UNIVERSITY OF NAIROBI

DEPARTMENT OF EARTH AND CLIMATE SCIENCES

EFFECTS OF CLIMATIC VARIABILITY ON NEMATODE DIVERSITY RICHNESS, DISTRIBUTION, AND USE OF RESISTANT POTATO VARIETIES FOR MANAGEMENT OF POTATO CYST NEMATODE (*Globodera rostochiensis*) IN NYANDARUA, IN KENYA

CALVINCE ORAGE

I58/38677/2020

Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Climate Change Adaptation of the University of Nairobi

2023

DECLARATION

I declare that this thesis is my original work and has not been presented elsewhere for research where other people's work has been used; this has been appropriately acknowledged and referenced, following the University of Nairobi's requirements. This thesis is my original work and has not been presented at any other university.

Signature: **Date:** 8th/September/2023

Name of student: Calvince Orage

Registration no: I58/38677/2020

This thesis has been submitted to the Department of Earth and the Climate Science University of Nairobi with my/our approval/knowledge as university supervisor(s).

Name of Supervisor: Prof. Catherine Lukhoba (Ph.D.)

Senior Lecturer, University of Nairobi, P.O Box 30197-00100, Nairobi, Kenya

Signature: **Date:** 8th-September-2023

Name of supervisor: Dr. James Kaoga, (Ph.D.)

Lecturer Department of Earth Sciences and Climate Studies, University of Nairobi, P.O Box 30197-00100, Nairobi, Kenya

Signature: **Date**: 8th-September-2023

Name of supervisor: Prof. Danny Coyne (Ph.D.)

Soil Health Scientist / Project Manager: East Africa banana breeding project.International Institute of Tropical Agriculture, P.O. Box 30709- 00100, Nairobi, Kenya

Signature: **Date:** 8th-September-2023

DEDICATION

I also extend my gratitude to my mother Tabitha Odongo, my wife Angelyne Anyango Orage and my daughter Leticia Orage, for their full support and prayers throughout the end of my project. Most importantly, I appreciate the Almighty God for the good health and knowledge.

ACKNOWLEDGEMENTS

I highly appreciate the financial support from my supervisor Professor Danny Coyne of the International Institute of Tropical Agriculture (IITA) Nairobi office, and Prof. Catherine Lukhoba and Dr. James Kaoga from the University of Nairobi for their full support and quick response whenever I needed their academic guidance in my entire thesis. Many thanks to Dr. James Kisaakye (*icipe*) for guiding me on the data analysis and the whole NemAfrica team for helping me during the processing of the samples. Finally, I highly appreciate The University of Nairobi for awarding me the scholarship.

ABSTRACT

Temperature, latitude, and altitude are critical in the soil nematode distribution. The documentation of macro-ecological diversity and geographic distribution patterns of soil-dwellingnematodes have received little attention in research. In Kenya, *Globodera rostochiensis* has been the cause of significant losses to potato crops. The management challenge of this nematode is its sound survival in the soil for many years without the presence of their host and the hatching of large number of eggs 400-500 per cyst. The aim of this study was to investigate, the effects of climatic variables on nematode diversity and distribution. Socioeconomic data were collected using targeting 50 potato farmers in Nyandarua County. Nematodes were extracted from the fifty soil samples collected from the farmlands hosting Irish potato. After processing the nematodes using Modified Baermann technique and Fenwick can methods, their identification, abundance, and diversity were established. A pot experiment with six replicates was set up in the greenhousefor three consecutive seasons at *icipe* Kasarani Campus. Effectiveness of two new breeding potatolines with H1gene imported from Scotland (UK), were compared with resistant cultivar Markies and susceptible Shangi. Three levels of PCN inoculum were obtained from the field in Nyandarua(low (5), high (600) *G. rostochiensis* levels, and *G. pallida*. The socio-economic data collected showed that 82% of farmers who applied cow manure had higher yields and lower levels of Plant Parasitic Nematodes (PPNs) than 18% of farmers who did not use it. There were also low PPN levels in sites where 66% of men and 30% of women practiced crop rotation compared to the 4%who did not practice any rotation. There was no correlation between elevation and Plant Parasitic Nematodes (PPN) distribution in Nyandarua ($P=0.25$, $R^2=0.0065$); However, there was a significant difference between the PPN and rainfall ($P=0.019$, $R^2=0.086$), and the temperature significantly impacted nematode distribution ($P=0.029$, $R^2=0.072$). Free-living nematodes were the most abundant in all sites per (ranging from 20779 to 64 per 100 grams of soil, followed by *Dorylaimus*, *Aphelenchus*, *Filenchus*, *Helicotylenchus*, *Tylenchus*, *Aphelenchoides*, *Pratylenchus*, *Globodera*, *Hoplolaimus*, *Meloidogyne*, *Trichodorus*, *Criconema*, *Rotylenchulus*, *Rotylenchus*, *Paratrichodorus* and lastly *Xiphinema*. In three consecutive seasons, the resistant varieties showed the ability to reduce nematode infection by 80-90%. One of the most impressing resistant potato lines was Line 7, which outperformed the rest. These lines had an excellent sprouting potential and matured within three months as the known susceptible variety cv. Shangi. In the pot experiment, all the potato varieties with H1-gene were able to suppress *G. rostochiensis* resulting in higher yields compared to known susceptible Shangi. Both temperature and rainfall significantly affected the nematode diversity and distribution. The identification of hotspot areas having the highest PPN levels could help in decision making for precise and effective management. The use of resistant potato varieties is highly recommended since they can improve food security and income generation. Climatic variables should be considered when dealing with nematode management technologies.

Key words; Effects of Climatic variable and PPNs on potato production.

TABLE OF CONTENTS

Table of Contents

LIST OF ABBREVIATIONS AND ACRONYMS

AMF-Automatic Mains Failure

ASGTS -Agriculture Sector Growth and Transformation Strategy COP-Conference of Parties.

EPPO -European and Mediterranean Plant Protection Organization FAO-Food and Agricultural Organization

FLN- Free -Living Nematode GDP- Gross Domestic Product

ICIPE- International Centre of Insect Physiology and Ecology IITA- International Institute of Tropical Agriculture

IPCC- Intergovernmental Panel on Climate Change

KALRO -Kenya Agricultural and Livestock Research Organization KCSAIF- Kenya Climate Smart Agriculture Implementation Framework KFC- Kentucky Fried Chicken

OM –Organic Matter

PCN –Potato Cyst Nematode PPNs- Plant Parasitic Nematodes PVY- Potato Virus Y

SDGs- Sustainable Development Goal

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

Despite the climate has been changing very fast globally and shall continue to do so for the anticipatable future, despite the measures taken (Streets et al., 2000). Climate change and extreme weather conditions continue to affect pest profiles in today's global food production system. In a changing climate, plant parasitic nematodes (PPN) cause significant economic damage to a wide range of agricultural and horticultural products (Dutta et al., 2023).

At the same time, their herbivory also accredits a range of ecosystem services, such as nutrient cycling, plant biomass distribution and turnover, formation of plant communities, and changing the consortium of rhizome microorganisms through changes in root exudation patterns. Thus, PPNs together with many free-living nematodes act as ecological factors. Due to direct exposure to the open environment, PPN biology and physiology are largely regulated by environmental factors such as temperature, precipitation, humidity, atmospheric and soil carbon dioxide levels, and extreme weather conditions (Dutta and Phani, 2023).

Phytoparasitic nematodes are threatening the world's food security. They show migratory or stationary parasitic activity and are biotrophic obligatory parasites (Ali *et al.,* 2017). In both situations, they take plant nutrients and cell sap while parasitizing. Plant parasitic nematodes (PPNs), which comprise over 4,300 nematode species and 7% of the phylum Nematoda, have been described (Decraemer and Hunt, 2006). Most PPNs nematodes establish favourable associations with various agricultural plants, including sugar beet, potato, tomato, and wheat (Triticum *aestivum* L.), *Solanum tuberosum* L. and *S. lycopersicum L*. The considerable yield losses in worldwide crops incurred by parasitic nematodes is approximately 157 million dollars annually (Abad *et al.*, 2008). Cyst and root-knot nematodes belonging to the family Heteroderidae are the main categories of phytoparasitic nematodes that normally parasitize many plant species (Ali *et al.,* 2017). More than 3,000 plant species, majorly crops, are attacked by the root-knot nematode *Meloidogyne incognita*. Knot cells, or root galls are caused by nematodes of the genus *Meloidogyne*. However, cyst nematodes in the genera *Heterodera* and *Globodera* producesyncytia in plant roots (Jones, 1981).

The effects of climate change such as global warming, elevated CO2, altered precipitation, and weather extremes including heat waves, droughts, floods, wildfires, and storms greatly influence the biogeographic range, distribution, abundance, survival, fitness, reproduction, and parasitic potential of the PPNs. Changes in these biological and ecological parameters associated with the PPNs exert a huge impact on agriculture (Dutta *et al*., 2023).

The United States and Canada have a long regulatory history of containing and eradicating the internationally recognized pests of potatoes namely *Globodera rostochiensis* and *G. pallida* *c*ollectively known as potato cyst nematodes (PCNs). PCNs top the list of economically devastating pests of potato production, and, if left uncontrolled, can reduce yield by up to 80%. Native to South America, *G. rostochiensis* is reported in 70 countries, and *G. pallida* is reported in 47 countries. In the United States, PCNs are now found in both the Northeast (New York) and the Northwest (Idaho); in Canada, PCN infestations are found in three provinces (British Columbia, Québec, and Newfoundland) (Contina *et al.,* 2018).

In the agricultural sector, there will be significant changes such as temperature increases, precipitation patterns change, and pests and disease outbreaks finding new ranges, leading to unknown risks such as food insecurity as it directly affects the farming activity of both small-scale and large-scale producers in Kenya (Chen *et al.,* 2016). Agriculture is the backbone of the economy in many developing countries (Shafique *et al*, 2017). However, climate change has undermined this dependence like never before. Fluctuating temperatures and rainfall have affected the seasonal climatic patterns, causing pest and disease distribution changes.

Plant parasitic nematodes (PPN) severely limit crop production, causing significant yield losses. *Globodera rostochiensis* potato nematode (PCN) is one of the most destructive potato pests. Although native to South America, it has spread to most Irish potato regions of the world and was first discovered as an invasive alien species in Kenya in 2015 (Mwangi *et al.,* 2015). The pest cysts which host 500-700 eggs, are known to remain dormant in the soil for many years. Upon stimulation by chemicals released from the potato roots, the eggs hatch and the juveniles are attracted towards the roots. To manage harmful nematode plant pests, various technologies, such as use of biodegradable banana paper, that promote growth of beneficial nematodes and reduce parasitic ones have been utilized by Nyandarua farmers (Ochola *et al*., 2022). However, there is still a need to combine climate-smart technologies to improve the country's food security and generate more farmer income. Therefore, this study focuses on using resistant plant cultivars to manage *Globodera rostochiensis*.

Globodera rostochiensis is native to South America but has since spread to most Irish potato growing regions of the world and was discovered as an invasive alien species in Kenya in 2015 (Mwangi *et al.,* 2015). This pest can remain dormant in the soil for many years without a host crop. Upon the planting of a host crop, chemical signals are released from the potatoroots, which stimulate the eggs to hatch and attract and guide the juveniles to the roots. Each cysthosts 500-700 eggs. To manage harmful nematode plant pests, various technologies, such as biodegradable banana paper that promote growth of beneficial nematodes and reduce parasitic ones have been utilized by Nyandarua farmers (Ochola *et al.*, 2022).

The eco-friendly paper has shown to promote the beneficial nematodes and reduce the PPNs. However, there is still a need to combine climate-smart technologies to improve the country's food security and generate more farmer income. Therefore, this study focuses on using resistant varieties to manage the PCN to enhance food security in the country and income generation for sustainability. The efficacy test of new breeding lines of potato to be adopted by the farmers is a climate-smart move to suppress the pest without interfering with our environment as it avoids using nematicides. These new cultivars will help solve the potato production supply to the market as KFC complained of a low supply of potatoes (Ochieng *et al*., 2022).

The economic importance of agriculture in Kenya is outlined in the goals of Vision 2030, African Agenda 2063 and Agricultural Sector Growth and Transformation Strategy (ASGTS, 2018) Medium Term Plan III. Agriculture is the main backbone of the Kenyan economy, accounting for approximately 25-30% of GDP directly and 27% indirectly through linkages with other economic sectors (FAO, 2020). This sector includes crop production, livestock production and fish production. Agriculture in Kenya is largely rain-fed, approximately (98%) dependent and therefore highly sensitive to climate change and variability. Approximately 83 - 89% of thecountry is arid and semi-arid, with an annual average rainfall of 400 mm. Therefore, it is likely toaffect the sector's contribution to food and nutrition security as one of the "Big Four Agenda" andUnited Nations Global Sustainable Development Goals (SDGs) Goals 1 and 2 (KCSAIF, 2018-

2027).

However, currently efforts are being made to increase farmers' awareness of the role of agriculture as a source of emission of greenhouse gases such as methane and nitrous oxide. Farmers must be aware that the current short-term weather events such as droughts, floods, extreme heat waves and severe cold are the result of climate change, which will affect their farms irreversibly for a long time (Ndambiri *et al*., 2013).

A comprehensive study of the regional distribution patterns and diversity of crop species and the variables that affect them is critical to understanding their biogeography and ecology. Such information is a valuable reference point and basis for regional and global biodiversity conservation. However, the extensive distribution patterns of the species are still controversial (Fonseca and Netto *et al,* 2015). Species richness often decreases fromtropical to boreal regions, with the maximum peak occurring near the equator.

Solanum tubersoum (Irish or English Potato), that belongs to the Solanaceae family, is a key staple food and cash crop majorly grown in the highlands of Kenya. Its production in the country plays a an important role in poverty alleviation, national food security, nutrition, and income generation. The Potato virus Y (PVY) in recent research has contributed to poor production in Irishpotato crops worldwide by lowering potato yield, and tuber quality. (Torrance & Talianksy, 2020)The viruses are typically transmitted by viral nematodes such as *xiphinema*, *Trichosurus and longidorus* (Crow, 2005). However, in 2015 PCN was confirmed in the country for the first time (Mwangi *et al*., 2015). This poses a significant threat to potato farmers and smallholders in rural areas.

In response to the catastrophe, the government has requested assistance from different research stations to develop effective and sustainable management strategies to stop the further spread of the pest. Adopting resistant varieties is considered an efficient and environmentally friendly practice of nematode control. Therefore, research is needed to identify more cultivars common and known to the farmers that will aid in reducing the population of this quarantined pest in the soil and still assure the farmers an economic yield (Ochieng *et al*., 2022).

Nematodes are the most prevalent and functionally varied organisms that impact plant productivity and play crucial roles in soil biodiversity. Plant parasitic nematode relations in the environment are less well understood; agricultural nematode interactions have received the most study attention. Here, we emphasize how nematodes might influence crop dynamics through top-down predation on species related to plants and direct adverse effects on plants. World climate change is modifying these interactions, where insights are rapidly needed to predict functional consequences better. More than 3,000 plant species, many of which are crops, are attacked by the root-knot nematode *Meloidogyne incognita* (Kofoid and White) Chit. Nematodes of the genus *Meloidogyne* cause the growth of root gall cells called node cells (Jones and Payne, 1978). On the other hand, *Heterodera* and *Globodera* cyst nematodes produce syncytia in plant roots (Wilschut & Geisen, 2021).

1.2 Background information

Nematodes, also called nematodes, are worms belonging to the genus Nematoda. Nematodes are one of the most common animals on earth. They occur as parasites in animals and plants, or as free-living forms in soil, fresh water, the marine environment, and even in such unusual places as vinegar, beer malt, and water-filled cracks deep in the earth's crust. There are approximately 20,000 named species, but probably only a small number of free-living forms have been identified. Many studies have been carried out on the parasitic forms, since most of them have medical, veterinary, or economic importance (Ahmed *et al.*, 2022).

Nematodes are divided into free-living nematodes (FLN) and plant-parasitic nematodes (PPN). FLNs are useful nutrients for host bacteria that contribute to organic biodegradation; and fungus gnats, which are indicators of contaminated or unstable soil. Plant Parasitic Nematodes (PPN) are the most dangerous and cause poor yield and yield quality leading to loss of livelihood and food insecurity for farmers in most parts of Kenya (Mai *et al*, 2018).

The common parasitic genera include *Pratylenchus, Radopholus, Globodera, Paratrichodorus, Helicotylenchus, Hoplolaimus, Trichodorus, Xiphinema,* and *Hemicyclophora* amongst others. The list of these devastating nematodes is very long, including the Root Knot Nematode, a polyphagous nematode that is very difficult to control. The PPNs can be found in both host roots and soil. Interestingly, most of the male nematodes typically die after mating hence the nematode community contains more females than males (Mai *et al.*, 2018)

Human disturbance and global climate change pose major challenges to biodiversity because they significantly affect biological populations and community structures (Bellard *et al.,* 2012). This is especially true for seasonally dry tropical forests (SDTF), which are one of the most vulnerable ecosystems in the world today due to widespread deforestation (Miles et al., 2006; Banda *et al*., 2016). Although widely dispersed and weakly connected, SDTFs are known for their closed canopies and distinct precipitation systems that vary between wet and dry seasons (Pennington et al., 2009; Banda *et al*., 2016).

While particular woodlands have a dry season spanning 3 to 6 months with a monthly rainfall of about 100 mm, the yearly rainfall is approximately 1800 mm (Banda *et al.,* 2016). The temperatures and rich soils of SDTFs have accelerated intensive agricultural production, increased human population densities, and cow pasture conversion (Rito *et al*., 2017). By 2100, it is anticipated that temperatures and evaporation in SDTFs will rise (Burkett *et al.,* 2014; Banda et al., 2016), causing more prolonged and severe droughts that might have an impact on the maintenance of nematode biodiversity.

The widespread distribution patterns of terrestrial living macroorganisms such as plants and vertebrates are relatively well documented, as body size, morphology and species boundaries are also easily determined (Tedersoo *et al.,* 2012). Nematodes as submicroscopic fauna (adult nematode length: 0.3–5.0 mm) are known as the most abundant metazoans, with 108 individuals per 1 m2 on Earth (Chen *et al.,* 2004). Nematode populations in soil can number several million individuals per center (Bloemers et al., 1997) and belong to more than 30 trophic groups (Bloemers *et al.,* 1997, Yeates, 1979). Plant parasites, omnivorous predators, bacterivores and fungivores are among the many forms of life they inhabit in most environments (Yeates *et al.,* 1993, Yeates, 1999).

Soil dwelling nematodes are critical in enhancing soil physical characteristics and supporting soil health. Therefore, it is essential to understand the distribution of substantial nematode communities. Yeates (1979) discovered that the abundance of nematodes in the tundra ecosystem is about a million m2 the highest documented, succeeded by green forests, temperate grasslands, deciduousforests, desert ecosystems, and rainforest ecosystems.

The biodiversity and abundance of soil nematodes in rainforest ecologies were predominantly higher than in temperate environments (Kitagami *et al.,* 2020), while (Nielsen *et al*. 2014) reported that nematode family abundance, diversity, and uniformity in polar deserts were lower at higher latitudes than lower altitudes. The temperature and moisture of the soil are critical vital environmental factors for soil nematode survival and reproduction with the optimum temperature ranging between 20 –25 °C. Soil nematode growth is suppressed below5°C or above 30°C (Bird and Wallace, 1965, Wang and Wu,1991). According to the IPCC report (Flato *et al.,* 2014), annual rainfall is expected to decline in the high latitudes, the tropical Pacific areas, wet and arid regions of mid-latitudes, and subtropical areas. Such projected changes can significantly impact soil nematode numbers and communities because soil nematodes normally absorb gap water, and their feeding is closely related to presence of water.

Various experiments have reported some effects of temperature and precipitation on nematode diversity (Matute *et al,* 2013. In addition, there are relatively few studies on the global distribution of soil nematodes, and most soil nematodes are poorly characterized.

Therefore, large-scale soil nematodes provide a basis for the distribution rules of nematode diversity in global terrestrial ecosystems and thus provide an advantage for understanding large-scale regions. The main objective of this study is to investigate whether nematode abundance and general soil conditions are present. there are large patterns in organism abundance across latitude and longitude, temperature, and precipitation.

1.2.1 Phyto-Parasitic Nematodes

Given their abundance and functional variety, nematodes are crucial to soil biodiversity animals affecting plant performance. Concerns have been expressed regarding how alien plants may modify the structure and functionality of soil organisms, such as nematodes, due to transcontinental introductions and range expansions brought on by climate change. Alien plants can modify belowground food webs by introducing unique litter and root traits. It has been determined that nematode populations under non-native plant species would either be depleted or dominated by opportunistic and stress-tolerant taxa, and alien plant species may cause the biotic homogeneity of nematode communities on a wide scale. However, these effects probably depend on the specific non-native plant since certain non-native plants may benefit nematode populations that are generally vulnerable to disturbance. While little is known about plant-nematode interactions in nature, most investigations on these interactions are centered on agriculture. (Torrance & Talianksy, 2020).

Nematodes can influence the dynamics of the vegetation by directly harming plants and indirectly benefiting them by predating on creatures that are linked with plants. These relationships are altered by global change. Therefore, more profound knowledge is required to predict functional outcomes. A fundamental understanding of important ecological concepts like plant-soil interactions and invasion dynamics will be attained through expanding our understanding of PPN interactions in natural systems and our biotic repertoire and potential for application in sustainable plant management. (Wilschut & Geisen, 2021)

1.2.2 The Nematode – plant interaction

The interactions between the different rhizosphere nematode groups and how this influences plant growth are displayed in Figure 1. They consist of the plant roots-eating root nematodes (R). The root nematodes (R), which consume the roots of plants, make up the rhizosphere nematode population. They lead to detrimental impacts on the plants (purple letters) and sometimes-positive impacts on the plants, e.g. (green letters or arrows), due to rhizome deformation—plant origin (blue dashed line). Bacterial nematodes (B) and fungi (F) deform rhizomes and inhibit plant growth. Plants can be used as biological nematode management agents because they attract pathogenic insect nematodes (E), which act as insect progeny control mediators. R, B, F, and E influence plant growth indirectly by top-down control of omnivorous nematodes. Other interactions between nematodes and nematodes (checked here) have further complicated the relationship between nematodes' central food web and plant growth (Wilschut & Geisen, 2021). The enormous taxonomic and functional variety of the nematode species' sensitivity to soil changes permitted the creation of several helpful nematode community indicators. (Wilschut & Geisen, 2021).

Figure 1. The Relationship of Nematode Functional Assemblies in the Rhizosphere and their Impacts on Plant Growth. (Source: https://ars.els-cdn.com/content/image/1-s2.0-S1360138520303307-gr1.jpg)

Due to differences in the sensitivity of nematode units to environmental disturbances, specific indicators of nematode populations that reflect soil conditions have been developed. For example, soil disturbances due to strict agricultural management have been associated with reduced levels of these nutrients, a relative increase in slow-growing nematodes, and fast-growing bacteria and fungi. This change lowers the maturity index and tissue index, or the asset index increases when an increase in nutrient content accompanies soil disturbance. Changes in monoculture resulted in more herbivores than other groups (e.g., the ratio of prey bacteria to roots). In contrast, soil treatment resulted in relative proportions of mycelium and, thus, fungal nematodes compared to herbivores that altered the primary degradation pathway. For example, the formation of nematode tubes). Although these measurements are designed to study soil health, they are also beneficial in deciphering plant properties in a given soil. Future research should consider whether nematode numbers may be utilized to forecast plant species yields. (Bonkowski *et al.*, 2000)

The nematode realm can provide insight into the functions of nematodes in nature and crops. Both direct and indirect have been distinguished effects of nematodes and show how globally changing factors can alter these interactions. Climate change factors modify nematode plant interactions with potential consequences for future vegetation. Finally, methodological advancespresented in the study of plant nematodes provide perspectives on understanding plant-soil interactions and how knowledge is exchanged between plants (Wilschut & Geisen *et al*, 2021)

1.2.3 Roles of Nematodes in Plant–Soil Feedbacks and Natural Succession

In agricultural systems, potato cyst nematodes (e.g., *Globodera* spp.) and, in general, root-knot nematodes (e.g. *Meloidogyne*) have been found as the key pest in the potato fields (Figure 2). Even in well-researched agricultural settings, molecular investigations continue to uncover a hidden variety of root nematodes. Naturally, nematodes that feed on plant parasitic roots are less visible as they have been seen as hidden enemies and have not been studied as much as the contribution of the rhizome group. This is different because of their role as plant pests, root nematodes are commonly found in agricultural systems. In contrast, only a few are found in uncultivated plants are known (e.g., *Heterodera betulae* found in the *Betula* spp.) Consequently, root nematodes have been partially ignored in nature at both the species level and strain level (i.e., disease type level), and future molecular studies are unlikely to be successful. Hybrids should emphasize frequency. Root nematodes are probably mostly restricted to settings with predictable and low-diversity plant populations. In communities such as the well-studied coastal dune pastures, root-knot nematodes can play an important role in natural succession by contributing to the death of species—non-host species—after dominant plant species (Figure 2) (Wilschut & Geisen, 2021).

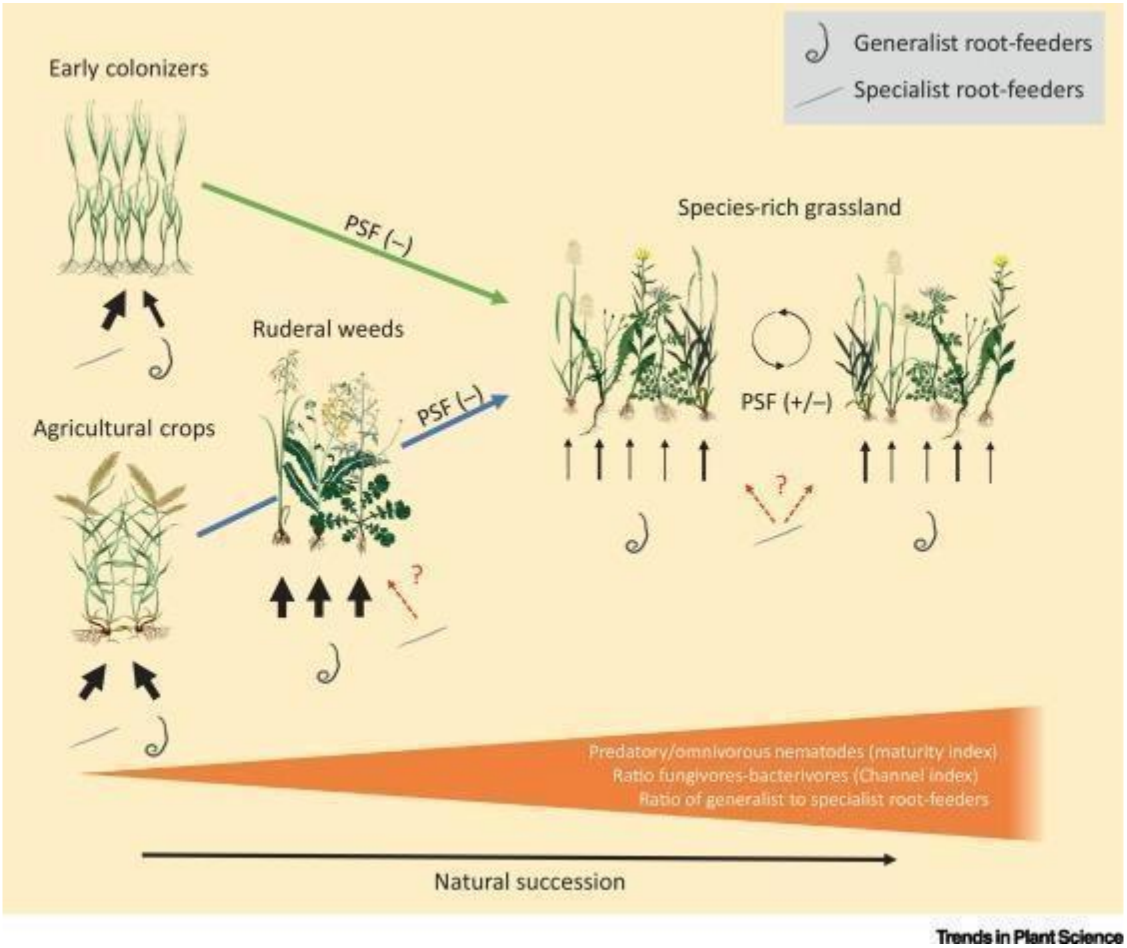

Figure 2. Role of natural succession (Source:https://ars.els-cdn.com/content/image)

Under situations of low plant diversity (such as coastal dunes and single crops), nematodes feeding on them play a critical role in contributing significantly to poor yield and crop quality. The natural system leads to the principal succession of seed-rich poor grasslands (green arrow). Throughout secondary inheritance after the neglect of agriculture (green arrow), phytoplankton groups generally accumulate many rooted nematodes that contribute to vegetation regeneration in various grassland communities. Plants that grow in these biomes typically have different protections against root-eating nematodes, accumulating species-specific and various nematodes, which contribute to negative feedback.

