 2.794), Wald $\chi^2_{(1)}$ = 9.385, p = 0.002 times respectively. A unit increase in preceding months' average monthly wind speed was significantly reducing flowering and fruiting activity indices of *C. procera* by 0.951 (95% CI, 1.131 to 7.491), Wald $\chi^2_{(1)}$ = 6.024, p = 0.037 and 0.983 (95% CI, 1.927 to 2.122), Wald $\chi^2_{(1)}$ = 7.753, p = 0.036 times respectively.

4.4.4. Number of flowers and fruits

The number of flowers and fruits per flowering and fruiting *C. procera* stem in the semi-arid regions of Tharaka and Makueni was decreasing in the periods of (June to August) 2018 to (September –November) 2019 and a slight increase in (February to April) 2020 in Tharaka and Makueni (Figure 4.9).

However, mixed reapeated ANOVA (Table 4.44) indicates that the mean number of flowers and fruits on flowering ($F_{(1,317)} = 9.135$, p= 0.003, $\eta p^2 = 0.228$) and fruiting ($F_{(1,317)} = 6.877$, $p = 0.009$, $\eta p^2 = 0.222$) *C. procera* stems varied significantly between the semi-arid regions of Tharaka and Makueni (Table 4.44). This implies that naturally growing *C. procera* in Makueni had higher number of flowers and fruits than those in Tharaka.

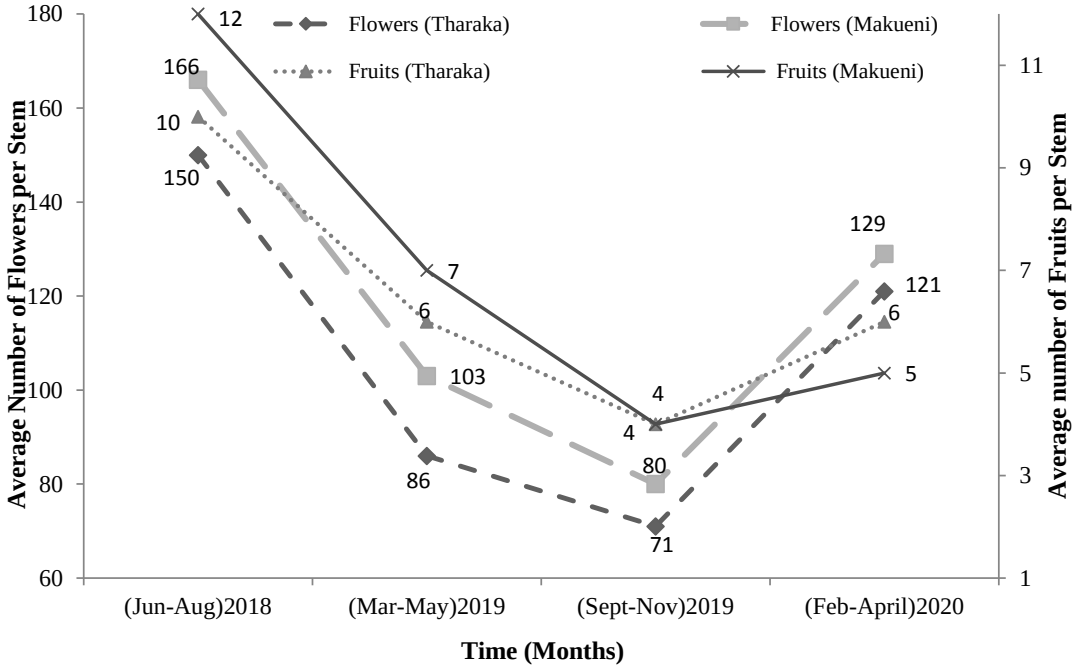

Figure 4.9: Number of Flowers and Fruits per *C. procera* Stem

Table 4.44: Between-Subjects Tests for *C. procera*'s Number of Flowers and Fruits

Source	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Tests Between-Subjects' Effects (Semi-Arid Regions) for Number of Flowers						
Region	44630.669	1	44630.669	9.135	0.003	0.228
Error	1548843.175	317	4885.941			
Tests Between-Subjects' Effects (Semi-Arid Regions) for Number Fruits						
Region	120.756	1	120.756	6.877	0.009	0.222
Error	5285.077	301	17.558			

Though data on number of flowers and fruits from flowering and fruiting stems in Tharaka violated the sphericity assumption with Mauchly's test $p < 0.001$, they all

met the homogeneity assumption with Levene's test $p > 0.05$. Therefore adjusted Greenhouse-Geisser with $p = 0.904$ and $p = 0.358$ for flowers and fruits in Tharaka and $p = 0.913$ and $p = 0.362$ for flowers and fruits in Makueni respectively were used for within-subject analysis.

Based on adjusted Greenhouse-Geisser, there were statistically significant differences in mean number of flowers ($F_{(2.713,548.095)} = 290.006$, $p < 0.001$, $\eta p2 = 0.589$) and fruits ($F_{(1.075,209.644)} = 2.499$, $p < 0.001$, $\eta p^2 = 0.928$) per flowering and fruiting *C. procera* stem within research time points in Tharaka (Table 4.45 part a and b). In Makueni, there were also statistically significant differences in the mean number of fllowers ($F_{(2.738,303.945)} = 223.116$, $p < 0.001$, $\eta p^2 = 0.668$) and mean number of fruits ($F_{(1.087,116.259)} = 1.117$, $p < 0.001$, $\eta p^2 = 0.913$) per flowering and fruiting *C. procera* stem within research time points (Table 4.45 part c and d).

Table 4.45: Within-Subject's Effects for *C. procera*'s Number of Flowers and Fruits in Tharaka and Makueni

Source		Type III Sum of Squares	df	Mean Square	F	*p.*	Partial Eta Squared
Part a: Tests Within-Subjects' Effects (Time) for Number of Flowers in Tharaka							
Time	Greenhouse-Geisser	1287809.305	2.713	474620.72	290.006	<0.001	0.589
Error (Time)	Greenhouse-Geisser	897007.695	548.095	1636.590			
Part b: Tests Within-Subjects' Effects (Time) for Number of Fruits in Tharaka							
Time	Greenhouse-Geisser	800561.178	1.075	744641.00	2.499	<0.001	0.928
Error(Time)	Greenhouse-Geisser	62472.283	209.644	297.992			
Part c: Tests Within-Subjects' Effects (Time) for Number of Flowers in Makueni							
Time	Greenhouse-Geisser	834573.179	2.738	304784.22	223.116	<0.001	0.668
Error(Time)	Greenhouse-Geisser	415199.321	303.945	1366.035			
Part d: Tests Within-Subjects' Effects (Time) for Number of Fruits in Makueni							
	Greenhouse-Geisser	424379.549	1.087	390580.45	1.117	<0.001	0.913
	Greenhouse-Geisser	40656.891	116.259	349.709			

Bonferroni's pair-wise analysis (Appendix VIIa) whose outputs summarized in Table 4.46 part a, b, c and d indicate that the mean number of flowers (71) and fruits (4) in Tharaka and mean number of flowers (80) and fruits (4) in Makueni recorded in (September to November) 2019 were significantly lower than the mean number of flowers and fruits recorded in (June to August) 2018, (March to May) 2019 and (February to April) 2020 (Table 4.46 parts a, b, c and d).

Table 4.46: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s number of Flowers and Fruits Within Time Points in Tharaka and Makueni

	(March-April) 2019	September–November) 2019	(February-April) 2020
Part a: Pairwise comparison of number of flowers in Tharaka			
(June-August) 2018	$P = 0.003$	$P < 0.001$	$P = 1.000$
(March-April) 2019		$P < 0.001$	$p < 0.001$
(September–November) 2019			$p<0.001$
Part b: Pairwise comparison of number of fruits in Tharaka			
(June-August) 2018	$P < 0.001$	$P < 0.001$	$P < 0.001$
(March-April) 2019		$P < 0.001$	$P < 0.001$
(September–November) 2019			$P < 0.001$
Part c: Pairwise comparison of number of flowers in Makueni			
(June-August) 2018	$P < 0.001$	$P < 0.001$	$P < 0.001$
(March-April) 2019		$P < 0.001$	$p < 0.001$
(September–November) 2019			$p<0.001$
Part d: Pairwise comparison of number of fruits in Makueni			
(June-August) 2018	$P < 0.001$	$P < 0.001$	$P = 1.000$
(March-April) 2019		$P < 0.001$	$P < 0.001$
(September–November) 2019			$P < 0.001$

4.4.5. Edaphic factors affecting number of *C. procera*'s flowers and fruits

Poisson loglinear regression (Table 4.47 part a) indicates that: soil exchangeable Na ($p = 0.030$) at (0-20) cm, available P ($p = 0.001$), exchangeable Mg ($p = 0.001$) at (20-40) cm, exchangeable Ca ($p = 0.007$) and exchangeable Na ($p = 0.039$ at (20-40) cm were significantly associated with number of fruits produced by *C. procera* in Tharaka. On fruits, soil exchangeable Na ($p < 0.001$) at (0-20) cm, OC content ($p = 0.012$) at (20-40) cm, available P ($p = 0.037$), exchangeable K ($p = 0.039$) at (20-40)

cm, exchangeable Mg (p = 0.024) at (20-40) cm, exchangeable Ca (p = 0.017) and exchangeable Na (p = 0.036) at (20-40) cm were significantly associated with number of fruits produced by *C. procera* in Tharaka.

In Makueni, soil OC content ($p < 0.001$), available P ($p < 0.001$), exchangeable Ca (p = 0.041) and exchangeable Na ($p < 0.001$) all at (20-40) cm were significantly associated with number of flowers (Table 4.47 part c). On the other hand, number of fruits per fruiting *C. procera* was significantly associated with OC content ($p < 0.001$), available P ($p < 0.001$), exchangeable K (p =0.005), exchangeable Ca ($p < 0.001$) and exchangeable Na ($p < 0.001$) at (20-40) cm (Table 4.47 part d).

Table 4.47: Edaphic Factors Affecting Number of *C. procera*'s Flowers and Fruits

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Edaphic Factors Affecting Number of Flowers in Tharaka			
(Intercept)	33.260	1	<0.001
pH at (0-20) cm	0.044	1	0.834
EC at (0-20) cm	0.002	1	0.966
N at (0-20) cm	0.005	1	0.944
OC at (0-20) cm	5.603	1	0.018
P at (0-20) cm	2.843	1	0.092
K at (0-20) cm	1.592	1	0.207
Mg at (0-20) cm	0.811	1	0.368
Ca at (0-20) cm	0.669	1	0.413
Na at (0-20) cm	4.684	1	0.030
pH at (20-40) cm	0.129	1	0.719
EC at (20-40) cm	0.433	1	0.510
N at (20-40) cm	2.995	1	0.084
OC at (20-40) cm	3.499	1	0.061
P at (20-40) cm	10.098	1	0.001
K at (20-40) cm	1.128	1	0.288
Mg at (20-40) cm	10.941	1	0.001
Ca at (20-40) cm	7.221	1	0.007
Na at (20-40) cm	4.259	1	0.039
Part b: Edaphic Factors Affecting Number of Fruits in Tharaka			
(Intercept)	22.883	1	<0.001
pH at (0-20) cm	0.096	1	0.757
EC at (0-20) cm	1.590	1	0.207
N at (0-20) cm	0.684	1	0.408
OC at (0-20) cm	0.139	1	0.709
P at (0-20) cm	0.161	1	0.688

Table 4.47: Edaphic Factors Affecting Number of *C. procera*'s Flowers and Fruits (Continued)

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
K at (0-20) cm	1.061	1	0.303
Mg at (0-20) cm	2.149	1	0.143
Ca at (0-20) cm	1.250	1	0.264
Na at (0-20) cm	17.681	1	<0.001
pH at (20-40) cm	0.093	1	0.761
EC at (20-40) cm	2.963	1	0.056
N at (20-40) cm	1.306	1	0.253
OC at (20-40) cm	10.017	1	0.012
P at (20-40) cm	10.000	1	0.037
K at (20-40) cm	11.693	1	0.039
Mg at (20-40) cm	11.376	1	0.024
Ca at (20-40) cm	11.880	1	0.017
Na at (20-40) cm	10.064	1	0.036
Part c: Edaphic Factors Affecting Number of Flowers in Makueni			
(Intercept)	66.515	1	<0.001
pH at (0-20) cm	0.030	1	0.862
EC at (0-20) cm	0.426	1	0.514
N at (0-20) cm	3.712	1	0.054
OC at (0-20) cm	0.736	1	0.391
P at (0-20) cm	1.198	1	0.274
K at (0-20) cm	0.255	1	0.614
Mg at (0-20) cm	0.789	1	0.374
Ca at (0-20) cm	0.445	1	0.505
Na at (0-20) cm	1.050	1	0.351
pH at (20-40) cm	1.364	1	0.243
EC at (20-40) cm	0.650	1	0.406
N at (20-40) cm	1.338	1	0.247
OC at (20-40) cm	9.246	1	<0.001
P at (20-40) cm	13.168	1	<0.001
K at (20-40) cm	0.015	1	0.903
Mg at (20-40) cm	2.370	1	0.301
Ca at (20-40) cm	4.837	1	0.041
Na at (20-40) cm	28.675	1	<0.001
Part d: Edaphic Factors Affecting Number of Fruits in Makueni			
(Intercept)	89.565	1	<0.001
pH at (0-20) cm	0.006	1	0.937
EC at (0-20) cm	30.525	1	<0.001
N at (0-20) cm	0.106	1	0.745
OC at (0-20) cm	10.719	1	0.001
P at (0-20) cm	1.229	1	0.268
K at (0-20) cm	0.013	1	0.909
Mg at (0-20) cm	0.429	1	0.513
Ca at (0-20) cm	0.046	1	0.829
Na at (0-20) cm	30.460	1	<0.001
pH at (20-40) cm	0.242	1	0.623

Table 4.47: Edaphic Factors Affecting Number of *C. procera*'s Flowers and Fruits (Continued)

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
EC at (20-40) cm	1.284	1	0.257
N at (20-40) cm	1.362	1	0.243
OC at (20-40) cm	53.090	1	<0.001
P at (20-40) cm	14.210	1	<0.001
K at (20-40) cm	7.711	1	0.005
Mg at (20-40) cm	41.846	1	<0.001
Ca at (20-40) cm	65.368	1	<0.001
Na at (20-40) cm	13.386	1	<0.001

Second level analysis by eliminating variables that were statistically insignificant in the first level indicates that soil exchangeable Na ($p < 0.001$) at (0-20) cm, available P ($p < 0.001$) at (20-40) cm, exchangeable Mg ($p < 0.001$) at (20-40) cm, exchangeable Ca ($p < 0.001$) at (20-40) cm and exchangeable Na ($p < 0.001$) at (20-40) cm were significantly associated with the number of flowers produced by *C. procera* in Tharaka (Table 4.48 part a). On fruits, soil exchangeable Na ($p < 0.006$) at (0-20) cm, OC content ($p < 0.001$), available P ($p < 0.002$), exchangeable K, ($p = 0.015$) exchangeable Mg ($p < 0.001$), exchangeable Ca ($p = 0.012$) and exchangeable Na ($p = 0.006$) were significantly associated with number of fruits produced by *C. procera* in in Tharaka (Table 4.48 part b)

In Makueni, soil OC content ($p < 0.001$), available P ($p < 0.001$), exchangeable Ca ($p < 0.001$) and exchangeable Na ($p < 0.001$) at (20-40) cm were significantly associated with number of flowers produced by *C. procera* in Makueni (Table 4.48 part c). Soil OC content ($p < 0.001$), available P ($p = 0.002$), exchangeable K, ($p = 0.031$) exchangeable Na ($p < 0.001$) and exchangeable Ca ($p < 0.001$) were significantly associated with number of fruits produced by *C. procera* in in Makueni (Table 4.48 part d).

Table 4.48: 2nd Level Test of Edaphic Factors Affecting Number of *C. procera*'s Flowers and Fruits in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Edaphic Factors Affecting Number of Flowers in Tharaka			
(Intercept)	26.976	1	<0.001
Na at (0- 20) cm	17.016	1	<0.001
P at (20-40) cm	14.323	1	<0.001
Mg at (20- 40) cm	19.016	1	<0.001
Ca at (20-40) cm	21.323	1	<0.001
Na at (20-40) cm	16.323	1	<0.001
Part b: Edaphic Factors Affecting Number of Fruits in Tharaka			
(Intercept)	6.386	1	0.012
Na at (0- 20) cm	7.675	1	0.006
OC at (20-40) cm	19.000	1	<0.001
P at (20- 40) cm	11.178	1	<0.001
K at (20-40) cm	6.023	1	0.015
Mg at (20-40) cm	16.681	1	<0.001
Ca at (20-40) cm	6.386	1	0.012
Na at (20-40) cm	7.675	1	0.006
Part c: Edaphic Factors Affecting Number of Flowers in Makueni			
(Intercept)	2906.638	1	<0.001
OC at (20-40) cm	55.145	1	<0.001
P at (20-40) cm	23.557	1	<0.001
Ca at (20-40) cm	51.748	1	<0.001
Na at (20-40) cm	51.899	1	<0.001
Part d: Edaphic Factors Affecting Number of Fruits in Makueni			
(Intercept)	194.621	1	<0.001
OC at (20-40) cm	67.819	1	<0.001
P at (20-40) cm	9.731	1	0.002
K at (20-40) cm	4.646	1	0.031
Ca at (20-40) cm	60.330	1	<0.001
Na at (20-40) cm	21.674	1	<0.001

Parameter estimates (Appendix VIIb part a) demonstrates that: a unit increase in soil exchangeable Na at (0-20) cm, available P at (20-40) cm, exchangeable Ca at (20-40) cm and exchangeable Na at (20-40) cm were significantly increasing the number of flowers produced by *C. procera* in Tharaka by 1.013, 1.039, 1.031 and 1.015 times respectively. On the other hand, a unit increase in exchangeable Mg was significantly reducing the number of flowers by 0.984 times (Appendix VIIb part a). On fruits, soil exchangeable Na at (0-20) cm, OC content at (20-40) cm, available P at (20-40) cm,

exchangeable K at (20-40) cm, exchangeable Mg at (20-40) cm and exchangeable Na at (20-40) cm were significantly increasing the number of fruits by 1.012, 1.016, 1.051, 1.054, 1.063 and 1.014 times. Contrary, a unit increase in exchangeable Ca was significantly reducing the number of fruits by 0.983 (Appendix VIIb part b).

In Makueni, a unit increase in soil exchangeable OC content, available P, exchangeable Ca, and exchangeable Na at (20-40) cm were significantly increasing the number of flowers by 1.015, 1.048, 1.002 and 1.005 times respectively (Appendix VIIb part c). On fruits, soil exchangeable OC content, available P, exchangeable K and exchangeable Na at (20-40) cm were significantly increasing the number of fruits by 1.027, 1.049, 1.044, and 1.009 times respectively (Appendix VIId part part d). Contrary, a unit increase in exchangeable Ca was significantly reducing the number of fruits by 0.996 times (Appendix VIIb part d).

4.4.6. Weather conditions affecting number of flowers and fruits produced by *C. procera* in Tharaka and Makueni

Table 4.49 (part a, b, c and d) indicate that monthly rainfall, temperature, wind speed and relative humidity were significantly associated with number of flowers and fruits in both Tharaka and Makueni.

Table 4.49: Test of Weather Conditions Affecting Number of Flowers and Fruits Produced by *C. procera* in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Weather conditions Affecting Number of Flowers Produced by *C. procera* in Tharaka			
(Intercept)	12.248	1	<0.001
Total monthly rainfall	27.026	1	<0.001
Mean monthly temperature	16.390	1	<0.001
Mean monthly wind speed	19.827	1	<0.001
Monthly relative humidity	24.384	1	<0.001

Table 4.49: Test of Weather Conditions Affecting Number of Flowers and Fruits Produced by *C. procera* in Tharaka and Makueni (Continued)

Part b: Weather conditions Affecting Number of Fruits Produced by *C. procera* in Tharaka			
(Intercept)	73.765	1	<0.001
Total monthly rainfall	30.567	1	<0.001
Mean monthly temperature	32.633	1	<0.001
Mean monthly wind speed	72.008	1	<0.001
Monthly relative humidity	11.765	1	0.001
Part c: Weather conditions Affecting Number of Flowers Produced by *C. procera* in Makueni			
(Intercept)	57.746	1	<0.001
Total monthly rainfall	81.447	1	<0.001
Mean monthly temperature	82.002	1	<0.001
Mean monthly wind speed	107.596	1	<0.001
Monthly relative humidity	86.797	1	<0.001
Part b: Weather conditions Affecting Number of Fruits Produced by *C. procera* in Makueni			
(Intercept)	58.143	1	<0.001
Total monthly rainfall	26.751	1	<0.001
Mean monthly temperature	77.953	1	<0.001
Mean monthly wind speed	45.911	1	<0.001
Monthly relative humidity	53.798	1	<0.001

In Tharaka, a unit increase in preceding monthly's average rainfall and relative humidity was significantly increasing the number of flowers by 1.001 and 1.049 times respectively. On the other hand, a unit increase in monthly average temperature and wind speed were significantly reducing the number of flowers by 0.904 and 0.795 times respectively (Appendix VIIc part a). On fruits, a unit increase in mean monthly rainfall, temperature and wind speed were significantly increasing the number of fruits by 1.007, 1.122 and 1.052 times respectively (Appendix VIIc part b). However, an increase in relative humidity was significantly reducing the number of fruits by 0.971 (Appendix VIIc part b).

In Makueni, a unit increase in preceding monthly's average rainfall and relative humidity was significantly increasing the number of flowers by 1.009 and 1.084 times respectively (Appendix VIIc part c). A unit increase in monthly average temperature and wind speed was significantly reducing the number of flowers by 0.792 and 0.844

times respectively (Appendix VIIc part c). On fruits, a unit increase in mean monthly rainfall, temperature and wind speed were significantly increasing the number of fruits by 1.056, 1.338 and 1.207 times respectively (Appendix VIIc part d). However, an increase in relative humidity was significantly reducing the number of fruits by 0.794 times (Appendix VIIc part d).

4.4.7. Phenophase intensity of *C. procera* in Tharaka and Makueni

The mean flower and fruit phenophase intensity of naturally growing *C. procera* in the semi-arid regions of Tharaka and Makueni showed a decreasing trend from (June to August) 2018 to (September to November) 2019 with a slight increase between (September to November) 2019 and (February to April) 2020) (Figure 4.10). A part from (February to April) 2020 where naturally growing *C. procera* in Tharaka recorded relatively high flower (69.99%) and fruit (55.39%) pheneophase intensities compared to Makueni, both flower and fruit phenophase intensities at all other research time points were relative high in Makueni than Tharaka (Figure 4.10).

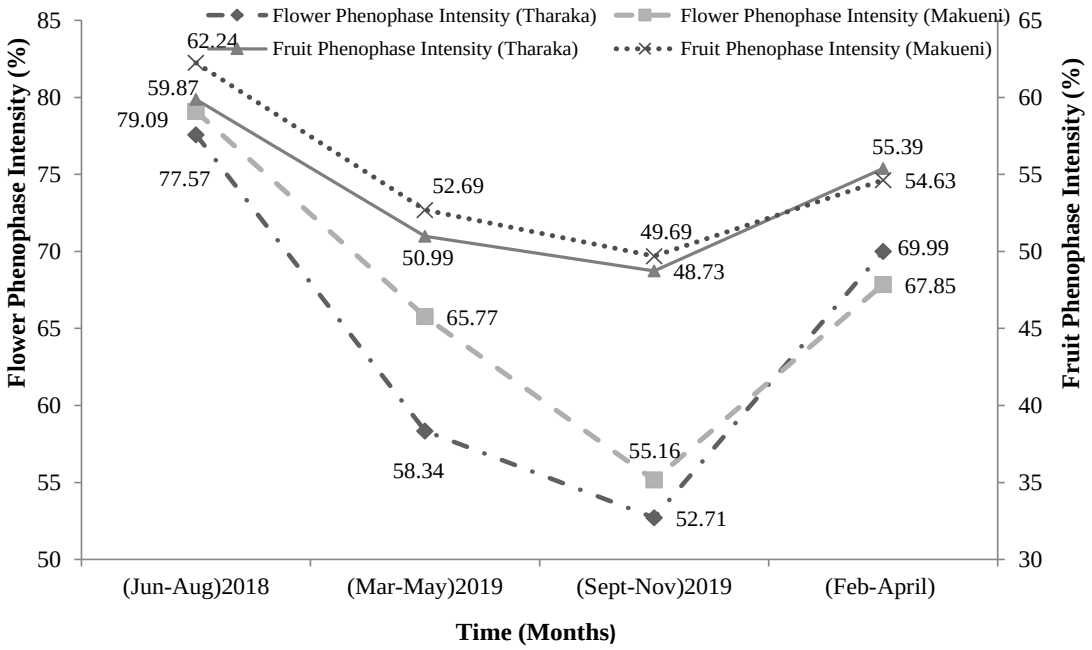

Figure 4.10: Flowering and Fruiting Phenophase Intensities of *C. procera* in Tharaka and Makueni

Flowering and fruiting phenophase intensities were not statistically significant between the two semi-arid regions of Tharaka and Makueni ($F_{(1,312)} = 2.13$, $p = 0.145$, $\eta p^2 = 0.007$) and ($F_{(1,312)} = 0.273$, $p = 0.602$, $\eta p^2 = 0.001$) respectively (Table 4.50).

