EFFECT OF CROP ROTATION PATTERN ON SOIL BACTERIAL WILT (*Ralstonia solanacearum*) POPULATION AND POTATO (*Solanum tuberusum* L.) YIELD IN NJORO, KENYA

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DEDICATION

This thesis is dedicated to my mother, Sarah Inzikuru, my wife Asenath Charity and sons, Hopehandy and Westfeelings, for their love, patience and support.

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ABSTRACT

Poor soil fertility and high disease incidences particularly BW are the main constraints to potato production in Njoro, Kenya. Reduction of potato yield of between 30 – 70% has been attributed to bacterial wilt alone. Against this back drop, a trial was conducted in 2012 as part of a short-term crop rotation experiment (2 years) to investigate the effect of crop-rotation on soil bacterial wilt population and potato yield. The experiment was set up in a randomized complete block design (RCBD) with six crop rotation treatments and replicated four times. Four vegetables commonly grown in Njoro area, namely Garden Pea (GP), Carrot(C), Cabbage (CB), and Kales (K) were selected for the crop rotation sequence. These were rotated in a four season-experiment as follows: CB-P-K-P, K-P-CB-P, C-P-C-P, GP-P-GP-P, K-P-K-P and P-P-P-P a no rotation control treatment of continuous potato. Data collected included selected soil chemical properties, soil BW pathogen count, BW incidence, plant growth and crop yield. The parameters measured in soil properties were pH, N, P K, and soil organic matter. Soil BW pathogen count and B.wilted plant were the biological parameters considered. Finally the stem heights at bulking and fresh potato weight at harvest were the parameters for plant vigor and yield. The results collected at the end of fourth season showed that crop rotation pattern at ($p < 0.05$) had effect on soil pH and available P in the control rotation pattern P-P-P-P. BW count was found to be below infection level (30 cfu g^{-1}) which does not cause infection. There was also significant effect of crop rotation sequence at $p < 0.05$ on BW incidence, plant vigor and potato yield compared to the control treatment P-P-P-P. Crop rotation therefore remains the most effective way of managing and controlling effect BW pathogen in potato production.

Keywords: Bacterial wilt, Crop rotation sequence, Bacterial wilt incidence

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CHAPTER ONE

INTRODUTION

1.1 Background Information

Potato (*Solanum tuberosum* L.) plays a major economic role in the world and has been considered a major staple food in developing countries such as Kenya where it ranks second to maize in terms of utilization (FAO, 2012). Importance of potato in Kenya is anchored on its role in alleviating poverty and fighting hunger as well as income generation, thereby playing a dual role as food and cash crop. The crop is traded both in fresh and processed forms and the value chain is a source of sustainable livelihoods. Potatoes are grown by over 800,000 farmers on 160,000 hectares of land and valued at Kenya Shillings 46 billion per annum at the consumer level (Riungu, 2011). Kenya, the fifth biggest potato producer in Sub-Saharan Africa had an output of 790,000 tons in 2006 (FAO, 2008).

Potato is grown by small scale farmers, under rain-fed conditions in the high altitude, (1500-3000 meters above sea level) where Kenya's main staple food, maize has no comparative advantage. These areas include slopes around Mount Kenya such as Meru, Embu, and Kirinyaga; parts of Laikipia and on both sides of the Nyandarua (Aberdare) range that coves parts of Nyeri, Muranga, Kiambu and Nyandarua Districts. They are also grown in the highlands on Mau Escarpment (Mau, Narok and Molo), Tinderet, Nandi Escarpment and Cherangani hills. Potato growing areas are characterized by a mean monthly temperature of 18ºC with an annual rainfall ranging between 1100 mm and 2600 mm (Jaetzold *et al*., 2007).