In addition to the continuous gradient, the nematode community shows an increase in maturity as the taxon number increases at higher nutritional levels, resulting in a taxon classified into low-level nutrients, including root-eating nematodes. Due to this, secondary inheritance is now subject to biological regulation, which may be followed by a switch from the bacterial to the fungal taxon, suggesting a modification of the primary degradation route (Wilschut & Geisen, 2021). It is still unclear what exactly the specific Nekobu nematode does in these plant ecosystems with diverse species. Several direct effects on plant disease epidemiology are expected, including survival of the primary inoculum, disease progression, and epidemic duration. These effects positively or negatively affect individual pathogens and the conditions that cause them.

Abiotic diseases associated with extreme environmental conditions are expected to increase. The interaction of biotic and abiotic factors greatly influences pests and diseases. The control of plant diseases also has its effect. In agriculture, breeding programs are expected to adapt many crops to longer growing seasons and increase their tolerance to drought and stress. There are also opportunities to introduce new plants and varieties, but there is a need to introduce effective systems to detect and prevent new pathogens from invading these new plants. Due to the long lifespan of trees, adaptation to forests tends to be slow,and therefore forest management plans need to consider the impact of climate change (Tripathi *etal.*, 2020).

Agriculture and forestry research infrastructure remain vital for successful migration and adaptation. (Boland *et al*., 2004). The necessity to feed the world's growing population is a big concern for farmers today. This expansion mainly occurs in developing countries, particularly in tropical countries, where most of the hungry dwell. One strategy to assist food production is reducing crop loss caused by tropical plant diseases. Plant-parasitic nematodes are frequently less important than other biological and biological constraints on plant development in the tropics, but they can still cause significant damage and yield losses.

The influence of agricultural, ecological, socioeconomic, and political changes on the outbreak and losses caused by plant-parasitic nematodes in the tropics is little researched. The most recent advancements provide new problems to tropical nematology. Uncertainty about the reliability of nematode species leads to practical problems related to quarantine and nematode management. Studies on the interaction of nematodes with other pathogens in the disease complex provide opportunities for interdisciplinary but poorly understood research by scientists from different disciplines. The difficulty of identifying new nematode threats can hinder the well-timed operation of management approaches and increase losses in yield. (De Waele & Elsen, 2007).

Recent reviews show new patterns in the global distribution of free-living soil nematode species, densities, and biomass (e.g., Yeates, 1979a; Sohlenius, 1980; Procter, 1979). However, collections have taken place in many parts of the world (see Ferris *et al.*, 1976; Procter, 1979; Sohlenius, 1980), enabling biogeographical studies. A distinctive feature of the high-latitude nematode fauna is its species richness compared to the mid-and low-latitude fauna (e.g., Mulvey, 1963; Kuzmin, 1973; Procter, 1977, 1979; Spaull, 1973a; Maslen, 1979).

Oostenbrink (1966) found that "the density and polyvalence of 103, 4 Procter nematodes in subtropical and tropical climates are generally lower than in temperate climates". Dao (1970) listed 426 plant-parasitic and soil-dwelling nematode species (temperate forest biomes) from the Netherlands, but only 177 species from Venezuela, including three tropical biomes (1970). Depending on the numeral of individuals and species that contributed, the genus *Plectus* is predominant or co-dominant in most high-latitude fauna (e.g. Behan, 1973; Cobb, 1921; Lagerl6f, Magnusson & Rosewall, 1975).

Plectid accounted for 70% of the specimens collected by Cobb (1921) from Canada`s Arctic and Alaska and contributed to five of the 11 species identified in Antarctica (Timm, 1971). Other predominant genera in high latitude habitats are *Tylenchus, Dorylaimus, Dorylaimus, and Teratocephalus* (e.g., Banage, 1963; Bunt, 1954; Kuzmin, 1973; Lagerl6f *et al*., 1975; Loof, 1971; Procter, 1977. The same genus seems to predominate in very high places (e.g., Thorne, 1929).

In contrast, *Plectide* contributes to a small number of individuals in most temperate and tropical habitats, while *Tylenchids*, including the genus *Tylenchus, Helicotylenchus, Tylenchorhynchus, and Ditylenchus, and Dorylaimide* in many of these habitats. (1975), we investigated the incidence of nematode-eating groups in several high-latitude habitats. We found that most of these faunas were dominated by microbial-eating nematodes (i.e., with the genus *Plectus*). Similarly, the death of micro-eating nematodes dominates fauna of the subantarctic and Antarctic (Bunt, 1954; Spaull, 1973b).

Of the 76 species recorded from Lake Hazen in the High Arctic, Mulvey (1963) and Anderson & Mulvey (1980), only two species known to eat higher plants are listed, as well as recorded in mainland Antarctica11. In contrast, confirmed parasites of higher plants such as Helicotylenchus, *Xiphinema*, and *Paratylenchus* are predominant in at least some temperate and tropical fauna (e.g., Willard *et al*., 1973).

During the past 20 years, several studies have been carried out in different regions and several insect nematodes have been identified (Hominick *et al.,* 1990; Gaugler *et al.,* 1992; Rosa et al., 2000). Research has identified entomopathogenic nematodes and some of the environmental factors influencing their survival. This study also clarified the relationship between nematode occurrence and various environmental factors from a Kenyan perspective. The Caenorhabditis elegans outbreak was intended to provide insight into Kenya's most insect-causing nematodes and predict ecological traits associated with nematode collection (Mwaniki *et al*., 2008).

1.2.4 Contribution of root nematodes to host plants and soil feedback in Kenya.

About 90% of cultivated plants, comprising most crops, especially grains, root vegetables, and horticultural plants, are in symbiotic relationships with arbuscular mycorrhizal fungi (AMF), which are soil microorganisms. The association between plants and microbes that is most generally beneficial is called arbuscular mycorrhizal (AM) symbiosis. According to several studies, they are necessary for plant nutrition and development under stress and for enhancing critical ecological functions. The effects of AMF on plant development and physiological aspects have been extensively studied in various species, including important crops such as Solanum lycopersicum. LAMF improved plant growth performance and uptake of several essential nutrients such as nitrogen and phosphorus in all these stressed species. This stimulation of growth is due to the ability of AMF to extend an excitable network across zones of rhizome nutrient depletion, providing free access to more soil (Diagne *et al.,* 2020).

1.2.5 Potato Production in Kenya

Potatoes are ranked second after maize in Kenya as the essential food crop. It belongs to the chestnut family and other plants such as eggplant, tomato, eggplant, tobacco, chili, and African chestnut. It can be nutritionally regenerated, and new plants can be grown from potato tubers, so-called seeds. Growth development comprises five stages: shoot development, vegetative growth, tuber germination, proliferation, and maturation. This crop faces many production restrictions, including climate change, low soil fertility, diseases, and pests (Janssens *et al*., 2014). However, the main problems that limit production are pests and diseases. As a result, farmers prefer varieties for resilience and disease resistance to other crops. Bacterial wilt disease is the most common (77%), followed by plague (67%) and viral disease (12%) (Wachira *et al*., 2010). Potato pests include aphids, whiteflies, moths, and even nematodes, the most common of which are potato cyst nematodes (PCNs). (Mwangi *et al*, 2015). This pest leads to severe yield losses and limits the worldwide transport of potatoes through quarantine restrictions. Infected potatoes discolour, wilt, and form fine fibers. Potato cyst nematodes often attack the roots of plants, impairing the host's ability to absorb water and nutrients necessary for plant growth, such as phosphorus, calcium, magnesium, and potassium. The second stage of the life cycle is infectious adolescence.

The larvae are attracted to the root tip and breeding grounds by the anti-chemical attraction contained in the exudate of the host plant. Once the appropriate site is found for the sensitive host, the puppy repeatedly attaches the probe to pierce the cell wall for access. Once in the root, J2 migrates to the vascular tissue by cutting the continuous layer of cells that introduce the supply side, syncytium (Evans *et al*., 1977).

Following FAO's Potato Industry Report, Kenya's FAO Crop Production Officer told all stakeholders about comprehensive pest control and control to restore national potato production for food production. Nyandarua County leads with a PCN infection rate of 91%, followed by Elgyo-Marakwet at 89%, Nakuru at 88%, and Narok at 88%. Transzoia, West Pokot, and Taita Taveta are the other 47 counties with high incidences of this pest. Therefore, additional strains should be tested for pest resistance in tropical conditions, especially in situations known to farmers.

Potato varieties grown in South Korea include Dutch Shangi, Sherekea, Marquis, and Robin.

Productivity is over 40t / ha. The awning has excellent resistance to plague, and the Yn virus is moderately resistant to X virus and immune to warts. Dutch robin is known to be resistant to PCN Ro1 type conditions, and testing resistance in tropical climates is fascinating (Catalog of Potato Varieties, 2017) (Islam et al., 2020). Sherekea potatoes are suitable for cultivation at an altitude of 1,883 above sea level. The average period is four months. The tubers are round, and the plants have many tubers, flesh-coloured and cream-colored. It is highly resistant to plagues and viruses and has an excellent shelf life, making it suitable for chopping and chopping. This high-yield variety is over 40 tons/hectare (Potato Variety Catalog, 2019). Destiny is an early mature variety that matures in less than 90 days and yields 40 t / ha. Ideal for pots with crispy surfaces, yellow skin, dull eyes, and many round tubers. The average dormancy period of tubers is years and 12 months. This strain is known for its resistance to the Potato Y virus, tuber blight, and the genus Erwinia. This level of PCN resistance is also essential for testing resistance in tropical climates. (Catalog of potato varieties, 2019).

Shangi is a popular potato variety among farmers and thrives in areas such as Nyandarua, Kiambu, Nyeri, Laikipia, and Meru. This precocious variety ripens within three months and has short tuber dormancy. However, the plague effect is moderate (Catalog of Potato Varieties, 2019). According to undocumented studies by research institutes such as the International Centre for Insect Physiology and Ecology (ICIPE), this strain is susceptible to PCN. This makes it suitable as a standard sensitivity regulator since it is the known susceptible variety. Cultivating this variety in Kenya is a big problem as it contributes to the multiplication of the PCN in areas already infested with this kind of pest.

1.3 Statement of The Problem

Climate change and its impact will continue to be felt across the agricultural spectrum. The effects of climate change have had high negative impacts on agricultural production in 2020 regarding potato yield, which will continue as projected in 2030 at (10-15% loss) and 2040 (Ochieng *et al.*, 2016). This means many plants parasitic nematodes might increase as many pests typically increase during high temperatures. The temperature and rainfall are changing and affecting nematode distribution richness and diversity. It is unclear how these climatic variables have so far impacted the nematode community in Kenya since very little attention has been given to the nematodes and climate change due to very few experts in these two fields.

The potato nematode is an economically important pest of the potato crop and has reached alarming levels in Kenya (Mburu et al., 2018). PCN was identified in Kenya in 2015 (Mwangi et al., 2015). With the support of the United Nations and the Food and Agriculture Organization (FAO), a survey was carried out in 20 counties in collaboration with other research centers including icipe, which showed that PCN infections are more than 70% in some important potatoes. growth areas (Mwangi *et al.*, 2015). The pest has continued to spread despite the regulatory measures onimporting potato varieties into the country. The pest population has continued to multiply in the significant potato growing regions in the country due to the continuous sharing of tubers, use of uncertified sources, lack of awareness of the existence of the pest, and climate change effects havealso contributed to the distribution and multiplication. Therefore, the earlier, the better to introducesuitable resistant varieties that can effectively manage PCN without applying any nematicides. (Mburu *et al.*, 2020). Indeed, the research has confirmed that the PCN contributes to low yield. However, we still need to develop resistant varieties, which the farmers can adopt as soon as possible to solve the food security problem in Kenya (Mburu *et al.*, 2020).

The populations of PCN have continued to multiply in the soil in the significant potato-growing regions in the country due to the continuous use of susceptible potato varieties like the common local variety, Shangi. Farmers prefer the variety despite its short shelf life (KALRO, 2013), which leaves the potato farmers counting losses at post-harvest. The variety is chosen from its short dormancy and short maturity period. The challenge the farmers face from this is the variety's moderate susceptibility to late blight disease (Potato Variety Catalogue, 2019). This leaves a need to provide the local farmer with alternative varieties they can adopt from their good qualities like early maturity and high yield.

1.4 Research questions/hypothesis

i) Increase in temperature results in lower soil nematode numbers.

ii) Species richness and diversity of soil nematodes will increase with increasing latitude and altitude.

iii) Species richness and diversity of soil nematodes will increase with increasing rainfall.

vi) Using resistant plant varieties will lead to lower PCN levels and crop yield compared to cv. Shangi variety.

1.5 Objectives

1.5.1 Main objective:

To examine the effects of climatic variability on nematode distribution richness, diversity, and use of resistant potato varieties in the management of Potato Cyst Nematode in Nyandarua County.

1.5.2 Specific objectives

i) To determine the effects of climatic variability on nematode diversity, distribution, and richness.

ii) To assess the effects of resistant potato cultivars on yield.

iii) To assess the effects of resistant potato cultivars on Potato Cyst Nematode levels (PCN).

1.6 Hypotheses

i. Different climatic variables have different effects on the distribution, diversity and species richness of nematodes.

ii. Resistant potato varieties suppress nematode populations.

iii. Resistant potato varieties suppress nematode populations.

1.7 Justification

Plant parasitic nematodes are becoming more and more prevalent due to climate change's effects. The majority of specialists demonstrated that the primary effects of climate change on Kenyan farmers included new pest strains (91%), low rainfall (68%), and crop loss by floods (59%), which resulted in an overall drop in potato output (86%) (Ogola *et al.*, 2021). The research has shown that the PCN can result in 80% yield loss, significantly threatening our food security as the Irish potato is the second consumed crop in Kenya. Suppose there is no research to locate where these pests have already been established, causing heavy losses. In that case, food security will still be a significant issue as the population increases.

1.8 Significance

The results will help develop climate change mitigation and adaptation strategies in agriculture and at the same time understand the impact of climate change on plant parasites and their impact on crop production. The number of plant parasites is expected to increase in the lowlands. In this case, the farmers should be warned about appropriate behavior in time to avoid loss of crops leading to food insecurity. The effects of soil nematodes, the most common animal on the planet, on crops have been studied mainly in agriculture, and natural populations are only partially understood. There is growing evidence of this *C. elegans* contributes to the negative feedback loop of plant oils, alters the rhizosphere microbial community, enhances natural plant nutrient cycling and reduces yield. Molecular approaches will promote and enhance this understanding by elucidating the molecular mechanisms underlying species specificity and interactions between plant nematodes. Moreknowledge will be generated to understand how the driving force of global change facilitates structural changes in the nematode community and to provide feedback on plant performance andcanopy composition. PCN management primarily uses nematode killers (Turvigo, Velum & Abamectin), crop rotation, resistant potato varieties, etc. (Brodie, 1984; Whitehead and Turner 1998). *C. elegans* are not readily available and emit greenhouse gases. This has a greenhouse effect that is harmful to the environment. PCN has already caused severe yield declines; the population continues to grow and creates a high demand for food. Since the Irish potato is the second key important crop in Kenya, the focus should be on improving food security with resistant potato varieties. It is a sustainable solution because it is environmentally friendly.

1.9 Outcomes, and Impacts

1.9.1 Outcomes

The study has revealed that temperature and rainfall affect the nematode distribution richness and diversity, while elevation does not. The resistant potato varieties affected PCN reduction in both soils with high and low PCN levels. The resistant varieties yielded double production compared to the susceptible Shangi variety.

1.9.2 The impacts

The resistant potato varieties have proved to be high yielding; hence the farmer's income can improve food security. The PCN levels can be gradually reduced as the resistant varieties have shown to be reducing the PCN levels with time. The hot spot areas, such as the Kinangop sub-county, have already been identified. Hence such sites should be given priority when deploying the management technologies for the Plant Parasitic Nematodes (PPNs).

1.10 Scope and limitations of the study

This study focused on Nyandarua County since most farmers heavily grow Irish potatoes for their main livelihood. Nyandarua is a highland that supports potato farming. However, the farmers have been experiencing 80% yield loss due to Potato Cyst Nematode infestations necessitating this study. These farmers usually have three seasons per year for the potato crop. During the interview, I realized that they typically recycle tubers for every planting season.
These kinds of use of uncertified tubers can be attributed to the high multiplication of the PCN levels in the farm since they majorly use susceptible cv. Shangi variety. Apart from potato farming, these farmers typically grow green peas, cabbages, and dairy livestock for milk production. Breeders have come up with resistant potato varieties, but the challenge has been the long dormancy, bad taste on chips, and boiled and mashed potato. Long cooking time, skin color,

appearance when cooked, and smell have been the factors that have led to the poor adoption of these potato cultivars. However, we checked all these parameters and came up with resistant varieties like cv. Change to help in the PCN reduction. The challenge with the Nyandarua farmers was that they did not have the knowledge and capacity to diagnose this devastating pest in the soil. This is due to the sub-microscopic nature of the PCN in the ground. The lack of awareness about this hidden enemy has been a big problem for the farmers. (Mburu *et al.,* 2018)

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The potato (Solanum tuberosum L), a member of the Solanaceae family, comes from the Andes Mountain region of South America. There are three thousand potato varieties only in the Andes, mainly in Peru, Bolivia, Ecuador, Chile and Colombia (Hijmans and Spooner, 2001). It has two critical subspecies of Solanum tuberosum: Andigena or Andien; and S. tuberosum (Zaheer and Akhtar, 2016). According to the FAO, more than 359 million tons of potatoes were produced in the world in 2020, which led to an increase from 333.6 million tons in 2010. It is an essential crop and is recommended by the United Nations as a food security crop.

Nematodes (submicroscopic worms) are statistically the most abundant animals on Earth, causing approximately 12% of crop losses worldwide, and their economic costs are estimated to be $160 billion Singh et al., 2015. Of these, potato nematodes (PCN), which affect potato roots, cause up to 70% potato yield loss. (Turner and Subbotin, 2006). PCN is widespread, with reports surviving for as long as 40 years (in the cyst stage) and to depths of 80 cm (Schomakerand Been, 2013).

Complete eradication of the nematode is not considered an option except in areas where infestation is locally detected, and steps have been taken to eliminate the nematode and prevent its spread. Therefore, in most of Northwest Europe and the United Kingdom, management measures are needed to reduce populations, prevent spread and preserve potato yields. In Europe, the cultivation of seed potatoes on soil containing PCN is prohibited. For stock potatoes, control of PCN can be achieved through planting traps, bio-spray, nematodes, flooding, biological control, crop rotation and application of apple varieties on resistant soils.

Agriculture is essential to the Kenyan economy and accounts for 26% of gross domestic product (GDP). According to the Food and Agriculture Organization of the United Nations, the sector employs more than 40% of the total population of Kenya and more than 70% of the rural population. The field improves nutrition by producing safe, varied and nutritious food. Given the importance of agriculture in rural areas of Kenya and in areas with widespread poverty, the contribution of the agricultural sector to poverty reduction cannot be assumed. Currently at the KALRO Nairobi research institute, potatoes are second only to maize in terms of consumption.

Mainly grown crops by small-scale farmers on more than 100,000 hectares of land nationwide and producing more than one million tons per year. With the appearance and detection of this pest, PCN potato production is threatened, with reports showing losses of up to 80% due to this pest (Mwangi *et al*., 2015).

Changes in community structure can adversely affect environmental services such as water treatment, nutrient recycling, and tidal sediment stabilization. This community is characterized by great taxonomic and functional diversity. According to the Insurance Hypothesis (IH), many communities will benefit from being able to protect ecosystems after as many species as possible are lost. Previously, the issue of functional redundancy in Caenorhabditis elegans was investigated in experimental systems using several functionally similar bacterial species. (Gingold *et al*., 2013).

Species redundancy studies in natural nematode populations are inadequate, but the complexity of the community's response to environmental impacts needs to be evaluated. Consistent with the masking effect, we believe that functional redundancy can be more significant in more diverse populations, which can affect the destructive role of nematodes. For the biodiversity and experimental treatment of diversity, evaluation of its stress tolerance and function concerning the quantity, individual and population biomass, and dietary richness.

2.2 Potato cyst nematode biology and symptoms of infestation

The potato cyst nematode, *Globodera pallida*, the pale nematode, and *Globodera rostochiensis*, the golden nematode, all originated in South America's Andes. (Randall, 2010) and spread to Europe with potatoes (Hock land *et al*., 2012). Their distribution has been influenced by sharing of potato tubers from infested fields despite subject to strict quarantine regulations worldwide (EPPO, 2013). Numerous potato-growing regions have confirmed the problem all over the world. According to the FAO report 2017, *G. rostochiensis* infestation was reported first in 2015 in Kenya (Mwangi *et al*. 2015) and has since then been reported in 20 counties, including Nyandarua, Elgeyo- Marakwet, Nakuru, and West Pokot.

A newly formed potato cyst nematode contains up to about 500 eggs and juveniles, and the eggs can survive for up to 20 years and with some retaining their viability Hatching is facilitated by stimulus exudate from the host root (Perry and Beane *et al*, 1988). The permeability of a lipoprotein membrane of the eggshell is what stimulates the hatching process (Atkinson and Ballantyne *et al*, 1977).

The infective juveniles (commonly called j2) from the cyst migrate and pierce the host root at a junction immediately beneath the root tip. After receiving a distinct signal, most likely chemical, the newly born juveniles migrate inside the origins and select a feeding spot. (Wyss and Zanke, 1986; Golinowski *et al*.1992, Endo, 1998). The saliva they inject causes the cells to enlarge and merge, forming giant cells filled with granules. The juvenile at this stage can become either male or female. When too many juveniles invade the roots, they compete for space forming giant cells; this may result in some failing to establish large enough 'giant cells,' and hence they become males or even die. On the other hand, where few invade the roots, most become females.

Once the juveniles are established in the roots, the juveniles enlarge but appear shorter than the juvenile three. The juvenile four-stage that still occurs within the roots appears curved, more enlarged, and faster compared with juvenile three. The adult stage for the males will have them regaining their worm-like shape and escaping to the soil. On the other hand, the females will enlarge, further rupturing the root cortex but remaining attached to their roots with their heads held in position by a cement-like substance secreted in the neck region.

In temperate conditions like Europe, the pest's lifecycle takes approximately 45 days. In Kenya, it takes about 90 days, during which the male's molt becomes vermiform and leaves the host root after fertilizing as many females as possible. The male nematodes usually die after about ten days final population exiting the root (Evans *et al*, 1970). Potato cyst nematode is a well-adapted parasite because the eggs remain encased and protected, with most remaining unhatched until a Solanaceae host plant is grown. The second stage juvenile (j2) uses stylet for piercing the Irish potato roots, then develops into an adult female with over 500-600 eggs and juveniles inside for three months, during which the crop matures. At this stage, the adult female attaches itself along the roots waiting for the next season when the potato is planted so that the exudates from the crop can stimulate their hatching, and the cycle continues.

Due to the small size of the nematodes, large numbers are required to cause significant damage. The wounds caused by the feeding juveniles have the potential to allow other pathogenic organisms, such as *Verticillium dahliae*, to penetrate and damage the roots. The giant cells are established while feeding, which lasts until the female dies, disorganizing root functioning and restricting root growth. Where there is a heavy infestation, growth stops altogether, and plant tops are observed as; yellow and sickly, and they die prematurely. Where potato is the crop being propagated season after season, the first signs of nematode attack will show as patches of poor plants. These later spreads, whereby the cysts later infest the entire field after spreading from the initial sites of infestation. The pest spreads through farm activities like weeding, cultivation, and planting uncertified seeds. The PCN life cycle starts from the eggs to juvenile 1 to Juvenile 4 which is the last stage when it forms the female cyst with numerous eggs inside (Mburu *et al.*, 2020).

2.3 Management strategies for potato cyst nematode

2.3.1 Control by crop rotation

A field rotation study was conducted to assess the impact of six rotation sequences on potato nematode, *Globodera rostochiensis* soil populations, and potato yield. In potato monoculture plots, tuber yield decreased from 35 to 34.6 t/ha (Riggs and Schunster *et al.,* 1998). But all other growth systems have kept the world at a higher level than it started. In monoculture practices, nematode densities increased from 0.1 to 265 larvae per gram of soil in the first three years. Three other cropping systems with alternating tolerant and susceptible cultivars, i.e., susceptible potatoes every 5 years and susceptible potatoes twice every 3 years, reduced nematode densities. decreased below economic thresholds (Riggs and Schuster *et al.,* 1998). However, according to the Food and Agriculture Organization (FAO), the number of small farmers growing potatoes is expected to be about 120,000. Few farmers are still using Solanaceae to lower PCN levels, as studies show (Vicente *et al.,* 2021).

Therefore, most smallholder farmers rely entirely on this enterprise for their livelihoods. This makes crop rotation challenging to practice. This leaves the option of using resistant cultivars as a more feasible technique for controlling this pest.

2.3.2 Use of Nematicides

Nematicides have been used on a large scale, especially in developed countries. Bio-fumigation has impacted food production through control of the nematodes and improved plant growth that has been observed with the plant. Other associated factors accounting for the yield increase include bio fumigation reducing the losses from diseases where the nematodes and other plant pathogens are jointly involved in the disease complex. The results, however, are usually uncertain when dealing with potato cyst nematodes and expensive as the nematodes are found distributed through the soil; hence more of the nematicides are required (Sikora *et al.*, 2021).

Negative findings were obtained from studies on nematicides used to control G. rostochiensis. Carbonate nematicides such as carbofuran, aldicarb, and oxarryl were utilized in this experiment. This, however, did not affect the population of G. rostochiensis (Desgarennes et al. 2006). This isn't the only issue; because of the excellent mobility of these compounds in the soil, they've caused several other issues. They have a deleterious impact on beneficial species and can contaminate groundwater (Haydock et al. 2006). They have a residual impact that lasts for 120 days. As a result, they can persist in the tuber until after harvesting, posing a risk to farmers and product consumers. (Mendes *et al.* 2005). The other challenge involves all fumigant nematicides being generally biocides. The halogen compounds can temporarily upset the normal soil nitrification process, which results in increased ammonia accumulation with the result that plants may suffer from ammonia toxicity. Where fumigation has been used, the crops also exhibited stunting. This was because of inadequate nutrition due to the destruction of vesicular mycorrhiza fungi (Affokpon *et al.*, 2011).

2.3.3 Use of resistant varieties

Soil treatment with chemicals and employing cultural practices are regarded as standard methods of nematode control. However, nematicides should not be the first consideration in nematode control programs as the most effective and economical procedure is resistant cultivars. Where a farmer can grow resistant varieties of potatoes in crop rotation is economical in gradually reducing the nematode populations in that field. Thus, this makes it possible to produce a susceptible cultivar as frequently without incurring an extra cost using nematicides.

The efficiency of resistance of a plant is determined by its genotype, whereby the main feature of resistance is evaluated by its effect on the reproduction of the nematode. Therefore, there are high variations in the cultivars, from high resistance to intermediate, determined by polygenic systems (Huijisman, 1974). With Potato cyst nematode, however, even the cultivars exhibiting high resistance have a certain degree of susceptibility. All the resistant cultivars will generally respond to the stimulus to form a syncytium in which the nematode feed and develop (Rospes *et al*. 1978) even if, for some, the nematode is not able to complete its lifecycle. Existing dominant genes, the common one against *G. rostochiensis* is the H1 gene govern resistance.

Resistant varieties have been widely used in temperate regions to control PCN. The roots of resistant potato varieties can produce the hatching factor and are infected by the infective juveniles. However, they fail to react by producing proper giant cells, which results in most juveniles becoming males with very few females, and the reproduction thus is almost stopped. Therefore, even when injured, the roots of these varieties have their function much less impaired than in the case where long-lasting giant cells are formed (Mburu *et al.*, 2020).