Table 4.50: Between-Subjects Tests for *C. procera*'s Phenophase Intensities in Tharaka and Makueni

Source	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Part a: Between-Subjects' Effects (Semi-Arid Regions) for Flowering Activity Index						
Region	1506.578	1	1506.578	2.130	0.145	0.007
Error	220688.817	312	707.336			
Part b: Between-Subjects' Effects (Semi-Arid Regions) for Fruiting Activity Index						
Region	365.158	1	365.158	0.273	0.602	0.001
Error	404205.055	302	1338.427			

The sphericity and homogeneity assumptions were met by flowering and fruiting phenophase intensities' data both in Tharaka and Makueni with Mauchly's test and Levene's test having $p > 0.05$. As a result, mixed ANOVA (Table 4.51 part a and b) shows a statistically significant difference in mean flowering ($F_{(3,600)} = 17.223$, $p < 0.001$, $\eta p^2 = 0.079$) and mean fruiting ($F_{(3, 576)} = 188.339$, $p < 0.001$, $\eta p^2 = 0.495$) phenophase intensities within research time points in Tharaka. There were also statistically significant differences in mean flowering ($F_{(3,327)} = 5.379$, $p = 0.001$, $\eta p^2 = 0.049$) and mean fruiting ($F_{(3, 327)} = 115.008$, $p < 0.001$, $\eta p^2 = 0.513$) phenophase intensities within research time points in Makueni (Table 4.51 part c and d).

Table 4.51: Within-Subject's Effects for *C. procera*'s Flowering and Fruiting Phenophase Intensities in Tharaka and Makueni

Source		Type III Sum of Squares	df	Mean Square	*F*	*p*	Partial Eta Squared
Part a: Tests Within-Subjects' Effects (Time) for Flower Phenophase Intensity in Tharaka							
Time	Sphericity Assumed	28243.231	3	9414.410	17.223	$p < 0.001$	0.079
Error (Time)	Sphericity Assumed	327964.307	600	546.607			

Table 4.51: Within-Subject's Effects for *C. procera*'s Flowering and Fruiting Phenophase Intensities in Tharaka and Makueni (Continued)

Source		Type III Sum of Squares	df	Mean Square	*F*	*p*	Partial Eta Squared
Part b: Tests Within-Subjects' Effects (Time) for Fruit Phenophase Intensity in Tharaka							
Time	Sphericity Assumed	255920.896	3	85306.965	188.33	$p < 0.001$	0.495
Error (Time)	Sphericity Assumed	260895.286	576	452.943			
Part c: Tests Within-Subjects' Effects (Time) for Flower Phenophase Intensity in Makueni							
Time	Sphericity Assumed	8150.564	3	2716.855	5.379	$p < 0.001$	0.047
Error (Time)	Sphericity Assumed	166671.897	330	505.066			
Part d: Tests Within-Subjects' Effects (Time) for Fruit Phenophase Intensity in Makueni							
Time	Sphericity Assumed	143582.519	3	47860.840	115.008	$p < 0.001$	0.513
Error (Time)	Sphericity Assumed	136081.703	327	416.152			

Bonferroni's pair-wise analysis (Appendix VIIIa) with outputs summarized in Table 4.52 part a, b, c and d indicate that the mean flowering (77.57%) and fruiting (62.24%) phenophase intensities in Tharaka and mean flowering (79.09%) and fruiting (62.24%) phenophase intensities in Makueni recorded in (June to August) 2018 were significantly higher than those recorded in, (March to May) 2019, (September to November) 2019 and (February to April) 2020.

Table 4.52: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s Phenophase Intensity Within Time Points in Tharaka and Makueni

	(March-April) 2019	September–November) 2019	(February-April) 2020
Part a: Pair-wise Comparison of Flower Phenophase Intensity in Tharaka			
(June-August) 2018	$p = 0.041$	$p < 0.001$	$p < 0.001$
(March-April) 2019		$p = 0.031$	$p < 0.001$
(September–November) 2019			$p < 0.001$
Part b: Pair-wise Comparison of Fruit phenophase Intensity in Tharaka			
(June-August) 2018	$p < 0.001$	$p < 0.001$	$p = 0.372$
(March-April) 2019		$p < 0.001$	$p = 0.022$
(September–November) 2019			$p < 0.001$

Table 4.52: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s Phenophase Intensity Within Time Points in Tharaka and Makueni (Continued)

	(March-April) 2019	September–November) 2019	(February-April) 2020
Part c: Pair-wise Comparison of Flower Phenophase Intensity in Makueni			
(June-August) 2018	$p < 0.001$	$p < 0.001$	$p < 0.001$
(March-April) 2019		$p = 0.105$	$p = 0.002$
(September–November) 2019			$p = 1.000$
Part d: Pair-wise Comparison of Fruit Phenophase Intensity in Makueni			
(June-August) 2018	$p < 0.000$	$p < 0.001$	$p < 0.001$
(March-April) 2019		$p < 0.001$	$p = 0.722$
(September–November) 2019			$p < 0.001$

4.4.8. Edaphic factors affecting C. *procera*'s phenophase intensities

In Tharaka, soil EC ($p = 0.019$) at (0-20) cm, total N ($p = 0.003$) at (20-40) cm, and available P ($p = 0.036$) at (20-40) cm were significantly associated with *C. procera*'s phenophase intensity (Table 4.53 part a). On the other hand, fruiting phenophase intensity was significantly associated with soil exchangeable Na ($p < 0.001$) at (0-20) cm, total N ($p = 0.003$) at (20-40) cm, available P ($p = 0.007$) at (20-40) cm and exchangeable Na ($p < 0.001$) at (20-40) cm (Table 4.53 part b).

In Makueni, flowering phenophase intensity of *C. procera* had no statistically significant association with soil parameters tested (Table 4.53 part c). However, fruiting intensity was significantly associated with soil available P ($p = 0.008$) at (20-40) cm (Table 4.53 part d).

Table 4.53: Effect Test of Edaphic Factors on Phenophase Intensities of *C. procera* in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Part a: Edaphic Factors Affecting Flowering Phenophase Intensity in Tharaka			
(Intercept)	24.451	1	<0.001
pH at (0-20) cm	0.743	1	0.389
EC at (0-20) cm	5.536	1	0.019
N at (0-20) cm	2.284	1	0.131
OC at (0-20) cm	0.054	1	0.817
P at (0-20) cm	3.780	1	0.052
K at (0-20) cm	3.515	1	0.053
Mg at (0-20) cm	3.098	1	0.056
Ca at (0-20) cm	1.267	1	0.636
Na at (0-20) cm	2.064	1	0.151
pH at (20-40) cm	0.340	1	0.560
EC at (20-40) cm	0.540	1	0.463
N at (20-40) cm	14.784	1	<0.001
OC at (20-40) cm	2.106	1	0.147
P at (20-40) cm	4.396	1	0.036
K at (20-40) cm	<0.001	1	0.998
Mg at (20-40) cm	1.990	1	0.621
Ca at (20-40) cm	1.834	1	0.521
Na at (20-40) cm	0.180	1	0.671
Part b: Edaphic Factors Affecting Fruiting Phenophase Intensity inTharaka			
(Intercept)	12.775	1	0.005
pH at (0-20) cm	0.927	1	0.336
EC at (0-20) cm	4.174	1	0.051
N at (0-20) cm	4.695	1	0.053
OC at (0-20) cm	2.909	1	0.088
P at (0-20) cm	0.160	1	0.690
K at (0-20) cm	0.005	1	0.942
Mg at (0-20) cm	0.458	1	0.499
Ca at (0-20) cm	0.768	1	0.381
Na at (0-20) cm	30.869	1	<0.001
pH at (20-40) cm	3.731	1	0.053
EC at (20-40) cm	3.567	1	0.059
N at (20-40) cm	8.913	1	0.003
OC at (20-40) cm	1.836	1	0.262
P at (20-40) cm	7.244	1	0.007
K at (20-40) cm	3.300	1	0.069
Mg at (20-40) cm	3.586	1	0.058
Ca at (20-40) cm	3.724	1	0.066
Na at (20-40) cm	35.130	1	<0.001
Part c: Edaphic Factors Affecting Flowering Phenophase Intensity in Makueni			
(Intercept)	51.319	1	<0.001
pH at (0-20) cm	0.275	1	0.600
EC at (0-20) cm	3.696	1	0.053
N at (0-20) cm	0.037	1	0.848
OC at (0-20) cm	3.706	1	0.054

Table 4.53: Effect Test of Edaphic Factors on Phenophase Intensities of C. procera in Tharaka and Makueni (Continued)

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
P at (0-20) cm	3.522	1	0.061
K at (0-20) cm	3.598	1	0.058
Mg at (0-20) cm	0.493	1	0.483
Ca at (0-20) cm	0.430	1	0.512
Na at (0-20) cm	0.106	1	0.744
pH at (20-40) cm	0.431	1	0.511
EC at (20-40) cm	0.586	1	0.444
N at (20-40) cm	0.047	1	0.828
OC at (20-40) cm	3.839	1	0.050
P at (20-40) cm	3.566	1	0.059
K at (20-40) cm	0.269	1	0.604
Mg at (20-40) cm	0.124	1	0.724
Ca at (20-40) cm	0.195	1	0.659
Na at (20-40) cm	0.047	1	0.828
Part d: Edaphic factors affecting Fruiting Phenophase Intensity in Makueni			
(Intercept)	17.694	1	<0.001
pH at (0-20) cm	1.075	1	0.300
EC at (0-20) cm	3.457	1	0.063
N at (0-20) cm	5.252	1	0.052
OC at (0-20) cm	3.742	1	0.063
P at (0-20) cm	2.984	1	0.105
K at (0-20) cm	0.581	1	0.446
Mg at (0-20) cm	1.697	1	0.193
Ca at (0-20) cm	1.459	1	0.227
Na at (0-20) cm	2.352	1	0.125
pH at (20-40) cm	1.013	1	0.314
EC at (20-40) cm	0.535	1	0.417
N at (20-40) cm	0.791	1	0.374
OC at (20-40) cm	5.590	1	0.018
P at (20-40) cm	7.128	1	0.008
K at (20-40) cm	0.161	1	0.689
Mg at (20-40) cm	2.478	1	0.138
Ca at (20-40) cm	1.260	1	0.230
Na at (20-40) cm	0.723	1	0.395

The second level analysis by eliminating edaphic factors that were insignificant in the first level analysis indicates that there were no significant association between edaphic factors and *C. procera*'s flowering and fruiting in both Tharaka and Makueni (Table 4.54 parts a, b and c).

Table 4.54: 2nd Level Test of Edaphic Factors on Phenophase Intensities of C. *procera* in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Edaphic Factors Affecting Flowering Phenophase Intensity in Tharaka			
(Intercept)	345.069	1	<0.001
EC at (0-20) cm	0.076	1	0.783
N at (20-40) cm	0.606	1	0.436
P at (20-40) cm	0.085	1	0.771
Na at (20-40) cm	5.069	1	0.251
Part b: Edaphic Factors Affecting Fruiting Phenophase Intensity in Tharaka			
(Intercept)	99.023	1	<0.001
pH at (0-20) cm	1.267	1	0.193
N at (20-40) cm	2.555	1	0.110
P at (20-40) cm	3.955	1	0.063
Na at (20-40) cm	3.159	1	0.076
Part c: Edaphic Factors Affecting Fruiting Phenophase Intensity in Makueni			
(Intercept)	14.401	1	<0.001
P at (20-40) cm	2.535	1	0.119

4.4.9. Weather conditions affecting *C. procera*'s flowering and fruiting phenophase intensities

Loglinear regression based on GEE shows that preceding month's average rainfall and temperature were significantly associated with *C. procera*'s flowering phenophase intensity in Tharaka and Makueni (Table 4.55 Part a and c). On fruits, preceding months' average rainfall, temperature and wind speed were significantly associated with fruiting phenophase intensity of *C. procera* in both Tharaka and Makunei (Table 4.55 Part b and d).

Table 4.55: Test of Weather Conditions Affecting *C. procera*'s Phenophase Intensities

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Weather Conditions Affecting Flowering Phenophase Intensity in Tharaka			
(Intercept)	6.966	1	0.008
Mean monthly rainfall	17.091	1	<0.001
Mean monthly temperature	8.365	1	0.004
Mean monthly wind speed	0.942	1	0.834
Monthly relative humidity	0.485	1	0.486

Table 4.55: Test of Weather Conditions Affecting *C. procera*'s Phenophase Intensities (Continued)

Source	Type III Wald Chi-Square	df	*p*
Part b: Weather Conditions Affecting Fruiting Phenophase Intensity in Tharaka			
(Intercept)	51.855	1	<0.001
Mean monthly rainfall	27.469	1	<0.001
Mean monthly temperature	35.153	1	<0.001
Mean monthly wind speed	31.855	1	<0.001
Monthly relative humidity	7.469	1	0.820
Part c: Weather Conditions Affecting Flowering Phenophase Intensity in Makueni			
(Intercept)	18.0536	1	<0.001
Mean monthly rainfall	12.984	1	0.021
Mean monthly temperature	11.983	1	0.024
Mean monthly wind speed	0.942	1	0.099
Monthly relative humidity	1.456	1	0.062
Part d: Weather Conditions Affecting Fruiting Phenophase Intensity in Makueni			
(Intercept)	18.0536	1	<0.001
Mean monthly rainfall	17.984	1	<0.001
Mean monthly temperature	15.942	1	<0.001
Mean monthly wind speed	12.536	1	0.031
Monthly relative humidity	1.983	1	0.072

Second level analysis (Table 4.56 part a, b, c and d) after eliminating variables that were statistically insignificant in the first level of analysis indicates that: preceding month's average monthly rainfall and temperature were significantly associated with flowering and fruiting phenophase intensities, while wind speed was associated with fruiting phenophase intensity in both Tharaka and Makueni.

Table 4.56: 2nd Level Test of Weather Conditions Affecting *C. procera*'s Phenophase Intensity in Tharaka and Makueni

Source	Type III Wald Chi-Square	Df	*p*
Part a: Weather Conditions Affecting Flowering Phenophase Intensity inTharaka			
(Intercept)	6.966	1	0.008
Mean monthly rainfall (mm/month)	17.091	1	<0.001
Mean monthly temperature (°C/month)	8.365	1	0.004
Part b: Weather Conditions Affecting Fruiting Phenophase Intensity in Tharaka			
(Intercept)	31.855	1	<0.001
Mean monthly rainfall (mm/month)	27.469	1	<0.001
Mean monthly temperature (°C/month)	53.153	1	<0.001
Mean monthly wind speed (m/s)	16.855	1	0.402
Part c: Weather Conditions Affecting Flowering Phenophase Intensity in Makueni			
(Intercept)	10.003	1	0.009
Mean monthly rainfall (mm/month)	11.610	1	0.002

Table 4.56: 2nd Level Test of Weather Conditions Affecting *C. procera*'s Phenophase Intensity in Tharaka and Makueni (Continued)

	Type III		
Source	**Wald Chi-Square**	**Df**	***p***
Mean monthly temperature (°C/month)	8.251	1	0.017
Part d: Weather Conditions Affecting Fruiting Phenophase Intensity in Makueni			
(Intercept)	31.490	1	<0.001
Mean monthly rainfall (mm/month)	18.826	1	<0.001
Mean monthly temperature (°C/month)	42.984	1	<0.001
Mean monthly wind speed (m/s)	20.025	1	<0.001

Parameter estimates (Appendix VIIIb part a and b) shows that: a unit increase in preceding monthly's average rainfall was associated with an increase in *C. procera*'s flowering and fruiting phenophase intensities by 1.557 and 1.266 times respectively in Tharaka. On the other hand, a unit increase in monthly temperature was associated with a decrease in flowering and fruiting intensities by 0.915 and 0.896 times respectively. A unit increase in wind speed was also associated with a decrease in *C. procera'*s fruiting by 0.982 times in Tharaka (Appendix VIIIb part b).

In Makueni, a unit increase in preceding monthly's average rainfall was associated with an increase in *C. procera*'s flowering and fruiting phenophase intensities by 1.121 and 1.508 times respectively in Tharaka (Appendix VIIIb part c and d). On the other hand, a unit increase in monthly temperature was associated with a decrease in flowering and fruiting intensities by 0.894 and 0.874 times respectively. A unit increase in wind speed was also associated with a decrease in *C. procera'*s fruiting by 0.979 times in Makueni (Appendix VIIIb part d).

4.5. Dieback Condition of *C. procera* in Tharaka and Makueni

Naturally growing *C. procera* stems in Tharaka and Makueni were experiencing crown dieback, discoloration of leaves and cankerous conditions (Plate 4.4).

Plate 4.4: Dieback Condition (a– crown dieback, b- leaf discolouration, c- cankerous condition)

(Source: Author, 2019)

4.5.1. Dieback prevalence and severity index of *C. procera*

Figure 4.11 indicates that dieback prevalence and severity indices on naturally growing *C. procera* in the semi-arid regions of Tharaka and Makueni showed an increasing trend from (June to August) 2018 to (September to November) 2019, with a slight decrease in (February to April) 2020. Between the two regions, while Tharaka maintained slightly high dieback prevalence levels in (June to August), (March to May) 2019 and (February to April) 2020, Makueni had higher prevalence in (September to Novemeber) 2019. On the other hand, *C. procera* in Tharaka maintained high levels of dieback severity at all time points compared to *C. procera* in Makueni. However, the differences experienced in dieback prevalence and severity indices on *C. procera* between Tharaka and Makueni were not statistically significant with ($F_{(1,102)} = 0.209$, $p = 0.649$, $\eta p^2 = 0.002$) and ($F_{(1,106)} = 0.652$, $p = 0.421$, $\eta p^2 = 0.006$) respectively.

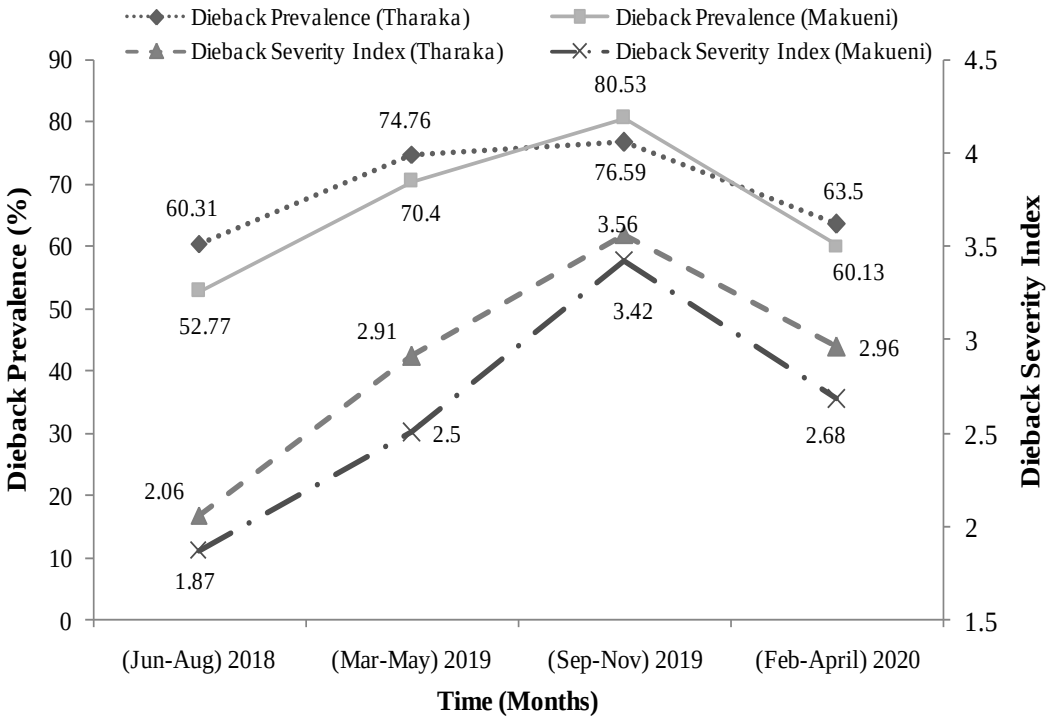

Figure 4.11: *Calotropis procera*'s Dieback Prevalence and Severity Index

For mixed repeated measure analysis to compare dieback prevalence and severity within research time points, the assumptions of sphericity and homogeneity of variance were met (p> 0.05) by both dieback prevalence and dieback severity.

Mixed ANOVA indicates that there were statistically significant differences in the mean dieback prevalence ($F_{(3, 207)} = 11.126$, $p = <0.001$, $\eta p^2 = 0.139$) and severity index ($F_{(3, 201)} = 25.623$, $p < 0.001$, $\eta p^2 = 0.316$ on naturally growing *C. procera* in the semi-arid regions of Tharaka at different time points (Table 4.57 part a and b). There were also statistically significant differences in mean dieback prevalence ($F_{(3,99)} = 10.341$, $p < 0.001$, $\eta p^2 = 0.239$) and severity index ($F_{(3, 117)} = 21.406$, $p < 0.001$, $\eta p^2 = 0.354$) on *C. procera* in Makueni at different time points (Table 4.57 parts a, b, c and d).

Table 4.57: Within-Subject's Effects for *C. procera*'s Dieback Prevalence and Severity in Tharaka and Makueni

Source		Type III Sum of Squares	Df	Mean Square	F	*P*	Partial Eta Squared
Part a: Within-Subjects' Effects (Time) for *C. procera's* Dieback Prevalence in Tharaka							
Time	Sphericity Assumed	15850.310	3	5283.437	11.126	< 0.001	0.139
Error (Time)	Sphericity Assumed	98302.715	207	474.892			
Part b: Within-Subjects' Effects (Time) for *C. procera's* Dieback Severity in Tharaka							
Time	Sphericity Assumed	76.868	3	25.623	30.988	< 0.001	0.316
Error (Time)	Sphericity Assumed	166.198	201	0.827			
Part c: Within-Subjects' Effects (Time) for *C. procera's* Dieback Prevalence in Makueni							
Time	Sphericity Assumed	14002.625	3	4667.542	10.341	< 0.001	0.239
Error (Time)	Sphericity Assumed	44685.402	99	451.368			
Part d: Within-Subjects' Effects (Time) for *C. procera's* Dieback Severity in Makueni							
Time	Sphericity Assumed	55.158	3	18.386	21.406	< 0.001	0.354
Error (Time)	Sphericity Assumed	100.493	117	0.859			

Bonferroni's pair-wise comparison (Appendix IXa) summarized in Table 4.58 parts a, b, c and d indicates that the mean dieback prevalence exhibited on *C. procera* in both Tharaka and Makueni in (June to August) 2018 and (February to April) 2020 were significantly lower than the mean dieback prevalence and severity conditions exhibited in (March to May) 2019 and (November to November) 2019. However, there were no significant differences in dieback prevalence conditions between (June to August) 2018 and (February to April) 2020, and between (March to May) 2019 and (September to November) 2019 in both Tharaka and Makueni. On the other hand, dieback severity indices on *C. procera* recorded in (June to August) 2018 in both Tharaka and Makueni were significantly lower than those recorded in (March to May) 2019, (September to November) 2019 and (February to April) 2020.

Table 4.58: Summarized Bonferroni's Pair-wise Analysis of *C. procera*'s Dieback Prevalence and Severity Index Within Time Points in Tharaka and Makueni

	(March-April) 2019	**September–November) 2019**	**(February-April) 2020**
Part a: Pair-wise Comparison of *C. procera*'s Dieback Prevalence in Tharaka			
(June-August) 2018	$p < 0.014$	$p = 0.001$	$P = 1.000$
(March-April) 2019		$p = 1.000$	$p = 0.001$
(September–November) 2019			$P < 0.001$
Part b: Pair-wise Comparison of *C. procera*'s Dieback Severity in Tharaka			
(June-August) 2018	$p < 0.001$	$p < 0.001$	$p < 0.001$
(March-April) 2019		$p = 0.003$	$p = 1.000$
(September–November) 2019			$p < 0.001$
Part c: Pair-wise Comparison of *C. procera*'s Dieback Prevalence in Makueni			
(June-August) 2018	$p = 0.002$	$p = 0.001$	$p = 0.233$
(March-April) 2019		$p = 0.480$	$p = 0.372$
(September–November) 2019			$p = 0.009$
Part d: Pair-wise Comparison of *C. procera*'s Dieback Severity in Makueni			
(June-August) 2018	$p < 0.001$	$p < 0.001$	$p < 0.001$
(March-April) 2019		$p = 0.002$	$p = 0.665$
(September–November) 2019			$P = 0.002$

4.5.2. Edaphic factors affecting *C. procera*'s dieback prevalence and severity

Linear regression based on GEE (Table 4.59 part a, b, c and d) indicates that no edaphic variable was significantly associated with dieback prevalence and dieback severity in both Tharaka and Makueni.

Table 4.59: Edaphic Factors Affecting *C. procera*'s Dieback Prevalence and Severity in Tharaka and Makueni

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
Part a: Edaphic Factors Affecting Dieback Prevalence on *C. procera* in Tharaka			
(Intercept)	3.617	1	0.057
pH at (0-20) cm	1.735	1	0.188
EC at (0-20) cm	0.059	1	0.808
N at (0-20) cm	1.597	1	0.206
OC at (0-20) cm	1.274	1	0.259
P at (0-20) cm	0.326	1	0.568
K at (0-20) cm	0.091	1	0.763
Mg at (0-20) cm	4.468	1	0.065
Ca at (0-20) cm	6.208	1	0.013
Na at (0-20) cm	3.489	1	0.062

Table 4.59: Edaphic Factors Affecting *C. procera*'s Dieback Prevalence and Severity in Tharaka and Makueni (Continued)

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
pH at (20-40) cm	2.252	1	0.133
EC at (20-40) cm	0.972	1	0.324
N at (20-40) cm	0.121	1	0.728
OC at (20-40) cm	0.811	1	0.368
P at (20-40) cm	0.327	1	0.567
K at (20-40) cm	0.487	1	0.485
Mg at (20-40) cm	0.000	1	0.987
Ca at (20-40) cm	0.037	1	0.848
Na at (20-40) cm	0.910	1	0.340
Part a: Edaphic Factors Affecting Dieback Severity in on *C. procera* in Tharaka			
(Intercept)	4.634	1	0.031
pH at (0-20) cm	0.091	1	0.762
EC at (0-20) cm	0.139	1	0.710
N at (0-20) cm	0.093	1	0.760
OC at (0-20) cm	0.085	1	0.771
P at (0-20) cm	1.781	1	0.186
K at (0-20) cm	0.041	1	0.840
Mg at (0-20) cm	1.751	1	0.186
Ca at (0-20) cm	0.316	1	0.574
Na at (0-20) cm	3.626	1	0.057
pH at (20-40) cm	0.344	1	0.558
EC at (20-40) cm	3.513	1	0.061
N at (20-40) cm	0.914	1	0.339
OC at (20-40) cm	1.951	1	0.166
P at (20-40) cm	1.604	1	0.205
K at (20-40) cm	2.077	1	0.150
Mg at (20-40) cm	0.121	1	0.728
Ca at (20-40) cm	2.077	1	0.150
Na at (20-40) cm	0.914	1	0.339
Part c: Edaphic Factors Affecting Dieback Prevalence on *C. procera* in Makueni			
(Intercept)	1.290	1	0.256
pH at (0-20) cm	0.395	1	0.530
EC at (0-20) cm	0.911	1	0.340
N at (0-20) cm	0.694	1	0.405
OC at (0-20) cm	0.683	1	0.412
P at (0-20) cm	1.127	1	0.261
K at (0-20) cm	1.213	1	0.271
Mg at (0-20) cm	1.030	1	0.310
Ca at (0-20) cm	1.044	1	0.307
Na at (0-20) cm	1.214	1	0.270
pH at (20-40) cm	1.127	1	0.288
EC at (20-40) cm	0.007	1	0.984
N at (20-40) cm	1.227	1	0.268
OC at (20-40) cm	1.172	1	0.274
P at (20-40) cm	0.634	1	0.409

Table 4.59: Edaphic Factors Affecting *C. procera*'s Dieback Prevalence and Severity in Tharaka and Makueni (Continued)

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
K at (20-40) cm	0.759	1	0.384
Mg at (20-40) cm	1.391	1	0.238
Ca at (20-40) cm	1.288	1	0.256
Na at (20-40) cm	0.681	1	0.409
Part c: Edaphic Factors Affecting Dieback Severity on *C. procera* in Makueni			
(Intercept)	23.364	1	<0.001
pH at (0-20) cm	1.241	1	0.265
EC at (0-20) cm	2.835	1	0.092
N at (0-20) cm	1.354	1	0.245
OC at (0-20) cm	2.583	1	0.108
P at (0-20) cm	0.359	1	0.549
K at (0-20) cm	0.741	1	0.389
Mg at (0-20) cm	2.964	1	0.086
Ca at (0-20) cm	2.313	1	0.128
Na at (0-20) cm	1.377	1	0.241
pH at (20-40) cm	0.491	1	0.483
EC at (20-40) cm	0.950	1	0.138
N at (20-40) cm	2.179	1	0.140
OC at (20-40) cm	3.359	1	0.054
P at (20-40) cm	3.643	1	0.056
K at (20-40) cm	2.699	1	0.100
Mg at (20-40) cm	0.584	1	0.474
Ca at (20-40) cm	0.851	1	0.147
Na at (20-40) cm	0.013	1	0.908

4.5.3. Weather conditions affecting *C. procera*'s dieback prevalence and severity

Linear regression based on GEE indicates that preceding month's average rainfall and temperature were significantly associated with dieback prevalence and severity (Table 4.60 part a, b, c and d). However, relative humidity was redundant in both Tharaka and Makueni.

Table 4.60: Test of Weather Conditions Affecting *C. procera*'s Dieback Prevalence and Severity in Tharaka and Makueni

Source	Type III Wald Chi-Square	Df	*p*
Part a: Weather Conditions Affecting *C. procera*'s Dieback Prevalence in Tharaka			
(Intercept)	11.525	1	0.046
Mean monthly rainfall (mm/month)	15.057	1	0.034
Mean monthly temperature (°C/month)	23.395	1	0.020
Mean monthly wind speed (m/s)	0.768	1	0.381
Mean monthly relative humidity (%)	0[a]	.	.
Part b: Weather Conditions Affecting *C. procera*'s Dieback Severity in Tharaka			
(Intercept)	7.065	1	0.008
Mean monthly rainfall (mm/month)	6.942	1	0.012
Mean monthly temperature (°C/month)	10.812	1	0.001
Mean monthly wind speed (m/s)	0.485	1	0.486
Mean monthly relative humidity (%)	0[a]		
Part c: Weather Conditions Affecting *C. procera*'s Dieback Prevalence in Makueni			
(Intercept)	43.966	1	<0.001
Mean monthly rainfall (mm/month)	21.964	1	<0.001
Mean monthly temperature (°C/month)	33.964	1	<0.001
Mean monthly wind speed (m/s)	1.026	1	0.311
Mean monthly relative humidity (%)	0[a]	.	.
Part d: Weather conditions Affecting *C. procera's* Dieback Severity in Makueni			
(Intercept)	8.548	1	0.003
Mean monthly rainfall (mm/month)	17.344	1	<0.001
Mean monthly temperature (°C/month)	6.232	1	0.013
Mean monthly wind speed (m/s)	0.408	1	0.523
Mean monthly relative humidity (%)	0[a]		

a. Set to zero because this parameter is redundant.

Second level analysis by eliminating variables that were statistically insignificant in the first level test shows that: dieback prevalence and severity were significantly associated with preceding monthly's average rainfall and temperature in both Tharaka and Makueni (Table 4.61 apart a, b, c and d).

Table 4.61: 2nd Levels Test of Weather Conditions Affecting Dieback Prevalence and Severity

Source	Type III Wald Chi-Square	Df	*p*
Part a: Weather Conditions Affecting Affecting Dieback Prevalence in Tharaka			
(Intercept)	49.888	1	<0.001
Mean monthly rainfall (mm/month)	15.930	1	<0.001
Mean monthly temperature (°C/month)	17.435	1	<0.001

Table 4.61: 2nd Levels Test of Weather Conditions Affecting Dieback Prevalence and Severity (Continued)

Source	Type III Wald Chi-Square	Df	*p*
Part b: Weather Conditions Affecting Dieback Severity in Tharaka			
(Intercept)	286.322	1	<0.001
Mean monthly rainfall (mm/month)	257.031	1	<0.001
Mean monthly temperature (°C/month)	103.700	1	<0.001
Mean monthly wind speed (m/s)	160.403	1	<0.001
Part c: Weather Conditions Affecting Affecting Dieback Prevalence in Makueni			
(Intercept)	19.848	1	<0.001
Mean monthly rainfall (mm/month)	14.017	1	0.001
Mean monthly temperature (°C/month)	13.288	1	0.002
Part d: Weather Conditions Affecting Dieback Severity in Makueni			
(Intercept)	35.857	1	<0.001
Mean monthly rainfall (mm/month)	20.860	1	<0.001
Mean monthly temperature (°C/month)	39.942	1	<0.001

In Tharaka (Appendix IXb part a and b) indicates that; a unit increase in preceding monthly's average rainfall was associated with a reduction in *C. procera*'s dieback prevalence and severity index by 0.813 and 0.688 times respectively. On the other hand, a unit increase in average monthly temperature was significantly increasing dieback prevalence and severity by 1.315 and 1.401 times respectively.

In Makueni, model estimates (Appendix IXb part c and d) indicates that: a unit increase in preceding months average monthly rainfall was associated with a statistically significant reduction in *C. procera*'s dieback prevalence and severity index by 0.714 and 0.696 times respectively. Contrary, a unit increase in average monthly temperature was significantly increasing dieback prevalence and severity by 1.427 and 1.380 times respectively.

4.5.4. Dieback causing agents on *C. procera* in Tharaka and Makueni

Dieback condition on naturally growing *C. procera* in the semi-arid regions of Tharaka and Makueni was caused by *Botryosphaeria, Fusarium, Phomopsis, Alternaria, Cladosporium,* and other unidentified agents (Plate 4.5).

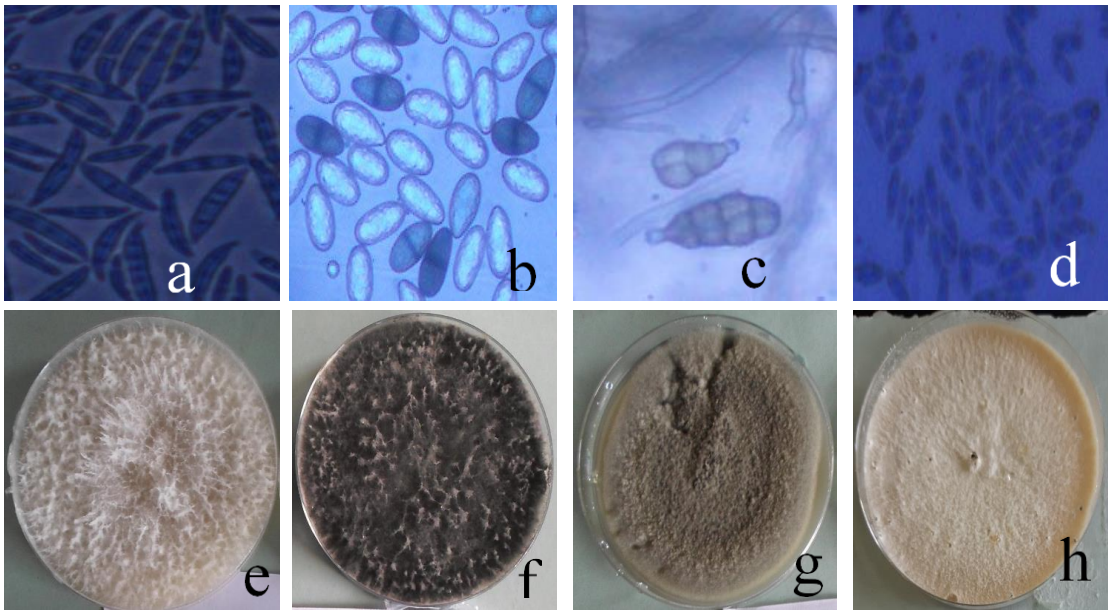

Figure 4.5: Common Causative Agents of Dieback Condition[a)*Fusarium* fungi spores, b) *Botryosphaeria* fungi spores, c) *Alternaria* fungi spores, and d) *Phomopsis* fungispores, all observed under dissecting microscope, e) *Fusarium* fungi, f) *Botryosphaeria* fungi, g) *Alternaria* fungi, and h) *Phomopsis* fungi, all growing on malt extract agar media].

(Source: Author, 2019)

Botryosphaeria and *Fusarium* fungi were the most dominant among the identified dieback causative agents (Table 4.62).

Table 4.62: Dominance of Dieback Causing Agents on *C. procera*

Region	Causative agent	Dominance of Causative Agent (%)			
		(June-August) 2018	(March-May)2019	(September-November)2019	(February-April) 2020
	Botryosphaeria	36.19	34.07	43.81	40.06
	Fusarium	41.89	43.38	38.57	39.42
	Phomopsis	10.08	9.80	8.81	8.65
	Alternaria	7.89	8.33	7.14	8.01
	Cladosporium	1.09	0.49	0.24	0.64
Tharaka	Unidentified Agents	2.63	5.39	2.38	4.17

Table 4.62: Dominance of Dieback Causing Agents on *C. procera* (Continued)

Region	Causative agent	Dominance of Causative Agent (%)			
		(June-August) 2018	(March-May)2019	(September-November)2019	(February-April) 2020
Makueni	*Botryosphaeria*	35.00	37.70	32.64	46.87
	Fusarium	43.00	42.06	39.93	32.29
	Phomopsis	11.00	9.52	10.76	9.72
	Alternaria	8.00	6.77	10.07	9.03
	Cladosporium	0.33	0.0	1.04	0.69
	Unidentified Agents	2.67	4.54	3.82	2.78

For a factorial analysis, data on the dominance dieback causing agents failed the normalcy test assumption with $p < 0.001$, but met homogeneity test with $p > 0.05$. A (6*4*2) factorial ANOVA (Table 4.63) shows a statistically significant difference in the mean dominance among the six agents ($F_{(5,1314)} = 319.308$, $p < 0.001$, $\eta p^2 = 0.549$). However, there was no statistically significant difference in mean dominance of dieback causing agents between the two semi-arid regions and among research time points. There were also no significant interactions.

Table 4.63: Factorial Analysis of *C. procera*'s Dieback Causing Agents

Source	Type III Sum of Squares	Df	Mean Square	*F*	*p*	Partial Eta Squared
Time	12.327	3	4.109	0.019	0.996	0.000
Region	10.512	1	10.512	0.049	0.825	0.000
Causative agent	342293.508	5	68458.702	319.308	<0.001	0.549
Time * region	18.147	3	6.049	0.028	0.994	0.000
Time * Causative agent	3868.036	15	257.869	1.203	0.262	0.014
Region * Causative agent	205.661	5	41.132	0.192	0.966	0.001
Time * region * Causative agent	3410.758	15	227.384	1.061	0.389	0.012
Error	281718.117	1314	214.397			
Total	1028263.285	1362				
Corrected Total	647436.189	1361				

Tukey's pairwise comparison (Appendix Xa) summarized in Table 4.64 shows that the mean dominance of *Botryosphaeria* and *Fussarium* fungi were significantly higher than other agents.

Table 4.64: Summarized Tukey's Pair-wise Analysis of Dieback Causative Agents

	Fussarium	***Phomopsis***	***Alternaria***	***Cladosporium***	**Unidentified Agent**
Botryosphaeria	$p = 0.701$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Fussarium		$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Phomopsis			$P = 0.836$	$P < 0.001$	$P < 0.001$
Alternaria				$P < 0.001$	$P = 0.008$
Cladosporium					$P = 0.326$

4.5.5. Edaphic factors affecting dominance of dieback causing agents on *C. procera*

Linear regression based on GLM indicates that no edaphic variable was significantly associated with the dominance of dieback causing agents on naturally growing *C. procera* (Table 4.65).

Table 4.65: Test of Edaphic Factors Affecting Dominance of Causative Agents on *C. procera*

	Type III		
Source	**Wald Chi-Square**	**df**	***p***
(Intercept)	2.181	1	0.140
pH at (0-20) cm	0.020	1	0.887
EC at (0-20) cm	0.066	1	0.798
N at (0-20) cm	1.616	1	0.204
OC at (0-20) cm	0.081	1	0.776
P at (0-20) cm	0.007	1	0.934
K at (0-20) cm	0.543	1	0.461
Mg at (0-20) cm	2.011	1	0.156
Ca at (0-20) cm	1.972	1	0.160
Na at (0-20) cm	2.392	1	0.122
pH at (20-40) cm	0.077	1	0.781
EC at (20-40) cm	2.160	1	0.142
N at (20-40) cm	1.113	1	0.291
OC at (20-40) cm	0.963	1	0.326
P at (20-40) cm	1.938	1	0.164
K at (20-40) cm	0.099	1	0.753
Mg at (20-40) cm	1.331	1	0.249
Ca at (20-40) cm	1.736	1	0.188
Na at (20-40) cm	0.010	1	0.920

4.5.6. Weather conditions affecting dominance of dieback causative agents

Linear regression based on GLM indicates that average monthly rainfall, temperature, wind speed and relative humidity had no statistically significant association with dominance of dieback causing agents (Table 4.66).

Table 4.66: Weather Conditions Affecting Dominance of dieback Causative Agents on *C. procera*

	Type III		
Source	**Wald Chi-Square**	**Df**	***P***
(Intercept)	0.099	1	0.753
Total monthly rainfall	0.009	1	0.925
Mean monthly temperature	0.018	1	0.895
Mean monthly wind speed	0.000	1	0.987
Monthly relative humidity	0.000	1	0.987

CHAPTER FIVE

DISCUSSIONS

5.1. Edaphic and Weather Conditions in Tharaka and Makueni

5.1.1. Soil properties in the semi-arid regions of Tharaka and Makueni

Semi-arid regions of Tharaka and Makueni have varied levels of soil chemical properties with some nutrients being deficient. For instance, soil pH of 6.8 in Makueni was adequate while pH of 7.3 in Tharaka was above the critical level (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). The soil pH levels in the two regions differed from the findings of Muya *et al*. (2011) who found soils in the arid and semi arid regions to have pH levels less that 6.5. This informs that soil pH differs from region to region depending on the soil horizon, parent material, topography, temperature and rainfall (Zhang *et al*., 2019). Temperature and rainfall influences the intensity of leaching and weathering such that in the event of humid conditions the pH of soil decreases over time leading to acidification unlike dry conditions where weathering and leaching are less intense leading to neutral or alkaline pH (Guoju *et al*., 2012; Onwuka & Mang, 2018). This explains the reason why the soils in Makueni were slightly acidic and those in Tharaka were alkaline throughout the study period.

Soil electrical conductivity in Tharaka was 0.12 mS/cm and 0.14 mS/cm at (0-20) cm and (20-40) cm soil depths respectively. In Makueni, soil electrical conductivity levels were 0.09 mS/cm and 0.11 mS/cm at (0-20) cm and (20-40) cm soil depths respectively. The findings showed that soil electrical conductivity levels in the two regions were below the critical level which indicates that soils in the regions are less saline (Okalebo *et al*., 2002; Horneck *et al*., 2011; Castro & dos Santos, 2020). However, soil electrical conductivity level in Tharaka was higher as compared to Makueni. This may be as a result of little rainfall received in the region that is

inadequate to leach away salts (Corwin, 2020). In addition, soils in Tharaka had high level of exchangeable sodium leading to high salinity level (Hussain *et al*., 2019).

Soil total nitrogen content in Tharaka was 0.15% and 0.18% at (0-20) cm and (20-40) cm depths respectively while in Makueni was 0.23% and 0.25% at (0-20) cm and (20-40) cm depths respectively. The nutrient levels in the two regions were within range of critical level between 0.12% and 0.25% (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). Comparatively, Makueni had higher level of total nitrogen compared to Tharaka. This is as a result of unoptimal temperature and soil moisture required for decomposition and mineralization process to occur so as to make nitrogen available (Hernán & Castellanos-Villegas, 2011). Based on the existing rocky conditions in Tharaka, the region has experienced soil disturbance due to quarrying that has affected richness and abundance of plants in the area thus making nitrogen mineralization heterogenous (Mohamed *et al*., 2019).

Soil organic carbon content in Tharaka was 3% and 2.92% at (0-20) cm and (20-40) cm soil depths respectively. The condition was not far from Makueni which had 3.08% and 2.63% at (0-20) cm and (20-40) cm soil depths respectively. The findings indicate adequate levels of soil organic carbon in the two regions which concurs with Marx *et al*. (1999), Okalebo *et al*. (2002) and Horneck *et al*. (2011) who established critical level of 1.5% to 3.0%. The increasing trend of soil organic carbon content in the two regions concurs with Mureva *et al*. (2018) who found a general increase in soil organic carbon in areas with low rainfall.

Available phosporus level in Tharaka was 4.78 ppm at a depth of (0-20) cm and 4.84 ppm at (20-40) cm depth. In Makueni, the available phosphorus level was 10.64 ppm at (0-20) cm and 10.76 ppm at (20-40) cm depth. The available P levels in both

regions were below the critical level of 20 ppm (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). This showed that soils in Tharaka and Makueni were deficient in available phosphorus. Despite the deficiency, soils in Makueni had higher levels of available phosphorus compared to Tharaka. Deficiency in available P in semi-arid soils concur with Koala *et al.* (1988) and Muya *et al*. (2011) studies that classified over 65.1% of soil samples from semi-arid regions as acutely deficient in available phosphorus. This deficiency in available phosphorus is as a result of imbalance in a number of biological and biochemical processes that are significantly influenced by soil organic matter, soil texture, biotic factors and abiotic characteristics of the region (Suñer & Galantini, 2015; Bhat *et al*., 2017). Therefore plant growth may negatively be influenced by deficiency of available phosphorus as it affects key roles in plant metabolism, structure, and energy transformation (Suñer & Galantini, 2015).

Exchangeable potassium in Tharaka was 118.18 ppm and 147.48 ppm at (0-20) cm and (20-40) cm depths respectively. On the other hand, Makueni had 211.44 ppm and 228.20 ppm at (0-20) cm and (20-40) cm depths respectively. The exchangeable potassium level in Tharaka was below critical level while that of Makueni was within the critical level range of 175 ppm to 300 ppm (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). This shows that soils in Tharaka were deficient in exchangeable potassium while those in Makueni had adequate level of exchangeable potassium. The inadequacy in Tharaka may be due to low level of organic carbon compared to Makueni. According to Shakeri and Abtahi (2018), exchangeable K is higher in subsurface soils with higher organi carbon content. Quarrying activities have been observed in Tharaka and this deteriorates soil nutrients by reducing organic matter and increases the levels of trace metal contents as a result of dust accumulation

(Rani *et al*., 2015; Rodríguez-Seijo & Andrade-Couce, 2017). However, soil properties may also vary from region to region depending on the prevailing parent rocks, topography and biological, physical and chemical processes (Dinesh *et al*., 2019).

Exchangeable magnesium in Tharaka was 77.76 ppm and 87.87 ppm at (0-20) cm and (20-40) cm soil depths respectively while in Makueni it was 103.61 ppm and 113 ppm at 0-20 cm and 20-40 cm depths respectively. The findings in the two regions were within the critical level range of 80-180 ppm (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). Nevertheless, the exchangeable magnesium levels in Makueni were higher than in Tharaka. The presence of orgarnic matter influences the amount of exchangeable Mg in soils and this concurs with Queiroz *et al.* (2018) that sand soil fraction together with low organic matter content influences drainage and leaching process. According to Saygin (2017), soil erosion, overgrazing and leaching are responsible for top soil degradation in ASALs.

Tharaka recorded low exchangeable calcium levels of 1040 ppm and 1130 ppm at (0-20) cm and (20-40) cm soil depth while Makueni had 1341 ppm and 1473 ppm at the same soil depths respectively. Despite the difference, exchangeable Ca levels in both regions were within the critical level range of 1000-1600 ppm (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). The difference realized might be explained by the difference in prevailing parent rocks, topography, biological and physio-chemical processes (Dinesh *et al*., 2019).

Exchangeable sodium was highly felt in Tharaka (112.5 ppm and 85 ppm) at (0-20) cm and (20-40) cm soil depths respectively. Makueni region recorded 75 ppm and 74 ppm at (0-20) cm and (20-40) cm respectively. The level at (0-20) cm depth in

Tharaka exceeded the critical level range of less than 100 ppm (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011). This is evidenced with a slightly high soil EC (0.12 mS/cm) at (0-20) cm depth in Tharaka. This is because high level of exchangeable sodium correlates positively with high salinity level (Hussain *et al*., 2019).