2.4 Impact of global change on earthworm communities

Given the susceptibility of the nematode network to environmental disturbances, including temperatures and rainfall availability, it's probable that environmental modifications particular to the Anthropocene affect the course network and adjusted interactions among flowers and nematodes. Such changes within the composition of nematode groups in reaction to worldwide extrude can now arise no longer most effective without delay, however; additionally, indirectly (for example, via modifications within the composition of the authentic biome) objects). A long-time grassland examination has proven that modifications in nematode groups can persist for many years (Ahmed *et al.*, 2022*)*.

This calls for knowledge of changes in nematode groups in reaction to worldwide extrude, affecting plant yields. Numerous worldwide converting elements affect nematode groups in herbal systems at a nearby scale. Since nematodes commonly stay in water movies in soil, expanded drought related to weather extrude is probable to have a more significant direct impact on nematode network shape. Indeed, droughts can lessen or burn up nematode groups, each immediately or via modifications within the composition of plant groups. This could cause a discount in plant growth, contributing to nematode group decomposition. However, a large-scale examination alongside aridity gradients shows that the reaction of nematode purposeful agencies to a boom in drought can be nonlinear, as fungi and nematodes in higher nutrient tiers had been proven to be greater touchy to the expanded deficit than bacterial species. Thus, drought might also adjust nematode network shape, as contemplated with the aid of using modifications in key nematode biome indices along with adulthood index and channel index... Thus, drought might also adjust the ratio between predatory nematodes and root nematodes to decrease root manipulation, which might also have terrible outcomes on crop yield (Figure 2). Likewise, drought also can lessen pinnacle-down manipulation of insect nematodes (Figure 2). (Wilschut & Geisen, 2021)

Compared with drought, the impact of excessive temperature on the shape of nematode groups can be much less substantial. However, warming in subarctic heathlands and numerous temperate grasslands will increase nematode densities, while such an impact is no longer observed in a single examined study inside the wilderness. Warming may also affect nematode network shape, both with the aid of using decreasing predatory nematodes - and consequently likely pinnacle-down manipulate over root nematodes, or with the aid of using decreasing nematode channel index, displaying a relative discount within side the number of fungal nematodes (Wilschut & Geisen, 2021).

The boom in CO awareness affected nematode abundance in grassland soil; however negatively affected nematode abundance in wooded area soil. High CO2 concentrations may additionally lessen the maturation index of nematode groups via the discount of omnivorous and long-lived nematodes. However, such an impact has no longer been observed in those studies. (Wilschut & Geisen, 2021) Studies searching on the outcomes of expanded pollutants and nitrogen deposition from in-depth agriculture display that nitrogen addition can lessen the maturation index of nematode groups, growing the dominance of nematodes. Short-lived bacterial nematodes or fungal nematodes in addition to decreased numbers of carnivorous nematodes (Wairimu *et al.,* 2022).

At the continental scale, land reclamation using agricultural sports has ended in organic homogenization of nematode groups via longitudinal gradients, which impacts their impact on surroundings functioning remains unknown. In general, maximum worldwide sellers of extrade can adjust nematode groups, frequently decreasing the taxa of perennial omnivorous and carnivorous nematodes. This can affect the underground meals net and may lessen the cap potential to govern from the pinnacle for root-consuming nematodes. However, the outcomes of worldwide extrade on nematode groups can be, highlighting the need to recognize the compositional elements of nematode groups within the surroundings of ecology. Furthermore, the outcomes of different drivers of worldwide extrade (e.g., plastic pollutants) remain largely unexplored. It is essential to observe that sellers of worldwide extrade are frequently co-taking place and active, influencing the composition and pastime of nematode groups (Wilschut & Geisen, 2021).

2.5 Interactions between nematodes and plants of non-local plant species

The formation of many plant species in regions typically past their herbal tiers because of transcontinental creation and variety growth resulting from weather extrade. The creation of recent buffers, root traits, and non-local flowers can adjust the subsoil meals net. Nematode groups of non-local plant species have been proven to be ruled by opportunistic and stress-tolerant taxa or usually depleted, and non-local plant species can result in large-scale organic homogeneity of nematode groups. However, such outcomes might also additionally depend upon the identification of non-local plant species, as a few non-local flowers can impact nematode agencies (Wilschut & Geisen *et al*, 2021)

Studies on plant-parasitic interactions of non-host species have additionally addressed the query of whether a decline in root nematode variety and abundance amongst early-distinguished flowers has been addressed early and non-local flowers boom the productiveness of a few non-local species of flowers out of doors their herbal variety. (Concept of liberation from the enemy). Indeed, a few non-local plant species acquire fewer root nematodes of their non-local tiers than their local tiers, even though those outcomes can be categorized as endoparasitic (semi) and observed most effective in positive plant species. Such a lower quantity of root nematodes at non-local tiers can be because of the discharge of host-particular taxa. However, the bad overall performance of root-consuming nematodes in an extension of flowers with exclusive root metabolomics shows that non-local flowers may gain from having a protection chemical to new species to defend them against nematodes that usually feed at the roots of the brand-new species. variety (Wilschut & Geisen, 2021)

2.6 Methodological developments to advance understanding of plant-nematode relations.

Many new molecular technologies have recently improved the clear understanding between the nematodes and plants. There is need to focus on: Established techniques for extraction and morphological identification of rhizome nematodes. Gained insight into the ecological factors that determine nematode abundance and community in soil are as follows. (iii) Identify many species and functionally comment on most of them. This information provided a soil quality assessment dataset (Box 1) that needed to be converted to understand better and predict nematode communities' direct and indirect effects on plants. (Wilschut & Geisen, 2021).

A new user-friendly molecular biological method has been developed that transfers the findings of the nematode expert to a larger group of scientists. These molecular techniques require intensive adjustment work to compete with traditional morphometry-based methods but focus on microorganisms and nematodes. It offers a unique opportunity to close the gap between studies. The data obtained from the sequence data using molecular apparatuses, including high-throughput amplicon sequencing (met barcode) can infer the individual biomass of the nematode in terms of nematode composition rather than microorganisms. In addition, the most widely used nematode extraction method requires nematode migration, so the information so far is minimal as it covers only 15 active taxa (Noia *et al.*, 2022)

Plant health (e.g., responding to factors of global change). Soil biome segmentation experiments that can remove nematodes from soil biomes help to understand the practical health effects of changes in the composition of nematode biomes. The information obtained can be used directly to correlate communities and abundances of active nematode taxa with plant species development, thereby providing immediate functional information on the role of nematodes in plant growth. (Mai, *et al.*, 2018).

The feeding sites of *C. elegans,* including rhizome effects and plant interactions, can be determined by stable isotope examination or actual pulse marking with 14CO2. Together, these techniques help to understand soil nematodes' taxonomic and practical diversity and their function in the crop yields. (Wilschut & Geisen, 2021) Information can be translated to understand species-specific interactions between a single plant species and nematodes. In particular, this helps to understand the evolution of a specific host, like root-eating nematodes. In addition, a sequence-based whole-genome approach enables the study of nematode distribution patterns. It helps to correlate plant yield variability with compositional spatial variability—distribution of nematode communities at the species level (Wilschut & Geisen, 2021).

Closer links and knowledge exchange between nematode-focused research disciplines and nematode expertise in agriculture and natural systems are essential. Advances in methodologies developed based on a variety of known agricultural pests should be transferred to nematode species to understand and improve their function in identifying plant growth in the environment. Natural nematode spoilage organisms contain vast biological reservoirs and require further research to identify potential new biological pest control agents (Lear *et al.*, 2018).

CHAPTER 3: MATERIALS AND METHOD

2.7 Study sites

Nyandarua County is located in the former Central Province of Kenya. The capital and largest city is Orcalau. Nyahururu is the former capital of Laikipia county. Nyandarua County has a population of 638,289 and an area of 3,304 square kilometers. The Aberdare Mountains are located in the northwestern part of Old Central. Nyandarua has five sub-districts: South and North, Kipipiri, Ndalagwa, Orkalau and Oljorolok. (Kamau *et al.*, 2015).

The county was selected for this study as it was the first area reported to have the potato cyst nematode in the country. Therefore, the survey will consist of soil sampling for the PCN and warm-like nematodes. Among the collection, sites will include the spot of the first report of the having *Globodera pallida* at Kipipiri Gidhioro in Nyandarua county (0.4667° S, 36.5000° E) and at Kanyawa (0.7276° S, 36.6539° E) an area reported to be having *Globodera rostochiensis* (a virgin land and cultivated land for potato). The sampling sites for the survey are indicated on the map of Nyandarua County (Figure 4).

Nyandarua County map showing study areas.

Key.
Blue spots - sampling sites.

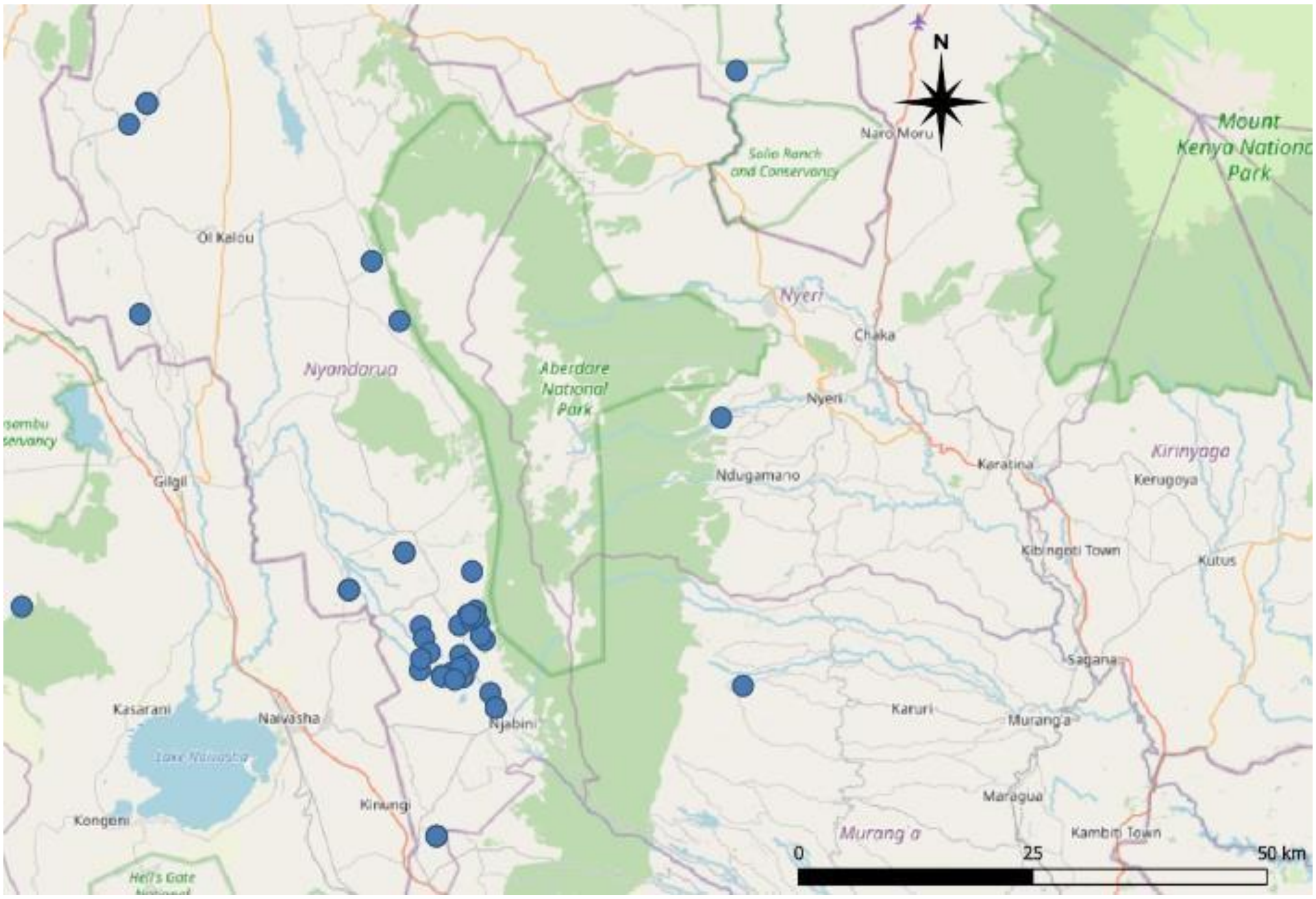

Figure 4. Map of Nyandarua County: (Source: GPS Coordinates, 2021)

2.7.1 Demographic data of Nyandarua County

Table 1. below shows the census's demographic information from 1979 to 2019.

Table 1: Historical population information for the whole of Nyandarua County.

Year	Population	±%
1979	233,302	-
1989	345,420	+48.1%
1999	479,902	+38.9%
2009	596,268	+24.2%
2019	638,289	+7.0%

The county has five constituencies and 25 wards. The five sub-counties are Kipipiri, Ndaragwa, Olkalou, Ol-Jorok, and Kinangop, the largest sub-county.

Table 2: Number of people living in Nyandarua County: Source: Census 2019

Sub-counties	Area km^2	Pop census 2019	Number of Wards	Wards
Kipipiri	544	95,338	4	Wanjohi, Kipipiri, Geta, Githioro
Ndaragwa	655	92,626	4	Leshau/Pondo, Kiriita, Central, Shamata
OlKalou	536	120,282	5	Karau, Kanjuire Ridge, Milangine, Kaimbaga, Rurii

Ol-Jorok	439	95,643	4	Gathanji, Gatimu, Weru, Charagita
Kinangop	935	192,379	8	Engineer, Gathara, North Kinangop, Murungaru, Njabini/Kibiru, Nyakio, Magumu, Githabai
Total	3,108	638,289	25	

2.7.2 . The livelihood of the Nyandarua people

Nyandarua District has productive land suitable for agriculture, manufacturing and processing. Interested local and discrete investors can invest in agriculture, production, processing and housing in the area. However, there are many challenges such as lack of good road network and adequate power and water distribution. (Kamau *et al.*, 2015).Their main economic activity in Nyandarua is agriculture (crops and milk production). In the 1990s, it was one of the main producers of pyrethrum; However, the Pyrethrum Kenya Board, the agency in charge of the procurement, processing and marketing of crops, collapsed due to mismanagement and corruption, severely affecting the livelihoods of many farmers. The county is known as a giant in Irish potato production. However, agriculture faces a number of challenges such as market volatility, poor road conditions, and potential pests and diseases such as PCN and crop diseases. County Nyandarua is a mountainous region where about 98% of Irish farmers grow potatoes as their main crop, helping to sustain their entire livelihood.

2.7.3 Nyandarua climatic conditions

The county lies at 2,667.11 meters (8,750.36 ft) above sea level; (Classification:csb). It's annual temperature is 19.03 oC (66.25 FF), -3.47% lower than the Kenyan average. The county typically receives about 120.38 mm (4.74 I nches) of rain and has 224.82 rainy days (61.59 percent of the time) per year (Kamau *et al.*, 2015).

Temperatures in the county range from mild to cold. The highest temperature was recorded in December, with an average temperature of 250 degrees Celsius, while the lowest temperature was recorded in July, an average temperature of 120 degrees Celsius. On clear nights, the cold air rises. up over the moors of the Aberdare Range and down the plateau through valleys to the west of the plateau. Temperatures in these valleys can range from 1.2oC to -1.30C and last several hours before dawn. Long rains from March to May with maximum rainfall of 1600 mm and short rains from September to December with maximum rainfall of 700 mm.district usual. Rain intensity varies considerably depending on location. Areas near the Aberdare slopes are known to receive sufficient rainfall. The plateau receives rare and irregular rainfall, which is unfavorable for agriculture in some of these areas. (Kamau *et al.*, 2015).

2.7.4 . Ecological Conditions

Some areas of the county are located in the highland steppe region, characterized by sparse trees and thick grass. The elevated areas increase tree cover, creating dense forests with dense undergrowth. However, some natural vegetation has been destroyed by humans for the benefit of agriculture and cities, posing environmental risks, including environmental degradation and requiring large amounts of fertile land. fat. Adverse consequences have been exacerbated by this, including reduced rainfall, global warming, soil erosion, climate change, poor health and reduced food production. (Kamau *et al.,* 2015).

2.7.5 Physical and Topographic Features

Flint, volcanic activity, and silt are physical features of the soil in Nyandarua. Most unconventional rock systems have weak points due to faults that create porosity and simple permeation. Volcanic in nature, the county's soils often have varying degrees of fertility and dispersion. The county benefits from moderately to very fertile land. The silty clay of the Kinangop and Ol' Kalou plateaus is poorly drained. However, the mixed clay in Ndaragwa, the northern half of Ol'Joro-Orok, and Ol'Kalou has good drainage. Various crop production potentials exist for these soils in agrotechnical engineering (Kamau *et al.*, 2015).

2.8 Survey and questionnaire for objective one

A well-structured questionnaire captured quantitative data on agronomic practices. The survey is usually done to detect the presence or absence of nematode pests in the soil, and this is only relevant to the Irish potato farmers in Nyandarua for this case of study. Therefore, 50 farmers per sub-county were interviewed and at least 10 per sub-county to represent the entire County. The survey covered five sub-counties (Kinangop South and North, Kipipiri, Ndaragwa, Olkalau, and Oljoro-rok.

The questionnaire captured the following data: the county, sub-county, gender, potato variety grown, source of seed, age of the crop, fertilizer used, Organic Matter (OM), cropping system, a previous crop grown and yield, size of the farm under potato cultivation, latitude, longitudes, and altitudes. The survey was only done on Irish potato crowing farms only. This was conducted during July. This time was selected because most farmers had just finished harvesting their crops, allowing the collection of a maximum number of nematode genera. This was to give an evident diversity and distribution since most of the nematodes are still actively feeding on the potato.

The number of collected samples depended on the cost, reliability of farmers, and willingness to allow their farms to be used for the study. However, the more the number of sub-samples/cores combined for per field sample, the more precise was the assessment (Perry and Moens *et al.*, 2013).

Meteorological data was extracted from the meteorological department on precipitation and temperature to determine the effects of the amount of rainfall on the nematode distribution richness and diversity (Planning,*et al.*, 2013).

2.9 Nematodes Collection and their storage from the field for objective one

The survey and nematode sampling were conducted in five sub-counties of Nyandarua County, namely Kinangop South and North, Kipipiri, Ndaragwa, Olkalau, and Oljoro-rok. This involved systematic sampling methods known as (M/W) where the soil was collected from the potato farms where a composite soil of two (2) kg from 60 sub-samples per site in an area of 50m by 5m in the depth of 30 cm around the root area of the Irish Potato was done. The soil samples were put in the sampling materials and labelled (site name, date, crop, and code). The bags were then put in a cooler box to maintain the soil temperature to maintain the nematodes live for the extraction process and delivered to the *icipe* lab for Modified Baermann's extraction. The cyst samples were air-dried before extraction by the Fenwick can floatation method (Coyne *et al.* 2013).

2.10 . Procedure for Laboratory and screen house experiments for the first, second,and third objectives.

Warm-like nematodes were extracted using a 20-micrometer sieve and put in a Falcone tube of 50 ml. The sample was allowed to settle and reduced to 10 ml for quantification and identification under the stereo and dissecting microscope. For the PCN, the samples were extracted using 1mm,850 & 250-micrometer sieves using Fenwick can and then filtered and allowed to dry for 24 hours after that, picked using embryo discs and forceps under the microscope.

Seventy-two 7 litre pots, containing 9 kg of soil/pot, planted with Markies, Shangi, Lines 7&6 potato varieties. The treatments used were resistant varieties: Markies, Line 6 &Line 7, and the known susceptible Shangi was a control. Soils were inoculated with different concentration of the nematodes (viz. low and high densities) of *G. rostochiensis*, and *G. pallida* replicated six times.

The pot experiment was conducted in the *icipe* greenhouse. At the start and end of the experiment, the Pi- and Pf –nematode populations levels of the soil samples were calculated. The Pi- and the Pf-PCN levels were compared per 200cc of soil until the end of season three. This determined how the resistant lines worked during the seasons.

The soil was sampled in three different farms from Nyandarua in and then extracted to get the number of PCN; The 9kg soil with low and elevated levels of PCN (*G.rostochiensis*), and the one assumed to be having G. pallida were put in a pot of seven liters.

The four potato cultivars were planted in each pot and then replicated six times in the greenhouse where Randomized Block Design (RBD)was applied; Water was applied using a watering can till maturity index (three months); Harvesting was done after three months, and the soil was collected to compare the initial population & final population (Pi & Pf of PCN) per pot. The grading and sorting were done, and weights recorded in grams; The Pf of PCN for season one served as the Pi for season two since the soil was re-used till the end of the seasons. The experiment was conducted for three seasons at the screen house.

2.11 Quantitative data collection for objectives two and three

On Growth parameters, the germination percentage, Plant height, Leaf number, and Number of stem branches were recorded for the entire three seasons. Crop yields data captured the number and weight of tubers, Sorting & Grading of tubers (quality) during the harvesting period. Soil & roots Analysis was done for PCN levels, Physical check of PCN on the roots. The data collected for the three seasons comprised cyst densities for Pi and Pf, growth parameters, and yield data.

2.12 Nematode Extraction Methods for both Survey and Pot Experiment Samples at IITA-*icipe* Lab

Figure 5 below represents procedures of how nematodes were sampled and processed for quantification and identification in the lab. It shows two extraction methods: the ModifiedBaerman technique for warm-like nematodes and the Fenwick can method for PCN extraction.

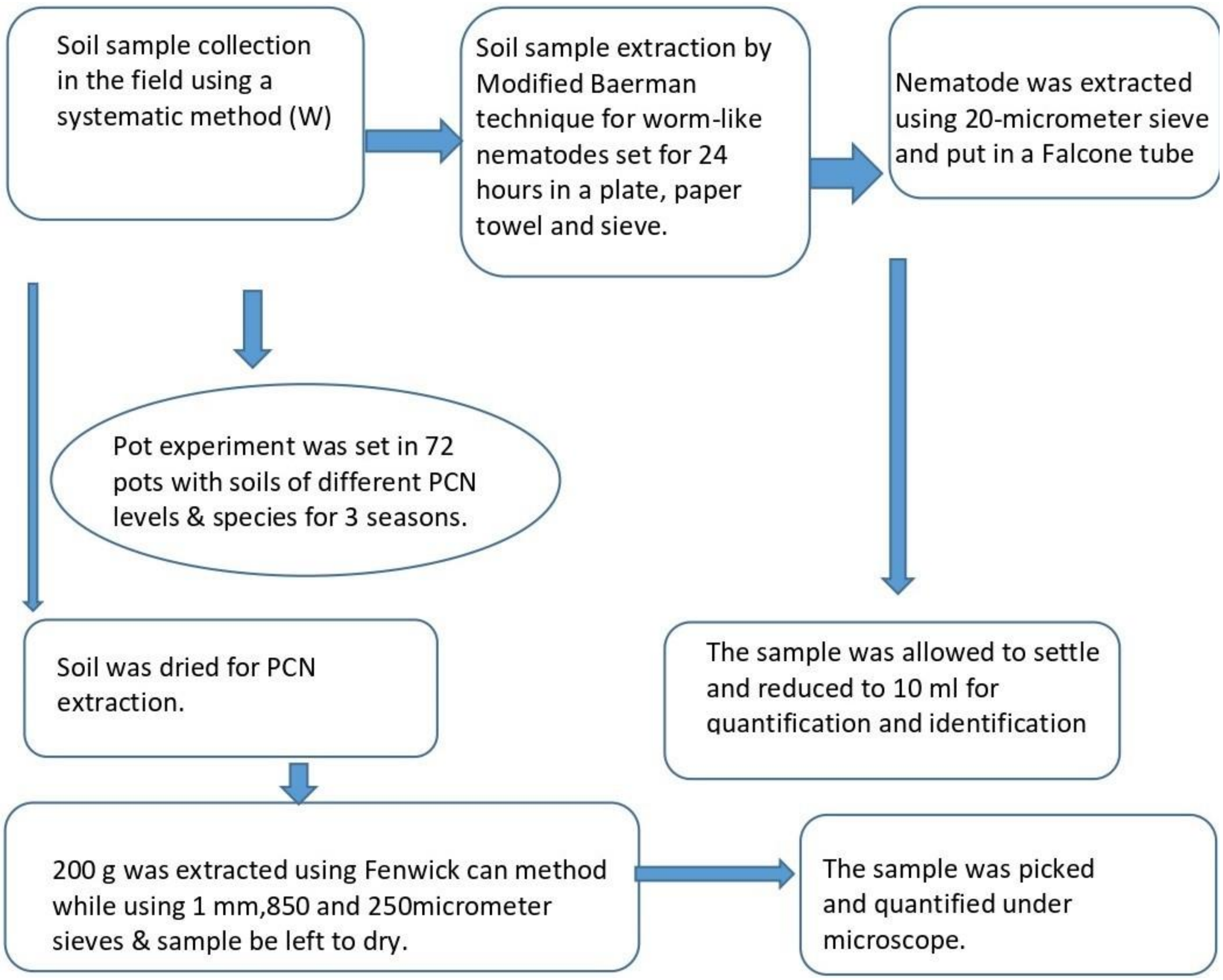

Figure 5. Nematode extraction procedures. (Coyne et al,2019)

Figure 5 describes the Modified Baermann technique for extraction of wormlike nematodes that takes 48 hours to 72 hours before the maximum number of nematodes can be extracted. For the PCN extraction, a Fenwick can, which uses a floatation method, is applied to get the cyst nematodes from the soil and this is done after drying the soil so that the cyst can easily get detached from the soil when water is passed into the Fenwick can with sieves of different sizes (Coyne *et al*,2019).

2.13 Conceptual Framework

The effect of climatic variables on the nematode distribution and abundance are shown in figure 6. The conceptual framework shows how to achieve high-quality yields for the farmers and lower the pest densities in the soil and maps out the distribution of the plant parasitic nematodes.

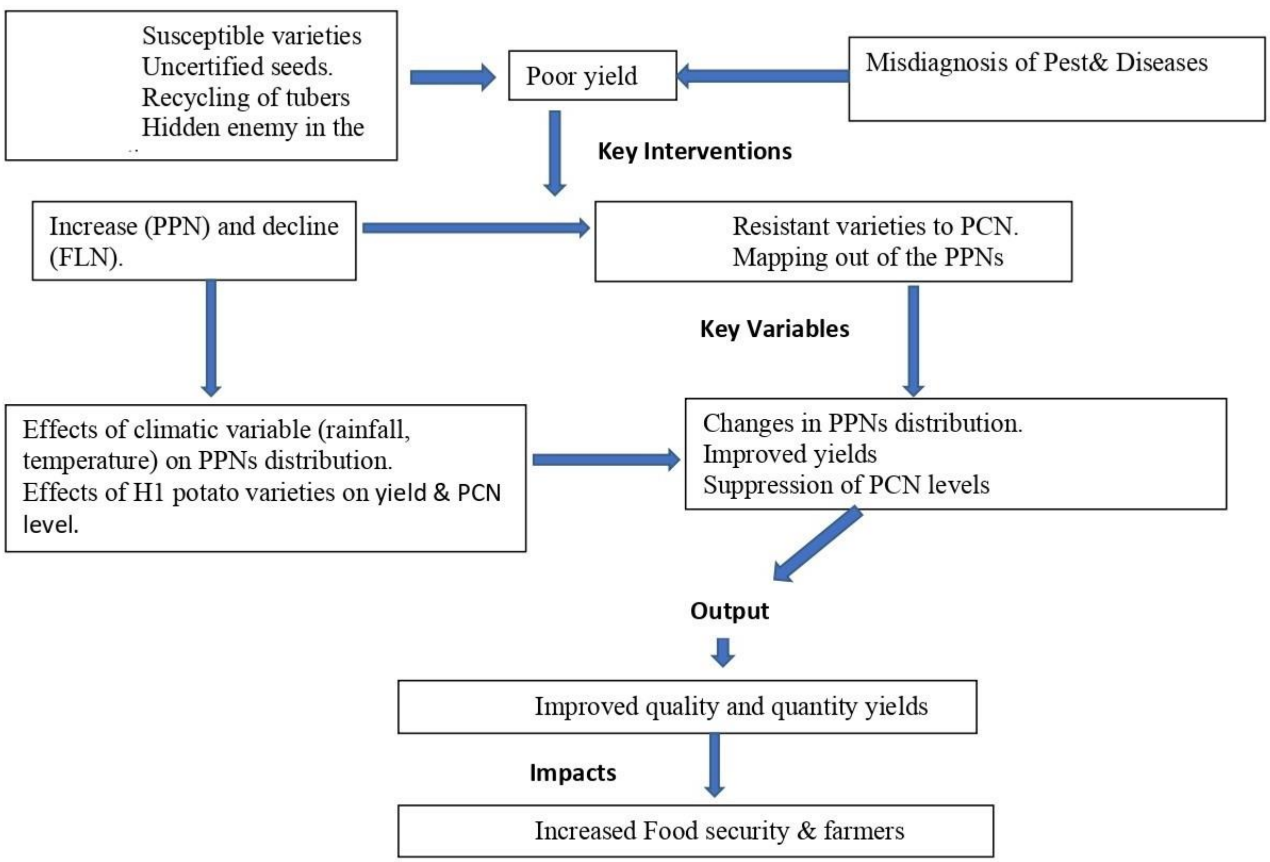

Figure 6. The Problem-Effects of climatic variables (rainfall, temperature & elevation on nematode distribution & High PCN Infestations in potato farming.

2.14 Desk Top Studies

Most researchers have surveyed and collected soil samples for PCN in Kenya but have never checked how temperature, precipitation, altitude, and latitude have affected nematode distribution and diversity. Some resistant lines have been introduced into Kenya without considering whether they will increase the population of *Globodera pallida* while suppressing the *Globodera rostochiensis*, which is exceedingly difficult to control. Therefore, this study focused on how the resistant potato varieties could reduce the PCN levels and yield increase, and the survey revealed the hot spot areas for Plant Parasitic Nematodes.

2.15 Field Work or Field Studies /Transdisciplinary Approach

The socioeconomic data on the questionnaire captured the county, sub-county, gender, potato variety grown, seed source, crop age, fertilizer used, OM, cropping system, previous crop, previous yield, size of the farm on potatoes, latitude, longitude, and altitudes. In Nyandarua County, the sampling was done in the following wards: Magumu, Charagita, Murungaru, Raitha, Njabini, Engineer, Rurii, and Kanjwiri ward. The shovel was used to collect soil samples at a depth of 15-20 cm; the model will be put in a plastic bag and labelled, then stored in the cooler box.

2.16 . Laboratory Analyses

The soil sample collected from the field were set for Modified Baerman extraction per 100cc to get the mobile nematodes after 24 hours, where a 20-micrometer sieve was used to collect the nematodes and put them into Falcone tubes. The samples were allowed to settle for 30 minutes and then reduced to 10 ml for quantification, done three times, and identification under a microscope.

The PCN soil samples were dried and extracted by Fenwick can, which applies the floatation method. Then allowed to dry after correct labelling was done, each sample was put in a modified glass disc, picked and put into the embryo disc, quantified under the microscope, and stored in the small Eppendorf tubes.

2.17 Data Analysis

Both field survey and pot experiment data were analyzed by R-software

R-Studio software was used to analyze the data for objectives two and three, where analysis of variance was applied to the PCN Data and the yield. The pie charts for socioeconomic were generated by advance excel. Analysis of Deviance Table (Type II tests) was conducted for all variables and BiodiversityR was used as well for diversity of nematodes. The normality test checked if the data was consistent. Weights/yield were different across all seasons, thus splitted and analyzed per season. Total nematode vs Climatic variable were subjected to Regression analysis. Correlation (Pearson) - for all climatic variables. The yield and socio-economic data were subjected to advance excel to generate chats/graphs. The means were separated using Fisher's LSD at $P \leq 0.05$

.

CHAPTER 4: ANALYSIS OF CLIMATE VARIABILITY ON NEMATODES DIVERSITY, DISTRIBUTION AND RICHNESS

2.18 4.1. Effect of Climatic factors on nematode distribution and diversity for objective one

The results in this chapter reveal the effects of climatic and socioeconomic factors distribution, richness and diversity. The data on impacts of socioeconomic activities on the PPNs and FLN distribution richness and diversity has been based on face-to-face interviews with the 50 farmers growing potatoes in Nyandarua County.

There was no significant difference in how elevation affects the Plant Parasitic Nematodes (PPN) distribution in Nyandarua (P=0.25, R2=0.0065) (Figure 7) below. The abline or regression line shows that as you move to a higher elevation, the lower, the number of PPN. Elevation of Nyandarua county Longitude: 36.4895161 · Latitude: -0.3994104 · Elevation: 2420m / 7940 feet on a higher elevation in all sampled areas. The correlation value was negative 0.14, showing no relationship between the Elevation and PPN.

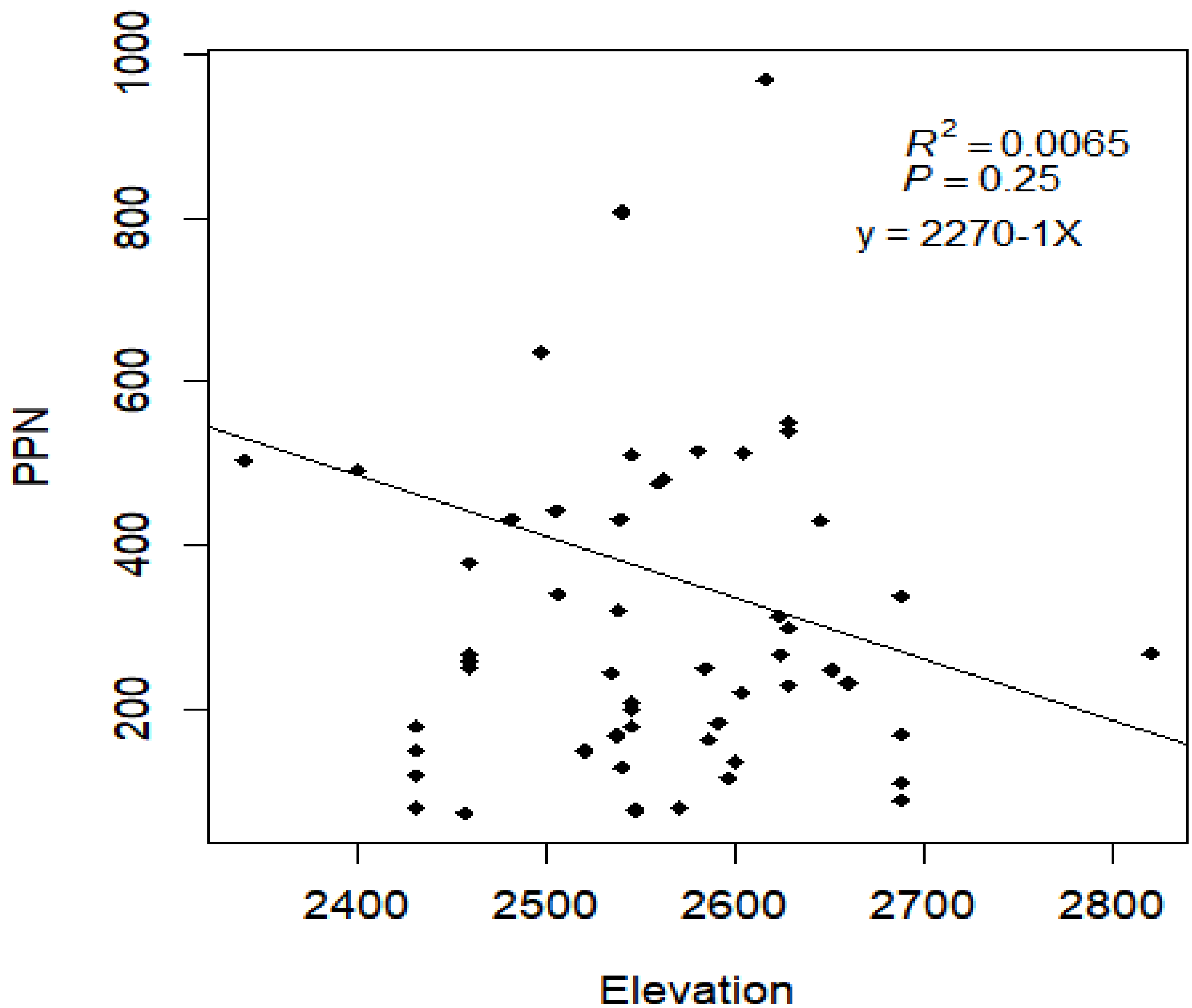

Figure 7. Effects of elevation in Meters above Sea Level (MSL) on Plant Parasitic Nematodes distribution richness/100g of soil in Nyandarua County.

There was a significant relationship between PPN distribution and rainfall amount (P=0.019, R2=0.086) (Figure 8 below). This was likely because the amount of precipitation varies from one sub-county to another, therefore, rainfall affects Plant Parasitic Nematodes (PPN) distribution across the five sub-counties. There was a negative correlation at 0.06 between the PPN and the rainfall, showing no relationship at all. Again, the nematodes are hydrophilic, so if the rainfall increases over time, there is likely hood to find more plant parasites that are well distributed across since they survive well in moist conditions than in dry areas.

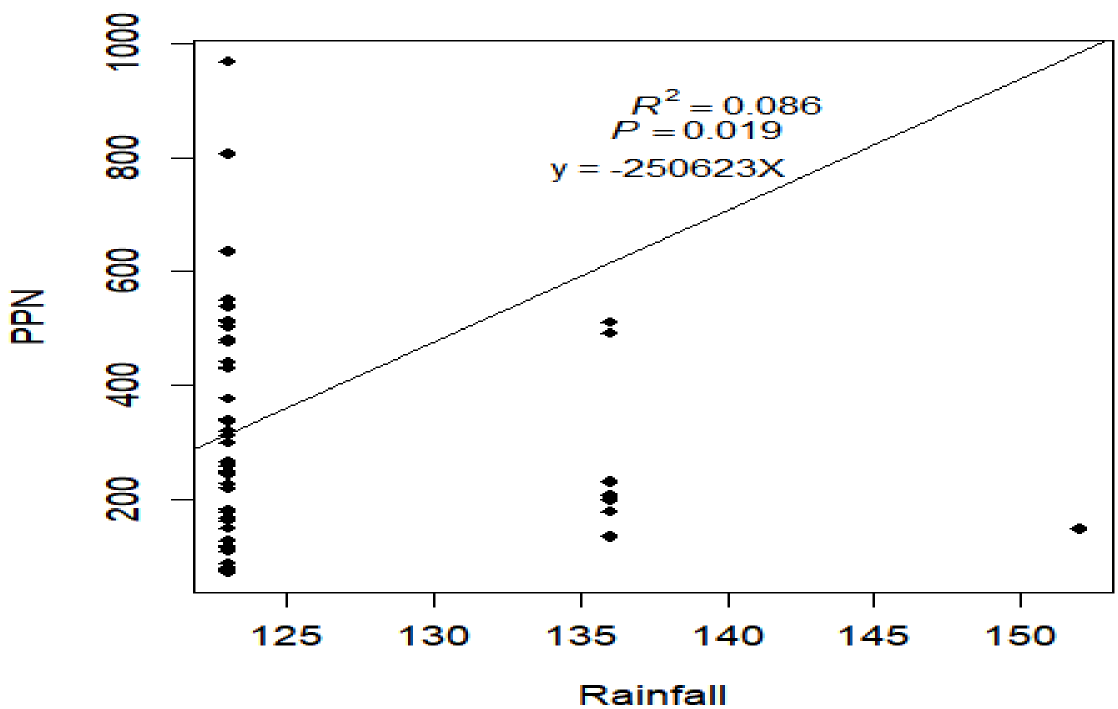

Figure 8. Effects of rainfall (mm) on Plant Parasitic Nematodes distribution richness/100g of soil in Nyandarua County.

The regression line graph in figure 9 below shows that the temperature significantly impacts nematode distribution (P=0.029, R2=0.072). As the temperature increases, the number of nematodes is hazardous to the farmers. There was a positive correlation at 0.3 between the temperature and the total number of nematodes per 10ml.

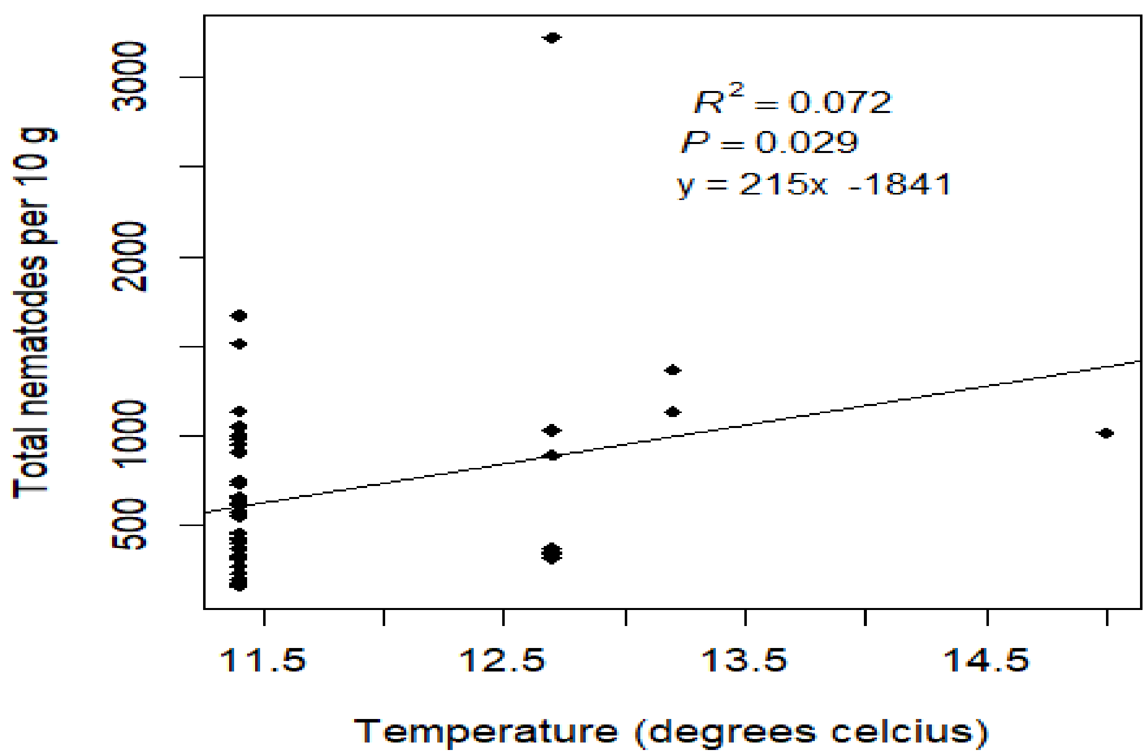

Figure 9. Effects of temperature on Free Living and Plant Parasitic Nematodes distribution richness in Nyandarua County.

There was no significant difference between the total number of nematodes, distribution, and the rainfall (P=0.12, R2=0.028) in figure10 below. There was a positive correlation at 0.22 between the total nematodes and the rain. This may be attributed to some of the Free-Living Nematodes (FLN) that can survive in all environments so long as good agronomic practices are wellmaintained and the rainfall is well distributed. Since Nyandarua is a highland, it really supports most nematodes' existence.

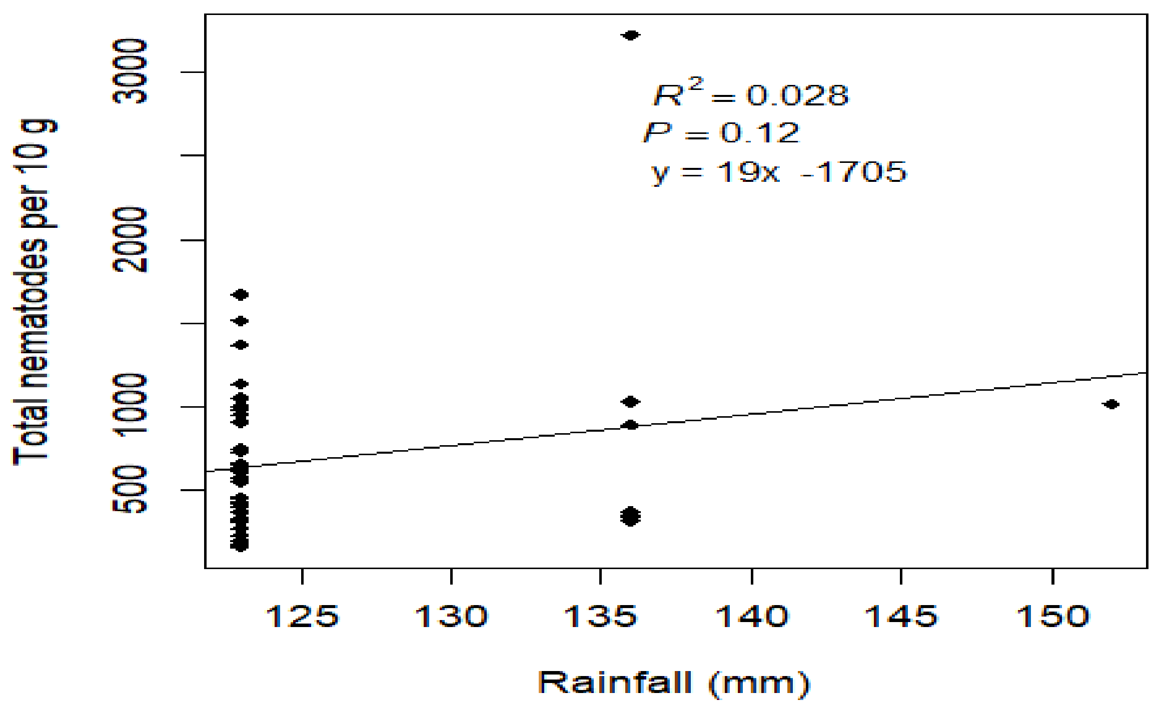

Figure 10. Effects of rainfall on total Free Living and Plant Parasitic Nematodes distribution richness per 100g of soil in Nyandarua County.

There was no significant difference between the temperature and the Plant Parasitic Nematodes (PPN) distribution (P=0.6, R2=-0.014) in figure 11 below, and this can be attributed to a close variation of temperature in July 2021 from 11-15°C in Nyandarua County. There was no relationship between the PPN and the temperature, as the correlation value was negative 0.03.

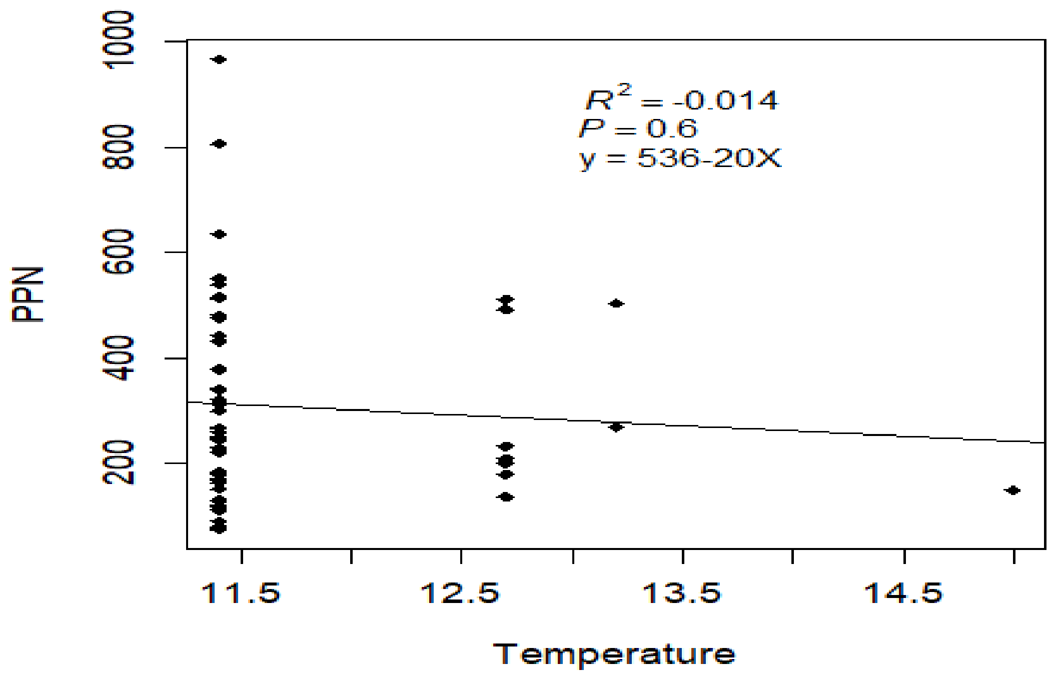

Figure 11. Effects of temperature in degrees Celsius on Plant Parasitic Nematodes distribution richness in Nyandarua County.

The most abundant genera us of nematodes at different temperatures, rainfall, and elevation

In table 3 below, Free-living nematodes were the most abundant in all sites at 20779 in number, followed by *Dorylaimus* at 3594, *Aphelenchus* at 2324, *Filenchus* at 2138, *Helicotylenchus* at 1870, *Tylenchus* at 1487, *Aphelenchoides* at 1366, *Pratylenchus* at 1355, *Globodera* at 975, *Hoplolaimus* at 881, *Meloidogyne* at 727, *Tichodorus* at 619, *Criconema* at 200, *Rotylenchulus* at 200, *Rotylenchus* and *Paratrichodorus* both at 163 and lastly *Xiphinema* at 64 in abundance.

Table 3: The most abundant genera of nematodes at different temperatures, rainfall, and elevation.

Nematode genus	Rank	Abundance
Free-living nematodes	1	**20779**
Dorylaimus	2	**3594**
Aphelenchus	3	**2324**
Filenchus	4	**2138**
Helicotylenchus	5	**1870**
Tylenchus	6	**1487**
Aphelenchoides	7	**1366**
Pratylenchus	8	**1355**
Globodera	9	**975**
Hoplolaimus	10	**881**
Meloidogyne	11	**727**
Tichodorus	12	**619**
Criconema	13	**200**
Rotylenchulus	14	**200**
Rotylenchus	15	**163**
Paratrichodorus	16	**163**
Xiphinema	**17**	**64**

Helicotylenchus was the highest in abundance, followed by the lesion nematode and the key pest *Globodera rostochiensis* became the third, *Homploaimus, Meloidogyne,Trichodora,Criconema,Paratrichodora,Tylenchus, andXiphinema* (the dagger) which is the viral vector was the least in abundance (Figure 12).

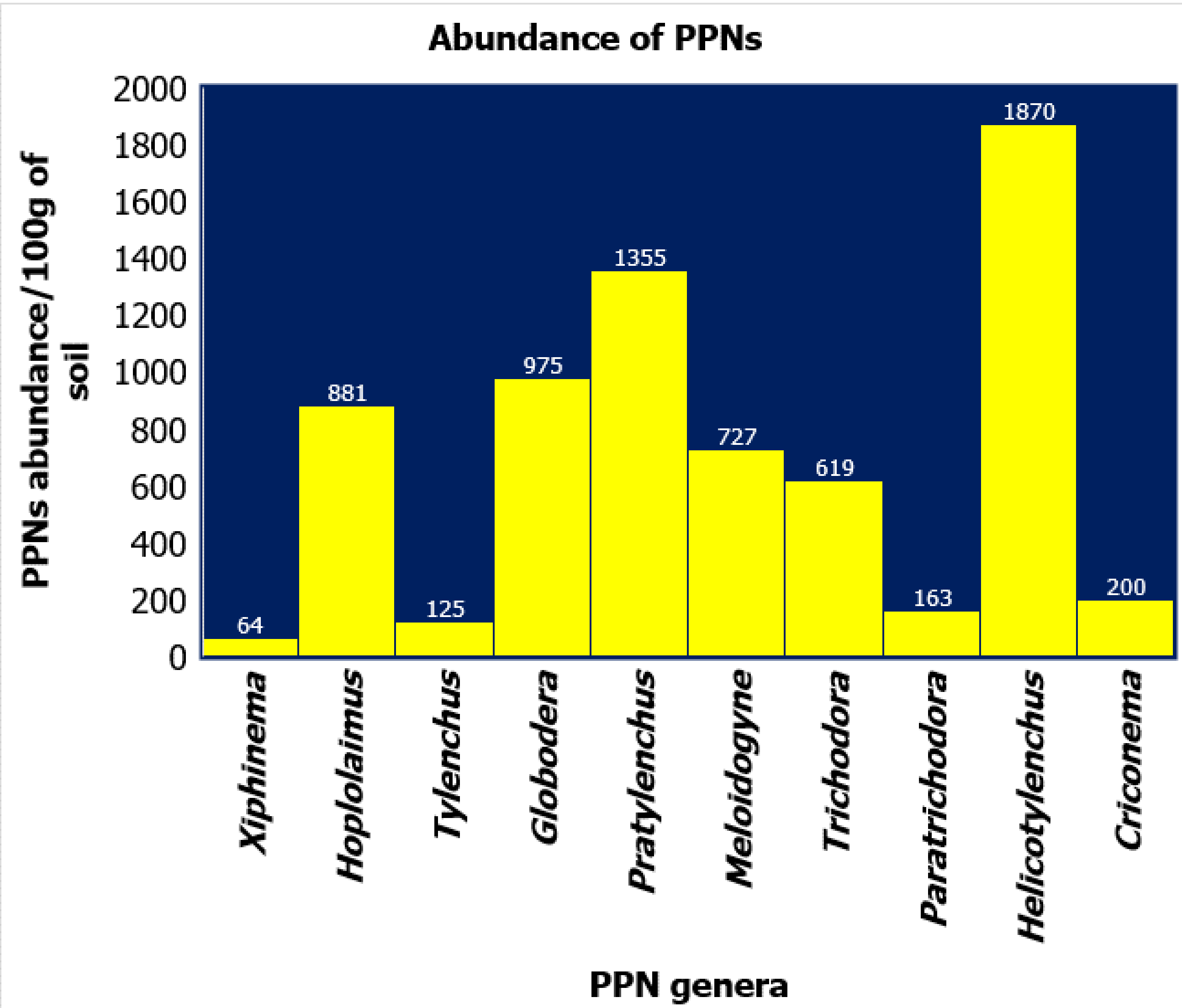

Figure 12. Effects of different temperatures, and rainfall on PPN abundance.

In the figure 13, Kianguyo had the highest nematode diversity and richness followed by Line Moja, then Brother -M and Gathara had the same richness, the fourth site was Munyaka, and lastly Kijiko all in Kinangop Sub County.

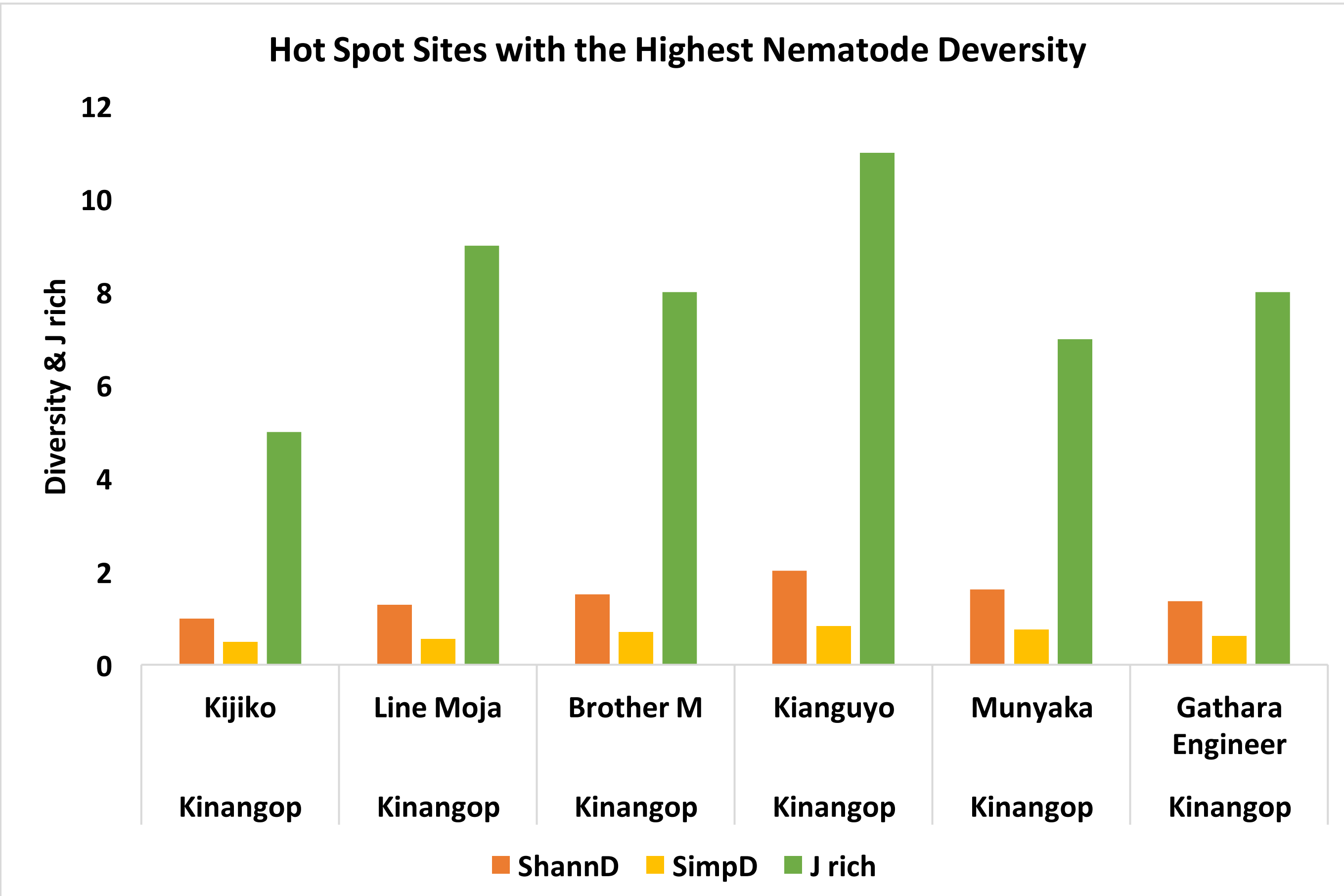

Figure 13. Hot spot area with the highest nematode diversity and richness.