The amount of soil properties including EC(0.12 mS/cm; 0.14 mS/cm), total N (0.15%; 0.18%), exchangeable K (118.18 ppm; 147.48 ppm), exchangeable Mg (77.76 ppm; 87.87 ppm), and exchangeable Na (112.5 ppm; 85 ppm) in Tharaka and EC(0.09 mS/cm; 0.11 mS/cm), total N (0.23%; 0.25%), exchangeable K (211.44 ppm; 228.2 ppm), exchangeable Mg (103.61 ppm; 113 ppm), and exchangeable Na (75 ppm; 74 ppm) in Makueni varied significantly between (0-20) cm and (20-40) cm soil depths respectively with high concentrations within (20-40) cm soil depth. This concur with Rani *et al*. (2015) and Nadir *et al*. (2018) that soil depth has significant effects on soil properties like available N and exchangeable Ca. However, more nutrients were concentrated on the lower soil depth (20-40) cm than the upper depth of (0-20) cm. This may be because high erosion had washed away most nutrients on top soils while leaching may have moved more nutrients deeper.

According to Ullah *et al*. (2019) and Meena *et al*. (2019), soil properties change over a period of time due to erosion, tillage and existing soil management practices. However, this study revealed that soil properties didn't change significantly from June 2018 to April 2020. This insignificant change may be attributed to a shorter period of monitoring; that is 23 months. It is on this basis that Bünemann *et al*. (2018) recommended that soil survey to monitor changes should be conducted over large time intervals to depict measurable changes, although they failed to provide specific time frame appropriate for soil evaluation.

The study revealed significant correlation among different soil properties like total N content at (0-20) cm correlated significantly with organic carbon, available P, exchangeable K, Mg, Ca, and Na nutrients at (0-20) cm and pH, electrical conductivity, total N, organic carbon, available P, exchangeable K, Mg, Ca, and Na nutrients at (20-40) cm depth. This correlation between and among soil nutrients is not unique as they influence each other's formation. According to Mucheru-Muna *et al.* (2007) and Iwuagwu *et al*. (2019), increasing soil pH results from increase in exchangeable cations (K, Ca, and Mg), which in turn affects soil alkalinity measured in terms of EC. This supports the argument by Szili-Kovács *et al*. (2011) that assessing soil quality requires a holistic approach of chemical, physical and biological processes because they are related.

5.1.2. Weather conditions in the semi-arid regions of Tharaka and Makueni

The study established that the highest and lowest average monthly rainfall recorded were 160.37 mm/month and 52.55 mm/month respectively for Makueni and 143.83 mm/month and 45.27 mm/month for Tharaka. These variations concur with Government of Makueni County (2018) and Recha *et al*. (2018) that the semi-arid regions of Makueni and Tharaka receive low, varied and unreliable rainfall. This is not different from other semi-arid regions which experiences greater inter- and intra-annual rainfall variation (Mutua *et al*., 2020). These high inter-annual variations of rains in semi-arid regions are explained by complex intrinsic features of global atmospheric circulations that affects structure and position of regional shallow circulations (Biasutti, 2019; Scholes, 2020).

Average monthly temperature ranged from 25.78°C to 28.15 °C in Tharaka and 24.92 °C to 28.74 °C in Makueni. These relatively high temperatures may be attributed to

high solar radiations, low cloud cover and their proximity to the equator (Scholes, 2020). High temperatures have negative impacts on growth and development of plants having no or few adaptation strategies (Hatfield & Prueger, 2016). Significant variations in temperature among research points are mainly explained by variations in degree of cloud cover. According to Betts *et al*. (2013), maximum temperature usually increases with a decrease in cloud cover level. However, proximity of the study areas to the equator may have influenced minimum temperature as the sun is always overhead around the equator.

Wind speed variations from 2.9 m/s to 3.6 m/s in Tharaka and 2.12 m/s to 3.07 m/s in Makueni were as a result of variations in temperature, cloud cover and earth's revolution. According to Wooten (2011), Betts *et al*. (2013) and Monahan and McFarlane (2013), cloud cover affects temperature which creates pressure difference between places that eventually affects wind speed. Therefore, under clear sky, the temperatures were high, creating high pressure differences that eventually increased wind speed.

There were no significant differences in relative humidity at different research time points and between the study sites despite significant variations in average monthly temperatures. This finding contradicts various studies like Bui *et al*. (2019) that indicated decreasing relative humidity with decreasing rains at high temperature. However, according to Rokonuzzaman and Rahman (2017), relative humidity is mostly influenced by air moisture content which is greatly affected by the amount of water that evaporates from water bodies and transpiration. The amount of water that evaporates depends on the warmth of oceans, lakes, rivers and streams as heated by sunlight among other factors. Therefore, it is not only temperature that influences

relative humidity but also other factors like transpiration and evaporation rates which did not form part of this research.

5.2. Morphological Characteristics of *C. procera* in Tharaka and Makueni

5.2.1. Leaf colour and size

The findings that (88.1%, 85.5%, 86%, 85.5%) and (94.2%, 93%, 87%, 92.9) of *C. procera* stems in Tharaka and Makueni respectively remained with green leaves throughout the four research time points concur with existing literature like Bairagi *et al*. (2018) and Brown (2013). The ability of *C. procera* to shed leaves during dry and hot seasons is very important as it increases photosynthetic efficiency of remaining leaves and minimize transpiration (Tomoki *et al*., 2018).

Though leaf surface area frequencies in class <50 cm^2, (50-<100) cm^2, (100-<150) cm^2 and (150-<200) cm^2 did not vary significantly between the two semi-arid regions of Tharaka and Makueni, they varied significantly within research time points. This within time variations concurs with Nicotra *et al*. (2011) and Garcia *et al.* (2014) and may be explained as variations in seasons of the year resulting to different stresses that may require different plant responses. This study therefore confirms Moustafa and Sarah (2017) argument that *C. procera* exhibit morphological plasticity like shedding leaves and reducing leaf size to survive during high temperatures and low rains.

5.2.2. Edaphic and Weather factors affecting *C. procera*'s leaf size

The study established that a unit increase in soil available P at (0-20) cm and (20-40) cm soil depth were associated with increasing the size of *C. procera* leaves in Tharaka. On the other hand, a unit increase in soil available P at (20-40) cm depth was associated with increasing the size of *C. procera* leaves in Makueni. This concurs

with Vose *et al*. (1994) and Razaq *et al*.(2017) that edaphic factors especially total N, available P and OC content affects the leaf surface area index of plants. However, the association was weak as indicated by odd ratios of 1.028 and 1.025 for available P at (0-20) cm, and (20-40) cm respectively in Tharaka and 1.059 for available P at (20-40) cm in Makueni. These weak associations contradict strong associations between leaf size with soil available P, total N and OC content established by Vose *et al*. (1994). However, this contradiction may be because Vose *et al*. (1994) compared morphology of pine plantations in areas with soil nutrient deficiency and those with optimal soil nutrients; leading soil nutrient gradient. However, there was no nutrient gradient in this study for both regions. Furthermore, *C. procera* is adapted to poor soils as it has a long taproot that absorbs nutrients from deeper soils (Csurhes, 2016; Muriira *et al*., 2015). Therefore, soil conditions at (0-20) cm and (20-40) cm deep may not affect the plants leaf surface area strongly.

The shrub's leaf surface area was also affected by weather conditions such that a unit increase in preceding average month's rainfall and relative humidity in Tharaka was associated with increase in size of *C. procera* leaves with odd ratios of 1.007 and 1.005 respectively. Similar weather conditions were associated with increase in leaf size of *C. procera* in Makueni with odd ratios of 1.012 and 1.005 respectively. On the other hand, preceding months' average temperature and wind speed was associated with decrease in leaf size of *C. procera* with odd ratios of (0.649, 0.987) in Tharaka and (0.610, 0.891) in Makueni respectively. This concurred with Giuliani *et al*. (2013) and Basu *et al*. (2016) that plants respond to high temperature and low rainfalls by reducing their leaf sizes to control evaporative demands created by such stressful environments. Relative humidity controls leaf size through enhanced or reduced turgor pressure. According to Lonagre and Patil (2017), high relative humidity under

low temperature leads to low transpiration that eventually results to high turgor pressure within leaf cells, forcing them to elongate. Such elongation of leaf cells result to leaf growth.

Reduction of leaf surface area as a result of high wind speed as indicated by low odd ratios of 0.987 in Tharaka and 0.891 in Makueni has also been reported in literature (Nobel, 1981; Onoda & Anten, 2011). High wind speed increases leaf transpiration rates by reducing boundary layer resistance, which in turn decreases turgor pressure in leaf cells especially in high temperature and water limiting conditions (Smith & Ennos, 2003; Burgess *et al*., 2016). Reduced turgor pressure leads to reduced leaf size.

However, the association of leaf surface area with rainfall, relative humidity, wind speed and temperature was weak as evidenced by low odd ratios of (1.007, 1.005, 0.649, 0.987) and (1.012, 1.005, 0.610, 0.891) in Tharaka and Makueni respectively. This may be because the plant's long taproot has the ability to draw soil moisture from deep soils to counter the effects of low rains, low relative humidity, high wind speed and temperatures.

5.2.3. Fruit size

Although fruits volume did not vary significantly between the two semi-arid regions of Tharaka and Makueni, they varied significantly within the research time points. This is as a result of increasing temperatures and decreasing rainfall experienced in the two regions in 1st, 2nd and 3rd instance of data collection. This concurred with Woźnicka *et al*. (2015), Houédjissin *et al*. (2015) and Gichimu and Omondi (2010) that fruit sizes may change not only as a result of environmental conditions like soil nutrients, rains and temperature, but fruits development stage as well. In this regard,

fruits may be small because of neither prevailing environmental conditions nor genetic conditions, but because they are still young and developing (Gichimu & Omondi, 2010; Guo *et al*., 2019).

However, insignificant difference in fruit volume between Tharaka and Makueni may be attributed to similar ecological conditions and genetic similarity. According to Nicotra *et al*. (2011) and Guo *et al*. (2015), external ecological stimuli can initiate gene modification in a species to either limit or enhance fruit expansion. This therefore concurs with Muriira *et al*. (2018) indicating that there are no genetic variations within *C. procera* in the two regions.

5.2.4. Edaphic and weather conditions affecting fruit size

A unit increase in soil total N and available P at (0-20) cm was associated with increase in fruit volume with odd ratios 1.093 and 1.070 in Tharaka respectively. At the depth of (20-40) cm available P was associated with increase in fruit volume in Tharaka. On the other hand, only available P at (20-40) cm was associated with an increase in fruit volume with odd ratio 1.001 in Makueni. The relationship between plant fruiting with weather and soil conditions is very complex, making it difficult to single out any particular parameter to describe its influence (Dolkar *et al.,* 2018). However, some studies like Shamshir *et al*. (2012) and Houédjissin *et al*. (2015) have singled out soil nutrients and climatic conditions that concur with this study in the sense that soil total N, available P, exchangeable K and climatic factors have significant association with fruit sizes. Soil nutrients like exchangeable K and total N mainly affect plant growth characteristics like trunk circumference which Houédjissin *et al*. (2015) found to be correlating positively with fruit length and width.

Soil nutrients like total N, available P and exchangeable K are essential macronutrients that are crucial in photosynthesis under optimal water availability, temperature and sunlight (Guo *et al*., 2019). In their review, Fischer *et al*. (2012) concluded that improved photosynthesis improves fruit growth and development. This is because optimal photosynthesis ensures adequate availability of carbohydrates to fruits and other non-photosynthetic organs. Availability of carbohydrates in fruits enhances their growth and development (Bustan *et al*., 2011).

A unit increase in preceding months'average rainfall and relative humidity were associated with an increase in fruit volume with odd ratios of 1.002 and 1.039 in Tharaka respectively. Similar weather conditions were associated with an increase in fruit volume with odd ratios of 1.042 and 1.007 in Makueni respectively. Such findings of fruits being larger during moderately high rainfall and high relative humidity were also observed in India by Shamshir *et al*. (2012) and Dolkar *et al*. (2018). High rainfalls and relative humidity according to Bradfield and Guttridge (1984) enhances transportation of water into fruits by creating root pressure. Under optimal temperature, the high water content in fruits causes expansion of fruits' cells, making the fruit larger (Lonagre & Patil, 2017).

However, an increase in preceding months' average temperature and wind speed were associated with a decrease in fruit volume of *C. procera'*s with odd ratios of (0.914, 0.810) and (0.788 , 0.929) in Tharaka and Makueni respectively. The negative effects of high temperature on *C. procera'*s fruit size established during the 2^{nd}, 3^{rd} and 4^{th} instance of data collection in both regions contradicts Warrington *et al*. (1999) findings that exposing apple fruits to temperatures above 22 °C increases their sizes. This contradiction may be attributed to low rainfalls that were being experienced in Tharaka and Makueni. According to Raza *et al*. (2019) the negative impacts of high

temperatures on crops are mostly experienced during prolonged drought conditions with high evaporation rates.

In terms of wind speed, Bock and Graham (2010) states that larger fruits are mostly susceptible to falls as a result of turbulence caused by wind speed. Moreover, high wind speed may also have negative effects on plant's photosynthetic efficiency especially under high temperatures, which in turn reduces availability of carbohydrates necessary for fruit growth and development (Burgess *et al*., 2016).

5.3. Population Distribution in Terms of Size Classification

5.3.1. Stem height, crown and root collar diameters of *C. procera*

A reducing trend in relative frequency (%) of *C. procera* with total height <1.5 m was established from 46.18% to 36.7% in Tharaka and 16.05% to 3.79% in Makueni between (June to August) 2018 and (February to April) 2020. Over the same period, the general trend indicates that the relative frequency (%) of stems with total height (3 to <4.5) m increased from 1.11% to 12.7% in Tharaka and 10.3% to 27.44% in Makueni though with fluctuations in (September to November) 2019. Similar trend was established with crown and root collar diameter classes in both regions. This showed that the ability of *C. procera* to increase in height and expand its crown and root collar diameter over time.

The presence of *C. procera* stems in all the stem height, crown and root collar diameter classes in the semi-arid regions of Tharaka and Makueni in Kenya was evidence of a natural population hierarchy of the shrub. This concurred with Rocky and Mligo (2012) and Peck *et al*. (2014) that in the wild, trees of same species and or age develop a population hierarchy of small, medium and larger stems. Therefore, *C. procera* stems growing naturally in semi-arid regions have similar growing

characteristics like other naturally growing trees and shrubs in the wild. These hierarchical characteristic may be attributed to genetic variations, soil condition, age difference and variations in microclimatic conditions within an ecosystem (Rocky & Mligo, 2012; Ehrlen & Morris, 2015). However, the issue of genetic variation may be ruled out because according to Muriira *et al*. (2018), *C. procera* species have no within species genetic variations in Kenya.

Larger *C. procera* stems with total height, crown diameter and root collar diameter ≥4.5 m, ≥ 120 cm and ≥ 8 cm respectively were least throughout research time points in both Tharaka and Makueni. These concur with Galal *et al*. (2015) that over 67% of *C. procera* stems in a stand are less than 1.5 m in height. This indicates that though *C. procera* can grow up-to 6m (Orwa *et al*., 2009; Jianchu, 2016), they have high juvenile mortality rates, larger stems frequently cut by humans for fodder, or most stems have lower growth potential especially during dry season (Orwa *et al.*, 2009; Vitelli *et al*., 2008; Csurhes, 2016; Galal *et al*., 2016). In case of high juvenile mortality rates, then the population of naturally growing *C. procera* in Tharaka and Makueni is in danger because smaller stems have less chances of producing next generation's offspring through seeds (Galal *et al*., 2016). However, the evidence of stems being cut for fodder indicates that the shrub will continue reproducing through stump sprouting (Muriira *et al*., 2015; Csurhes, 2016).

During the 23-month research period, *C. procera* stems showed significant variations in stems' total height within time points and between semi arid regions. The mean ranks of *C. procera*'s height class distribution in (June to August) 2018 was lower than in (March to May) 2019, (September to November) 2019 and (February to A pril) 2020. This shows the ability of the plant to change in size over time thus an indicator of vertical growth. The variations in height within time may be explained by

a switch in plant strategy as a result of change in environmental conditions over time (Moles *et al*., 2009). The variation in height between semi arid regions may be due to differences in site conditions where Tharaka was rocky and quarrying conditions may imply shallow and poor soils. Galal (2011), Rocky and Mligo (2012) and Ehrlen and Morris (2015) adds that, age, competition and genetic variations within a species from different regions may result to differences in size distribution of a plant.

Calotropis procera stems showed significant variations in stems' crown and root collar diameter within time points and between semi arid regions. The mean ranks of *C. procera*'s crown and root collar diameter class distribution in (June to August) 2018 was lower than in (March to May) 2019, (September to November) 2019 and (February to A pril) 2020. This shows the ability of the shrub to grow horizontally by expanding its crown and collar diameters. This concurs with Hatfield and Prueger (2015) and Galal *et al*. (2016) that mean crown and collar diameters of the shrub may vary within time of the year depending on seasons and other conditions like plant health that affects plant growth. It was observed that stem density of *C. procera* stems in Tharaka was high compared to Makueni; a situation that may lead to intra-species competition. According to Gioria and Osborne (2014), competition leads to sharing of limited resources like nutrients and water, a condition that reduces plant's fitness components. Reduced fitness may lead to slow growth rate or death.

However, the stem height, crown and root collar diameters in 2^{nd}, 3^{rd} and 4^{th} successive research time points were not significantly different in both regions. This may be because prevailing conditions between (March – May) 2019 and (September – November) 2019 could have been harsh that the growth rate was slow, leading to insignificant difference in height, average crown and root collar diameters. Under harsh conditions like prolonged drought, *C. procera* shed leaves and experience

dieback conditions that may hinder its growth rate (Orwa *et al*., 2009; Galal *et al*., 2016; Moustafa & Sarah, 2017).

Root collar diameter expansion is very important to plants as it supports larger crowns without breaking especially during windy conditions and enhances the plant's ability to withstand attacks by cutworms. According to Mutiso *et al*. (2017), Cutworms mainly attack juvenile *C. procera* stems before the stems expand and harden. Taller and large stems provides enough space for heavy branching, which eventually increases the average crown diameter that increases fibre production as most branches becomes floral at reproduction stage to produce more fruits (Mutiso *et al*., 2017; Sobrinho *et al*., 2013).

5.3.2. Edaphic factors affecting stem height, crown and root collar diameters of *C. procera*

Soil properties were found to be playing an important role in increasing stem height of *C. procera* in the semi-arid regions of Tharaka and Makueni. In Tharaka a unit increase in soil available P at (0-20) cm, EC at (20-40) cm, available P at (20-40) cm, exchangeable K at (20-40) cm and total N at (20-40) cm were significantly associated with increasing the chances of *C. procera*'s stem height to be in ≥ 4.5 m class with odd ratios of 1.015, 1.003, 1.025, 1.030 and 1.174 respectively. On the other hand, a unit increase in soil total N and available P at (20-40) cm were significantly associated with increasing the chances of *C. procera*'s stem height to be in ≥ 4.5 m class with odd ratios of 1.081 and 1.001 respectively. However, the soils in both regions were deficient in available phosphorus. Considering that the species density was high in Tharaka, inter species competition also affects plant growth height. This concurs with Mutiso *et al*. (2017) that soil nutrients which are influenced by stem

spacing affect the growth of *C. procera*. Deficiency in soil nutrients like exchangeable Ca, exchangeable K, total N and exchangeable Mg leads to stunted growth among plants as a result of reduced photosynthetic rates and lower resistances to diseases (Hopkins & Huner, 2009; Bustan *et al*., 2011; Cruz *et al*., 2017; Guo *et al*., 2019). Available P also plays key roles in plant metabolism, structure, and energy transformation (Suñer & Galantini, 2015).

In Tharaka, a unit increase in soil EC, total N, available P, exchangeable K and exchangeable Mg at (20-40) cm were increasing the chances of crown diameter to be ≥ 120 cm class with odd ratios of 1.050, 1.048, 1.001 and 1.001 respectively. In Makueni, a unit increase in soil EC, OC content, available P and exchangeable Ca at (20-40) cm were associated with an increase in chances of crown diameter to be ≥ 120 cm class with odd ratios of 1.071, 1.056, 1.059 and 1.002 respectively. The soils in Tharaka were deficient of both potassium and available phosphorus. Deficiency in Ca, Mg, N and K may lead to slow growth rates of plant shoot and leaves and crop stunting due to low rates of photosynthesis thus affecting cown diameter (Hopkins & Huner, 2009). These findings concur with Razaq *et al*. (2017) who found a combination of N and P resulting to maximum growth in terms of height and root collar diameter that eventually determines crown size of the plant.

A unit increase in soil EC, total N and exchangeable Mg at (20-40) cm were associated with an increase in chances of root collar diameter to be in ≥ 8 cm class with odd ratios of 1.027, 1.046 and 1.092 respectively in Tharaka. In Makueni, a unit increase in soil pH at (0-20) cm, soil EC and total N at (20-40) cm were increasing the the odds of root collar diameter to be in ≥ 8 cm class with odd ratios of 1.075 and 1.089 respectively. Low soil pH below 6.5 leads to deficiency in basic cations like exchangeable Ca, exchangeable Mg and exchangeable K, while high pH leads to

deficiency in nutrients like Fe and Mn (Villalobos & Fereres, 2016). It should be noted that the soil EC was within required limits of < 0.15 (Marx *et al*., 1999; Okalebo *et al*., 2002; Horneck *et al*., 2011), meaning that the soils in semi-arid regions of Tharaka and Makueni were not saline. Otherwise, high salinity limits plant growth by creating osmotic and nutritional imbalances that reduces nutrient cycling and water stress around the root zone (Dmuchowski *et al*., 2011; Parnes, 2013; Zhang *et al*., 2017). However, studies have found *C. procera* to be tolerant to saline soils (Moustafa & Sarah, 2017), meaning that even high salinity could not have affected its growth. However, it is unclear why soil pH was not affecting height and crown diameter class distribution in this study.

The ability of *C. procera* to grow in rocky and quarrying environment in Tharaka shows the potential of the species to be used in rehabilitating degraded quarry zones in the semi-arid regions. This concurs with Orwa *et al*. (2009) and Moustafa and Sarah (2017) that *C. procera* can be used in production of green manure to improve soil fertility.

5.3.3. Weather conditions affecting stem height, crown and root collar diameter of *C. procera*

A unit increase in average monthly rainfall was significantly associated with an increase in chances of *C. procera*'s height, crown and root collar dimeter to be in ≥ 4.5 m, ≥ 120 cm and ≥ 8 cm classes in Tharaka and Makueni. On the other hand a unit incresease in average monthly temperature, wind speed and relative humidity was associated with a decrease in chances of *C. procera*'s height, crown and root collar diameter to be in higher classes in Tharaka and Makueni. This proves that though *C. procera* can survive in areas with as low as 45.27 mm/month and temperature as high

as 28.74 °C, the extreme weather conditions affects the plant's growth ability (Moustafa & Sarah, 2017; Coêlho *et al*., 2019). Higher temperature leads to reduced cell water content that eventually reduce the sizes of cells that are responsible for growth; leading to growth inhibition. In addition, high temperatures and extremely low temperatures reduce photosynthetic activities by altering enzyme activities, reduces closure and opening of stomata; hence reducing photosynthetic abilities of plants negatively (Kepova *et al*., 2005; Hasanuzzaman *et al*., 2013; Bita & Gerata, 2013). Reduced photosynthesis leads to reduced available food, which leads to stunted growth.

Rainfall improves soil moisture that provides important water for plant growth. Water stresses damage plant cells and reduce stomata opening and closure that negatively affects plant growth (Basu *et al*., 2016). However, presence of deep taproot enables *C. procera* to survive under harsh water deficit conditions (Ibrahim, 2013; Galal *et al*., 2016). A plant like *C. procera* also has latex, which is a protein that regulates ABA response, meaning that over-expression of latex helps plants to tolerate droughts (Wang *et al*., 2016). This was the major reason why the shrub survived in Tharaka with rains less than 50 mm/month in (March to May) 2019 and (September – November) 2019.

The effects of wind speed on decreasing height and crown diameter concur with Zhang *et al*. (2021) as wind increases evapotranspiration rate and carry disease causing agents that may affect the plants growth. Gardiner *et al.* (2016) and Peterson *et al*. (2019) adds that high wind speed break branches, sometimes plant tops and uprooting of the plant, and this may be the reason why root collar diameter was not influenced by wind speed.

Relative humidity was significantly associated with decrease of height, crown and collar diameters in both Tharaka and Makueni. Low relative humidity affects photosynthesis indirectly by increasing transpiration that leads to water deficit and also increases mesophyll resistance that prevents carbon dioxide intake (Chater *et al*., 2014).