2.19 SOCIO-ECONOMIC DATA FOR SURVEY

Agronomic practices such as use of organic manure, crop rotation, type of crop grown, fungicide and fertilizer application, have shown to have impact on PPNs density in the soil. The chats below show the results on the socio-economic activities on nematodes density and richness.

2.19.1 The effect of agronomic activities affects the nematode population.

In figure 14, 64% of farmers were using Mancozeb, Tata Master 16%, Ridomil 9%, Unizeb, Agrozeb and Dithane at 2% and 5% did not give any information on which type of fungicide they use to control blight.

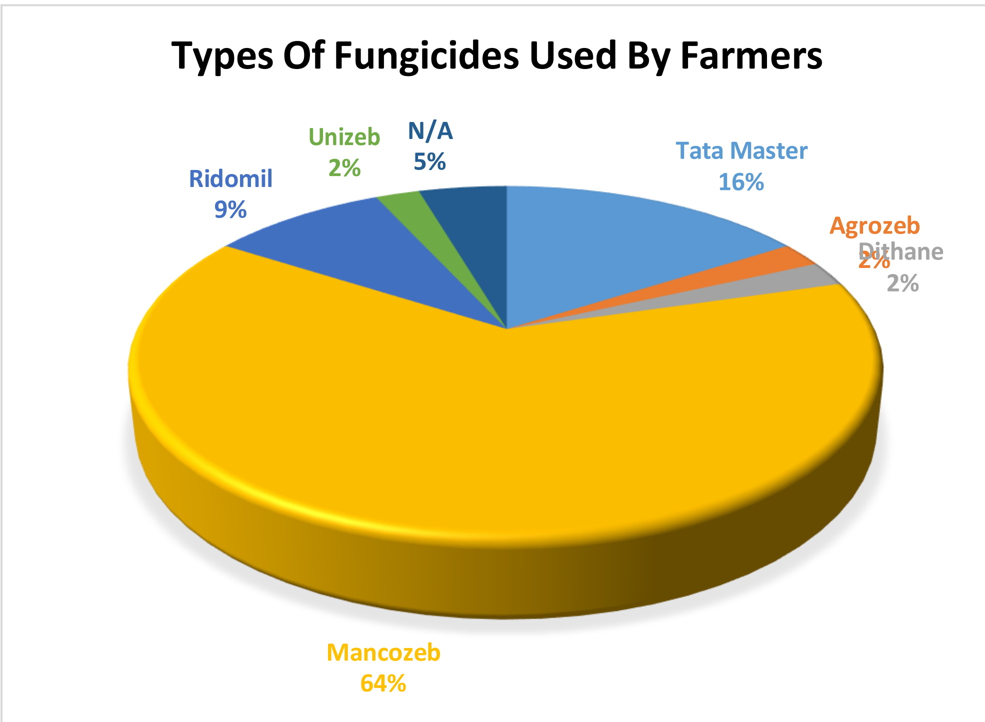

Figure 14. The percentage of farmers applying different fungicides on their potato farms to manage both early and late blight.

In figure 15, 18% of farmers applied compost manure while 82% did not.

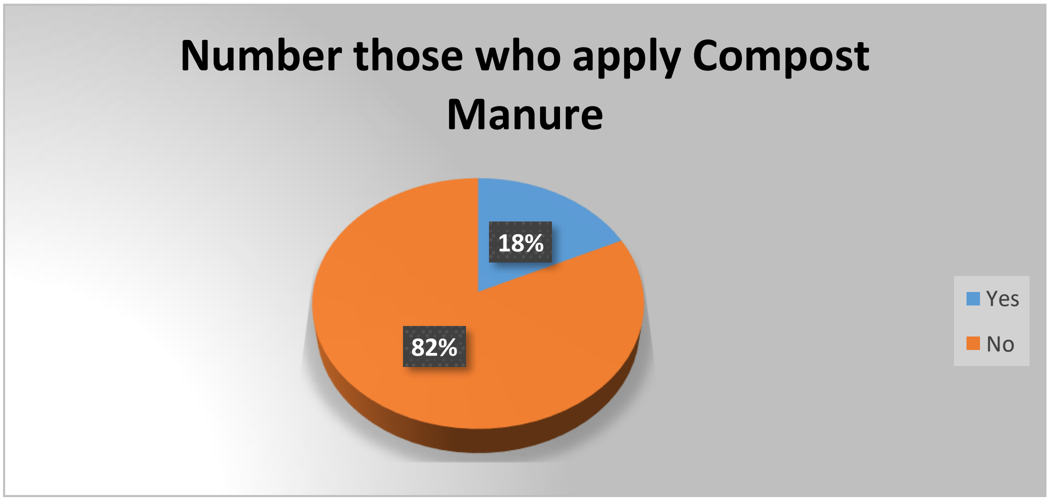

Figure 15. Percentage of farmers using non-applicant compost manure on their farms.

In the figure 16, 92% of the farmers applied fungicide and 8% did not apply.

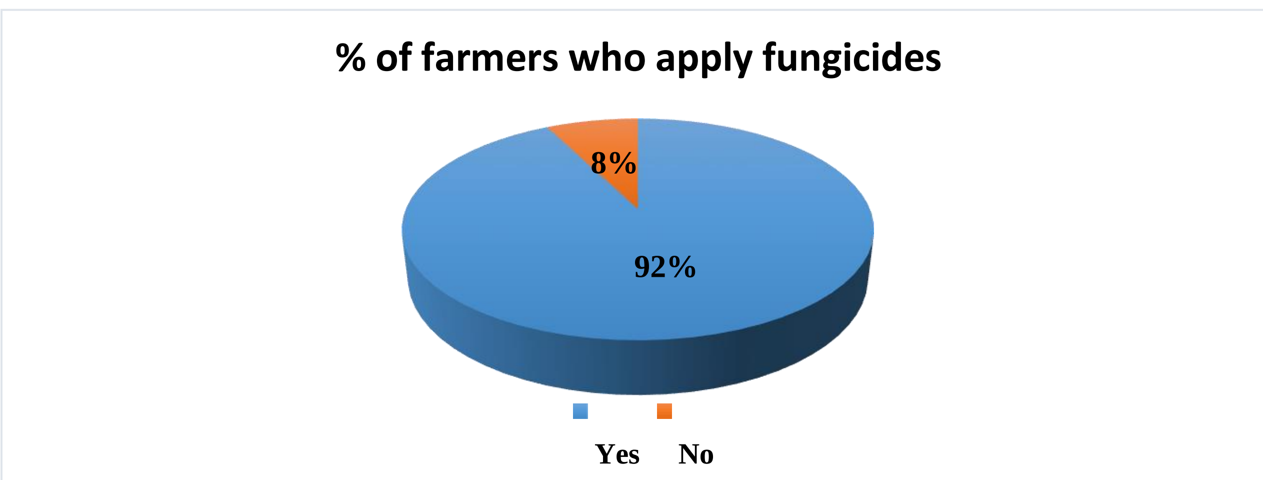

Figure 16. The percentage use of applicant vs. non-applicants' fungicides in their potato farms in managing both early blight and late blight.

In the figure 17, 87% of the farmers applied DAP, 6% did not provide any information, 5% NPK, and CAN at 2%, was the least used by farmers during their farm activities.

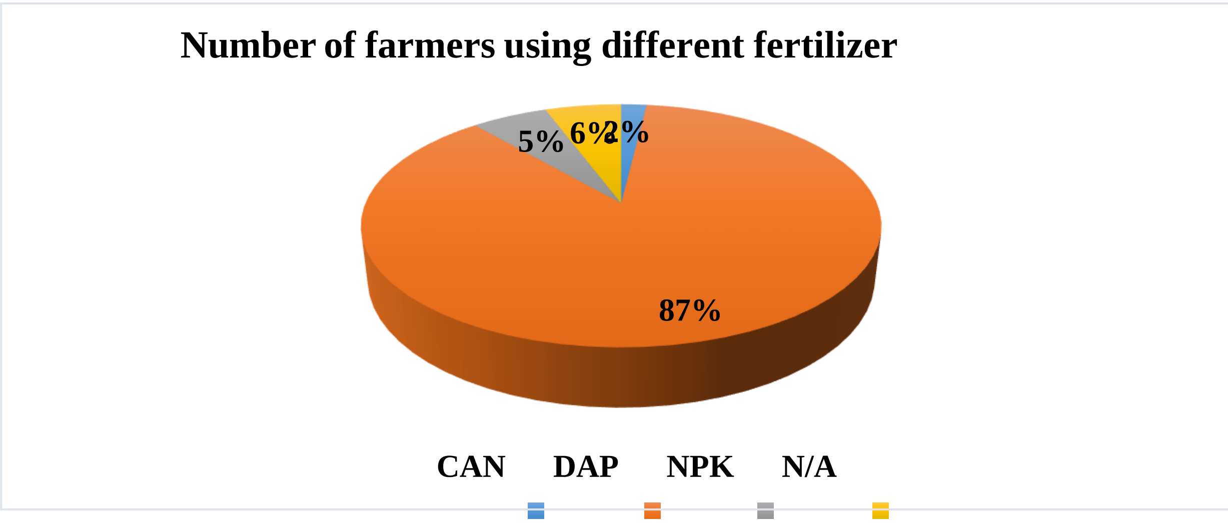

Figure 17. Percentage of farmers using distinct types of fertilizer to improve soil fertility.

In figure 18, only 18% of farmers applied cow manure during the planting while the rest did not.

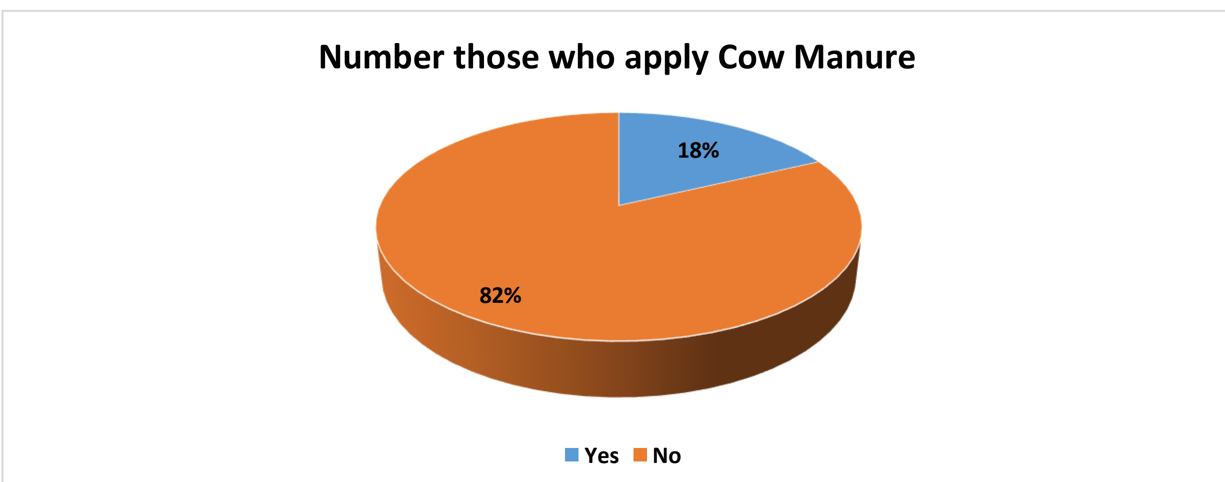

Figure 18. Percentage farmers who apply cow manure in their farms.

In the figure 19, Shangi variety was the most preferred by 66% of farmer, Sherekea at 25% and 9% used Unica for planting.

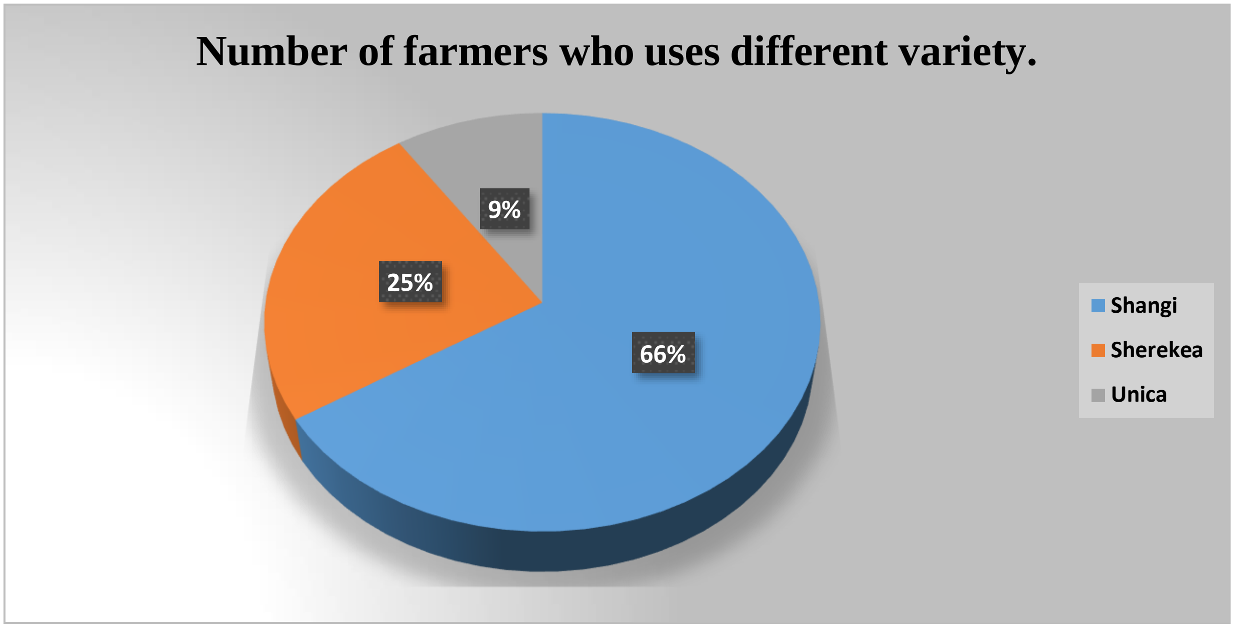

Figure 19. The percentage of farmers who use different potato varieties in production.

In figure 20, 51% of the farms were owned by men,6% by female,39% were owned by all and the 4% did not give any information.

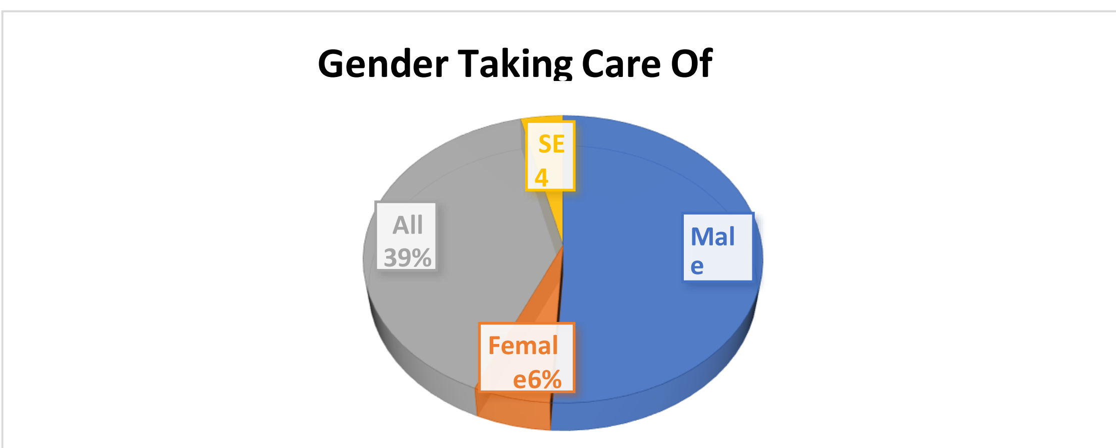

Figure 20. Percentage of different gender and categories of people taking care of farms.

The highest number interviewed was male at 68% and the rest were female (Figure 21).

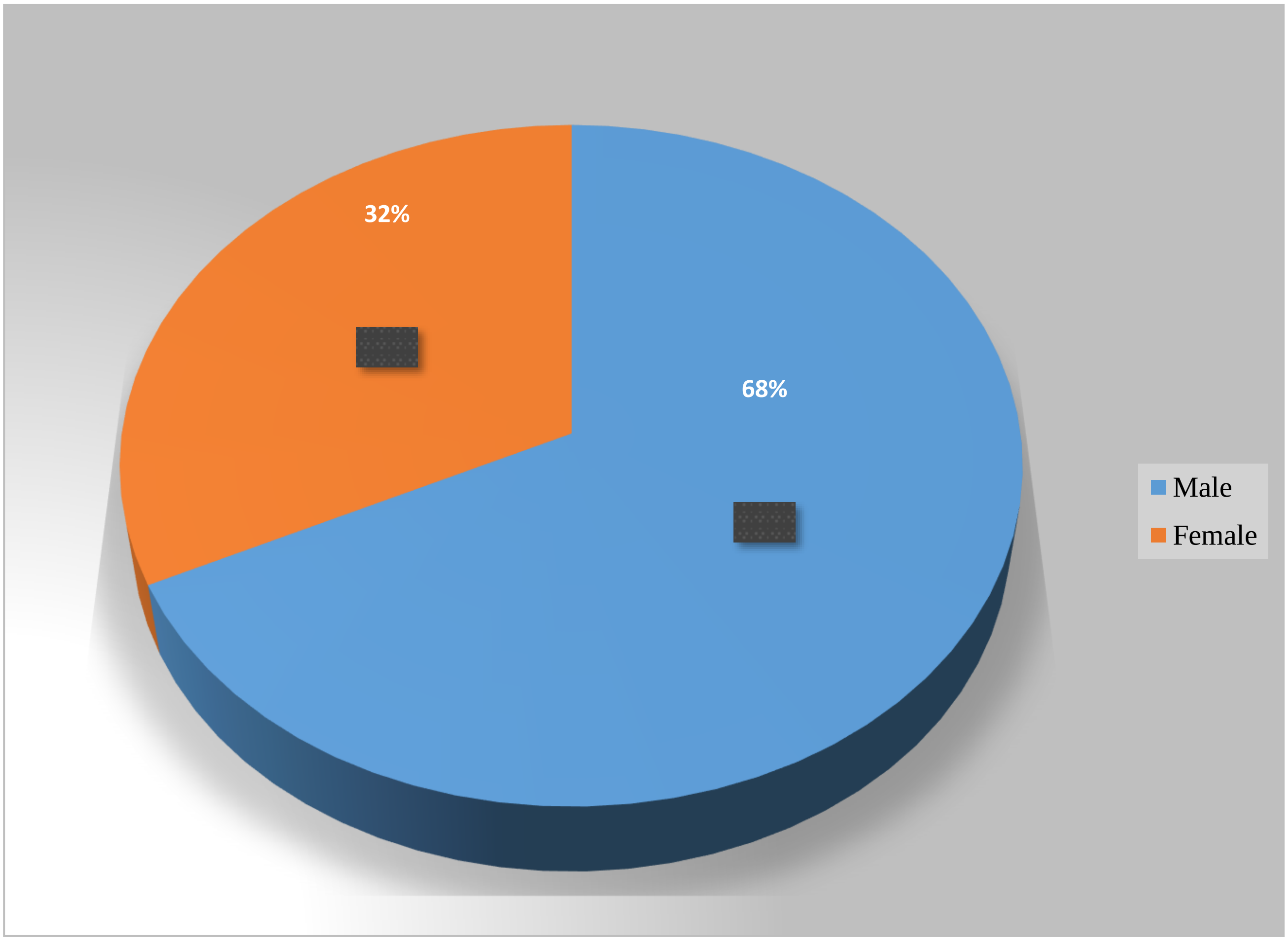

Figure 21. Percentage of the gender interviewed during the survey.

In the study area, it was observed that crop rotation was a common practice with 66% of male and 30% of females involved over the seasons. Only a small proportion did not participate in this activity (Figure 22).

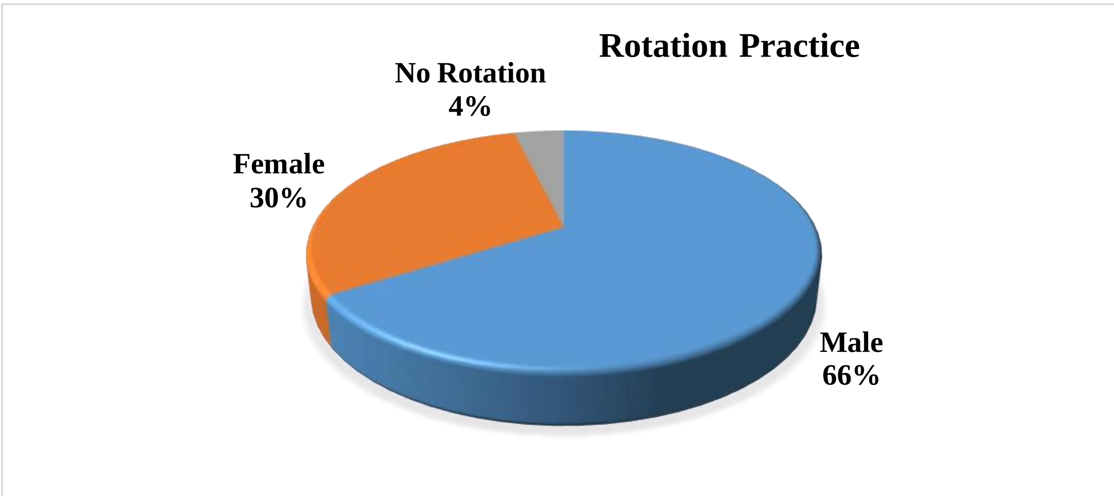

Figure 22. Percentage of farmers practicing crop rotation.

Only a paltry12% of the farmers were aware about the PCN infection with the majority 88% not knowing about this hidden pest (Figure 23).

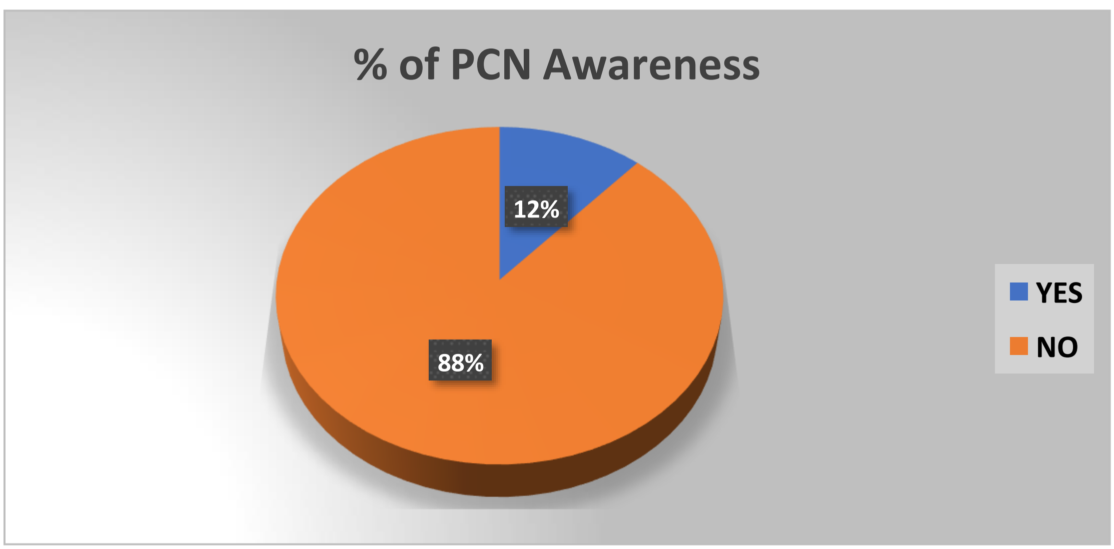

Figure 23. PCN awareness among the farmers interviewed.

2.20 Impact of Socio-Economic on PCN & PPP Levels

In the figure 24, Yes represent farmers who applied crop rotation, cow dung and compost manure in their farms, when the PPNs from Modified Baermann were analysed and PCN extracted from the Fenwick can, their farms recorded the lowest number compared to those who were not applying the same. This could be due to their nematicidal effects.

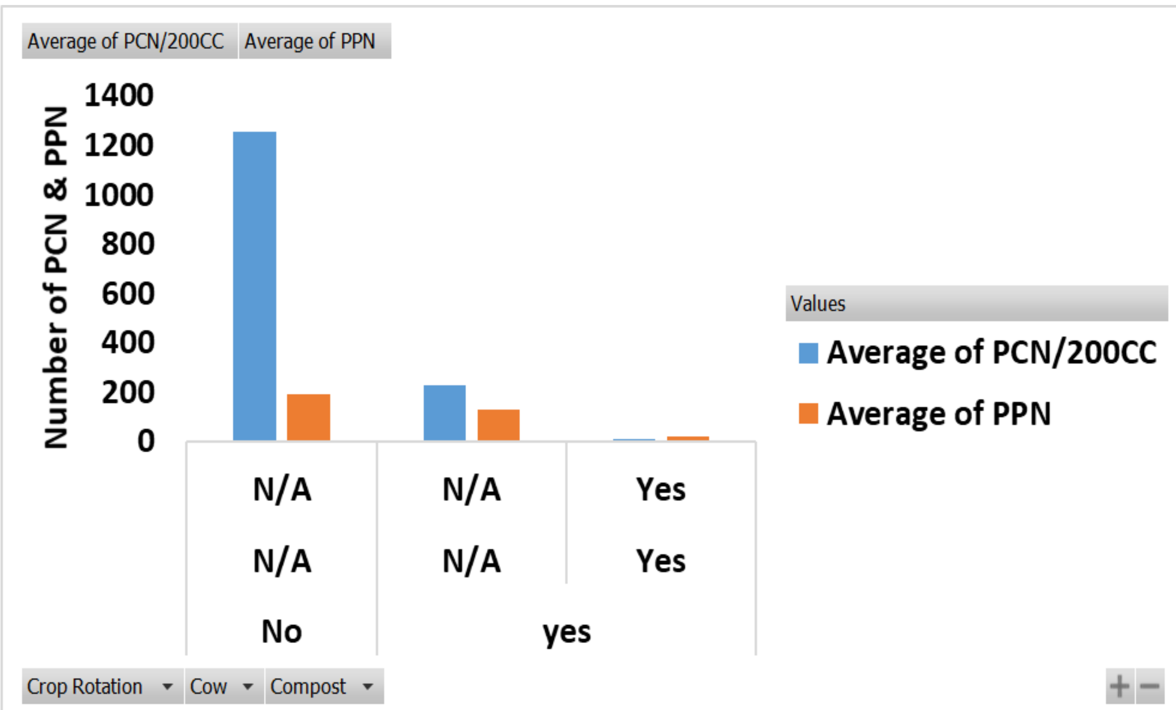

Figure 24. Effects of socioeconomic activities on PCN and other PPNs.