5.4. Phenology of *C. procera* in Semi-Arid Regions of Tharaka and Makueni

5.4.1. Activity index, number of flowers and fruits and phenophase intensity

Calotropis procera growing naturally in the semi-arid regions of Tharaka and Makueni in Kenya exhibited over 48.05% and 42.57% flowering and fruiting activity indices respectively throughout research time point. Over 71 flowers and 4 fruits per stem with over 52.71% and 48.73% flowering and fruiting phenophase intensities were also exhibited in Tharaka and Makueni respectively for the entire period of data collection. This concurs with Sobrinho *et al*. (2013), Hassan *et al*. (2015) and Moustafa and Sarah (2017) that *C. procera* has continuous flowering and fruiting potential throughout the year. Therefore, *C. procera* depicts a rare flowering and fruiting trait that only exist among few plants growing and adapted to arid and semi-arid conditions (El-Tantawy, 2000). This means that the shrub is well adapted to the environmental conditions experienced in Tharaka and Makueni as it can flower and fruit all year long (Mutiso *et al*., 2017). However, the number of flowers was much higher than fruits per stem in all time points: meaning that the shrub has either low fertility rate, high drop of floral buds or high flower abortion after anthesis (Almeida *et al*., 2019). However, this is a common characteristic among Asclepiadaceae plant species (Wyatt & Broyles, 2012).

The number of flowers (150, 166), fruits (10, 12) per stem, flower activity indices (75.97%, 83.06%) and fruit activity indices (64.97%, 69.6%) in Tharaka and Makueni respectively for the period of (June-August) 2018 were lower than 959 flowers/stem, 22 fruits/stem, and over 76% activity indices reported by El-Tantawy (2000) and Sobrinho *et al*. (2013); implying that the species may be less invasive in Kenya. According to Payal and Sharma (2015) and Moustafa and Sarah (2017), invasive species have high phenological plasticity in terms of high number of flowers, fruits and phenophase activities that enable them establish and grow faster under harsh conditions like drought and varied temperatures.

Contrary, the shrub's invasive potential should not be ruled out based on flowering and fruiting phenophase intensities and activity indices. This is because based on observation, *C. procera* in Tharaka and Makueni were also establishing through vegetative sprouting of stumps just as found in other places like Egypt (Moustafa & Sarah, 2017). According to Gao *et al*. (2018), invasive species have more than one reproductive mode though sexual reproduction is the main mode.

Continuous fruiting contradicts Menge *et al*. (2017) that *C. procer*a fruit only during warm months of the year especially when pollinators remain active. This difference may arise because the semi-arid regions of Tharaka and Makueni were experiencing warm climatic conditions during the entire period of research, and according to Moustafa and Sarah (2017), the shrub has non-specialized pollination system.

Calotropis procera showed significant differences in flowering and fruiting activity indices, number of flowers and number of fruits per stem, flowering and fruiting phenophase intensities across research time points in the two regions peaking in (June to August) 2018. This concur with Sobrinho *et al*. (2013), Paradiso and Pascale

(2014), and Moustafa and Sarah (2017) that *C. procera* show peak and low phenology traits at different times of the year depending on prevailing environmental conditions like precipitation and temperature. Moustafa and Sarah (2017) add that flowering and fruiting reduces when temperatures are extremely high or low. This is because extreme temperatures reduce the photosynthetic activity of the plant through stomata changes and affects the pollination process and fertility of pollen grains (Bita & Gerata, 2013; Hatfield & Prueger, 2015). Singh and Kushwaha (2006) and Omondi *et al*. (2016) add that the difference in flowering and fruiting phenology of plants may be attributed to tree/shrub characteristics. For instance, there exist significant relationship between leafing and phenology in a manner that higher leafing correlates with higher flowering and fruiting despite the presence of time lag between them. This was evident by a slight increase in phenology in (February to April) 2020 when stems were recovering from severe dieback conditions and leaf shedding in Tharaka.

The shrub also showed significant differences in flowering activity index and number of flowers and fruits between the semi-arid regions of Tharaka and Makueni. The presence of degraded lands with rocks and quarrying in Tharaka may have influenced the soil depth and nutrients that eventually affects the phenology of *C. procera*. This is because shallow soils with hard pan and rocks prevent deep rooting system to enhance access to deeper soil nutrients and moisture (Leeuwen, 2010; Moustafa & Sarah, 2017), leading to inadequacy in soil moisture and nutrients. Inadequate nutrients like phosphorus, calcium and magnesium reduces the rate of flowering and fruiting (Wan *et al*., 2007; Hopkins & Huner, 2009; Aparna, 2014).

Flowering (p = 0.145) and fruiting (p = 0.602) phenophase intensities and fruiting activity index (p = 0.610) were not significantly different between the two semi-arid regions. This feature may be unique since all other phenological traits varied between

the semi-arid regions. However, it may be explained by a suggestion by Hamann (2004) that environmental factors including climatic and soil conditions are not the only factors affecting the proportion of trees with certain phenological traits of tree species at a particular time. Taffo *et al*. (2019) adds that phenological traits of tropical trees may be affected by altitude and genetic factors.

5.4.2. Edaphic factors affecting Phenology of *C. procera*

In Tharaka, a unit increase in soil available P at (0-20) cm and at (20-40) was significantly increasing *C. procera*'s flowering activity index by 1.128 and 1.172 times respectively. In Makueni, a unit increase in soil available P at (20-40) was also associated with a significant increase of *C. procera*'s flowering activity index by 1.238 times. However, the association of soil edaphic factors and phenological traits was weak as evidenced by low odd ratios. This minimal relationship between edaphic factors and phenology contradicts various literature including Hopkins and Huner (2009) and Aparna (2014) that phosphorus, calcium and magnesium deficiency leads to aborted fruits and flowers.

However, the average number of flowers (≤ 166) and fruits (≤ 12) per stem in Tharaka and Makueni were very low compared to 959 flowers/stem, 22 fruits/stem reported by El-Tantawy (2000). This could have been contributed by low levels of available P in Tharaka (4.78 – 4.84) ppm and Makueni (10.64 – 10.76) ppm at (0-20) cm and (20-40) cm depth compared to the international standards of between 20 to 40 ppm as stipulated by Marx *et al*. (1999), Okalebo *et al*. (2002) and Horneck *et al.* (2011). This is because deficiency in soil available P impairs female reproductive organs of plants and reduces pollen viability, leading to reduced number of flowers and fruits and low phenophase intensities (Erel *et al*., 2016).

The effects of available exchangeable K on phenology was only felt minimally on number of fruits with odd ratio of 1.001 despite being low in Tharaka (118.18 - 147.48) ppm and adequate in Makueni (211.44 - 228.20) ppm compared to critical levels of (175-300) ppm. This is despite Teixeira *et al*. (2011) and Hasanuzzaman *et al*. (2018) conclusion that low soil K content leads to poor flowering and formation of pollen grains especially under high saline and drought conditions; leading to poor phenological traits.

However, the results concurred with Moustafa and Sarah (2017) that *C. procera* can tolerate soils with low nutrient content due to its intensive root system that ensure reaching nutrients and moisture beyond 40 cm depth. Therefore, edaphic factors including salinity (high EC) can not deter the invasive capacity of the shrub due to its adaptive avoidance mechanism to salinity stresses (Ibrahim, 2013; Leal *et al*., 2013).

5.4.3. Weather conditions affecting phenology of *C. procera*

A unit increase in preceding months' average monthly rainfall was significantly increasing *C. procera*'s flowering and fruiting activity indices by (1.234, 1.163) and (1.158, 1.075) times in Tharaka and Makueni respectively. However, a unit increase in preceding month's average monthly temperature was significantly reducing *C. procera*'s flowering and fruiting activity indices by (0.941, 0.867) and (0.974, 0.879) times in Tharaka and Makueni. Generally, phenological traits were significantly associated with preceding months' average rainfall and temperature. This concurs with studies like Moore and Lauenroth (2017) that temperature and rainfall influences phenological events especially in arid and semi-arid regions. This is because phenology development requires optimal temperature and adequate moisture that is influenced by rainfall (Moore *et al*., 2015). Temperature influences pollen and ovule

viability and affects visitation by pollinators (Bita &Gerata, 2013; Hatfield &Prueger, 2015; Kooi *et al*., 2019).

However, the association was weak with low odd ratios. This is because other factors like plant size especially in terms of crown diameter influences phenology traits like number of flowers, fruits and duration (Bustamante & Búrquez, 2008). Large crowns provide more space for flowers and fruits. Moreover, weak association between phenological traits with monthly average rainfall and temperature of preceding months may be attributed to the ability of *C. procera* to withstand harsh climatic conditions including high temperatures and low rainfall (Yassin *et al*., 2016; Coêlho *et al*., 2019).

A unit increase in wind speed was associated with a decrease in *C. procera's* fruiting by 0.982 and 0.979 times in Tharaka and Makueni respectively. According to Saúco (1993), high wind speeds causes traumatic flower and fruit fall before maturity. It also discourages flower visitation by pollinators by desiccating flower parts, making them unattractive; hence lowering fertilization rates in blackberries (Young *et al*., 2018). However, high wind speed increases the chances of self-pollination assisted by wind (Saúco, 1993; Young *et al*., 2018).

A unit increase in relative humidity was significantly reducing the number of fruits by 0.971 and 0.794 times in Tharaka and Makueni respectively. Relative humidity according to Lonagre and Patil (2017) affects phenology of plants indirectly by affecting pollination, photosynthesis and disease occurrence. High relative humidity may lead to reduced number of fruits as it impedes dispersal of pollen grains from anthers and increase disease instances by favouring fungal growth (Shemahonge,

2013). On the other hand, low relative humidity increases transpiration, leading to water deficit for photosynthesis (Chater *et al*., 2014).

5.5. *Calotropis procera*'s Dieback Condition in Tharaka and Makueni

5.5.1. Dieback prevalence and severity on *C. procera*

Naturally growing *C. procera* stems in the semi-arid regions of Tharaka and Makueni were experiencing crown dieback, cankerous, leaf scorching and discoloration; which according Bergdahl and Hill (2016) are indicators of dieback disease. It was established that the shrub experienced dieback conditions at all research time points from June 2018 to April 2020. This concurs with Kumar and Khurana (2017) that found serious leaf spot dieback problem on almost every naturally growing *C. procera* stem in India at all times regardless of existing climatic conditions. According to McKinney *et al*. (2014), it is difficult to find a stand without dieback condition at any instance because even young stems may be infected by their parents especially when the cause is fungal, pathogen and insects.

Dieback prevalence and severity varied significantly at different time points of the year with highest prevalence (76.59%, 80.53%) and severity index (3.56, 3.42) preceding the driest months of between June and August 2019 in Tharaka and Makueni respectively. These variations concurred with Handiso and Alemu (2017) that seasons and site conditions contribute significantly to the prevalence and severity of dieback conditions. Seasons contribute to dieback variations because different seasons pose varying levels of environmental stresses like drought and extreme temperatures that affect plants differently (Kozlowski & Pallardy, 1997). For instance, dieback prevalence on *C. procera* in India was 90% between January and February 2017 when the region was experiencing drought and high temperatures (Kumar &

Khurana, 2017). However, the findings of this study contradict Zarafi and Abdulkadir (2013) that found insignificant variations of dieback instances on Jatropha for the entire period of study. The difference may be explained by differences in methodology between the two studies. This is because Zarafi and Abdulkadir (2013) concentrated on dieback caused by one fungal pathogen (*Fusarium* spp.) on Jatropha, while this study looked at dieback conditions caused by multiple causative agents on *C. procera*. In addition, the plant species of these two studies were different. This contradiction implies that dieback prevalence/incidence depends on the plant species and causative agents.

There was an insignificant variation ($p = 0.649$, $p = 0.421$) in dieback prevalence and severity on *C. procera* between the semi-arid regions of Tharaka and Makueni respectively. These findings contradict Handiso and Alemu (2017) and Mukhtar *et al*. (2014) that reported variations in dieback prevalence and severity between regions. This contradiction is because according to Tharaka Nithi County Government (2018) and Government of Makueni County (2018), the study areas (Tharaka and Makueni) experience almost similar environmental conditions, are located within the same agro-ecological zone V and have almost similar altitude. Therefore, a difference in dieback prevalence and severity reported by Mukhtar *et al*. (2014) was as a result of a study conducted in different agro-ecological zones. Different agro-ecological zones mean different environmental and site conditions that influences dieback conditions.

5.5.2. Edaphic factors affecting dieback prevalence and severity

There were no significant association ($p > 0.05$) between edaphic factors with dieback prevalence and severity in Tharaka and Makueni. These findings contradict Mukhtar *et al*. (2014) and Turczański *et al*. (2020) that found significant impact of soil pH and

soil organic matter on dieback prevalence and severity on Shisham stems and other understorey vegetation. According to Turczański *et al*. (2020), soil pH plays an important role in either promoting or inhibiting the development of fungus causing dieback. According to Rousk *et al*. (2009), fungal growth increases with a decrease in soil pH from 8.3 to 4.5, and then decreases sharply below pH of 4.5. Therefore, insignificant association between soil pH and dieback prevalence and severity in this study may be attributed to low range of soil pH ranging from 6.8 to 7.3 in Makueni and Tharaka respectively. This means the soil pH in the study areas were almost neutral.

In their review, Bal *et al*. (2014) indicated that dieback conditions especially on sugar maple was as a result of deficiency in soil nutrients or their antagonistic behaviours. This concurs with Long *et al*. (2009) that deficiency in soil exchangeable Ca accompanied by high Aluminum (Al) reduces plant tolerance to other environmental stresses like drought. However, in this study, soil exchangeable Ca and other nutrients except available P in Tharaka and Makueni were within international stands as stipulated by Marx *et al*. (1999), Okalebo *et al*. (2002) and Horneck *et al.* (2011); hence minimum impacts on dieback condition. However, insignificant association may be as a result of *C. procera'*s ability to strive in degraded soils (Payal & Sharma, 2015; Moustafa & Sarah, 2017).

5.5.3. Weather conditions factors affecting dieback prevalence and severity

A unit increase in preceding average monthly rainfall was associated with a statistically significant reduction in *C. procera*'s dieback prevalence and severity index by 0.714 and 0.696 times respectively. Contrary, a unit increase in average monthly temperature was significantly increasing dieback prevalence and severity by

1.427 and 1.380 times respectively in Tharaka and Makueni. The significant association between dieback prevalence and severity of *C. procera* with average monthly rainfall and temperature concur with Sevanto *et al*. (2014), Brunner *et al*. (2015) and Vose *et al*. (2016). This is because high temperatures and low rainfalls subject plants to hydraulic failure that makes plants lose water through transpiration. This condition creates high xylem water tension that leads to the loss of cavitations and conductivity of xylem which restrict water up-take that eventually leads to wilting and dieback (Brunner *et al*., 2015; Kennelly *et al*., 2012). According to Velásquez *et al*. (2018), extreme environmental stresses including high temperature and low rainfall makes plants susceptible to pathogens and diseases. This is because extreme environmental conditions affect the plant's effector-triggered and pattern-triggered immunities, which eventually affect plant's resistance to pathogens and diseases (Couto & Zipfel, 2016).

However, the odd ratios of $\geq$ 0.696 and $\leq$1.427 for rainfall and temperature respectively signify that the association between dieback conditions with rainfall and temperature is not very strong. This is in support with Ahmad *et al.* (2019) that environmental factors alone may not strongly explain dieback conditions on plants. This is because plants like *C. procera* have long tap roots that enable them to draw water at higher depth to offset water lost through transpiration (Hassan *et al*., 2015). According to Robin-Abbott and Pardo (2015) and Kang *et al.* (2016), dieback condition may be as a result of interaction between climatic, genetic and soil depth factors. Therefore, lack of strong association between climatic factors and *C. procera* dieback condition may imply that other factors like soil depth and tree genetics were playing a role in the interaction.

5.5.4. Causative agents of dieback on *C. procera*

In this study, six dieback causative agents were identified, namely: *Botryosphaeria, Fusarium, Phomopsis, Alternaria, Cladosporium* and other unidentified agents that did not form part of this study. Amongst the six, *Fusarium* and *Botryosphaeria* species were the most dominant at all four research time points in the two semi-arid regions. *Botryosphaeria* species has been reported to be causing stem and branch canker by colonizing and killing phloem and cambium (Mehl *et al*., 2013).

Fusarium species have been identified in Kenya as a dieback causing fungi in passion fruits (Amata *et al*., 2009). This fungus is normally soil-borne, meaning that they degrade roots to a level that causes vascular wilts through root rot and root necrosis invasion (Zarafi & Abdulkadir, 2013; Davison, 2014). They also proliferate xylem and phloem where they block water, mineral and food transportation within the plant; causing dieback. According to Mukhtar (2007), the dominance of *Fusarium* is expected to be low in *C. procera* because the plant has high extract contents that inhibit fungal growth. However, it is unclear why the dominance of a vascular wilt (*Fusarium* species) remained high in Tharaka and Makueni with dominance ranging from 32.29% to 43.38%.

In Kenya, Amata *et al*. (2009) reported that *Alternaria* species are notable dieback causing fungi among citrus fruits. However, the presence of *Alternaria* species on *C. procera* is not new as it has been reported in India and other regions (Kumar & Khurana, 2017). According to Kumar and Khurana, (2017), the fungus grows on leaves as dark brown bloom, which reduces the photosynthetic area of the plant that eventually affects its photosynthetic abilities. Although Kumar and Khurana, (2017) found that the prevalence of *Alternaria* species on *C. procera* were high in wastelands

(desert and uncultivated regions), it is unclear why in this study, *Alternaria*'s dominance was low (6.77% to 10.07%) compared to *Botryosphaeria* and *Fusarium* species. However, this may be because all samples were taken from stems and branches, but not leaves where *Alternaria* was reported to be prominent.

Cladosporium species has also been reported as a known dieback causing agents on *C. procera* especially during rainy seasons (Barreto *et al*., 1999; Korekar & Chavan, 2015). These species forms black soot on leaves that eventually causes leaf distortion especially during rainy seasons (Barreto *et al*., 1999; Talgo *et al*., 2011). *Phomopsis* species are also known to cause abnormal bunching and discoloration of foliage, thus resulting to dieback (Mahadevakumar & Janardhana 2016). In this study, it was found that the dominance of *Phomopsis* remained low ranging from 8.65% to 11.00% and did not vary significantly at different times of the year. These findings contradict Janis (2015) that found higher dominance of *Phomopsis* species in spring where new growth was still wet. The reason may be that Tharaka and Makueni were all located in semi-arid regions experiencing very low amount of rainfalls with high temperatures. These harsh conditions may have inhibited the growth of *Phomopsis* species.

Unidentified agents included all agents that either did not indicate fungal properties on the growing nutrient media, or the specimen on the plate did not grow any agent. According to Mukhtar *et al.* (2014), there are other edaphic, biotic and abiotic factors excluding fungi that cause dieback. Therefore, the category of unidentified agents was other agents that might have been outside the scope of this research, meaning that they were not individually isolated and determined. For instance, high temperatures, low rainfall, the presence of aphids, spiders and insects may have contributed to dieback condition.

In this study, the dominance of each dieback causing agent did not vary significantly from time to time and from region to region. This contradicts Amata *et al*. (2009) that fungi causing dieback differ from one region to the other depending on the prevailing ecological condition. This contradiction may be because the study areas (Tharaka and Makueni) are located in the same agro-ecological zone, meaning that the prevailing ecological conditions were almost the same.

5.5.5. Edaphic and weather conditions affecting causative agents of dieback on *C. procera*

There were no significant associations between dominance of dieback causing agents with edaphic and weather conditions ($p > 0.05$). This meant that dominance of dieback causing agents was neither affected by edaphic nor climatic conditions. These findings contradict the findings by Turczański *et al*. (2020) that dieback causing fungi are dominant in soils with lower pH and high moisture mainly influenced by rainfall. This contradiction may be attributed to neutral soil pH and low rainfall that could not alter the existing conditions significantly at all research time points. Therefore, insignificant association between dominance of dieback causing agents with climatic and edaphic factors may explain the presence of statistically significant variations of dominance within time points and between the two semi-arid regions.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1. Conclusions

6.1.1. Edaphic and weather conditions in Tharaka and Makueni

1) Semi-arid regions of Tharaka and Makueni in Kenya experienced low monthly rainfalls, medium temperatures and wind speed that varied from time to time.

2) While soil pH, EC, total N, OC, exchangeable Mg, Ca and Na were within critical levels, Soils in the semi-arid regions of Tharaka were deficient in available P and exchangeable K, while soils from Makueni were deficient in available P. These may be a matter of concern during *C. procera'*s cultivation as available P and exchangeable K play key role in flowering and fruiting.

6.1.2. Morphological characteristics of *C. procera* and factors affecting them

1) *Calotropis procera* strives well in the semi-arid regions of Tharaka and Makueni as leaves remained green throughout research period though with some shedding leaves during harsh climatic conditions. However, the shrub's leaf sizes varied from time to time as they are affected by available P in both regions. Fruit sizes also varied from time to time as they were affected by soil available P, total N and exchangeable K in Tharaka while in Makueni they were affected by available P. Weather conditions had an association with both leaf and fruit sizes in both regions.

6.1.3. Size classification of *C. procera* and factors affecting them

1) Naturally growing *C. procera* population in Tharaka and Makueni formed a natural hierarchy with large, medium and small sized stems though few stems reaching a height, crown and root collar diameters of ≥4.5 m, ≥120 cm and ≥8 cm respectively.

2) Edaphic factors mainly total N, exchangeable K, available P and exchangeable Mg, had positive impact on *C. procera*'s size class distribution in Tharaka and Makueni. However, a soil pH of 7.3 in Tharaka may be a problem as it may affect availability of soil basic cations.

3) Low and prolonged droughts accompanied by high temperatures and high wind speed had negative impacts on population distribution of *C. procera* in Tharaka and Makueni.

6.1.4. Phenology of *C. procera* and factors affecting them

1) Naturally growing *C. procera* in Tharaka and Makueni exhibited continuous flowering and fruiting phenological traits throughout the year with peak and low levels occurring in (June-August) 2018 and (September-November) 2019 respectively. This was dependent on prevailing weather conditions like temperature and rainfall which strongly affected phenological traits of the plant.

2) Edaphic factors mainly available P, exchangeable Na, OC content, exchangeable K and exchangeable Ca affected *C. procera'*s phenological traits in Tharaka and Makueni.

6.1.5. Dieback conditions of *C. procera* and factors affecting them

1) Calotropis procera exhibited dieback condition at all times.

2) Dieback condition was mainly caused by *Botryosphaeria, Fusarium, Phomopsis, Alternaria* and *Cladosporium* fungi species. The most dominant causing agents were *Botryosphaeria* and *Fusarium* fungi in Tharaka and Makueni.

6.2. Recommendations

This study makes the following recommendations

1) Farmers in the semi-arid regions of Tharaka needs to add soil P and K while in Makueni needs to add P in their soils through organic and or inorganic fertilizers so as to reach critical level range required.

2) To ensure production of optimal fruit sizes that ensure optimal quantity of calotrope fibre, this study recommend that farm owners with naturally growing *C. procera* in Tharaka and Makueni should not only improve their soil's P, OC and K, but also engage in soil moisture conservation mechanisms like mulching to prevent severe impacts of prolonged droughts.

3) Since a larger root collar diameter provides stability to support larger crowns that provide space for more flowers and fruits, this study recommends that farmers in Tharaka need to improve their *C. procera*'s root collar and crown diameter. They can achieve this by thinning to improve spacing between stems and reduce intra-species competition.

4) To improve flowering and fruiting phenological traits of *C. procera* not for its reproduction but calotrope fibre production, this study recommends that farmers need to use organic and or inorganic fertilizers to improve soil nutrients especially available P.

5) To manage dieback condition on *C. procera* caused by identified fungi, farmers need to be educated by forest and agricultural extension officers on the need to avoid wounding the plant, apply appropriate cultural systems, detecting the condition at an early stage and spray with appropriate fungicides. In addition, there is need for irrigation to avoid dieback conditions caused by long droughts.

6.3. Recommendations for Further Research

1) Soil depth is an important parameter that may either hinder or allow deep rooted plants to acquire nutrients and moisture from deeper soil horizons. Since *C. procera* is a deep rooted shrub, it has the ability to obtain nutrients at deep horizons. There is need to establish the effect of soil depth on phenology and dieback conditions of the shrub.

2) This study also recommends further research on the optimal amounts of rainfall and temperatures that will ensure optimal flowering and fruiting of the shrub at minimized dieback condition. This is because this study has established that an increase in rainfall and reduction in temperature favours *C. procera'*s flowering and fruiting and minimizes dieback. This will help in establishing irrigation levels during domestication and on-farm cultivation for calotrope fibre production.