The P-values generated from R-software indicates that indeed crop rotation (P=**4.39e-07 *****), cow dung manure (P=**0.0264 *)** and use of compost manure (P=**0.034)** significantly affected thePPNS. In the questionnaire, YES stands for those who used the amendments while NO is for the non-applicants and N/A are farmers who did not respond. The 200cc is the quantity of the soil extracted for the nematodes.

2.21 Socioeconomic impacts on nematode levels and yield production

The socio-economic practices positively impacted potato production from data showing 82 % of the farmers who applied cow manure in (figure 18) had higher yields. The PPNs levels were incredibly low compared to 18% of farmers who did not use it. There were also low PPN levels in sites where 66 % of men and 30 % of women practiced crop rotation compared to the 4% who did not practice any rotation (figure 24). The 66% of farmers using cv. Shangi variety had PCN levels compared to Sherekea and unica since cv. Shangi variety is very susceptible to PCN in (figure 19). Only 12% of the farmers were aware of the PCN in (figure 23), proving the PCN was a hidden enemy to the farmers.

CHAPTER FIVE-EFFECTS OF CULTIVARS ON YIELD

2.22 Yield Data On Pot Experiment Seasons One-Three

In table 4, weights were different across all 3 seasons, thus split and analyze per season.

Table 4. Yield weight of tubers in different seasons

Season	emmean	SE	DF	lower.CL	upper.CL	.group
S3	103	7.07	180	99.7	107	a
S1	237	7.07	180	233.7	240	b
S2	241	7.07	180	237.4	244	b

Seasons 1 and 2 had a significantly higher yield than season three, which means that seasons one and two had no significant differences in the yield output. (b-not significantly different and a-significantly different)

There was a significant difference on how potato cultivars performed in the presence of PCN levels infestations. The letters Aab, Ab, Aa, Bb , Ba, dA, cA, bA, Da,and bB show how different the PCN levels were suppressed (Table 5).

Table 5. Yield performance in both resistant and susceptible potato varieties in different PCN levels.

Season	PCN level	Potato lines			
		Line 7	**Line 6**	**Markies**	**Shangi**
1	Pallida	434.5 ± 17.3 aAB	246.6 ± 10.9 bB	196.2 ± 15.2 bA	46.2 ± 5.5 cA
	RostoLow	387.5 ± 6 aB	312.7 ± 25.6 bA	179 ± 18.3 cA	46.5 ± 15.4 dA
	RostoHigh	449.8 ± 13.5 aA	328.3 ± 16.5 bA	168.2 ± 33.2 cA	49.3 ± 4.8 dA
2	Pallida	455.2 ± 22.9 aA	256.1 ± 9.4 bB	193.2 ± 19.5 Bc	7.5 ± 4.3 dA
	RostoLow	434.2 ± 21.2 aA	346.7 ± 20.4 bA	178.5 ± 18.4 cA	26 ± 3.6 dA
	RostoHigh	485.8 ± 15.5 aA	360.3 ± 26.4 bA	134.8 ± 38.4 cA	11.2 ± 3.2 dA
3	Pallida	7.1 ± 7.1 bB	162.4 ± 32.6 aA	55.9 ± 27.6 abA	*
	RostoLow	144.6 ± 41.6 aA	235.9 ± 13.8 aA	141.5 ± 46.2 aA	3.4 ± 3.4 b
	RostoHigh	160.3 ± 37.3 aA	210.5 ± 60.1 aA	112.1 ± 49.4 abA	3.9 ± 3.9 b

In season one, Line 7 with H1 gene had a significantly higher yield than the rest while Line 6 and Markies performed significantly differently to cv. shangi in the pots with *Globodera pallida*. In the pots with Low *Globodera rostochiensis*, Line 7 still had a significantly high yield than the rest of all varieties, followed by Line 6, Markies, and finally Shangi with the lowest yield. In the pots with high *Globodera rostochiensis*, Line 7 had significantly higher yield than the rest, while Line 6 was the second, followed by Markies and lastly Shangi. They all performed differently (figure 25).

In season two, Line 7 significantly yielded higher than the rest of the potato varieties, this was followed by Line 6, Markies and lastly Shangi in the pots with *Globodera pallida*, In the pots with Low *Globodera rostochiensis*, Line 7 still had significant high yield than the rest of all varieties followed by Line 6, Markies and finally Shangi with the lowest yield. They all performed differently. In the pots with high *Globodera rostochiensis*, Line 7 had higher significant yield than the rest while Line 6 was the second followed by Markies and lastly, cv.Shangi (figure 26).

In season three, Line 6 had a higher significant yield than Line 7, but Line 6 and Markies were not different in terms of yield performance, cv. Shangi did not reach the flowering stage; hence no yield in the pots with *Globodera pallida.* The pots with low *Globodera rostochiensis* Line 7, 6, and Markies had no significant differences but were significantly different from Shangi. In the pots with high *Globodera rostochiensis,* Line 7, 6, and Markies had no significant differences but were significantly different from cv. Shangi (figure 27).

In summary, in seasons one and two, the trend on how the lines have performed is similar, but this is not maintained in season three. These significant differences in yield in the three seasons may be due to continuous reduction of soil nutrients and increment in the PCN population across the seasons.

2.23 Performance in Season One

Lines 6, and 7, Shangi (susceptible to PCN) and Markies (Resistant to PCN). The soil with low & high *Globodera rostochiensis* and *Globodera pallida* were used in 7-liter pots.

In season one for the yield experiment, Line 7 and 6 had a significant difference compared to Shangi in both low and high PCN levels. Markies also had a significant difference compared to shangi but the two Lines 7 & 6 had a significantly higher yield than the rest.

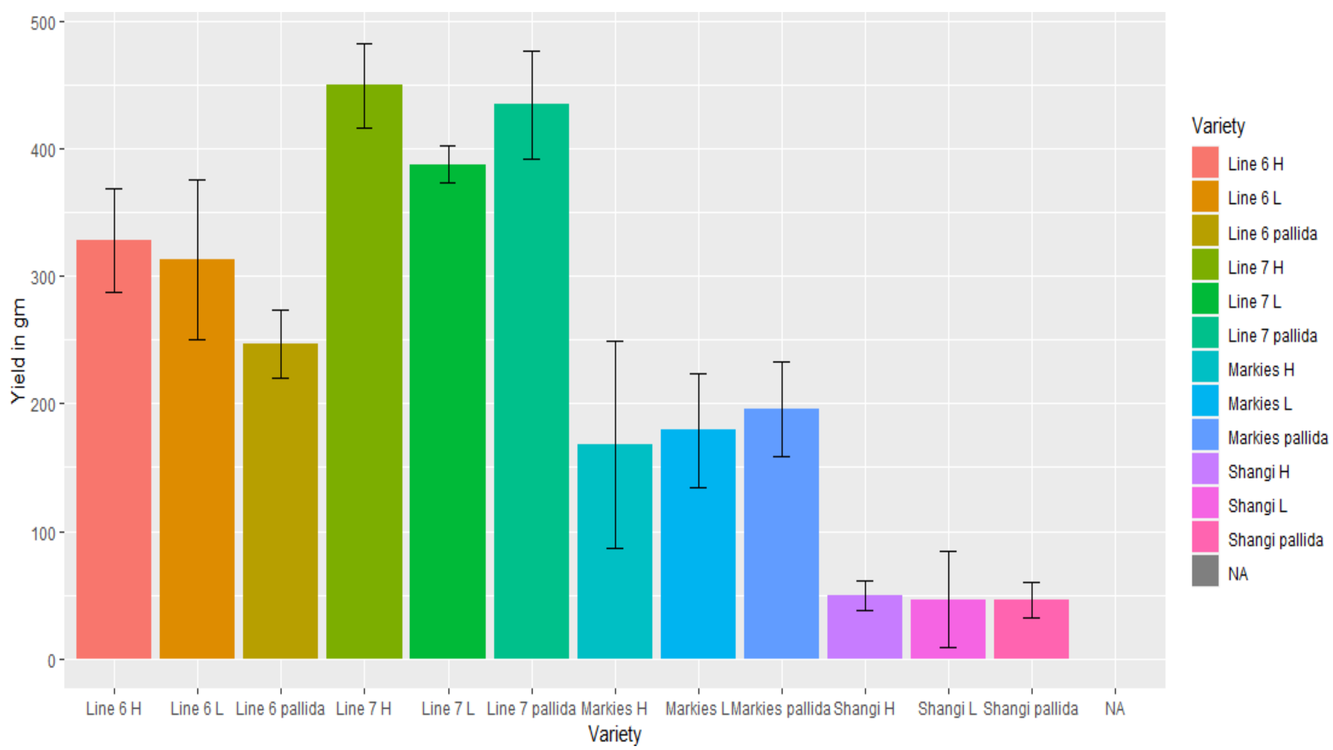

Figure25: Yield performance of both resistant and susceptible potato cultivars exposed to different levels of PCN in season one.

The first and the second seasons' yield performance was significantly consistent, which was evident that the UK cultivars are tripling the yield over seasons. In season two for the yield experiment, Line 7 and 6 had a significant difference compared to Shangi in both low and high PCN levels. Markies also had a significant difference compared to Shangi, but the two Lines 7 & 6 had a significantly higher yield than the rest (figure 25 & 26).

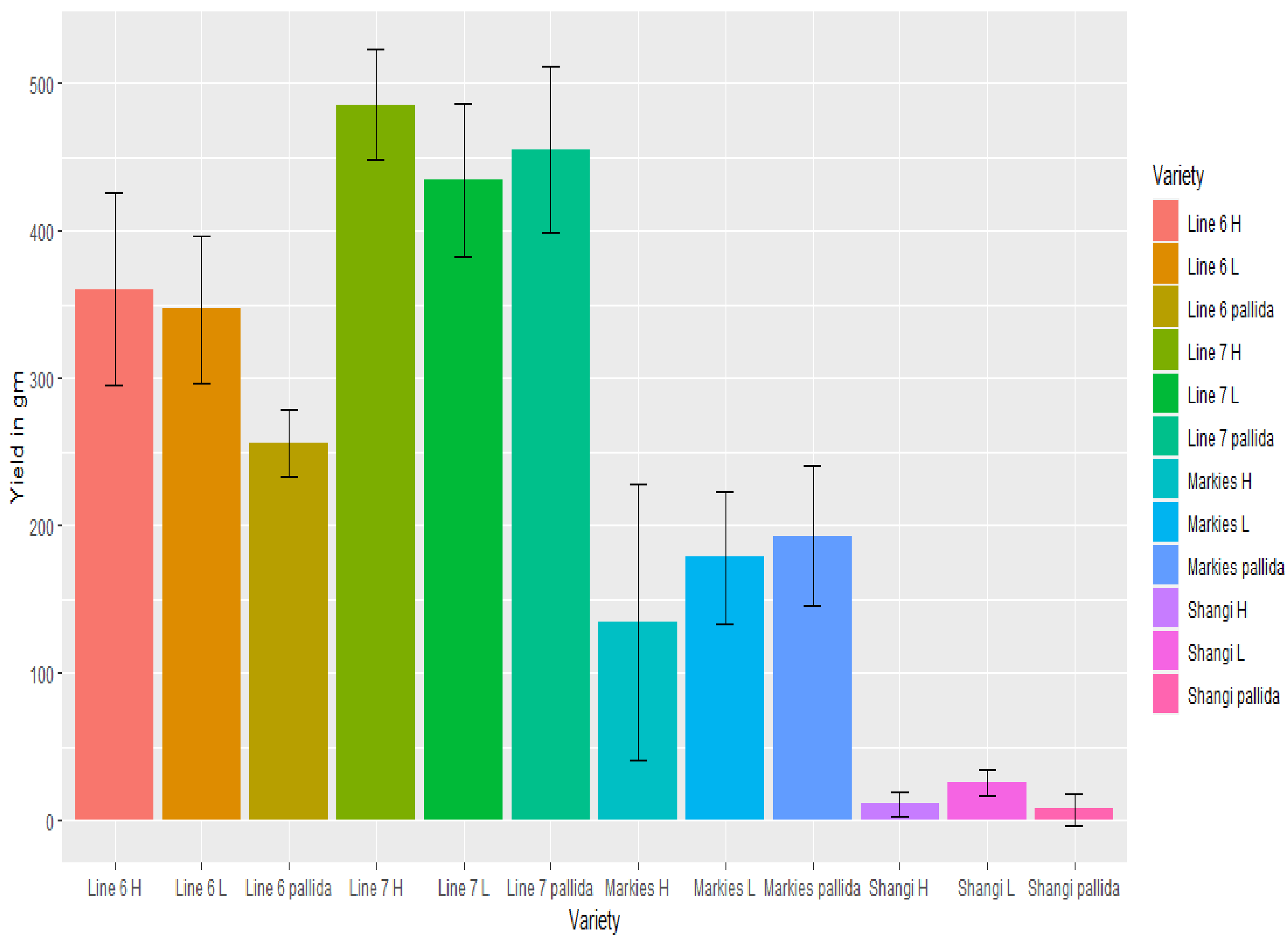

Figure 26: Yield performance of both resistant and susceptible potato cultivars exposed to different levels of PCN in season two.

In season three for the yield experiment, Line 7 and 6 had a significant difference compared to Shangi in both low and high PCN levels. Markies, too, had a significant difference compared to Shangi; however, this season, there were no significant differences among the resistant varieties to the PCN.

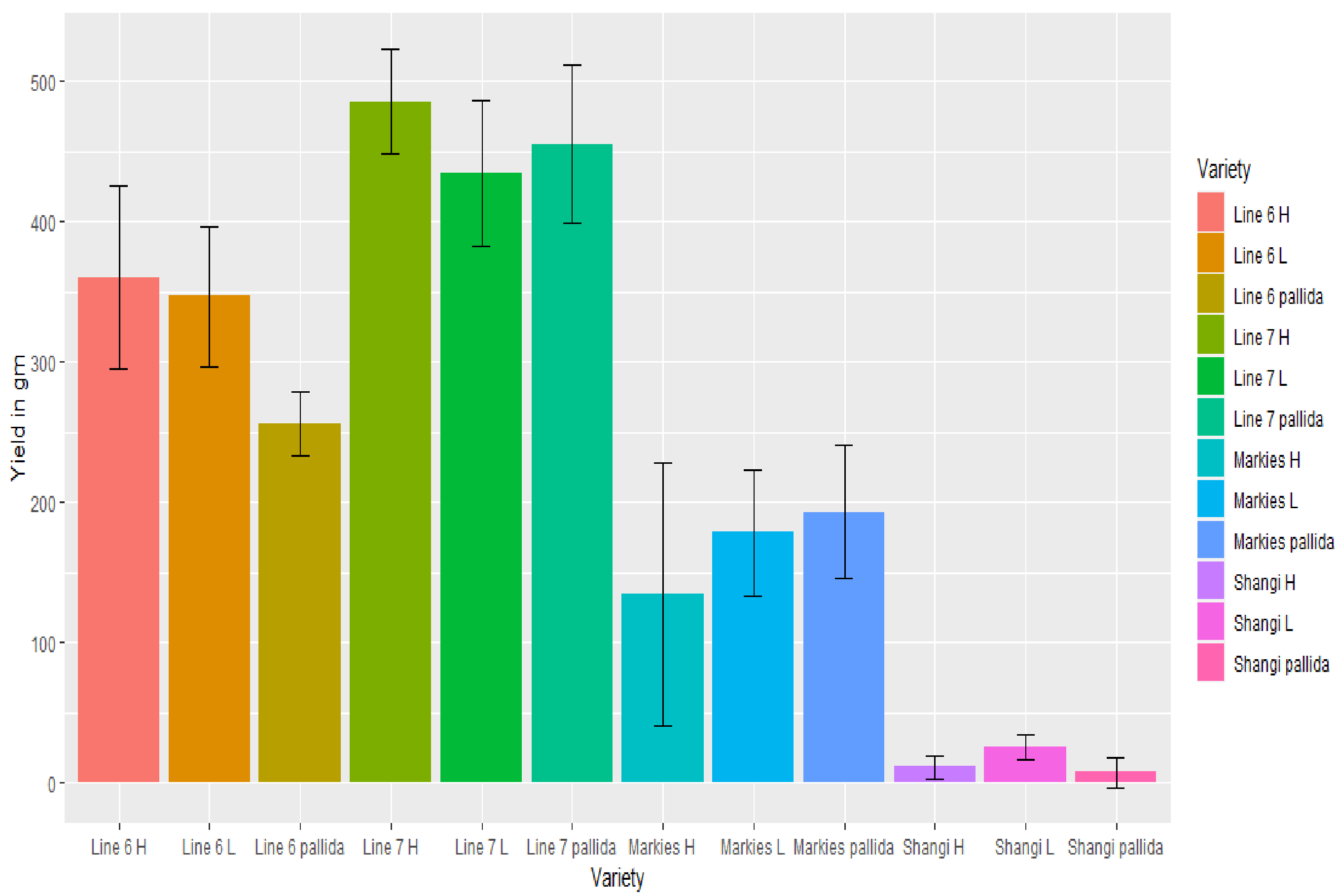

Figure 27: Yield performance of both resistant and susceptible potato cultivars exposed to different levels of PCN in season three.

CHAPTER 6: EFFECTS OF RESISTANT POTATO CULTIVARS ON POTATOES CYSTS NEMATODES LEVELS

In Kenya, resistant varieties such as Markies, Manitou, and Rudolph exist, but they are still faced with lots of challenges hence not easily adopted. However, Lines 6 and 7 from the UK have the same characteristics as Shangi, the dominant variety in Kenya except for the presence of the H1-gene. In figure 28, across the three seasons in of the combined seasons, the yield increased in season two while in season three there was a decline. Line 7 yield the highest above 450g per pot followed by line 6 averagely above 350g per pot, Markies was the third and Shangi was significantly very low compared to the rest in all seasons.

Figure 28. Yield data for different PCN levels with other varieties.

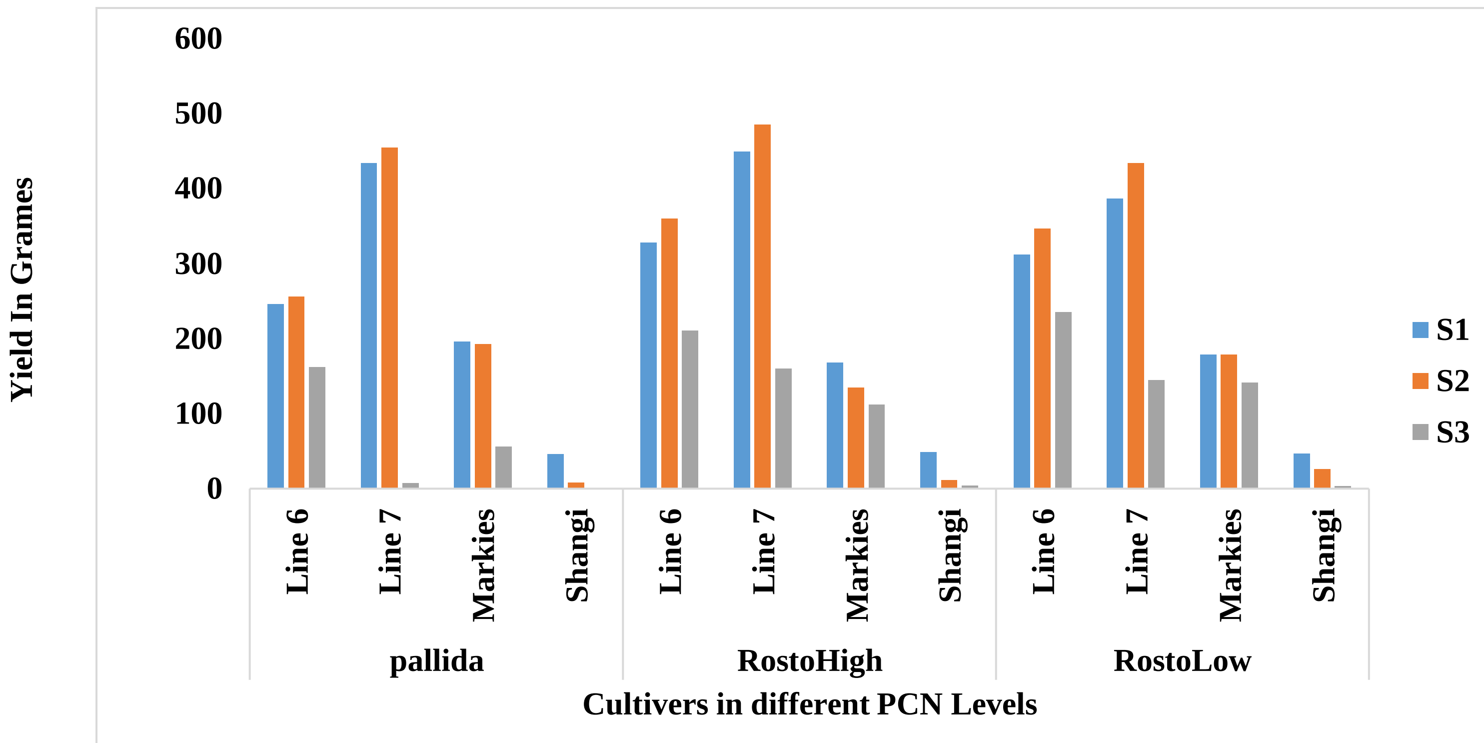

Figure 28. Trend in yield production of potato cultivars from season one to three

The PCN levels in the different cultivars varied according to the season (figure 29). The series 1 and 2 represented the initial and final populations (figure 30).

2.24 PCN Level Trend line for season one to four.

In figure 29, there was a decline in PCN levels in line 7,6 and Markies in pots with low levels of PCN while in pot with high PCN, the decline was only significant on line line 7. Shangi as susceptible variety had a significant increase across all levels of PCN in the pots.

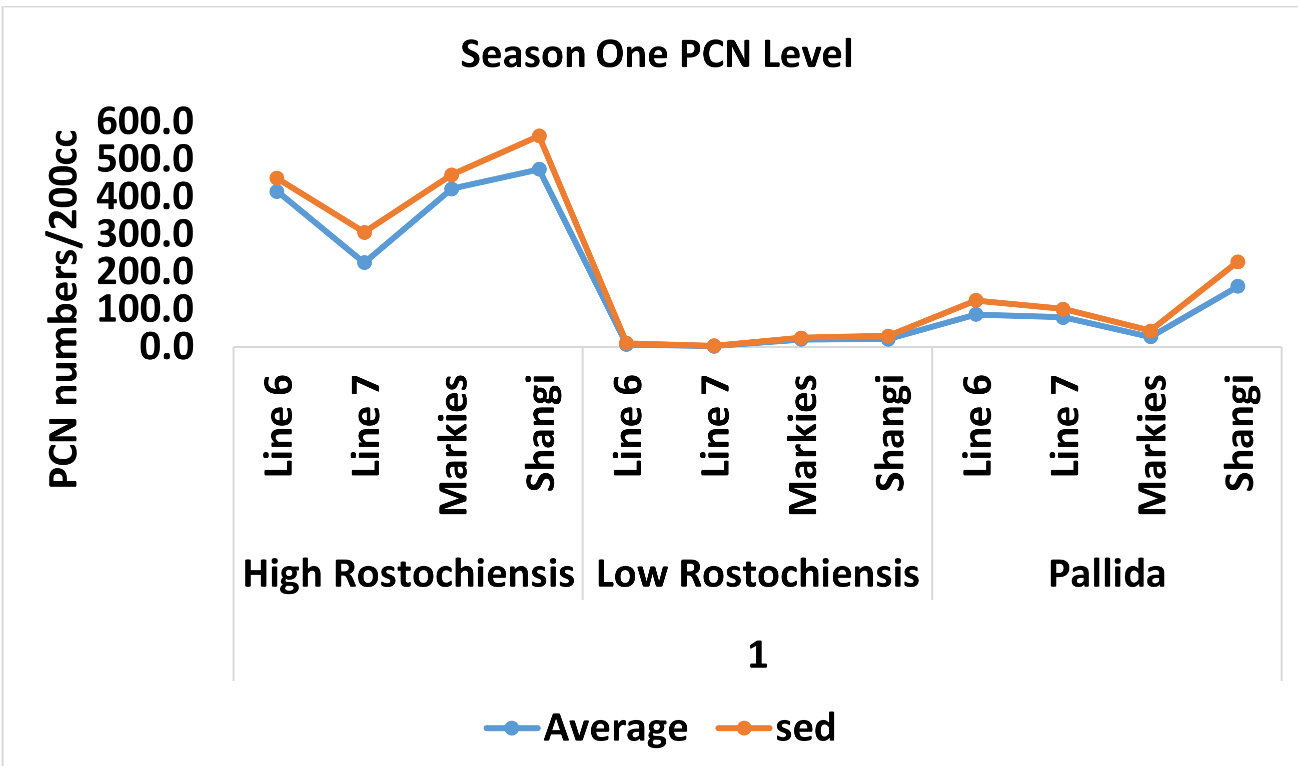

Figure 29. Trends of yield in both resistant lines and susceptible potato variety behavior whenexposed to different levels of PCN.

There was a significant difference between the resistant cultivars (Line 7& 6 and Markie's) and the susceptible Shangi variety to the PCN levels in figure 30.

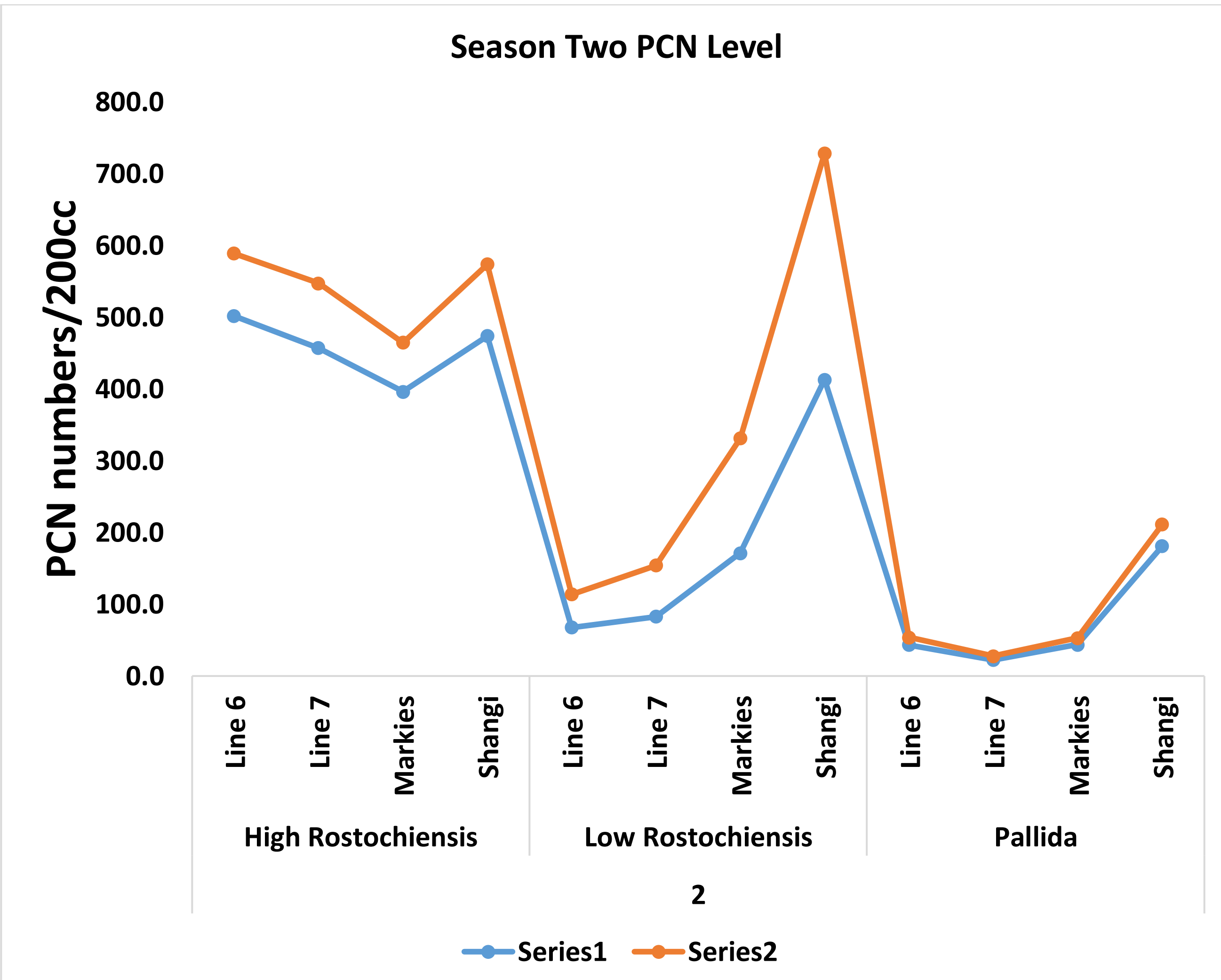

Figure 30. Trends in both resistant lines and susceptible potato variety behavior when exposed todifferent levels of PCN.