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APPENDICES

Appendix I: Data Collection Sheets

Data collection sheet 1: Edaphic Factors

Date of data collection: ..... Region: ..... Block Name: ..... Plot No:...

Parameter	Soil Depth	Results
pH(H_2O)	(0-20) cm	
	(20-40) cm	
Conductivity(mS/cm)	(0-20) cm	
	(20-40) cm	
% Nitrogen	(0-20) cm	
	(20-40) cm	
% Organic carbon	(0-20) cm	
	(20-40) cm	
Phosphorus (ppm)	(0-20) cm	
	(20-40) cm	
Potassium (ppm)	(0-20) cm	
	(20-40) cm	
Magnesium(ppm)	(0-20) cm	
	(20-40) cm	
Calcium (ppm)	(0-20) cm	
	(20-40) cm	
Sodium (ppm)	(0-20) cm	
	(20-40) cm	

Data collection sheet 2: Weather conditions

Period of collected data: ..... Region: ..... .

GPS Coordinates	Parameter	Results
	Average monthly rainfall (mm/month)	
	Average monthly temperature (°C/month	
	Average monthly wind speed at 5m high (m/s)	
	Average Monthly Relative humidity (%)	

Data collection sheet 3: Leaf measurement

Region: ……Block Name:…….. Plot No:… sub-plot no :….. Date of Data Collection……..

Stem No	Leaf No	Leaf length	Leaf width	Leaf Surface area	Surface area class
1	1				
	2				
	3				
	4				
	5				
	6				
	7				
	8				
	9				
	10				
	11				
	12				
	13				
	14				
	15				

Data collection sheet 4: Fruit measurement

Region: ……Block Name:…….. Plot No:… sub-plot no :….. Date of Data Collection……..

Stem No	Fruit No	Fruit length	Horizontal fruit diameter	Perpendicular fruit length	Average Fruit Diameter	Fruit Volume	Volume class
1	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						
2	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						

Data collection sheet 5: height, Crown and Collar Dimaters

Region ……Block Name …….Plot No… Date of Data Collection……

Stump No	Shrub Stem No	Total shrub Heght (m)	Height class	E-W crown D (cm)	S-N crown D (cm)	Average crown D (cm)	Crown class	collar D (cm)	Collar D class
1	1								

Data Collection Sheet 6: Phenology; Activity Indices

Region …… Block Name …… Plot No… Sub-plot no… Date of Data Collection……

Shrub No	Flowers present	Flowers absent	Flowering AI	Fruits present	Fruits absent	Fruiting AI
1						
2						
3						
4						
5						
6						
7						

Data collection sheet 7: Phenology: number of flowers and fruits on branches

Region:……Block Name…….. Plot No…. Sub-plot no… Date of Data Collection….

Shrub No	B/ No	No of flowers	Total no of flowers	FlowerPI	No of fruits	Total No fruits	Fruit PI
1	1						
	2						
	3						
	4						
	5						
	6						
	7						
	8						
	9						
	10						
	11						
	12						
	13						

Data collection sheet 8: prevalence)

Region …… Block Name …… Plot No…… Date of Data Collection……

Sub-plot	Total number of mature shrubs	Total number of infected shrubs	Prevalence (%)
1			
2			
3			
4			
5			

Data collection sheet 9: Severity

Region …… Block Name…… Plot No… Date of Data Collection……

Stump No	Stem No	Part of shrub infected	Level of infection (0%, ...65%)	Severity scale (0-5)	SPSi
Sub plot					

Data collection sheet 10: Dieback Causative Agents

Region …….. Block Name ……. Date of Data Collection……..

Sample No	Plate No.	Replicates	Causative agent(s)	Frequency of occurrence/plate	Dominance of dieback causing agent
Sample 1:	1	1			
		2			
		3			
		4			
	2	1			
		2			
		3			
		4			
	3	1			
		2			
		3			
		4			
	4	1			
		2			
		3			
		4			

Appendix II: Soil Analysis Tables

Appendix IIa: Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	**df**	***p***	**Statistic**	**df**	***p***
pH(H2O)	0.205	276	0.062	0.802	276	0.059
Conductivity(mS/cm)	0.222	276	0.070	0.675	276	0.051
% Nitrogen	0.099	276	0.175	0.948	276	0.071
% Organic carbon	0.149	276	0.100	0.995	276	0.079
Phosphorus (ppm)	0.148	276	0.100	0.945	276	0.069
Potassium (ppm)	0.149	276	0.100	0.907	276	0.063
Magnesium(ppm)	0.030	276	0.200	0.992	276	0.127
Calcium (ppm)	0.031	276	0.200	0.991	276	0.079
Sodium (ppm)	0.080	276	0.184	0.913	276	0.065

Appendix IIb: Levene's Test of Equality of Error Variances of Soil Properties

		Levene Statistic	**df1**	**df2**	***p***
pH(H2O)	Based on Mean	1.660	15	264	0.059
	Based on Median	1.428	15	264	0.134
	Based on Median and with adjusted df	1.428	15	141.119	0.142
Conductivity(mS/cm)	Based on Mean	1.197	15	264	0.273
	Based on Median	0.474	15	264	0.952
	Based on Median and with adjusted df	0.474	15	143.169	0.950
% Nitrogen	Based on Mean	1.100	15	264	0.357
	Based on Median	0.958	15	264	0.500
	Based on Median and with adjusted df	0.958	15	213.847	0.501
% Organic carbon	Based on Mean	0.633	15	264	0.846
	Based on Median	0.529	15	264	0.923
	Based on Median and with adjusted df	0.529	15	168.469	0.922
Phosphorus (ppm)	Based on Mean	0.704	15	264	0.780
	Based on Median	0.467	15	264	0.955
	Based on Median and with adjusted df	0.467	15	141.238	0.953
Potassium (ppm)	Based on Mean	1.588	15	264	0.077
	Based on Median	0.880	15	264	0.587
	Based on Median and with adjusted df	0.880	15	193.156	0.587
Magnesium(ppm)	Based on Mean	1.107	15	264	0.350
	Based on Median	0.943	15	264	0.517
	Based on Median and with adjusted df	0.943	15	237.998	0.517
Calcium (ppm)	Based on Mean	1.329	15	264	0.184
	Based on Median	1.065	15	264	0.390
	Based on Median and with adjusted df	1.065	15	230.505	0.391
Sodium (ppm)	Based on Mean	1.682	15	260	0.055
	Based on Median	1.325	15	260	0.187
	Based on Median and with adjusted df	1.325	15	134.301	0.195

Appendix IIc: Factorial ANOVA Test of Soil Properties

Source	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Soil pH						
Research time	1.542	3	0.514	0.286	0.836	0.003
Region	16.686	1	16.686	9.269	0.003	0.034
Depth	0.024	1	0.024	0.013	0.908	0.000
Research time * Region	0.105	3	0.035	0.019	0.996	0.000
Research time * Depth	0.395	3	0.132	0.073	0.974	0.001
Region * Depth	1.972E-5	1	1.972E-5	0.000	0.997	0.000
Research time * Region * Depth	0.146	3	0.049	0.027	0.994	0.000
Error	475.247	264	1.800			
Soil E-Conductivity (mS/cm)						
Research time	0.001	3	0.000	0.038	0.990	0.000
Region	0.071	1	0.071	5.504	0.020	0.020
Depth	0.050	1	0.050	3.914	0.049	0.015
Research time * Region	0.000	3	4.413E-5	0.003	1.000	0.000
Research time * Depth	0.000	3	4.985E-5	0.004	1.000	0.000
Region * Depth	0.001	1	0.001	0.083	0.773	0.000
Research time * Region * Depth	9.383E-5	3	3.128E-5	0.002	1.000	0.000
Error	3.395	264	0.013			
Available Nitrogen (%)						
Research time	0.037	3	0.012	0.463	0.709	0.005
Region	6.389	1	6.389	242.066	<0.001	0.478
Depth	0.105	1	0.105	3.987	0.047	0.015
Research time * Region	0.007	3	0.002	0.082	0.970	0.001
Research time * Depth	0.006	3	0.002	0.072	0.975	0.001
Region * Depth	0.004	1	0.004	0.142	0.707	0.001
Research time * Region * Depth	0.011	3	0.004	0.137	0.938	0.002
Error	6.968	264	0.026			
Organic Carbon Content (%)						
Research time	1.878	3	0.626	0.240	0.869	0.003
Region	401.215	1	401.215	153.544	<0.001	0.368
Depth	0.006	1	0.006	0.002	0.963	0.000
Research time * Region	1.409	3	0.470	0.180	0.910	0.002
Research time * Depth	0.213	3	0.071	0.027	0.994	0.000
Region * Depth	0.332	1	0.332	0.127	0.722	0.000
Research time * Region * Depth	0.126	3	0.042	0.016	0.997	0.000
Error	689.840	264	2.613			
Available Phosphorus (ppm)						
Research time	7.082	3	2.361	0.285	0.837	0.003
Region	2378.700	1	2378.700	286.703	<0.001	0.521
Depth	0.073	1	0.073	0.009	0.925	0.000
Research time * Region	1.666	3	0.555	0.067	0.977	0.001
Research time * Depth	0.818	3	0.273	0.033	0.992	0.000
Region * Depth	0.534	1	0.534	0.064	0.800	0.000
Research time * Region * Depth	0.521	3	0.174	0.021	0.996	0.000
Error	2190.336	264	8.297			

Appendix IIc: Factorial ANOVA Test of Soil Properties (Continued)

Source	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Exchangeable Potassium (ppm)						
Research time	2995.348	3	998.449	0.128	0.944	0.001
Region	550736.871	1	550736.871	70.473	<0.001	0.211
Depth	42892.471	1	42892.471	5.489	0.020	0.020
Research time * Region	10079.977	3	3359.992	0.430	0.732	0.005
Research time * Depth	1598.952	3	532.984	0.068	0.977	0.001
Region * Depth	4460.813	1	4460.813	0.571	0.451	0.002
Research time * Region * Depth	5854.152	3	1951.384	0.250	0.862	0.003
Error	2063132.987	264	7814.898			
Exchangeable Magnesium (ppm)						
Research time	3642.722	3	1214.241	0.741	0.529	0.008
Region	45128.398	1	45128.398	27.529	<0.001	0.094
Depth	6523.625	1	6523.625	3.980	0.047	0.015
Research time * Region	812.836	3	270.945	0.165	0.920	0.002
Research time * Depth	318.798	3	106.266	0.065	0.978	0.001
Region * Depth	5.053	1	5.053	0.003	0.956	0.000
Research time * Region * Depth	215.883	3	71.961	0.044	0.988	0.000
Error	432777.144	264	1639.307			
Exchangeable Calcium (ppm)						
Research time	807383.887	3	269127.962	0.972	0.406	0.011
Region	7296016.324	1	7296016.324	26.363	<0.001	0.091
Depth	863663.501	1	863663.501	3.121	0.078	0.012
Research time * Region	218424.359	3	72808.120	0.263	0.852	0.003
Research time * Depth	196106.435	3	65368.812	0.236	0.871	0.003
Region * Depth	31509.543	1	31509.543	0.114	0.736	0.000
Research time * Region * Depth	53932.792	3	17977.597	0.065	0.978	0.001
Error	73061989.154	264	276749.959			
Exchangeable Sodium (ppm)						
Research time	326.339	3	108.780	0.050	0.985	0.001
Region	46236.270	1	46236.270	21.271	<0.001	0.076
Depth	17309.644	1	17309.644	7.963	0.005	0.030
Research time * Region	212.700	3	70.900	0.033	0.992	0.000
Research time * Depth	79.773	3	26.591	0.012	0.998	0.000
Region * Depth	7105.063	1	7105.063	3.269	0.072	0.012
Research time * Region * Depth	214.503	3	71.501	0.033	0.992	0.000
Error	565151.558	260	2173.660			

Appendix II d: Correlation Analysis of Soil Properties

		EC at (0-20)	N at (0-20)	OC at (0-20)	P at (0-20)	K at (0-20)	Mg at (0-20)	Ca at (0-20)	Na at (0-20)	pH at (0-20)	EC at (0-20)	N at (0-20)	C at (0-20)	P at (0-20)	K at (0-20)	Mg at (0-20)	Ca at (0-20)	Na at (0-20)
pH at (0-20)	Pearson Correlation	-0.084	0.039	0.052	-0.015	0.044	-0.082	-0.039	0.090	0.234	-0.050	-0.150	0.020	-0.036	0.068	0.035	0.024	0.022
	Sig. (2-tailed)	<0.001	0.002	<0.001	0.233	0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	0.111	0.004	<0.001	0.006	0.064	0.093
EC at (0-20)	Pearson Correlation		-0.132	-0.085	-0.130	0.040	-0.036	-0.035	0.100	0.214	0.250	0.071	0.125	0.137	0.074	-0.016	0.030	0.027
	Sig. (2-tailed)		<0.001	0.000	<0.001	0.002	0.004	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.208	0.021	0.044
N at (0-20)	Pearson Correlation			0.553	0.676	0.409	0.402	0.395	0.154	-0.150	-0.104	0.348	0.380	0.472	0.272	0.141	0.154	-0.274
	Sig. (2-tailed)			0.000	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
OC at (0-20)	Pearson Correlation				0.814	0.471	0.324	0.289	-0.029	-0.094	0.104	0.387	0.341	0.431	0.417	0.254	0.267	-0.059
	Sig. (2-tailed)				<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P at (0-20)	Pearson Correlation					0.484	0.379	0.321	-0.189	-0.158	0.013	0.525	0.404	0.457	0.425	0.335	0.345	-0.132
	Sig. (2-tailed)					<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
K at (0-20)	Pearson Correlation						0.214	0.167	-0.197	-0.023	-0.087	0.352	0.274	0.442	0.263	0.378	0.377	-0.039
	Sig. (2-tailed)						<0.001	<0.001	<0.001	0.074	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003
Mg at (0-20)	Pearson Correlation							0.905	0.125	-0.072	-0.069	0.090	-0.003	0.050	0.010	0.035	0.035	-0.157
	Sig. (2-tailed)							<0.001	<0.001	<0.001	<0.001	<0.001	0.787	<0.001	0.450	0.007	0.006	<0.001
Ca at (0-20)	Pearson Correlation								0.128	-0.048	-0.097	0.038	0.072	0.143	-0.026	-0.030	-0.034	-0.206
	Sig. (2-tailed)								<0.001	<0.001	<0.001	0.003	<0.001	<0.001	0.043	0.021	0.009	<0.001
Na at (0-20)	Pearson Correlation									0.198	0.172	-0.211	-0.060	-0.076	-0.213	-0.277	-0.283	0.045
	Sig. (2-tailed)									<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
pH at (20-40)	Pearson Correlation										0.122	-0.094	0.077	0.034	0.034	-0.006	-0.006	-0.015
	Sig. (2-tailed)										<0.001	<0.001	<0.001	0.007	0.008	0.645	0.647	0.253
EC at (20-40)	Pearson Correlation											-0.008	0.021	-0.047	0.148	-0.029	-0.030	-0.009
	Sig. (2-tailed)											0.530	0.099	<0.001	<0.001	0.024	0.021	0.496
N at (20-40)	Pearson Correlation												0.445	0.585	0.270	0.278	0.295	-0.060
	Sig. (2-tailed)												<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
OC at (20-40)	Pearson Correlation													0.834	0.206	0.126	0.153	-0.258
	Sig. (2-tailed)													<0.001	<0.001	<0.001	<0.001	<0.001
P at (20-40)	Pearson Correlation														0.249	0.236	0.243	-0.151
	Sig. (2-tailed)														<0.001	<0.001	<0.001	<0.001
K at (20-40)	Pearson Correlation															0.240	0.247	-0.009
	Sig. (2-tailed)															<0.001	<0.001	0.496
Mg at (20-40)	Pearson Correlation																0.984	0.481
	Sig. (2-tailed)																<0.001	<0.001
Ca at (20-40)	Pearson Correlation																	0.481
	Sig. (2-tailed)																	<0.001

AppendixIII: Weather Conditions Analysis Tables

Appendix IIIa: Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	*p*	Statistic	df	*p*
Total monthly rainfall	0.177	52	0.200	0.972	52	0.224
Mean monthly temp	0.177	52	0.200	0.976	52	0.385
Mean monthly wind speed	0.075	52	0.200	0.971	52	0.224
Monthly relative humidity	0.091	52	0.200	0.980	52	0.542

Appendix IIIb: Levene's Test of Equality of Error Variances of Weather Conditions

		Levene Statistic	**df1**	**df2**	***p***
Total monthly rainfall	Based on Mean	2.164	7	44	0.056
	Based on Median	1.124	7	44	0.366
	Based on Median and with adjusted df	1.124	7	21.744	0.384
Mean monthly temperature	Based on Mean	4.829	7	44	0.059
	Based on Median	3.195	7	44	0.120
	Based on Median and with adjusted df	3.195	7	23.006	0.138
Mean monthly wind speed	Based on Mean	1.946	7	44	0.085
	Based on Median	0.802	7	44	0.590
	Based on Median and with adjusted df	0.802	7	28.549	0.593
Monthly relative humidity	Based on Mean	2.058	7	44	0.069
	Based on Median	0.771	7	44	0.615
	Based on Median and with adjusted df	0.771	7	21.561	0.618

Appendix IIIc: Two-Way ANOVA Test for Weather Conditions

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	***p***	**Partial Eta Squared**
Average Monthly Rainfall						
Research time	104266.072	3	34755.357	35.589	<0.001	0.708
Region	1578.531	1	1578.531	1.616	0.210	0.035
Research time * Region	513.199	3	171.066	0.175	0.913	0.012
Error	42969.199	44	976.587			
Average Monthly Temperature						
Research time	96.574	3	32.191	19.069	<0.001	0.565
Region	0.847	1	0.847	0.502	0.482	0.011
Research time * Region	5.786	3	1.929	1.143	0.342	0.072
Error	74.278	44	1.688			
Average Monthly Wind Speed						
Research time	5.830	3	1.943	5.361	0.003	0.268
Region	5.018	1	5.018	13.844	0.001	0.239
Research time * Region	0.058	3	0.019	0.053	0.984	0.004
Error	15.950	44	0.362			
Average Monthly Relative Humidity						
Research time	448.524	3	149.508	1.155	0.338	0.073
Region	2.342	1	2.342	0.018	0.894	0.000
Research time * Region	96.049	3	32.016	0.247	0.863	0.017
Error	5693.682	44	129.402			

Appendix IIId: Post Hoc Test for Weather Conditions in Tharaka and Makueni

(I) Time of research	(J) Time of research	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval Lower Bound	Upper Bound
Average Monthly Rainfall						
(Jan-Jun)2018	(Jul2018-Mar2019)	79.6225*	11.64633	<0.001	48.5267	110.7183
	(April-Sep)2019	88.1483*	12.75792	<0.001	54.0846	122.2121
	(Oct2019-Feb2020)	-15.0398	13.38062	0.677	-50.7662	20.6865
(Jul2018-Mar2019)	(Jan-Jun)2018	-79.6225*	11.64633	<0.001	-110.7183	-48.5267
	(April-Sep)2019	8.5258	11.64633	0.884	-22.5699	39.6216
	(Oct2019-Feb2020)	-94.6623*	12.32532	<0.001	-127.5710	-61.7537
(April-Sep)2019	(Jan-Jun)2018	-88.1483*	12.75792	<0.001	-122.2121	-54.0846
	(Jul2018-Mar2019)	-8.5258	11.64633	0.884	-39.6216	22.5699
	(Oct2019-Feb2020)	-103.1882*	13.38062	<0.001	-138.9145	-67.4618
Average Monthly Temperature						
(Jan-Jun)2018	(Jul2018-Mar2019)	-2.8640	0.48421	<0.001	-4.1569	-1.5712
	(April-Sep)2019	-3.0846	0.53043	<0.001	-4.5008	-1.6683
	(Oct2019-Feb2020)	-0.4766	0.55632	0.827	-1.9620	1.0088
(Jul2018-Mar2019)	(Jan-Jun)2018	3.0846	0.53043	<0.001	1.6683	4.5008
	(April-Sep)2019	0.2206	0.48421	0.968	-1.0723	1.5134
	(Oct2019-Feb2020)	2.6080	0.55632	<0.001	1.1226	4.0934
(April-Sep)2019	(Jan-Jun)2018	0.4766	0.55632	0.827	-1.0088	1.9620
	(Jul2018-Mar2019)	-2.3874	0.51244	<0.001	-3.7557	-1.0192
	(Oct2019-Feb2020)	-2.6080	0.55632	<0.001	-4.0934	-1.1226
Average Wind Speed						
(Jan-Jun)2018	(Jul2018-Mar2019)	-0.5033	0.22438	0.128	-1.1024	0.0958
	(April-Sep)2019	-0.8806*	0.24579	0.005	-1.5369	-0.2243
	(Oct2019-Feb2020)	-0.0922	0.25779	0.984	-0.7805	0.5961
(Jul2018-Mar2019)	(Jun-Jul)2018	0.5033	0.22438	0.128	-0.0958	1.1024
	(April-Sep)2019	-0.3773	0.22438	0.345	-0.9764	0.2218
	(Oct2019-Feb2020)	0.4111	0.23746	0.320	-0.2230	1.0451
(April-Sep)2019	(Jan-Jun)2018	0.8806*	0.24579	0.005	0.2243	1.5369
	(Jul2018-Mar2019)	0.3773	0.22438	0.345	-0.2218	0.9764
	(Oct2019-Feb2020)	0.7884*	0.25779	0.019	0.1001	1.4767

Appendix IIIe: Correlation Analysis of Weather Conditions

		Average monthly temperature	Average monthly wind speed	Average Monthly relative humidity
Average monthly rainfall	Pearson Correlation	-0.670	-0.525	0.405
	Sig. (2-tailed)	<0.001	<0.001	0.003
	N	52	52	52
Average monthly temperature	Pearson Correlation		0.328	-0.350
	Sig. (2-tailed)		0.017	0.011
	N		52	52
Average monthly wind speed	Pearson Correlation			-0.145
	Sig. (2-tailed)			0.307
	N			52

Appendix IV: Morphology Analysis Tables

Appendix IVa: Parameter Estimates of Association between Edaphic Factors with Leaf Surface Area

Parameter		Estimate	Wald	df	*p*	Lower Bound	Upper Bound	Exp_ B	Lower	Upper
Part a: Parameter Estimates for Edaphic Factors affecting Leaf Surface Area Class Distribution in Tharaka										
Threshold	[Surface area class = (<50 cm^2)]	-2.301±0.055	447.238	1	<0.001	-1.717	-1.531	0.245	0.120	0.146
	[Surface area class = (50-<100) cm^2]	0.508±0.052	93.952	1	<0.001	-0.029	0.146	1.239	1.071	1.2037
	[Surface area class = (100-<150) cm^2]	1.794±0.057	980.449	1	<0.001	1.251	1.434	2.848	2.495	3.146
	[Surface area class = (150-<200)cm^2]	3.033±0.070	1.857E3	1	<0.001	2.469	2.685	3.711	3.511	4.752
Location	P at (0 - 20) cm	-1.161±0.055	46.218	1	<0.001	2.895	3.171	1.028	1.067	1.086
	P at (20 - 40) cm	0.076±.009	77.969	1	<0.001	.059	0.093	1.025	1.042	1.188
Part b: Parameter Estimates for Edaphic Factors affecting Leaf Surface Area Class Distribution in Makueni										
Threshold	[Surface area class = (<50 cm2)]	-1.478±0.078	359.683	1	<0.001	-1.630	-1.325	0.445	0.120	0.146
	[Surface area class = (50-<100) cm2]	0.223±0.074	8.995	1	0.003	0.077	0.369	1.139	1.071	1.2037
	[Surface area class = (100-<150) cm2]	1.498±0.078	371.416	1	<0.001	1.346	1.650	0.868	2.495	3.146
	[Surface area class = (150-<200)cm2]	2.722±0.090	923.588	1	<0.001	2.546	2.898	0.775	3.511	4.752
Location	P at (20-40) cm	0.008±0.007	1.549	1	0.021	-0.005	0.021	1.059	0.002	1.000

Appendix IVb: Parameter Estimates of Association between Weather Conditions with Leaf Surface Area