In table 6, there was a significant difference between the resistant lines to the PCN levels (P value =0.00099). The significance between pots with high *Globodera rostochiensis* and *G.pallida* did not differ, but pots with low *Globodera rostochiensis* were significantly different from the two in table 6. The pot with low *Globodera rostochiensis* were significantly reduced by the resistant cultivars compared to the pot with High *Globodera rostochiensis* and *G. pallida.*

Table 6. The effects of potato varieties on the PCN infection levels.

Response: Rf		
LR Chisq Df Pr(>Chisq)		
Trt 13.829 2 0.0009935 ***		
Trt emmean SE df asymp.LCL asymp.UCL .group		
High Rosto 2.06 3.84 Inf 0.221 3.91 a		
Pallida 3.59 3.84 Inf 1.746 5.43 a		
Low Rosto 20.29 3.84 Inf 18.445 22.13 b		

In the figure 31, there was a decline in PCN levels in line 7,6 and Markies in pots with low levels of PCN while in pot with high PCN, the decline was only significant on line line 7. Shangi as susceptible variety had a significant increase across all levels of PCN in the pots.

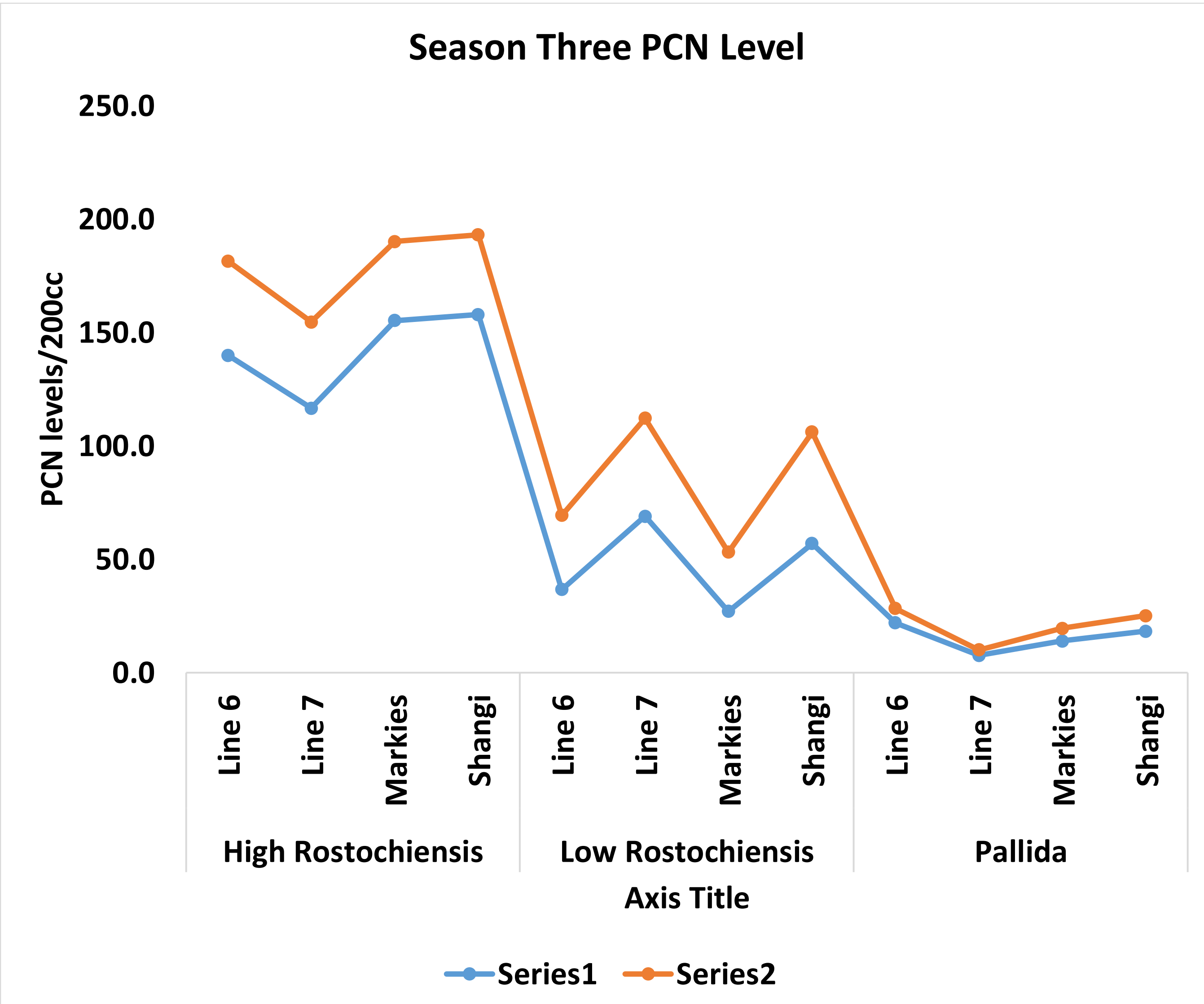

Figure 31. Trends on both resistant lines and susceptible potato variety behavior when exposed to different levels of PCN.

In the table 7, there was a significant difference between the resistant lines to the PCN levels. The P value was =0.0087, pots with high *Globodera rostochiensis* and *G. pallida* did not differ, but pots with low *Globodera rostochiensis* were vastly different from the two.

Table 7: Showing the significant differences among the potato varieties and the PCN levels.

Response: Rf LR Chisq Df Pr(>Chisq)	
Trt 9.4837 2 0.008722 **	
Trt emmean SE df asymp.LCL asymp.UCL .group	
Low Rosto 0.145 0.0564 Inf 0.118 0.172 a	
Pallida 0.319 0.0564 Inf 0.292 0.346 ab	
High Rosto 0.382 0.0564 Inf 0.355 0.410 b	

2.25 Effects of resistant cultivars and susceptible variety on PCN Levels from SeasonOne to Three

The UK-Lines of Irish Potato had a significant PCN reduction compared to Shangi variety. Line 7 and 6 have shown a significant difference in Low PCN soil at 100% suppression levels compared to Shangi and Markies throughout the seasons. Line 7 has significantly reduced the PCN level in the pots with high PCN levels compared to the rest of Line 6, cv. Shangi and Markies. In the pots assumed to have Globodera pallida, Line 7 also showed significant differences by 100% PCN suppression compared to the rest, followed by Line 6, which showed a significant difference in PCN reduction compared to Markies and Shangi.

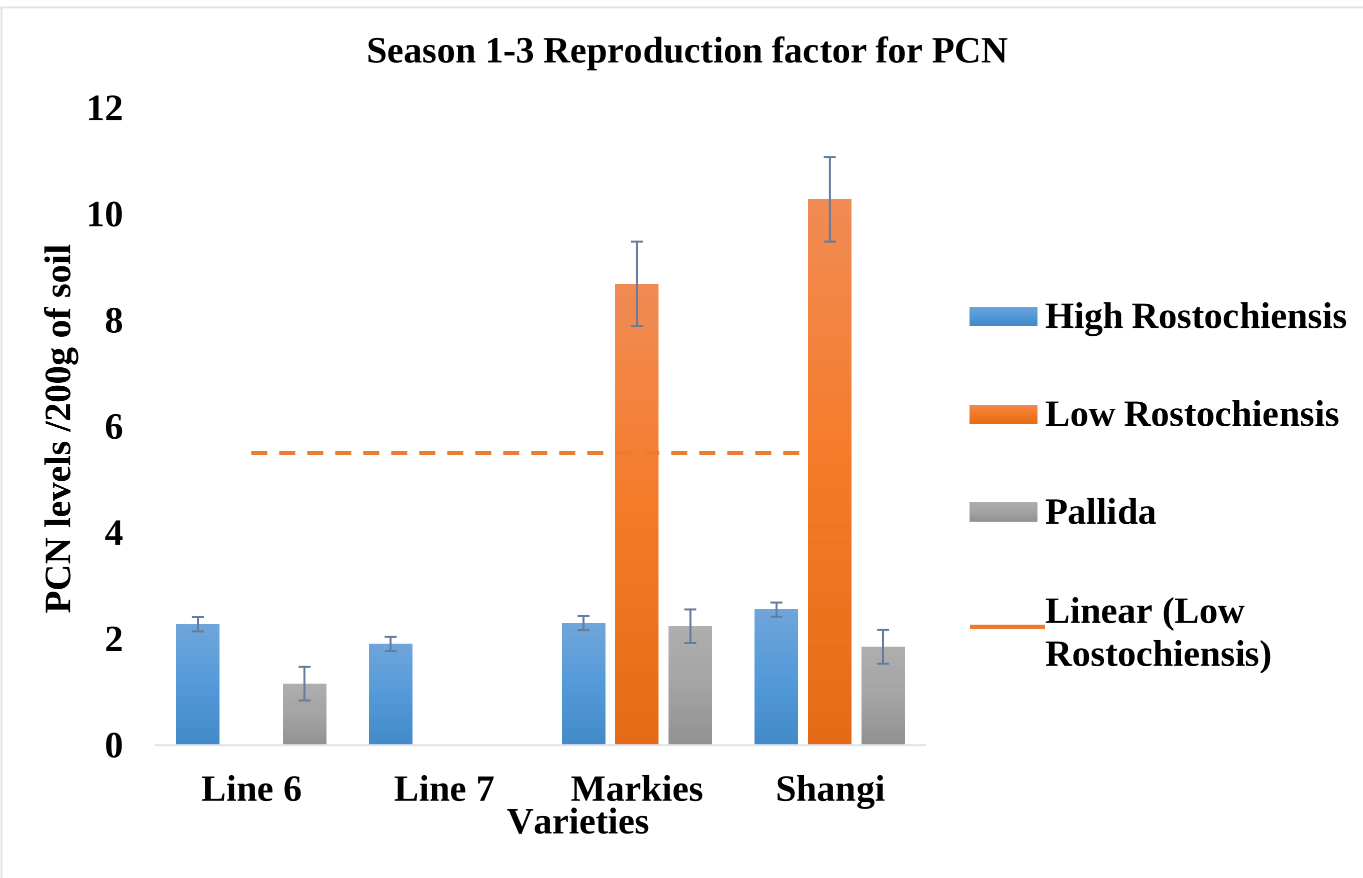

Figure32. Effects of resistant lines and susceptible variety on PCN levels

PCN table shows how the interaction between seasons one and two but significantly different from season three in terms of PCN suppression levels (Table 8).

Table 8. PCN levels differences in three seasons.

Season	emmean	SE	df	asymp.LCL	asymp.UCL	.group
3	0.646	1.62	Inf	-0.128	1.42	a
1	6.511	1.58	Inf	5.755	7.27	b
2	6.773	1.58	Inf	6.017	7.53	b

a- Significant difference b- not significantly different

The PCN levels were significantly different in season three compared to the other two seasons both of which showed no significant difference.

In table 9, and ab represent how the cultivars were significantly different from the rest. Shangi as the known susceptible variety performed differently compared to the resistant cultivars. The P value was **2.224 0.0244 *. (a,b-significantly different, ab-not significantly different)**

Table 9. Effects of potato lines on PCN levels based on R-analysis

Lines	lsmean	SE	DF	lower.CL	upper.CL	.group
Shangi pallida	46.2	149	60	-396.66	489	a
Shangi low	46.5	149	60	-396.32	489	a
Shangi high	49.3	149	60	-393.49	492	a
Markies high	168.2	149	60	-274.66	611	ab
Markies Low	179.0	149	60	-263.82	622	ab
Markies pallida	196.2	149	60	-246.66	639	ab
Line 6 pallida	246.5	149	60	-196.32	689	ab
Line 6 high	328.3	149	60	-114.49	771	ab
Line 7 low	387.5	149	60	-55.32	830	ab
Line 7 pallida	434.5	149	60	-8.32	877	ab
Line 7 high	449.8	149	60	7.01	893	ab
Line 6 low	812.7	149	60	369.84	1255	b

	Df	Sum Sq.	Mean Sq.	F value	PR (>F)	
Factor (lines)	11	3261513	296501	2.224	0.0244	*

Line 6 in low levels of PCN performed significantly higher than the rest when exposed to low PCN level. The yield performance of the susceptible variety Shangi was observed to be significantly the lowest and different in all levels of PCN.

This makes cv. Shangi is an un-fit variety, which cannot support higher production, leading to low income for potato-growing farmers in farmers infested with PCN in Kenya; hence should not be relied on to support the livelihood of farmers in such areas for food production. The P value is 0.0244 showing high significance levels in the yield performance of resistant varieties vs. susceptible ones.

5.1 PCN Trend line

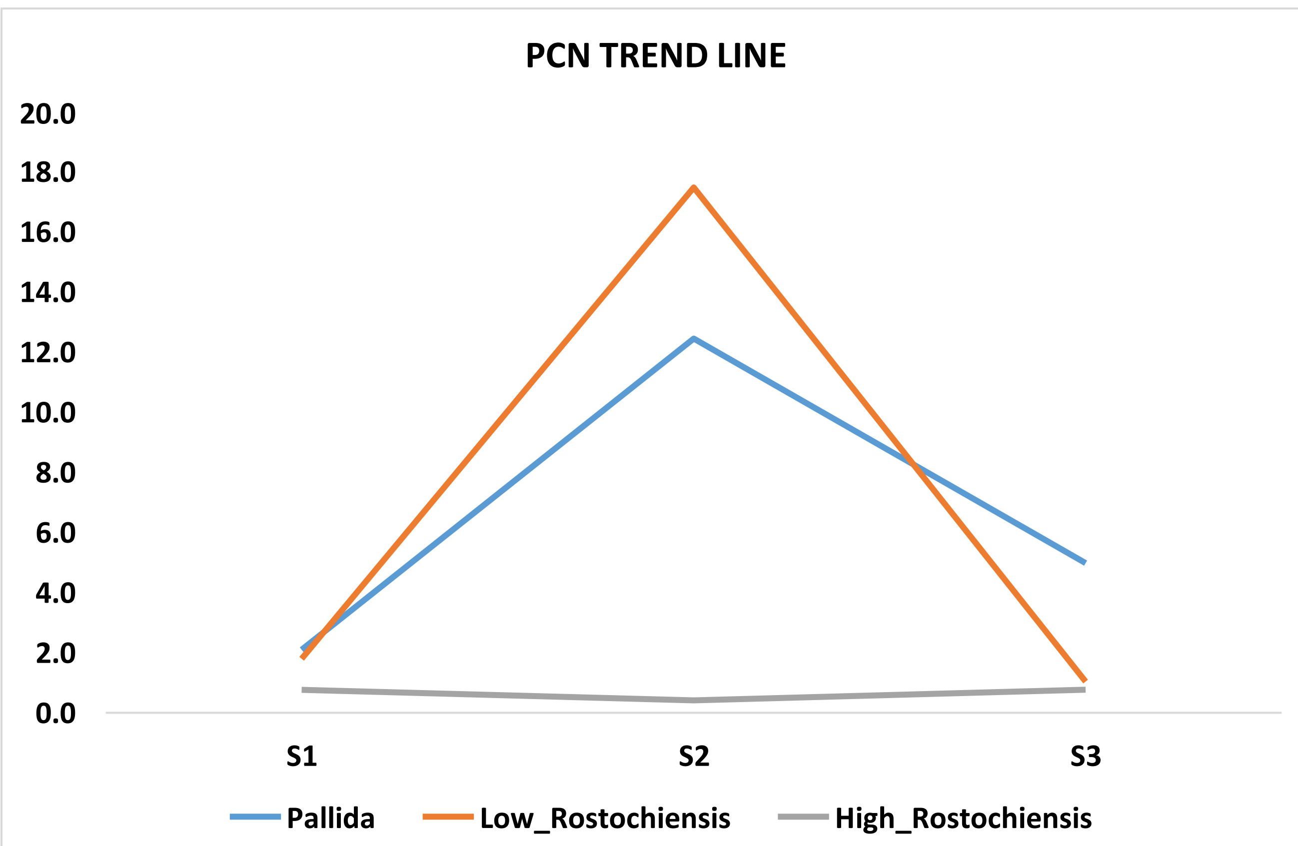

Figure 34. PCN Trend line.

The trend line shows that from season one, the pots with low PCN and *Globodera pallida* had increased yields in season two, then dropped in season three. The pots with high PCN gradually decreased throughout the entire season. This shows how the resistant lines gradually reduced the PCN levels, over-time changes.

In the table 9, the PCN levels were significantly different across all seasons but there was a gradual reduction of PCN levels from season one to three this is evident as season three recorded the lowest average.

Table 9. How different PCN levels were suppressed per season.

	PCN Level	Average	sd	n	se	±
Season one	Pallida	2.1	2.5	24	0.51	2.1 ± 0.51
	Low Rostochiensi	12.5	14.0	24	2.86	12.5 ± 2.86
	High Rostochiensi	5.0	2.3	24	0.47	5 ± 0.47
Season two	Pallida	1.8	3.0	24	0.61	1.8 ± 0.61
	Low Rostochiensi	17.5	37.9	24	7.74	17.5 ± 7.74
	High Rostochiensi	1.0	1.3	24	0.26	1 ± 0.26
Season three	Pallida	0.8	0.6	23	0.12	0.8 ± 0.12
	Low Rostochiensi	0.4	0.4	22	0.09	0.4 ± 0.09
	High Rostochiensi	0.8	0.7	24	0.14	0.8 ± 0.14

CHAPTER 7: DISCUSSION, CONCLUSION AND RECOMMENDATIONS

2.26 DISCUSSION

In Kenyan Irish potato farming regions, plant parasitic nematodes in the genera *Tylenchida* and *Dorylaimida* occurred. According to Chitwood (2011), these plant parasitic nematodes result in more than $120 billion (about $370 per person in the US) in annual production losses worldwide. Using sustainable Climate Smart Technologies to manage them has proven difficult (Thoden *et al*, 2011). Without adequate nematode, the economic losses in Irish potato farming will continue to rise. Due to nematode interactions with bacterial, fungal, and viral pathogens, it is expected to induce increased harm to the potato (Barker *et al.*, 1994).

When the *Globodera rostochiensis* juveniles of the second stage hatch, they often enter into the plant roots causing a decrease in water and nutrient intake, which results in stunted growth and poor harvests. The largest concentration of Potato Cyst Nematodes populations was seen in Nyandarua County, which resulted in poor potato yields on sensitive Shangi cultivars. It is incumbent on the farmers to adopt the use the resistant potato varieties presently available in Kenya, in order to reverse the trend of attaining low yields. Due to the abundance of penetration sites and the Irish potato's still-tender roots, *Globodera rostochiensis* production is particularly strong during the first three to four weeks after the emergence of the plant. When root tubers achieve maturity index, the surface of the tuber develops cracks and bends, lowering its quality and market value (Lawrence et al. 1986). *Pratylenchus*, a migratory endoparasites that differs from *Globodera rostochiensis* and Meloidogyne, a stationary endoparasites, are the third most significant PPN globally. Due to its endoparasite's restricted root development, plants become stunted. (Jones *et al.*, 2013).

The sub-counties in Nyandarua with the most outstanding PV values (45.35 to 75.50%) reported the presence of the nematode genera: *Helicotylenchus, Pratylenchus, Hoplolaimus, Globodera rostochiensis,* and *Meloidogyne.* On Irish potatoes, the development of *Pratylenchus* differs from that of *Meloidogyne*, although result in stunting of the potato. The impact of temperature and rainfall fluctuation from one site to the next may be seen in the observed association between PPN abundance and diversity. These species "prune" roots, which reduces heavy output (Clark and Wright 1983). Practical alternatives for management strategies usually depend on understanding how different nematode species interact.

For instance, *Meloidogyne's* presence during concurrent infections on the Irish potato or other plants prevent *Rotylenchulus* from reproducing (Thomas and Clark 1983). The soil may also impact the competitive equilibrium of these nematodes (Godefroid *et al.,* 2013).

According to the heat map analysis, *Criconema* was found in the Charagitta, Raitha, and Njabini wards, Oljoro-rok, and Kinangop sub-counties, respectively, where monthly rainfall was lower (136-123 mm), and temperatures were higher (12.7 to 11.4 degrees Celsius) than in the other three sub-counties. A contributing cause to the existence of this species in Oljoro-rok and Kinangop sub-county may be the low rainfall.

This study found a substantial correlation between rainfall and temperature and the amount of plant parasitic nematodes (PPNs) present throughout the sample period. However, elevation had little impact on nematode density. Rainfall affected the abundance and diversity of PPNS, as the P value was 0.019. Other environmental factors may have masked the effect of temperature on total nematode abundance and diversity. Areas with temperatures less than 12 degrees Celsius and rainfall greater than 152mm recorded the highest nematode abundance and variety than those with temperatures greater than 12 degrees Celsius and rainfall less than 123mm, as in figure 17. With the anticipated high precipitation and changes between the wet and dry seasons, the impact of rain on nematode abundance might become more noticeable (IPCC 2013). The amount and variety of PPN grows with an increase in yearly temperature worldwide (Nielsen *et al.,* 2014). The maximum and lowest temperatures in all five sub-counties increased annually, according to an analysis of long-term temperature data in the areas where soil samples were gathered. The PPN assemblages in Irish potato fields may be impacted if the trend of rising temperatures persists. Bird (1972) found that Meloidogyne and Pratylenchus grow and reproduce more quickly when temperatures exceed 25 °C. (Duyck *et al.,* 2012).

Low-rainfall regions may have more Pratylenchus and Rotylenchulus than usual (Boag 1980). Another species that does well in warm regions is Pratylenchus, which can eat in temperatures ranging from 0.5 to 42.4 °C (Boag 1980). Furthermore, warmer temperatures may increase fungal diseases (Pritchard 2011), which may reduce Irish potato yields even more by forming disease complexes between fungi and nematodes. In New Zealand, ongoing climate change is anticipated to pose a risk to agricultural productivity because of the probable rise in Meloidogyne spp. Abundance (Watson and Pottinger 1990). Boag et al. (1991) projected that global warming will alter viral vector nematodes like *Xiphinema* and cause Meloidogyne invasions to become more common in Brazil's coffee agroecosystems attributed to warming (Ghini *et al.,* 2008). Although it may take some time for changes in the spatial distribution of PPNs associated with Irish potatoes because of a rise in temperature (Boag *et al.,* 1991; Neilson and Boag 1996), the sharing of planting supplies among farmers may speed up PPN mobility between fields. According to the current study, a large variety of PPNs causes economic harm in Kenyan Irish potato farms. These potato-growing regions' rainfall and temperature trends are also altering, which might significantly impact the quantity and makeup of PPNs. (Nielsen *et al.,* 2014). Numerous direct and indirect influences, including modifications to the plant community, agronomic methods, and soil qualities, might have an impact on PPN in Irish potato agro-ecosystems when temperature and moisture are changed (Colagiero and Ciancio 2011; Kardol *et al.,* 2011; Pritchard2011). Additionally, the spread of Irish potato PPN may be impacted by the interactions between several mechanisms related to hosting presence, abundance, diversity, and susceptibility.

The use of potato varieties with H1-gene, which confer resistance to the PCN, is one of the best Climate Smart options to adopt to improve the high potato yields and income generation among the farmers, as the study has proved that these resistant varieties have the potential to suppress the PCN levels and double the yields. One of the most impressive potato lines is Line 7, which outperforms the rest and is not affected by the soft rots and blight. These lines have an excellent germinability/sprouting potential and mature within three months as the known susceptible variety Shangi. Markies showed some level of resistance but were not like the rest. The trend observed from season one to the third revealed that these varieties with the H1-genes lose their resistant vigour when recycled over time. Therefore, recycling tubers should be stopped after the second generation is attained. In the first season of February 2020, several meteorological stations recorded rainfall above 125% of their February long-term means in the second season and third, from November 2021 to May 2022, the rain was below 100%, with the highest temperature above 82 degrees Celsius (KMD. 2020. State of the Climate in Kenya 2020).

The potential impact of changes in temperature and rainfall on diversity distribution and abundance of PPN in Kenyan Irish potato agroecosystems may not be as easy to predict. The nematode abundance and diversity reported in this survey study could also vary depending on the methods used in the extraction (Den Nijs and Van Den Berg (2013). Nevertheless, the bottom line of this research is that this study provides a source of information from which sustainable Climate Smart Innovation options can be adopted in the nematode management strategies to mitigate yield losses that may result from PPN and eventually improve the income of potato farmers in Nyandarua as this crop production remains their main source of livelihood.

It is evident that applying organic amendments and crop rotation with non-host have nematicidal effects, thus reducing the PPNs in the soil and masking some of the environmental factors affecting the nematode distribution richness and diversity. The farmers use cv. Shangi variety for all seasons recorded the highest number of PCN due to its susceptibility. The rest of the farms where farmers grew other varieties had very low PCN levels. Therefore, we should not only rely on the climatic variables alone as we question the nematode abundance and diversity as this research bridges the gap.

The distribution likelihood maps serve as an additional tool (PDM). Their application allows for the identification of potential dangers associated with pest movement above and below the soil, vectors, or plant diseases. They are typically calculated using a combination of local pest occurrence records, climate data, and subsequent research statistical analysis (Colagiero and Ciancio *et al.*,2011) They clearly indicate the areas where a given organism is likely to colonize or endemism (Morales and Jones *et al.*, 2004). This tool has numerous practical advantages, such as the ability to identify pest invasion areas early or the potential to predict epidemic outbreaks for secondary pests, which are already available in sizes with sub-optimal life cycle conditions. PDMs must monitor various climatic variables at the regional scale and at a given resolution level, as well as implement an early warning and detection system (Brandon and Jones *et al.*, 2004). This will be extremely beneficial to farmers, allowing them to adapt adequately and accurately in order to manage these devastating Plant Parasitic Nematodes.

2.27 CONCLUSION

As a preventive measure against "biological surprises," adaptive solutions for integrated or biological monitoring of Plant Parasitic Nematodes in high-altitude locations will be required. As a result, the likelihood of survey map distribution will allow for identifying possible dangers associated with the spread of critical nematode species such as PCN and other PPNs. The research involving introducing resistance genes into potato types should consider their durability in a changing environment and how long they will be helpful in production. Protecting natural biodiversity is an "adaptive approach" that requires a rapid and flexible reaction. Invasive species models, potential implications of climate change, and merging a global climate model with local, specialized sub-models are other essential tools. Still, they need a continuous check for their fitness and reliability. In conclusion, not all the climatic changes projected for the next decades may result in adverse penalties. Knowledge base prevention plays a key role, such as consideration of minor species that might become insurgents as novel pests.

This study reveals that rainfall and temperature significantly affected the nematodes' diversity and abundance/richness at $P = 0.019$ and $P=0.029$, respectively. Elevation did not affect the nematode distribution in this case as the $P=0.25$. Both rainfall and temperature contributed to nematodes' diversity and abundance/richness at 8.6% and 7.2 %, respectively, as in figures 8 and 9. This means that socioeconomic activities, including crop rotation, application of different potato cultivars, use of organic amendments, fertilizer application, fungicide and pesticide application, and continuous tilling of the land, can heavily influence the nematode's diversity and abundance/richness.

The application of organic amendments and crop rotation with non-host have nematicidal effects, thus reducing the PPNs in the soil and masking some of the environmental factors that affect the nematode distribution richness and diversity.

Therefore, we should not only rely on the climatic variables alone as we question the nematode abundance and diversity as this research bridge the gap. This knowledge can be fundamental to the farmers, so they should be very aware that the agronomic activities they perform on their farms could influence Plant Parasitic Nematodes distribution in their farms. Therefore, they should be vigilant while handling their farm activities in sustainable options such as adopting Climate Smart Agriculture, which includes applying resistant varieties.