Parameter		Estimate	Wald	df	*p*	Lower Bound	Upper Bound	Exp_B	Lower	Upper
Part a: Parameter Estimates for Weather Conditions Affecting Leaf Surface Area Class Distribution in Tharaka										
Threshold	[Surface area class = (<50 cm^2)]	47.365±1.880	47.396	1	<0.001	33.880	60.849	0.245	1.203	2.291
	[Surface area class = (50-<100) cm^2]	49.095±1.881	50.911	1	<0.001	35.609	62.581	2.241	1.071	1.292
	[Surface area class = (100-<150) cm^2]	50.447±1.883	53.714	1	<0.001	36.956	63.937	2.000	2.570	3.136
	[Surface area class = (150-<200)cm^2]	51.721±0.885	56.434	1	<0.001	38.227	65.215	1.201	3.921	4.921
Location	Mean monthly rainfall (mm/month)	0.012±0.003	17.221	1	< 0.001	0.006	0.017	1.007	1.014	1.020
	Mean monthly temperature (°C/month)	2.592±0.309	70.420	1	< 0.001	1.987	3.197	0.649	0.614	0.713
	Mean monthly wind speed (m/s)	-4.823±0.368	171.398	1	0.010	-5.545	-4.101	0.987	0.323	0.471
	Monthly relative humidity (%)	5.447±6.883	3.714	1	< 0.001	36.956	63.937	1.005	1.007	1.049
Part b: Estimates for Weather Conditions Affecting Leaf Surface Area Class Distribution in Makueni										
Threshold	[Surface area class = (<50 cm2)]	-36.952±1.794	40.675	1	<0.001	-48.308	-25.596	0.445	0.120	0.146
	[Surface area class = (50-<100) cm2]	-35.177±0.793	36.876	1	0.003	-46.531	-23.823	1.139	1.071	1.2037
	[Surface area class = (100-<150) cm2]	-33.843±0.790	34.159	1	<0.001	-45.192	-22.494	0.868	2.495	3.146
	[Surface area class = (150-<200)cm2]	-32.592±1.789	31.695	1	<0.001	-43.939	-21.246	0.775	3.511	4.752
Location	Mean monthly rainfall (mm/month)	-0.018±.003	41.724	1	< 0.001	0.006	0.017	1.012	1.021	1.139
	Mean monthly temperature (°C/month)	-1.337±0.252	28.031	1	< 0.001	1.987	3.197	0.610	0.902	1.000
	Mean monthly wind speed (m/s)	-0.106±0.343	.095	1	0.036	-5.545	-4.101	0.891	0.791	0.992
	Monthly relative humidity (%)	-0.028±0.033	42.324	1	0.041	36.956	63.937	1.005	1.004	1.063

Appendix IVc: Parameter Estimates of Association between Edaphic Factors with Fruit Volume

Parameter		Estimate	Wald	df	*p*	Lower Bound	Upper Bound	Exp_B	Lower	Upper
Part a: Parameter Estimates for Edaphic Factors Affecting Fruit Volume Class Distribution in Tharaka										
Threshold	[Fruit volume class = <100 cm^3]	0.458±0.240	3.644	1	< 0.056	-0.012	0.928	3.358	0.356	2.227
	[Fruit volume class = (100-<200) cm^3]	1.7210±0.246	48.956	1	< 0.001	1.239	2.204	2.903	2.435	7.059
	[Fruit volume class = (200-<300)] cm^3]	2.870±0.265	17.576	1	< 0.001	2.351	3.389	1.792	22.769	21.378
Location	N at (0 - 20) cm	-1.053±0.535	33.868	1	0.049	-2.102	-0.004	1.093	1.098	1.914
	P at (0 - 20) cm	-0.033±0.028	21.453	1	0.028	-0.088	0.021	1.070	1.024	1.830
	N at (20 - 40) cm	1.773±0.425	17.439	1	< 0.001	0.941	2.606	1.003	1.000	1.009
	P at (20 - 40) cm	0.046±0.027	12.876	1	0.030	-0.007	0.098	1.034	1.000	1.535
	K at (20 - 40) cm	-0.002±0.001	16.435	1	0.011	-0.004	0.000	1.097	1.569	1.907
Part b: Parameter Estimates for Edaphic Factors Affecting Fruit Volume Class Distribution in Makueni										
Threshold	[Fruit volume class = <100 cm^3]	0.920±0.164	31.656	1	< 0.001	0.600	1.241	2.784	0.356	2.227
	[Fruit volume class = (100-<200) cm^3]	2.144±0.175	49.928	1	< 0.001	1.801	2.487	12.894	2.435	7.059
	[Fruit volume class = (200-<300) cm^3]	3.500±0.212	71.989	1	< 0.001	3.084	3.916	11.297	1.036	1.091
Location	P at (20-40) cm	0.046±0.016	18.316	1	0.004	0.015	0.078	1.001	1.000	1.003

Appendix IVd: Parameter Estimates of Association between Weather Conditions with Fruit Volume

Parameter		Estimate	Wald	df	*p*	Lower Bound	Upper Bound	Exp_B	Lower	Upper
Part a: Parameter Estimates for Weather Conditions Affecting Fruit Volume Class Distribution in Tharaka										
Threshold	[Fruit volume class = <100 cm^3]	-8.823±0.569	23.284	1	0.044	-41.298	23.653	4.832	0.129	0.953
	[Fruit volume class = (100-<200) cm^3]	-7.571±0.570	13.209	1	0.008	-40.047	24.905	2.672	0.286	0.488
	[Fruit volume class = (200-<300) cm^3]	-6.427±1.570	16.150	1	0.049	-38.904	26.050	3.631	0.152	0.593
Location	Mean monthly rainfall (mm/month)	-0.010±0.008	11.612	1	0.024	-0.024	0.005	1.002	1.009	1.106
	Mean monthly temperature (°C/month)	-0.065±0.716	17.008	1	0.027	-1.468	1.338	0.914	0.851	1.086
	Mean monthly wind speed (m/s)	-2.221±0.833	17.111	1	0.008	-3.853	-0.589	0.810	0.589	1.110
	Monthly relative humidity (%)	-2.162±0.085	12.950	1	0.049	-38.904	26.050	1.039	1.008	1.273
Part b: Estimates for Weather Conditions Affecting Fruit Volume Class Distribution in Makueni										
Threshold	[Fruit volume class = <100 cm^3]	3.248±1.536	24.344	1	0.037	-7.603	14.099	2.445	1.120	1.146
	[Fruit volume class = (100-<200) cm^3]	4.468±0.537	76.651	1	0.042	-6.385	15.320	6.868	4.495	4.146
	[Fruit volume class = (200-<300) cm^3]	5.821±0.538	32.105	1	0.029	-5.034	16.676	5.775	3.511	4.752
Location	Mean monthly rainfall (mm/month)	1.003±0.051	12.344	1	0.048	-0.007	0.012	1.042	1.031	1.139
	Mean monthly temperature (°C/month)	0.102±0.176	17.337	1	0.032	-0.243	0.447	0.788	0.942	1.000
	Mean monthly wind speed (m/s)	-1.008±0.388	21.000	1	0.024	-0.768	0.752	0.929	0.761	0.888
	Monthly relative humidity (%)	0.005±.005	17.248	1	0.037	-0.007	0.012	1.007	1.006	1.041

Appendix V: Size Distribution Analysis Tables

Appendix Va: Parameter Estimates of Edaphic Factors Affecting Height sizes

Parameter		B	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	*p*		Lower	Upper
Part a: Parameter Estimates for Edaphic Factors Affecting Height Size Distribution in Tharaka										
Threshold	[The height class <1.5 m]	0.330±0.1265	0.578	2.082	6.816	1	0.009	0.719	0.561	0.921
	[The height class = (1.5-<3) m]	2.005±0.1437	1.724	2.287	194.867	1	0.000	7.429	5.606	9.845
	[The height class = (3-<4.5) m]	4.147±0.2283	3.700	4.594	330.019	1	0.000	63.240	40.428	98.924
P at (0-20) cm		0.015±0.0098	0.035	3.424	12.472	1	0.026	1.015	1.066	1.524
EC at (20-40) cm		1.236±0.3673	0.516	1.956	11.330	1	0.001	1.003	1.676	7.074
P at (20-40) cm		0.025±0.0135	0.052	0.918	13.553	1	0.059	1.025	0.949	1.001
K at (20-40) cm		0.759±0.0005	0.001	0.007	11.022	1	0.008	1.030	1.999	2.001
N at (20-40) cm		0.777±0.1996	0.386	1.168	15.148	1	0.000	1.174	1.470	3.215
Part b: Parameter Estimates for Edaphic Factors Affecting Height Size Distribution in Makueni										
Threshold	[The height class <1.5 m]	1.933±0.1946	2.314	3.552	98.644	1	0.000	0.145	0.099	0.212
	[The height class = (1.5-<3) m]	1.476±0.1806	1.122	1.830	66.781	1	0.000	4.374	3.070	6.231
	[The height class = (3-<4.5) m]	3.674±0.2572	3.170	4.178	204.099	1	0.000	1.042	3.813	5.262
N at (20-40) cm		1.338±0.2594	0.830	1.847	26.617	1	.000	1.081	2.293	3.338
K at (20-40) cm		0.003±0.0013	1.003	3.002	16.553	1	0.016	1.001	1.997	2.032

Appendix Vb: Parameter Estimates of Weather Conditions Affecting Height Sizes

Parameter		B	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	*p*		Lower	Upper
Part a: Parameter Estimates for Weather Conditions Affecting Height Size Distribution in Tharaka										
Threshold	[Height class <1.5 m]	-57.219±03.7852	4.638	-49.800	228.514	1	<0.001	1.4135	8.475	2.355
	[Height class = (1.5-<3) m]	-54.869±03.7635	2.245	-47.493	212.560	1	<0.001	1.481	9.273	2.367
	[Height class = (3-<4.5) m]	-52.726±03.7508	6.077	-45.375	197.610	1	<0.001	1.263	8.105	1.968
Total monthly rainfall (mm/month)		0.018±0.0013	0.020	-0.015	90.599	1	<0.001	1.028	1.980	2.985
Mean monthly temperature (°C/month)		-2.704±0.1782	-3.053	-2.354	30.112	1	<0.001	0.867	0.047	0.095
Mean monthly wind speed (m/s)		-3.372±0.2271	-2.927	0.817	22.528	1	<0.001	0.937	0.671	0.941
Monthly relative humidity (%)		-0.419±0.0271	-0.002	0.895	12.116	1	<0.001	0.993	0.021	0.471
Part b: Parameter Estimates for Weather Conditions Affecting Height Size Distribution in Makueni										
Threshold	[Height class <1.5 m]	2.370±0.926	5.014	6.026	50.024	1	<0.001	10.481	3.316	3.342
	[Height class = (1.5-<3) m]	3.323±0.921	7.538	9.787	62.614	1	<0.001	13.319	4.137	4.287
	[Height class = (3-<4.5) m]	2.411±2.919	9.674	11.338	73.765	1	<0.001	11.76	3.500	3.951
Total monthly rainfall (mm/month)		0.007±0.113	1.012	1.030	32.587	1	<0.001	1.007	1.005	1.010
Mean monthly temperature (°C/month)		-1.057±0.255	0.370	0.644	21.644	1	<0.001	0.859	0.487	0.862
Mean monthly wind speed (m/s)		-1.026±0.136	-1.527	-0.689	22.111	1	<0.001	0.974	0.183	0.354
Monthly relative humidity (%)		-1.039±0.185	-0.368	-0.003	15.765	1	<0.001	0.981	0.855	0.988

Appendix Vc: Parameter Estimates of Edaphic Factors Affecting Crown Diameter

Parameter		B	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	*p*		Lower	Upper
Part a: Parameter Estimates for Edaphic Factors Affecting Crown Diamter Size Distribution in Tharaka										
Threshold	[Crown diameter <40cm]	-0.110±0.127	-0.361	0.140	0.743	1	0.389	0.896	0.697	1.151
	[Crown diameter = (40-<80) cm]	1.260±0.138	0.988	1.532	82.596	1	<0.001	3.525	2.687	4.626
	[Crown diameter =(80-<120) cm]	2.456±0.170	2.123	2.790	28.271	1	<0.001	11.659	8.352	16.276
EC at (20-40) cm		1.714±0.361	1.005	2.422	12.482	1	<0.001	1.050	2.733	11.271
N at (20-40) cm		0.377±0.087	0.010	.745	4.046	1	0.044	1.048	1.010	2.107
P at (20-40) cm		0.024±0.002	0.049	0.281	4.602	1	0.047	1.034	1.052	2.001
K at (20-40) cm		0.001±0.006	0.002	1.000	5.500	1	0.019	1.001	1.998	3.000
Mg at (20-40) cm		0.024±0.009	0.003	0.035	11.073	1	<0.001	1.001	1.748	2.831
Part b: Parameter Estimates for Edaphic Factors Affecting Crown Diamter Size Distribution in Makueni										
Threshold	[Crown diameter <40 cm]	-0.955±0.203	-1.363	-0.546	21.007	1	<0.001	0.385	0.256	0.579
	[Crown diameter = (40-<80) cm]	0.132±0.198	0.257	0.521	0.441	1	0.507	1.141	0.773	1.683
	[Crown diameter =(80-<120) cm]	0.838±0.198	0.448	1.227	17.739	1	0.000	2.311	1.565	3.412
EC at (20-40) cm		1.312±0.479	0.373	2.252	7.493	1	0.006	1.071	1.452	9.504
OCat (20-40) cm		0.055±0.006	0.003	0.106	4.255	1	0.039	1.056	1.003	1.112
P at (20-40) cm		0.456±0.002	2.123	2.790	8.271	1	0.004	1.059	8.352	16.276
Ca at (20-40) cm		2.725±0.072	5.000	8.472	5.227	1	0.033	1.002	1.000	1.000

Appendix Vd: Parameter Estimates of Weather Conditions Affecting Average Crown Diameter

Parameter		B	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	*p*		Lower	Upper
Part a: Parameter Estimates for Weather Conditions Affecting Crown Diameter in Tharaka										
Threshold	Crown diameter <40 cm	1.135±02.302	7.504	16.545	14.864	1	<0.001	11.254	13.949	21.893
	Crown diameter (40-<80) cm	2.313±0.012	8.785	17.841	24.852	1	<0.001	7.308	15.963	24.730
	[Crown diameter (80-<120) cm]	4.639±02.219	9.737	18.800	18.948	1	<0.001	5.903	9.035	10.164
Total monthly rainfall		0.003±00.021	0.001	0.005	11.259	1	0.002	1.032	1.023	1.198
Mean monthly temperature		-0.850±0.068	0.677	1.022	41.852	1	<0.001	0.901	0.641	0.983
Mean monthly wind speed		-0.849±0.146	-1.950	-1.449	17.932	1	<0.001	0.967	0.264	0.486
Monthly relative humidity		-0.055±0.032	-0.067	-0.043	23.002	1	<0.001	0.988	0.782	0.831958
Part b: Parameter Estimates for Weather Conditions Affecting Crown Diameter in Makueni										
Threshold	[Crown diameter <40 cm]	2.835±0.351	7.574	13.850	27.186	1	<0.001	1.667	2.968	7.953
	Crown diameter (40-<80) cm	1.213±0.316	4.853	8.649	33.209	1	<0.001	6.050	9.046	15.976
	[Crown diameter (80-<120) cm]	1.872±0.399	10.732	10.784	38.090	1	<0.001	1.573	4.936	9.067
Total monthly rainfall		0.423±0.010	0.423	0.932	14.962	1	0.002	1.022	2.182	5.842
Mean monthly temperature		-1.840±00.088	9.348	11.936	32.398	1	<0.001	0.843	0.056	0.174
Mean monthly wind speed		-0.812±0.139	-1.950	-1.449	13.717	1	<0.001	0.974	0.462	0.641
Monthly relative humidity		-0.955±0.022	-0.067	-0.043	16.374	1	<0.001	0.988	0.164	0.438

Appendix Ve: Parameter Estimates of Edaphic Factors Affecting Collar Diameter sizes

Parameter		B.	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
Part a: Parameter Estimates of Edaphic Factors Affecting Collar Diameter sizes in Tharaka										
Threshold	[Collar diameter = <4 cm]	-1.658±0.208	-2.070	-1.247	32.481	1	<0.001	0.190	0.126	0.287
	[Collar diameter = (4-<8) cm]	0.218±0.212	-0.198	0.634	10.053	1	0.035	1.243	0.820	1.884
pH at (0-20) cm		-0.106±0.024	-0.153	-0.058	19.139	1	<0.001	0.900	0.858	0.943
EC at (20-40) cm		-1.313±0.330	-0.960	0.335	12.894	1	0.034	1.027	1.383	2.398
N at (20-40) cm		1.757±0.173	-1.097	-0.417	19.037	1	<0.001	1.046	1.334	2.659
Mg at (20-40) cm		0.054±0.008	-0.005	-0.002	24.690	1	<0.001	1.096	3.995	5.998
Part b: Parameter Estimates of Edaphic Factors Affecting Collar Diameter sizes in Makueni										
Threshold	[Collar diameter = <4 cm]	-0.021±0.1098	-0.295	0.253	0.022	1	0.882	0.979	0.745	1.288
	[Collar diameter = (4-<8) cm]	1.618±0.042	1.336	1.901	125.999	1	<0.001	5.045	3.803	6.693
EC at (20-40) cm		1.749±0.098	0.770	2.729	12.247	1	<0.001	1.075	2.159	15.316
N at (20-40) cm		1.033±0.208	0.623	1.442	24.458	1	<0.001	1. 089	1.865	4.229

Appendix Vf: Parameter Estimates of Weather Conditions Affecting Collar Diameter Class Distribution

Parameter		B	95% Wald Confidence Interval		Hypothesis Test			Exp (B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	*p*		Lower	Upper
Part a: Parameter Estimates for Weather Conditions Affecting Root Collar Diameter in Tharaka										
Threshold	[Collar diameter = <4 cm]	-64.943±0.572	-73.905	-55.981	201.719	1	<0.001	6.244	8.004	14.871
	[Collar diameter = (4-<8) cm]	-63.072±0.549	54.988	71.156	192.227	1	<0.001	4.0588	5.446	13.023
Average monthly rainfall (mm/month)		0.524±0.001	0.027	0.120	179.687	1	<0.001	1.136	1.973	1.980
Mean monthly temp (°C/month)		2.174±0.054	2.473	3.867	196.898	1	<0.001	1.114	1.084	1.155
Monthly relative humidity (%)		-0.146±0.010	-0.166	-0.126	212.021	1	<0.001	0.864	0.847	0.881
Part b: Parameter Estimates for Weather Conditions Affecting Root Collar Diameter in Makueni										
Threshold	[Collar diameter = <4 cm]	22.123±0.174	13.942	30.305	28.088	1	< 0.001	4.059	1.027	1.449
	[Collar diameter = (4-<8) cm]	23.735±0.202	15.497	31.972	31.893	1	< 0.001	2.031	5.054	7.676
Average monthly rainfall (mm/month)		0.015±0.002	0.009	0.021	22.836	1	< 0.001	1.015	1.009	1.021
Mean monthly temp (°C/month)		0.853±0.019	0.549	1.157	30.329	1	< 0.001	1.347	1.732	3.179

Appendix VI: Activity Index Analysis Tables

Appendix VIa: Pairwise Analysis of Flowering and Fruiting Activity Indices in Tharaka and Makueni

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part i: Flowering Activity Index in Tharaka						
(Jun-Aug) 2018	(Ma-May) 2019	21.634	3.952	< 0.001	13.714	29.555
	(Sep-Nov) 2019	27.820	4.251	< 0.001	19.301	36.338
	(Feb-April) 2020	14.215	4.149	0.001	5.900	22.530
(Mar-May) 2019	(Sep-Nov) 2019	6.186	4.015	0.129	-1.860	14.231
	(Feb-April) 2020	-7.419	4.377	0.096	-16.190	1.352
(Sep-Nov) 2019	(Feb-April) 2020	-13.605	3.693	0.001	-21.006	-6.203
Part ii: Fruiting Activity Index in Tharaka						
Jun-Aug) 2018	(Mar-May) 2019	19.426	4.442	< 0.001	10.523	28.328
	(Sep-Nov) 2019	22.840	4.660	< 0.001	13.500	32.179
	(Feb-April) 2020	12.583	4.039	0.003	4.490	20.677
(Mar-May) 2019	(Sep-Nov) 2019	3.414	4.608	0.462	-5.821	12.649
	(Feb-April) 2020	-6.843	4.133	0.103	-15.124	1.439
(Sep-Nov) 2019	(Feb-April) 2020	-10.257	5.024	0.046	-20.325	-0.188

Appendix VIa: Pairwise Analysis of Flowering and Fruiting Activity Indices in Tharaka and Makueni (Continued)

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part ii: Flowering Activity Index in Makueni						
Jun-Aug) 2018	(Mar-May) 2019	21.082	5.399	0.003	5.958	36.206
	(Sep-Nov) 2019	32.580	5.692	< 0.001	16.633	48.527
	(Feb-April) 2020	17.527	4.911	0.007	3.768	31.285
(Mar-May) 2019	(Sep-Nov) 2019	11.497	6.831	0.609	-7.641	30.636
	(Feb-April) 2020	-3.555	5.923	1.000	-20.150	13.039
(Sep-Nov) 2019	(Feb-April) 2020	-3.555	5.923	1.000	-20.150	13.039
Part ii: Fruiting Activity Index in Makueni						
Jun-Aug) 2018	(Mar-May) 2019	18.292	5.596	0.015	2.614	33.970
	(Sep-Nov) 2019	25.965	6.152	0.001	8.729	43.201
	(Feb-April) 2020	21.984	5.869	0.004	5.540	38.427
(Mar-May) 2019	(Sep-Nov) 2019	7.673	5.680	1.000	-8.240	23.587
	(Feb-April) 2020	3.692	7.024	1.000	-15.987	23.371
(Sep-Nov) 2019	(Feb-April) 2020	-3.982	6.959	1.000	-23.477	15.513

Appendix VIb: Parameter Estimates of Edaphic Factors Affecting Flowering Activity Index

		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp(B)**	**Lower**	**Upper**
Part a: Parameter Estimates of Edaphic Factors Affecting Flowering Activity Index in Tharaka									
(Intercept)	3.980±0.132	4.351	7.610	19.578	1	<0.001	6.113	4.020E23	9.297
P at (0-20) cm	0.972±0.042	2.332	4.389	11.959	1	0.016	1.128	0.097	1.475
P at (20-40) cm	0.158±0.019	2.002	3.319	12.072	1	0.008	1.172	0.367	3.738
Part b: Parameter Estimates of Edaphic Factors Affecting Flowering Activity Index in Makueni									
(Intercept)	69.141±0.250	58.844	79.439	17.181	1	<0.001	1.066	3.594	3.162
P at (20-40) cm	0.386±0.055	1.436	2.663	15.521	1	0.047	1.123	1.238	2.941

Appendix VIe: Table 4.39: Parameter Estimates of Weather Conditions Affecting Activity Indices

		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp (B)**	**Lower**	**Upper**
Part a: Weather Conditions Affecting Flowering Activity Index in Tharaka									
(Intercept)	-1.08 ±0.5383	-1.445	3.003	8.043	1	0.005	<0.001	1.000	1.191
Mean monthly rainfall	0.360 ±0.0170	0.053	0.668	5.266	1	0.022	1.234	1.054	2.951
Mean monthly temperature	-1.858 ±0.6563	3.253	92.464	10.738	1	0.001	0.941	1.254	3.434
Mean monthly wind speed	-3.242 ±0.2456	-0.763	4.722	14.790	1	<0.001	0.992	1.372	2.391
Part b: Weather Conditions Affecting Fruiting Activity Index in Tharaka									
(Intercept)	-1.065 ±0.3736	-15.413	-5.102	5.262	1	0.022	1.000	1.000	4.365
Mean monthly rainfall	0.381 ±0.1970	0.005	0.767	6.733	1	0.033	1.163	0.995	2.153
Mean monthly temperature	-4.702 ±0.4293	14.661	94.743	7.170	1	0.007	0.867	1.360	2.400
Mean monthly wind speed	-3.330 ±0.6540	-11.771	-3.889	13.422	1	<0.001	0.956	1.304	9.533
Part c: Weather Conditions Affecting Flowering Activity Index in Makueni									
(Intercept)	1.141 ±0.216	2.872	3.130	7.851	1	0.005	2.862	4.963	8.084
Mean monthly rainfall	0.544 ±0.181	0.900	1.189	9.014	1	0.003	1.158	1.407	2.828
Mean monthly temperature	-1.472 ±0.302	-7.345	-5.600	5.134	1	0.023	0.974	0.567	1.004
Mean monthly wind speed	-4.522 ±0.265	-2.836	1.881	6.024	1	0.037	0.951	1.131	7.491
Part d: Weather Conditions Affecting Fruiting Activity Index in Makueni									
(Intercept)	1.435 ±0.247	7.292	12.281	12.122	1	<0.001	2.903	2.688	3.940
Mean monthly rainfall	0.744 ±0.214	1.165	4.324	12.045	1	0.001	1.075	0.312	0.723
Mean monthly temperature	-4.677 ±0.847	-9.657	-1.696	9.385	1	0.002	0.879	1.154	2.794
Mean monthly wind speed	-1.427 ±0.695	-2.975	-0.830	7.753	1	0.036	0.983	1.927	2.122

Appendix VII: Number of Flowers and Fruits Analysis Tables

Appendix VIIa: Pairwise Analysis of number of Flowers and Fruits

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	p^b	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part a: Number of Flowers in Tharaka						
(Jun-Aug) 2018	(Ma-May) 2019	13.345*	3.764	0.003	3.317	23.373
	(Sep-Nov) 2019	74.325*	3.764	<0.001	64.296	84.354
	(Feb-April) 2020	-36.133*	4.470	<0.001	-48.043	-24.223
(Mar-May) 2019	(Sep-Nov) 2019	60.980*	3.389	<0.001	51.949	70.011
	(Feb-April) 2020	-49.478*	4.079	<0.001	-60.345	-38.610
(Sep-Nov) 2019	(Feb-April) 2020	-110.458*	3.326	<0.001	-119.321	-101.596
Part b: Number of Fruits in Tharaka						
Jun-Aug) 2018	(Mar-May) 2019	1.505	0.255	<0.001	0.826	2.184
	(Sep-Nov) 2019	-73.446	1.449	<0.001	-77.307	-69.584
	(Feb-April) 2020	-0.510	0.266	0.339	-1.219	0.199
(Mar-May) 2019	(Sep-Nov) 2019	-74.951	1.469	<.001	-78.866	-71.035
	(Feb-April) 2020	-2.015	0.204	<0.001	-2.558	-1.472
(Sep-Nov) 2019	(Feb-April) 2020	72.935*	1.451	<.001	69.069	76.802
Part c: Number of Flowers in Makueni						
(Jun-Aug) 2018	(Ma-May) 2019	23.554	4.601	<0.001	11.194	35.914
	(Sep-Nov) 2019	91.411	4.573	<0.001	79.127	103.695
	(Feb-April) 2020	-24.357	5.043	<0.001	-37.904	-10.810

Appendix VIIa: Pairwise Analysis of number of Flowers and Fruits (Continued)

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	p^b	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
(Mar-May) 2019	(Sep-Nov) 2019	67.857	3.735	<0.001	57.823	77.891
	(Feb-April) 2020	-47.911	5.296	<0.001	-62.137	-33.685
(Sep-Nov) 2019	(Feb-April) 2020	-115.768	4.908	<0.001	-128.952	-102.584
Part d: Number of Fruits in Makueni						
Jun-Aug) 2018	(Mar-May) 2019	2.204	0.308	<0.001	1.375	3.033
	(Sep-Nov) 2019	-71.442	2.134	<0.001	-77.177	-65.706
	(Feb-April) 2020	0.546	0.439	1.000	-0.633	1.726
(Mar-May) 2019	(Sep-Nov) 2019	-73.645	2.125	<.001	-79.357	-67.934
	(Feb-April) 2020	-1.657	0.383	<0.001	-2.687	-0.627
(Sep-Nov) 2019	(Feb-April) 2020	71.988	2.138	<0.001	66.240	77.736

Appendix VIIb: Parameter Estimates of Edaphic Factors Affecting number of Flowers and Fruits

		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp(B)**	**Lower**	**Upper**
Part a: Estimates of Edaphic Factors Affecting Number of Flowers in Tharaka									
(Intercept)	0.059±0.045	0.146	1.060	26.976	1	<0.001	1.375	0.180	0.216
Na at (0-20) cm	1.342±0.047	1.434	3.828	17.016	1	<0.001	1.013	0.972	1.157
P at (20-40) cm	2.577±0.055	2.685	3.161	14.323	1	<0.001	1.039	3.494	4.195
Mg at (20-40) cm	-0.034±0.005	-0.044	0.034	19.016	1	<0.001	0.984	0.811	1.666
Ca at (20-40) cm	0.089±0.019	0.125	1.085	21.323	1	<0.001	1.031	1.057	1.076
Na at (20-40) cm	0.075±0.009	0.093	1.077	16.323	1	<0.001	1.015	1.051	1.118
Part b: Estimates of Edaphic Factors Affecting Number of Fruits in Tharaka									
(Intercept)	0.008±0.001	0.006	0.011	6.386	1	0.012	2.488	1.005	1.020
Na at (0-20) cm	0.582±0.062	0.704	-0.460	7.675	1	0.006	1.012	0.494	0.631
OC at (20-40) cm	0.690±0.074	0.835	-0.545	19.000	1	<0.001	1.016	0.434	0.580
P at (20-40) cm	0.029±0.011	0.008	0.050	11.178	1	<0.001	1.051	1.008	1.051
K at (20-40) cm	0.841±0.250	0.352	1.330	6.023	1	0.015	1.054	1.265	1.704
Mg at (20-40) cm	0.037±0.012	0.013	0.061	16.681	1	<0.001	1.063	1.013	1.059
Ca at (20-40) cm	0.001±0.000	0.000	0.002	6.386	1	0.012	0.996	1.000	1.002
Na at (20-40) cm	1.283±0.229	0.835	1.731	7.675	1	0.006	1.014	1.304	1.646
Part c: Estimates of Edaphic Factors Affecting Number of Flowers in Makueni									
(Intercept)	4.192±0.078	4.040	4.345	96.638	1	<0.001	2.171	6.817	7.065
OC at (20-40) cm	0.015±0.021	0.200	0.217	55.145	1	<0.001	1.015	1.181	1.270
P at (20-40) cm	0.047±0.009	0.028	0.065	23.557	1	<0.001	1.048	1.028	1.068
Ca at (20-40) cm	0.002±0.002	0.001	0.002	51.748	1	<0.001	1.002	1.001	1.002
Na at (20-40) cm	0.005±0.006	0.006	0.003	51.899	1	<0.001	1.005	1.094	1.097
Part d: Estimates of Edaphic Factors Affecting Number of Fruits in Makueni									
(Intercept)	3.384±0.242	2.909	3.859	94.621	1	<0.001	2.488	1.330	4.438
OC at (20-40) cm	0.027±0.001	0.206	0.334	67.819	1	<0.001	1.027	1.228	1.397
P at (20-40) cm	0.050±0.001	0.082	0.019	9.731	1	0.002	1.049	1.079	1.099
K at (20-40) cm	0.006±0.001	0.003	0.000	4.646	1	0.031	1.001	1.000	1.003
Ca at (20-40) cm	-0.014±0.005	-0.005	-0.003	60.330	1	<0.001	0.996	0.995	0.997
Na at (20-40) cm	0.009±0.002	0.005	0.013	21.674	1	<0.001	1.009	1.005	1.013

Appendix VIIc: Parameter Estimates of Weather Conditions Affecting number of Flowers and Fruits

		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp (B)**	**Lower**	**Upper**
Part a: Weather Conditions Affecting Number of Flowers in Tharaka									
(Intercept)	7.530±0.022	2.314	17.373	12.248	1	<0.001	2.740	0.099	3.507
Mean monthly rainfall	0.000±0.003	-0.005	0.006	27.026	1	<0.001	1.001	1.000	1.006
Mean monthly temperature	-0.092±0.147	-0.196	0.379	16.390	1	<0.001	0.904	0.822	1.461
Mean monthly wind speed	-0.229±0.169	-0.561	0.103	19.827	1	<0.001	0.795	0.570	1.109
Monthly relative humidity	0.048±0.026	0.003	0.099	24.384	1	<0.001	1.049	0.997	1.104
Part b: Weather Conditions Affecting Number of Fruits in Tharaka									
(Intercept)	25.491±02.967	19.674	31.308	73.765	1	<0.001	11.76	3.500	3.951
Mean monthly rainfall	0.007±00.001	0.005	0.010	30.567	1	<0.001	1.007	1.005	1.010
Mean monthly temperature	1.057±00.095	0.870	1.244	32.633	1	<0.001	1.122	1.387	3.470
Mean monthly wind speed	1.026±00.120	1.263	2.789	72.008	1	<0.001	1.052	1.283	3.454
Monthly relative humidity	-0.029±00.008	-0.046	-0.013	11.765	1	0.001	0.971	0.955	0.988
Part c: Weather Conditions Affecting Number of Flowers in Makueni									
(Intercept)	19.514±1.553	16.468	22.559	57.746	1	<0.001	2.983	1.419	2.682
Mean monthly rainfall	0.009±0.001	0.011	0.007	81.447	1	<0.001	1.009	1.021	1.093
Mean monthly temperature	-0.709±0.052	-0.812	-0.606	82.002	1	<0.001	0.792	0.444	0.546
Mean monthly wind speed	-0.813±0.056	-0.923	-0.702	107.596	1	<0.001	0.844	0.397	0.496
Monthly relative humidity	0.080±0.008	0.063	0.097	86.797	1	<0.001	1.084	1.066	1.102
Part d: Weather Conditions Affecting Number of Fruits in Makueni									
(Intercept)	5.536±2.286	47.050	56.018	58.143	1	<0.001	2.148	4.690	3.664
Mean monthly rainfall	0.054±0.001	0.052	0.056	26.751	1	<0.001	1.056	1.053	1.058
Mean monthly temperature	0.201±0.059	2.085	2.318	77.953	1	<0.001	1.338	8.046	10.152
Mean monthly wind speed	0.129±0.087	3.158	3.500	45.911	1	<0.001	1.207	23.518	33.115
Monthly relative humidity	-0.231±0.009	-0.250	-0.211	53.798	1	<0.001	0.794	0.779	0.809

Appendix VIII: Phenophase Intensity Analysis Tables

VIIIa: Pairwise Analysis of Phenophase Intensity

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part a: Flowering Phenophase Intensity in Tharaka						
(Jun-Aug) 2018	(Ma-May) 2019	6.098*	2.231	0.041	0.152	12.043
	(Sep-Nov) 2019	-1.295	2.479	<0.001	-7.902	5.311
	(Feb-April) 2020	-10.474*	2.065	<0.001	-15.977	-4.970
(Mar-May) 2019	(Sep-Nov) 2019	-7.393*	2.615	0.031	-14.361	-.425
	(Feb-April) 2020	-16.571*	2.162	<0.001	-22.332	-10.810
(Sep-Nov) 2019	(Feb-April) 2020	-9.178*	2.395	0.001	-15.559	-2.797
Part b: Fruiting Phenophase Intensity in Tharaka						
Jun-Aug) 2018	(Mar-May) 2019	2.259	2.431	<0.001	-4.223	8.741
	(Sep-Nov) 2019	40.966*	1.983	<0.001	35.681	46.252
	(Feb-April) 2020	-4.406	2.346	0.372	-10.661	1.850
(Mar-May) 2019	(Sep-Nov) 2019	38.708*	2.062	<0.001	33.211	44.205
	(Feb-April) 2020	-6.664*	2.261	0.022	-12.692	-.636
(Sep-Nov) 2019	(Feb-April) 2020	-45.372*	1.857	<0.001	-50.323	-40.421
Part a: Flowering Phenophase Intensity in Makueni						
(Jun-Aug) 2018	(Ma-May) 2019	9.936*	2.619	0.001	2.898	16.973
	(Sep-Nov) 2019	2.644	2.922	<0.001	-5.208	10.496
	(Feb-April) 2020	-1.031	2.960	<0.001	-8.985	6.922
(Mar-May) 2019	(Sep-Nov) 2019	-7.292	3.024	0.105	-15.417	0.834
	(Feb-April) 2020	-10.967*	2.973	0.002	-18.954	-2.980
(Sep-Nov) 2019	(Feb-April) 2020	-3.675	3.529	1.000	-13.157	5.807

VIIIa: Pairwise Analysis of Phenophase Intensity

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part b: Fruiting Phenophase Intensity in Makueni						
Jun-Aug) 2018	(Mar-May) 2019	2.567	3.403	<0.001	-6.578	11.712
	(Sep-Nov) 2019	41.734*	2.448	<0.001	35.154	48.313
	(Feb-April) 2020	-2.014	2.590	<0.001	-8.973	4.945
(Mar-May) 2019	(Sep-Nov) 2019	39.167*	2.740	<0.001	31.804	46.529
	(Feb-April) 2020	-4.581	2.926	0.722	-12.443	3.282
(Sep-Nov) 2019	(Feb-April) 2020	-43.747*	2.247	<0.001	-49.786	-37.709

Appendix VIIIb: Parameter Estimates of Weather Conditions Affecting Phenophase Intensities

		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp (B)**	**Lower**	**Upper**
Part a: Weather Conditions Affecting Flowering Phenophase Intensity in Tharaka									
(Intercept)	1.150±0.668	0.734	1.567	6.966	1	0.008	1.024	5.000	7.267
Mean monthly rainfall	0.443±0.107	0.233	0.653	17.091	1	<0.001	1.557	1.262	1.921
Mean monthly temperature (°C/month)	-1.897±0.5709	2.058	3.736	8.365	1	0.004	0.915	2.675	8.998
Part b: Weather Conditions Affecting Fruiting Phenophase Intensity in Tharaka									
(Intercept)	-2.893±0.221	0.585	5.121	31.855	1	<0.001	0.762	2.973	9.041
Mean monthly rainfall (mm/month)	1.323±0.091	1.503	4.143	27.469	1	<0.001	1.266	0.222	0.319
Mean monthly temperature (°C/month)	-1.241±0.972	-1.947	0.535	53.153	1	<0.001	0.896	1.481	2.180
Mean monthly wind speed (m/s)	-7.776±0.349	-1.420	0.132	16.855	1	0.402	0.981	2.982	3.006
Part c: Weather Conditions Affecting Flowering Phenophase Intensity in Makueni									
(Intercept)	6.263±02.673	6.700	14.173	10.003	1	0.009	1.002	7.240	15.0111
Mean monthly rainfall	0.114±0.090	0.062	0.291	11.610	1	0.002	1.121	1.940	3.338
Mean monthly temperature (°C/month)	-2.292±04.577	-6.680	11.264	8.251	1	0.017	0.894	1.001	2.169
Part b: Weather Conditions Affecting Fruiting Phenophase Intensity in Tharaka									
(Intercept)	-1.262±0.881	-7.700	-2.182	31.490	1	<0.001	0.800	1.000	2.009
Mean monthly rainfall (mm/month)	0.411±00.0947	0.225	0.597	18.826	1	<0.001	1.508	1.253	1.816
Mean monthly temperature (°C/month)	-5.456±0.9838	-0.888	0.024	42.984	1	<0.001	0.874	0.490	0.842
Mean monthly wind speed (m/s)	-1.481±0.869	-1.665	1.298	20.025	1	<0.001	0.979	0.029	0.207

Appendix IX: Dieback Prevalence and Severity Analysis Tables

Appendix IXa: Pairwise Analysis of dieback Prevalence and Severity

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	p^b	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
Part a: Dieback Prevalence in Tharaka						
(Jun-Aug) 2018	(Ma-May) 2019	-14.447	4.578	0.014	-26.883	-2.011
	(Sep-Nov) 2019	-16.277	4.053	0.001	-27.285	-5.268
	(Feb-April) 2020	-0.759	3.432	1.000	-10.082	8.564
(Mar-May) 2019	(Sep-Nov) 2019	-1.830	3.514	1.000	-11.375	7.716
	(Feb-April) 2020	13.688	3.194	<0.001	5.010	22.366
(Sep-Nov) 2019	(Feb-April) 2020	15.518*	3.114	<0.001	7.058	23.977
Part b: Dieback Severity in Tharaka						
Jun-Aug) 2018	(Mar-May) 2019	-0.846	0.166	<0.001	-1.298	-0.393
	(Sep-Nov) 2019	-1.496	0.161	<0.001	-1.932	-1.059
	(Feb-April) 2020	-0.697	0.132	<0.001	-1.057	-0.337
(Mar-May) 2019	(Sep-Nov) 2019	-0.650	0.176	0.003	-1.129	-0.171
	(Feb-April) 2020	0.149	0.142	1.000	-0.237	0.534
(Sep-Nov) 2019	(Feb-April) 2020	0.799	0.154	<0.001	0.380	1.218
Part c: Dieback Prevalence in Makueni						
(Jun-Aug) 2018	(Ma-May) 2019	-17.629	4.469	0.002	-30.172	-5.085
	(Sep-Nov) 2019	-27.765	6.742	0.001	-46.689	-8.841
	(Feb-April) 2020	-10.366	4.819	0.233	-23.892	3.160
(Mar-May) 2019	(Sep-Nov) 2019	-10.137	5.613	0.480	-25.891	5.618
	(Feb-April) 2020	7.263	3.759	0.372	-3.288	17.814
(Sep-Nov) 2019	(Feb-April) 2020	17.399*	5.001	0.009	3.362	31.437
Part d: Dieback Severity in Makueni						
Jun-Aug) 2018	(Mar-May) 2019	-0.834	0.180	<0.001	-1.197	-0.471
	(Sep-Nov) 2019	-1.656	0.178	<0.001	-2.015	-1.297
	(Feb-April) 2020	-0.929	0.188	<0.001	-1.309	-0.549
(Mar-May) 2019	(Sep-Nov) 2019	-0.822	0.251	0.002	-1.329	-0.316
	(Feb-April) 2020	-0.095	0.218	0.665	-0.536	0.345
(Sep-Nov) 2019	(Feb-April) 2020	0.727	0.220	0.002	0.282	1.172

Appendix IXb: Parameter Estimates of Weather Conditions Affecting Dieback Prevalence and Severity

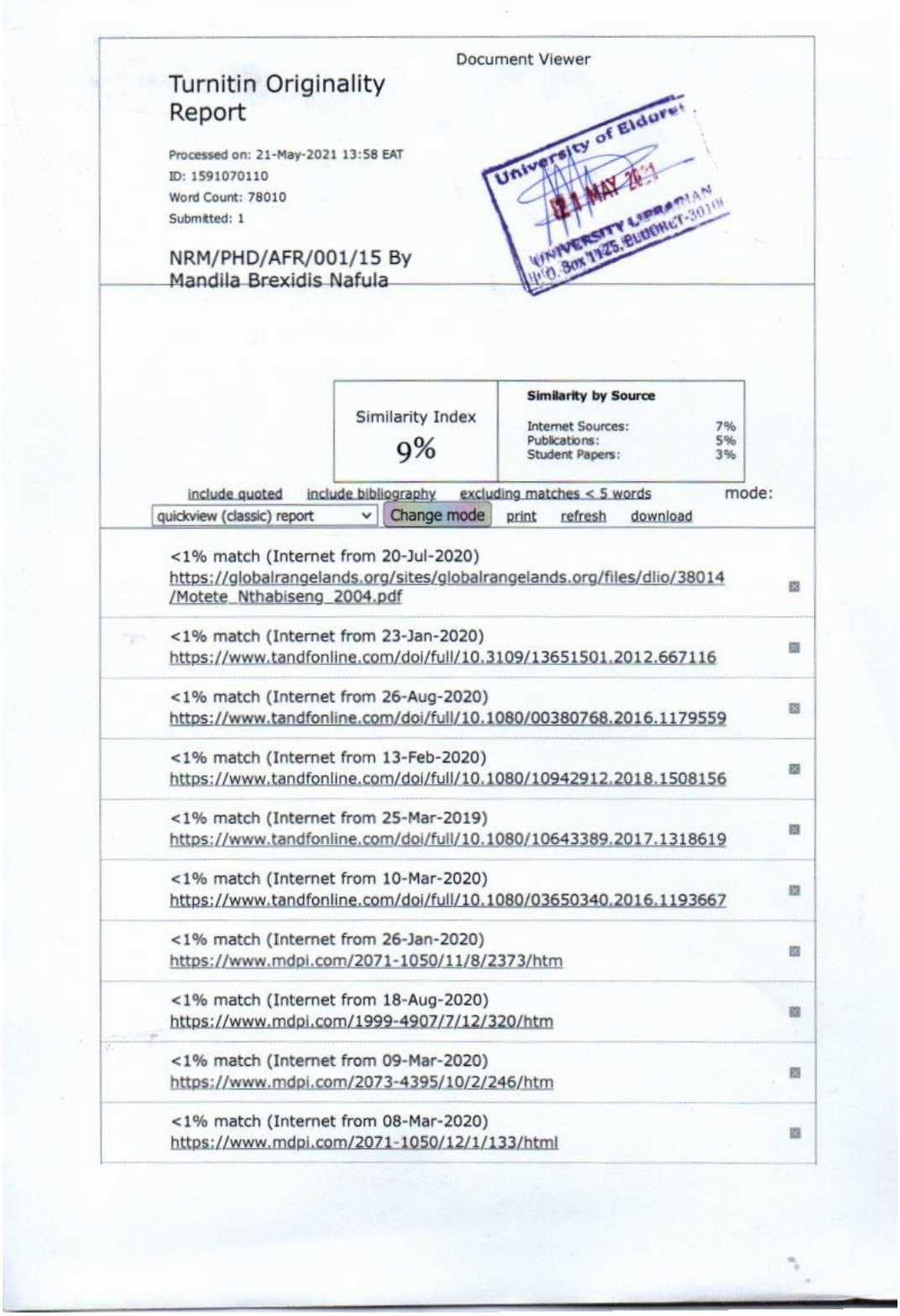
		95% Wald Confidence Interval		Hypothesis Test				95% Wald Confidence Interval for Exp(B)	
Parameter	**B**	**Lower**	**Upper**	**Wald Chi-Square**	**df**	***p***	**Exp(B)**	**Lower**	**Upper**
Part a: Weather Conditions Affecting Dieback Prevalence in Tharaka									
(Intercept)	15.36±0.289	18.643	19.096	49.888	1	<0.001	2.017	1.524	2.668
Mean monthly rainfall (mm/month)	-0.131±0.03	0.067	0.196	15.930	1	<0.001	0.813	0.069	0.216
Mean monthly temperature (°C/month)	3.649±0.87	5.362	11.936	17.435	1	<0.001	1.315	1.005	2.144
Part b: Weather Conditions Affecting Dieback Severity in Tharaka									
(Intercept)	38.296±0.59	45.610	60.982	73.952	1	<0.001	1.014	1.151	3.142
Mean monthly rainfall (mm/month)	-0.443±0.04	0.359	0.527	77.618	1	<0.001	0.688	0.591	1.698
Mean monthly temperature (°C/month)	1.061±1.71	5.430	8.691	64.645	1	<0.001	1.401	1.987	2.000
Part c: Weather Conditions Affecting Dieback Prevalence in Makueni									
(Intercept)	30.109±1.99	31.50	41.969	19.848	1	<0.001	2.100	1.035	1.087
Mean monthly rainfall (mm/month)	-2.482±0.49	-7.372	2.408	14.017	1	0.001	0.714	1.001	1.909
Mean monthly temperature (°C/month)	8.853±0.791	20.679	26.974	13.288	1	0.002	1.427	2.790	3.303
Part b: Weather Conditions Affecting Dieback Severity in Tharaka									
(Intercept)	-20.661±0.2	-34.060	-17.262	35.857	1	<0.001	1.170	0.614	0.986
Mean monthly rainfall (mm/month)	-0.016±0.03	-0.022	0.009	20.860	1	<0.001	0.696	0.723	0.834
Mean monthly temperature (°C/month)	0.948±0.150	0.654	1.242	39.942	1	<0.001	1.380	1.231	3.461

Appendix X: Dieback Causing Agents Analysis Tables

Appendix Xa: Pairwise Analysis of Dieback Causative Agent

(I) Causative agent	(J) Causative agent	Mean Difference (I-J)	Std. Error	*p*	95% Confidence Interval	
					Lower Bound	Upper Bound
Botryosphaeria	*Fusarium*	-1.9818	1.37440	0.701	-5.9042	1.9407
	Phomopsis	28.4878*	1.37440	<0.001	24.5653	32.4102
	Alternaria	30.1404*	1.37440	<0.001	26.2180	34.0629
	Cladosporium	37.6658*	1.37440	<0.001	33.7434	41.5882
	Unidentified Agent	34.8765*	1.37440	<0.001	30.9541	38.7989
Fusarium	*Phomopsis*	30.4695*	1.37440	<0.001	26.5471	34.3919
	Alternaria	32.1222*	1.37440	<0.001	28.1998	36.0446
	Cladosporium	39.6475*	1.37440	<0.001	35.7251	43.5700
	Unidentified Agent	36.8582*	1.37440	<0.001	32.9358	40.7807
Phomopsis	*Alternaria*	1.6527	1.37440	0.836	-2.2697	5.5751
	Cladosporium	9.1780*	1.37440	<0.001	5.2556	13.1004
	Unidentified Agent	6.3887*	1.37440	<0.001	2.4663	10.3111
Alternaria	*Cladosporium*	7.5253*	1.37440	<0.001	3.6029	11.4478
	Unidentified Agent	4.7360*	1.37440	0.008	0.8136	8.6585
Cladosporium	Unidentified Agent	-2.7893	1.37440	0.326	-6.7117	1.1331

Appendix XI: Similarity Report



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