The composition of nematode populations in Nyandarua County is closely related to soil characteristics and climatic variables. These elements may serve as important environmental filters in the formation of nematode communities. It is critical to emphasize that the effects of these variables on the nematode community cannot be investigated separately. Because socioeconomic activity, temperature, and rainfall alter soil structure and, as a result, the richness and diversity of the nematode community, these must be viewed in terms of their integrative impact. Our findings show that understanding the impact of nematode community structure on socioeconomic activities on the land, as well as the effect of climate and ecosystem properties on community structure, can be used to forecast the impact of changes in soil use, climate, and ecosystem properties.

The resistant cultivars (Line 7 and 6) with H1 gene confers resistance to PCN (90%) compared to susceptible Shangi. They proved to be resistant cultivars to *Globodera rostochiensis* and could help reduce pesticide application frequencies hence climate smart innovation. The two new breeding cultivars are high yielding compared to the Markies and Shangi varieties.

2.28 RECOMMENDATIONS

1. Based on the favorable performance of the of the two resistant potato cultivars Lines 7 and 6 for in yield performance and reduction of PCN levels, I recommend theme for furtherfield research and organoleptic tests to ascertain their market acceptability. This means that by adopting these varieties, the communities' livelihoods will be significantly improved since the PCN will no longer reduce their yield to 80%, as the research has revealed.

2. Farmers in different agro-regional zones should invest more effort in consolidating and implementing policies that prevent destruction of natural environments and ensure that crop insurance as a risk coping mechanism has a solid framework, which can help enhanceits uptake. Given that anthropogenic activities are the key drivers of climate variability andchange, it is necessary to invest in national, county, and farm adaptation measures, especially in the potato growing regions, to build farmers' resilience.

REFERENCES

Affokpon, A., Coyne, D. L., Htay, C. C., Agbèdè, R. D., Lawouin, L., & Coosemans, J. (2011). Biocontrol potential of native Trichoderma isolates against root-knot nematodes in West African vegetable production systems. Soil Biology and Biochemistry, 43(3), 600–608. https://doi.org/10.1016/j.soilbio.2010.11.029

Ahmed, S., Marimuthu, N., Tripathy, B., Julka, J. M., & Chandra, K. (2022). Earthworm community structure and diversity in different land-use systems along an elevation gradient in the Western Himalaya, India. Applied Soil Ecology, 176, 104468. https://doi.org/10.1016/j.apsoil.2022.104468

Atkinson H.J, Ballantyne AJ, 1977. Changes in the adenine nucleotide content of cysts of Globodera rostochiensis are associated with the hatching of juveniles. Annals of Applied Biology, 87(2):167-174

Bakonyi G, Nagy P, Kovacs-Lang E, Kovacs E, Barabas S, Repasi V, Seres A (2007) Soil nematode community structure as affected by temperature and moisture in temperate semiarid shrubland. Appl Soil Ecology 37:31–40

Barker KR, Hussey RS, Krusberg LR, Bird GW, Dunn RA, Ferris H, Ferris V, Freckman DW, Gabriel CJ, Grewal PS, Macguidwin AE, Riddle DL, Roberts PA, Schmitt DP (1994) Plant, and soil nematodes: Societal impact and focus for the future. J Nematol 26:127137

Bebber DP, Holmes T, Gurr SJ (2014) the global spread of crop pests and pathogens. Glob Ecol Biogeography 23:1398–1407 Bird F (1972) Influence of temperature on embryogenesis in Meloidogyne javanica. JNematol4:206–213

Bird, A.F., Wallace H.R., (1965). The influence of temperature on Meloidogyne hapla and M. javanic .Nematologica, 11:581-589.

Boag and Yeates, 1998, B. Boag, B., G.W. Yeates, G.W. (1998).Soil nematode biodiversity in terrestrial ecosystems. Biodivers. Conserv. 7: (1998), pp. 617-630.

Boag B (1980) Effects of temperature on the rate of feeding of the plant parasitic nematodes Pratylenchus robustus, Xiphinema diversicaudatum, and Hemicycliophora conidia. J Nematol 12: 193–195

Boag B, Crawford JW, Neilson R (1991) the effect of potential climatic changes on the geographical distribution of the plant parasitic nematodes Xiphinema and Longidorus in Europe. Nematologica 37: 312–323

Brandon-Jones, D., Eudey, A. A., Geissmann, T., Groves, C. P., Melnick, D. J., Morales, J. C., Shekelle, M., & Stewart, C.-B. (2004). Asian Primate Classification. International Journal of Primatology, 25(1), 97–164. https://doi.org/10.1023/B:IJOP.0000014647.18720.32

Chen, S., Chen, X., & Xu, J. (2016). Impacts of climate change on agriculture: Evidence from China. Journal of Environmental Economics and Management, 76, 105–124. https://doi.org/10.1016/j.jeem.2015.01.005

Chitambo, O., Haukeland, S., Fiaboe, K. K. M., and Grundler, F. M. 2018. First report of Meloidogyne hapla and Meloidogyne javanica co-infection on Parthenium hysterophorus in Kenya. Plant Dis. 103:162. https://apsjournals.apsnet.org/doi/abs/10.1094/PDIS-06-18-0964-PDN.Chitambo, O., Haukeland, S., Fiaboe, K. K. M., Kariuki, G. M., and Grundler, F. M. W. 2016. The first report of the root-knot nematode Meloidogyne enterolobii parasitizing African nightshades in Kenya. Plant Dis. 100:1954.

Chitwood DJ (2011) Research on plant-parasitic nematode biology conducted by the United States Department of Agriculture-Agricultural Research Service. Pest Manag Sci 59:748–753

Clark CA, Wright VL (1983) Effect and reproduction of Rotylenchulus reniformis on sweet potato selections. J Nematol 15:197–203

Climate Nyandarua: Temperature, climate graph, Climate table for Nyandarua—Climate-Data.org. (n.d.). Retrieved 16 December 2021, from https://en.climate-data.org/africa/kenya/nyandarua-1673/

Climate Nyandarua: Temperature, climate graph, Climate table for Nyandarua—Climate-Data.org. (n.d.). Retrieved 16 December 2021, from https://en.climate-data.org/africa/kenya/nyandarua-1673/

Colagiero M, Ciancio A (2011) Climate changes and nematodes: Expected effects and perspectives for plant protection. MEDIA 94: 113–118

Colagiero, M., & Ciancio, dr A. (2011). Climate changes and nematodes: Expected effects and perspectives for plant protection. Redia, 94, 113–118.

Contina, J. B., Dandurand, L. M., & Knudsen, G. R. (2018). A Spatial Analysis of the Potato Cyst Nematode Globodera pallida in Idaho. Phytopathology®, 108(8), 988–1001. https://doi.org/10.1094/PHYTO-11-17-0388-R

Coyne DL, Talwana HAL, Maslen NR (2003) Plant-parasitic nematodes associated with root and tuber crops in Uganda. Afr Plant Protect 9: 87–98

Den Nijs LJMF, Van Den Berg W (2013) the benefit of proficiency tests: choosing the proper method for extracting Meloidogyne second-stage juveniles from the soil. Nematology 15:143–151

Desaeger J, Rao MR (1999) the root-knot nematode problem in Sesbania fallows and scope for managing it in western Kenya. Agrofor Syst 47:273–288

Development Core Team R (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna Duyck PF, Dortel E, Tixier P, Vinatier F, Loubana PM, Chabrier C, Quénéhervé P (2012) Niche partitioning based on soil type and climate at the landscape scale in a community of plant-feeding nematodes. Soil Biol Biochem 44:49–55

Diagne, N., Ngom, M., Djighaly, P. I., Fall, D., Hocher, V., & Svistoonoff, S. (2020). Roles of Arbuscular Mycorrhizal Fungi on Plant Growth and Performance: Importance in Biotic and Abiotic Stressed Regulation. Diversity, 12(10), 370. https://doi.org/10.3390/d12100370

Dutta, T. K., & Phani, V. (2023). The pervasive impact of global climate change on plant-nematode interaction continuum. Frontiers in Plant Science, 14. https://www.frontiersin.org/articles/10.3389/fpls.2023.1143889.

Evans K,and Brodie BB, (1980). The origin and distribution of the golden nematode and its potential in the USA. American Potato Journal.

Fiscus D, Neher D (2002) Distinguishing sensitivity of free-living soil nematode genera to physical and chemical disturbances. Ecol Appl 12:565–575.

Ghini R, Hamada E, Júnior MJP, Marengo JA, Ribeiro R, Goncalves D (2008) Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. Pesq Agrop Bras 43:187–194.

Godefroid M, Delaville L, Marie-Luce S, Quénéhervé P (2013) spatial stability of a plant-feeding nematode community in relation to macro-scale soil properties. Soil Biol Biochem 57:173–181

Griffin GD, Asay KH, Horton WH (1996) Factors affecting population trends of plant-parasitic nematodes on rangeland grasses. J Nematol 28:107–114 .

Haougui A, Doumma A, Toufique B, Kollo IA (2011) Survey of plant parasitic nematodes associated with sweet potato in Niger. Asian J Agric Sci 3:32–36.

Hoang MHH, Namirembe S, van Noordwijk M, Catacutan D, Öborn I, Perez-Teran ASS, Nguyen HQQ, Dumas-Johansen MKK (2014) Farmer portfolios, strategic diversity management and climate-change adaptation – implications for policy in Vietnam and Kenya. Clim Dev 6: 216–225.

Hockland, S., B. Niere, E. Grenier, V.Blok, M. Phillips, L. Den Nijs, G. Anthoine, G. Pickup, and N. Viaene, (2012). ; An evaluation of the implications of virulence in non Europeannon-European populations of Globodera pallida and G. rostochiensis for potato cultivation in Europe. Nematology 14:, 1-13.

Hooper DJ (1990) Extraction and processing of plant and soil nematodes. In: Luc M, Sikora RA, Bridge J (eds) Plant Parasitic Nematodes in Subtropical and Tropical Agriculture. CAB International, Wallingford, pp 45–68.

IPCC (2013) Summary for Policymakers. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J (eds) Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate Change. Cambridge University Press, Cambridge Jaetzold R, Schmidt H (1983) Farm management handbook of Kenya, vol II/C. Ministry of Agriculture, Nairobi. 78 pp

Jones JT, Haegeman A, Danchin EGJ, Gaur HS, Helder J, Jones MGK, Kikuchi T, Manzanilla-López R, Palomares-Rius JE, Wesemael WIMML, Perry RN (2013) Top 10 plant-parasitic nematodes in molecular plant pathology. Mol Plant Pathol 14:946–961

Kamau, S. W., Kuria, D. N., & Gachari, M. K. (2015). Crop-land Suitability Analysis Using GIS and Remote Sensing in Nyandarua. http://repository.dkut.ac.ke:8080/xmlui/handle/123456789/263

Kamau, S. W.; Kuria, D. N.; Gachari, M. K., 2015: Crop-land Suitability Analysis Using GIS and Remote Sensing in Nyandarua.

Kardol P, Reynolds WN, Norby RJ, Classen AT (2011) Climate change affects soil microarthropod abundance and community structure. Appl Soil Ecol 47:37–44.

Kitagami, Y., Tanikawa, T., & Matsuda, Y. (2020). Effects of microhabitats and soil conditions on structuring patterns of nematode communities in Japanese cedar (Cryptomeria japonica) plantation forests under temperate climate conditions. Soil Biology and Biochemistry, 151, 108044. https://doi.org/10.1016/j.soilbio.2020.108044.

Klute, A. (Ed.), (1986). Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, Agronomy Monograph 9, American Society of agronomy-Soil Science Society of America, Madison, pp.363-375.

Lear, G., Dickie, I., Banks, J., Boyer, S., Buckley, H. L., Buckley, T. R., Cruickshank, R., Dopheide, A., Handley, K. M., Hermans, S., Kamke, J., Lee, C. K., MacDiarmid, R., Morales, S. E., Orlovich, D. A., Smissen, R., Wood, J., & Holdaway, R. (2018). Methods for the extraction, storage, amplification and sequencing of DNA from environmental samples. New Zealand Journal of Ecology, 42(1), 10-50A.

Mai, W., 2018: Plant-Parasitic Nematodes: A Pictorial Key to Genera. Cornell University Press.

Mburu, H., Cortada, L., Haukeland, S., Ronno, W., Nyongesa, M., Kinyua, Z., Bargul, J. L., & Coyne, D. (2020). Potato Cyst Nematodes: A New Threat to Potato Production in East Africa. Frontiers in Plant Science, 11, 670. https://doi.org/10.3389/fpls.2020.00670

Mburu, H., Cortada, L., Mwangi, G., Gitau, K., Kiriga, A., Kinyua, Z., Ngundo, G., Ronno, W., Coyne, D., Holgado, R., & Haukeland, S. (2018). First Report of Potato Cyst Nematode Globodera pallida Infecting Potato (Solanum tuberosum) in Kenya. Plant Disease, 102(8), 1671–1671. https://doi.org/10.1094/PDIS-11-17-1777-PDN

Mburu, H., Cortada, L., Mwangi, G., Gitau, K., Kiriga, A., Kinyua, Z. M., Ngundo,G., Ronno, W., Coyne, D. L., Holgado, R., and Haukeland, S. 2018. First report of potato cyst nematode Globodera pallida (Stone, 1973) infecting potato (Solanum tuberosum L.) in Kenya. Plant Dis.

Mugniéry, D., Phillips, M.S., Rumpenhorst, H.J., Stone, A.R., Truer, A. and Trudgill, D.L. (1989). Assessment of partial resistance of potato to, and pathotype and virulence differences in, potato cyst nematodes. Oecologia, 111 :(1997: 575-582.

Mwangi, J. M., Kariuki, G. M., Waceke, J. W., & Grundler, F. M. (2015). First report of Globodera rostochiensis infesting potatoes in Kenya. New Disease Reports, 31, 18–18. https://doi.org/10.5197/j.2044-0588.2015.031.018.

Ndambiri, H. K.; Ritho, C. N.; Mbogoh, S. G., 2013: An evaluation of farmers' perceptions of and adaptation to the effects of climate change in Kenya.

Noia, M. D., Poole, R., Kaufmann, J., Waters, C., Adams, C., McGinnity, P., & Llewellyn, M. (2022). Towards an in situ non-lethal rapid test to accurately detect the presence of the nematode parasite, Anguillicoloides crassus, in European eel, Anguilla anguilla. Parasitology, 149(5), 605–611. https://doi.org/10.1017/S0031182021002146

Nyandarua (County, Kenya)—Population Statistics, Charts, Map, and Location. (n.d.). Retrieved 21 March 2022, from http://www.citypopulation.de/en/kenya/admin/central/18_nyandarua/

Nyandarua, KE Climate Zone, Monthly Weather Averages and Historical Data. (n.d.). Retrieved 21 March 2022, from https://tcktcktck.org/kenya/nyandarua

Nyandarua, KE Weather In April 2020 (Weather History Apr 2020). (n.d.). Retrieved 16 March 2022, from https://tcktcktck.org/nyandarua/april-2020

Ochieng, B. O., 2022: Management of Potato Cyst Nematodes Using Host Resistance, Organic Amendments and Biocontrol Agents in Nyandarua County, Kenya (Thesis). University of Nairobiin thesisRetrieved from http://erepository.uonbi.ac.ke/handle/11295/162350.

Ochieng, J., Kirimi, L., & Mathenge, M. (2016). Effects of climate variability and change on agricultural production: The case of small-scale farmers in Kenya. NJAS - Wageningen Journal of Life Sciences, 77, 71–78. https://doi.org/10.1016/j.njas.2016.03.005

Ochola, J., Cortada, L., Mwaura, O., Tariku, M., Christensen, S. A., Ng'ang'a, M., Hassanali, A., Pirzada, T., Khan, S., Pal, L., Mathew, R., Guenther, D., Davis, E., Sit, T., Coyne, D., Opperman, C., & Torto, B. (2022). Wrap-and-plant technology to manage potato cyst nematodessustainably in East Africa. Nature Sustainability, 5(5), 425–433. https://doi.org/10.1038/s41893-022-00852-5

Ogola, R. J. O., Ouko, K., Kirina, T., & Droppers, B. (2021). Assessment of Experts' Opinion on Irish Potato Farmers' Perceptions about Climate Change and the Use of Climate Smart Agriculture Adaptation Strategies in Kenya. 7, 957–967.

Perry, R. N., & Moens, M. (2013). Plant Nematology: 2nd Edition. CABI.

Perry, R.N., Jones, J.T. (1998). The use of molecular biology techniques in plant nematology: past, present, and future. Russian Journal of Nematology, 6(1):47-56; 48.

Planning, K. M. of D. and, 2013: Nyandarua County. Government Printer, South Africa.

Pylypenko, L. (2018). Resistance and tolerance to potato cyst nematodes among Ukrainian potato cultivars and breeding materials. Plant Protection Science. 38. 189-194.

Shafique, M. (2017). Agriculture in Pakistan and its Impact on Economy―A Review. International Journal of Advanced Science and Technology, 103, 47–60. https://doi.org/10.14257/ijast.2017.103.05

Sheridan, J.P., Miller, A.J., Perry, R.N. (2004) early responses of resistant and susceptible potato roots during the invasion by the potato cyst nematode *Globodera rostochiensis*. J Exp Bot., 55:751-760.

Sikora, R. A.; Desaeger, J.; Molendijk, L., 2021: Integrated Nematode Management: State-of-the-art and Visions for the Future. CAB International.

STATE OF THE CLIMATE 2020_14042021.pdf. (n.d.). Retrieved 22 August 2022, from https://meteo.go.ke/sites/default/files/downloads/STATE%20OF%20THE%20%20CLIMATE%202020_14042021.pdf

Streets, D. G.; Glantz, M. H., 2000: Exploring the concept of climate surprise. Global Environmental Change., 10, 97–107.

Suicidal Hatch' a potential management strategy for potato cyst nematodes | icipe—International Centre of Insect Physiology and Ecology. (n.d.). Retrieved 25 February 2022, from http://www.icipe.org/news/%E2%80%98suicidal-hatch%E2%80%99-potential-management-strategy-potato-cyst-nematodes

Torrance, L., & Talianksy, M. E. (2020). Potato Virus Y Emergence and Evolution from the Andes of South America to Become a Major Destructive Pathogen of Potato and Other Solanaceous Crops Worldwide. Viruses, 12(12), 1430. https://doi.org/10.3390/v12121430

Tripathi, D. K.; Singh, V. P.; Chauhan, D. K.; Sharma, S.; Prasad, S. M.; Dubey, N. K.; Ramawat, N., 2020: Plant Life under Changing Environment: Responses and Management. Academic Press.

Turner, S.J., (1998). Sample preparation, soil extraction, and laboratory facilities for detecting potato cyst nematode. In: R.J Marks, and B.B. Brodie (Eds.).Potato cyst nematode biology, Wallingford, distribution and control, CAB International PPNS National Potato catalog, 2009

Vicente, C. S. L.; Hasegawa, K.; Palomares-Rius, J. E.; Siddique, S., 2021: Protecting Our Crops - Approaches for Plant Parasitic Nematode Control. Frontiers Media SA.

Wairimu, W. J., Kimenjul, J. W., Muiru, W. M., & Wachira, P. M. (2022). Interactions between soil additives and a variety of naturally occurring nematode-demolishing fungi in banana fields of

Meru and Embu Counties, Kenya. Cell Biology and Development, 6(2), Article 2. https://doi.org/10.13057/cellbioldev/v060204

Wairimu, W. J.; Kimenjul, J. W.; Muiru, W. M.; Wachira, P. M., 2022: Interactions between soil additives and a variety of naturally occurring nematode-demolishing fungi in banana fields of Meru and Embu Counties, Kenya. Cell Biology and Development., 6.

Whitehead, A.G., Turner, S.J. (1998). Management and regulatory control strategies for potato cyst nematodes (Globodera rostochiensis and Globodera pallida). In: Marks R.J., Brodie, B.B. (Eds) Potato cyst nematodes: biology, distribution, and control. CABI, Wallingford pp135-152

Wilschut, R. A., & Geisen, S. (2021). Nematodes as Drivers of Plant Performance in Natural Systems. Trends in Plant Science, 26(3), 237–247. https://doi.org/10.1016/j.tplants.2020.10.006

Wilschut, R.A., and Geisen, S. (2021). Nematodes as Drivers of Plant Performance in Natural Systems. Trends in Plant Science, 26(3): 237–247.

Wyss, U. (2002) Feeding behavior of plant parasitic nematodes. In: Lee DL (Ed,) the biology of nematodes. Taylor and Francis, London, pp 233-2.

Zaheer, K., & Akhtar, M. H. (2016). Potato Production, Usage, and Nutrition—A Review. Critical Reviews in Food Science and Nutrition, 56(5), 711–721. https://doi.org/10.1080/10408398.2012.724479

APPENDICES

A well-structured questionnaire was used to capture the socioeconomic activities of the Nyandarua potato farmers. This covered 50 farmers, where ten farmers came from each five sub-county. The GPS device was used to record the location of the eastings and southings and metersabove sea level. This was conducted in the willing farmer's presence by face-to-face communication.

SURVEY FOR PLANT PARASITIC NEMATODES DISTRIBUTION & DIVERSITY IN NYANDARUA KENYA.

Consent

My name is………**Calvince Orage**………………………. I am a student at The University of Nairobi conducting research on EFFECTS OF CLIMATIC VARIABILITY ON NEMATODE DIVERSITY RICHNESS, DISTRIBUTION AND USE OF RESISTANT POTATO VARIETIES FOR MANAGEMENT OF POTATO CYST NEMATODE (Globodera rostochiensis) IN KENYA. I am part of a team of researchers from the International Institute of Tropical Agriculture International Centre of Insect Physiology and Ecology (icipe).

I am studying potato soil-born pests, and we would like to know about different nematodes in your potato crop. This includes data collection on a soil sample from your potato farm and information related to the agronomic practices applied on your farm associated with the management of the same and the decision-making at the household level. After this interview, we will take soil samples of about 500 grams from your farm for further lab analysis to quantify and identify nematodes. No payments will be provided for the sampling of your farm. The partners of this consortium are committed to informing and sharing with you the results of the analyses conducted from the soil samples obtained from your farm.

We are requesting your consent before doing this survey. You do not have to answer any questions that you do not feel comfortable answering. If you decide you do not want to participate, you can stop without consequences, and the samples will be discarded.

Please sign if you agree to participate:

Date of interview (day/month/year): …………………………………….

Phone number of interviewer: **Organization:**

SECTION 1: GENERAL INFORMATION RELATED TO FIELD METADATA, GENDER, AND AGRONOMIC PRACTICES.

1.1- Farmer Name:	**1.2- Gender**: Female Male	**1.3- Age:**
1.4- Phone number of interviewee:	**1.5- Altitude:**	**1.6- GPS coordinates**:
1.7- District:	**1.8- Sub- County**:	**1.9- Village:**

<table>
<tr><td>1.10.- Age of current crop (in months):</td><td colspan="2">1.11.- Crop in previous planting season:</td></tr>
<tr><td rowspan="4">1.12.- Do you practice rotation?
Yes No</td><td rowspan="4">1.13.- If YES to 1.12,
what is the sequence followed?</td><td>Season (-1):</td></tr>
<tr><td>Season (-2):</td></tr>
<tr><td>Season (-3):</td></tr>
<tr><td>Season (-4):</td></tr>
<tr><td></td><td></td><td>Main variety:</td></tr>
</table>

1.14.- Where did you obtain your potatoseed for this season?

Note to interviewers: multiple responses allowed; please tick as many as the farmer provides and rank them in order of importance, from 1 -being the most relevant- to 7 being the least relevant);

Source	Rank
Own	
Other farmers	
NAADS	
Certified source research organization	
Local Market	
Traders	
Others, please explain: ………………………………	

1.15.- What is the name of the potato varieties you are currently growing?	2nd ranked: 3rd ranked:

1.16.- What is the name of the potato varieties you are currently growing?

Main variety:	Acreage: ; Seed planted:
2nd ranked:	Acreage: ; Seed planted:
3rd ranked:	Acreage: ; Seed planted:

Note to interviewers: data shall be collected preferably for acreage; if unknown by the farmer, indicate that information is not available (NA) and collect data on seed planted.

INFORMATION RELATED TO GENDER ROLES AT THE HOUSEHOLD LEVEL ON CROP HUSBANDRY AND PEST AND DISEASE MANAGEMENT			
1.17 - Who is the owner of the crop?	**Myself** Female Male	**My Spouse** Female Male	**Someone else**
1.18- Who is responsible for buying potato seeds at the HH level?	**Myself** Female Male	**My Spouse** Female Male	**Someone else**
1.19- Who decides on the potato variety to be grown each season?	**Myself** Female Male	**My Spouse** Female Male	**Someone else**
1.20- Who is mainly in charge of managing pests and diseases in the crop?	**Myself** Female Male	**My Spouse** Female Male	**Someone else**
1.21a- Who is mainly in charge of the rest of the agronomic practices of the crop?	**Myself** Female Male	**My Spouse** Female Male	**Someone else**
1.21b.- Additional information related to 1.21a:			

<table>
<tr><th colspan="6">INFORMATION RELATED TO GOOD AGRONOMIC PRACTICES USED IN THE POTATO CROPS: USE OF FERTILIZERS/SOIL AMENDMENTS</th></tr>
<tr><td colspan="2">1.22.- Do you use inorganic fertilizer when planting potatoes?</td><td>1.23.- At what stages of the crop do you use fertilizer? Note to interviewers: tick if farmer responds YES</td><td>1.24.- Indicate the commercial name of the fertilizer used for each category, if applicable:</td><td>1.25.- Indicate the rate of application of the fertilizer Note to interviewers: provide data as Kg/ha</td><td>1.26- What is the frequency of application of the fertilizer per season?</td></tr>
<tr><td rowspan="3">Yes</td><td rowspan="3">No</td><td>Planting</td><td>Planting:</td><td></td><td>1, 2, 3 ,5 or >5</td></tr>
<tr><td>As top dressing</td><td>As top dressing:</td><td></td><td>1, 2, 3 ,5 or >5</td></tr>
<tr><td>In foliar application</td><td>In foliar application:</td><td></td><td>1, 2, 3 ,5 or >5</td></tr>
</table>

1.27.- Do you use manure/other organic amendments	**1.28.- What type of organic amendment do you use?**	**1.29.- Indicate at what stages of the crop do you use manure/other organic**	**1.30.- Indicate rate of application of organic**	**1.31- What is the frequency of application of the organic amendment per**

			amendment	**season?**

when planting potato?		**Note to interviewers:** tick the option responded by farmer	**amendments when planting potato?**	**Note to interviewers:** provide data as Kg/ha	
Yes	No	Cow		Cow	1, 2, 3 ,5 or >5
		Chicken		Chicken	1, 2, 3 ,5 or >5
		Sheep/Goat		Sheep/Goat	1, 2, 3 ,5 or >5
		Compost		Compost	1, 2, 3 ,5 or >5
		A mix of the previous		A mix of the previous	1, 2, 3 ,5 or >5

SECTION 2: NEMATODES DATA COLLECTION **(Collect randomly three tubers & 3 root systems for analyses)**

INFORMATION ON SOIL SAMPLE	
SAMPLE code:	
Several cores taken:	
Condition of the soil:	Water saturation; Wet/humid; Dry

GNERAL OBSERVATION IN THE FIELD

Symptoms	**Tick where applicable**
Generalized wilting	Yes/No
Crop's patchiness	Yes/No
Stunted Growth	Yes/No

Plant No.	Galls observed in roots (Score)	Nematode symptoms observed in tubers? **Note to interviewers:** tick in each symptom if any tubers/plant are observed with the symptoms below	Did cyst observe in roots/tubers?	
1	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
2	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
3	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
4	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
5	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
6	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
7	1 2 3	Skin Flaking	Yes	No

	4 5	Skin Cracking		
8		Skin Flaking	Yes	No

	1 2 3 4 5	Skin Cracking		
9	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		
10	1 2 3 4 5	Skin Flaking	Yes	No
		Skin Cracking		

Galling Score: (1= no galls observed, healthy feeder roots and tubers, 2 = at least onegall observed on roots, 3 = galls obvious,

4 = numerous galls & tuber size reduced 5 = heavy galling on tubers).

END OF SURVEY; BEFORE LEAVING THIS FARM, MAKE SURE ALL THE INFORMATION ON THE QUESTIONNAIRE IS COMPLETE AND CLEAR AND THAT ALL SAMPLES HAVE BEEN TAKEN AND CORRECTLY LABELLED.