Despite being grown on some of the most productive soils, potato production in Kenya is facing an extreme situation of low (and in some cases) decreasing productivity per unit area (Gildemacher, 2010). The major constraints to potato production in the cool highlands of Kenya including Njoro are rapid decline in soil fertility. This is occasioned by continuous cultivation without adequate replenishment of mined nutrients particularly (N), and (P), leading to negative balances of these nutrients in the soil. Soil that is low in (P) 2.9 ppm, and total N (below 0.15 %) has been reported in some potato growing areas. The situation is exacerbated by the inherent soil acidity with pH values of 4 to 5 in some regions where potatoes are grown (Kaguongo *et al*., 2008). Besides low soil fertility, the other major factor limiting potato production is occurrence of diseases such as late blight (*Phytophthora infestans*) and bacterial wilt (*R. solanacearum)*. More than 90% of potato seed planted in Kenya is uncertified, making them a major source of seed-borne diseases such as bacterial wilt. There is a huge disparity between the yield of potatoes grown under experimental field station and those in farmers' fields. While experimental fields have a potential of 40 tons ha^{-1} yield of potato the reality in farmers fields remain at an average of 7.7 tons ha^{-1}, revealing a lag in appropriate farming practices in the later case (FAO 2008). Attempts to address the decline in soil fertility through application of fertilizer has resulted in lower production because the rate being applied by farmers (13 kg N ha^{-1} on average application rate that farmers use) is below the recommended rate of 90 kg N $ha-^{1}$ and also partly because farmers with small land holding continuously plant crops on the same piece of land, practicing intensive cropping systems that mainly involve double and relay cropping of different crops without a fallow period (Kaguongo *et al*., 2008).

Of the common potato diseases, bacterial wilt (BW) is considered more problematic than late blight since it has no known chemical control procedures and many farmers do not know how to control it (Kaguongo *et al*., 2008). While it could be controlled through crop rotation and fallowing, this is not feasible due to small farm sizes which hinder effective rotation programs. In addition, there is inadequate access of certified seeds to the extent that farmers almost solely depend on informal seed sources (farm-saved, local markets or neighbors). Self-supply is the major source of seed for most farmers (Kaguongo *et al*., 2008). The quantities of certified seed potato produced are not only inadequate but also highly priced with the implication that majority of farmers resort to using seed of doubtful quality from various sources (Mureithi, 2000). This exacerbates the spread of seed-borne diseases especially bacterial wilt. However beneficial effects of rotation have been reported to include improvements in soil moisture, soil nutrients and soil structure; balanced soil microbial community; suppression of weeds and phytotoxic compounds as well as proliferation of growth promoting substances originating from crop residue. Crop rotation sequence experimented in potato cropping system is therefore expected to improve soil fertility, control soil BW and improve potato yield. Rotations of potatoes with high value crops, that improve soil fertility and suppress BW in soil not only increase potato yield but also income from the sale of the high value crops. The purpose of this study was to identify alternative crop rotation sequences that address the major constraints of potato production, namely soil fertility and bacterial wilt, with an ultimate goal of increasing potato yields.

1.2 Statement of the Problem and Significance of the Study

In spite of potato being the second most consumed crop in Kenya, there are major constraints limiting its production in the cool highlands of Kenya including Njoro. These include but not limited to, rapid decline in soil fertility because of continuous cultivation without adequate replenishment of mined nutrients particularly Nitrogen (N), Phosphorus (P), leading to negative balances of these nutrients in the soil. Applying low fertilizers and manures in, inherently low fertile tropical soils are often acidic and low in P. Diseases particularly BW (*R. solanacearum)* is of concern to farmers because; farmer-saved uncertified seed which are many times infected by BW are used by farmers. This contributes to potato yield decline. BW is soil-borne and therefore control becomes difficult. Lack of quality control during storage also leads to spread of infestation from sick to healthy tubers and there is yet no known chemical treatment of BW.

1.3 Justification of the Study

Potato is important source of food, employment and income in Kenya and an important staple food crop after maize. Potato also plays a major role in national food and nutritional security. Nevertheless, in the potato growing districts, depletion of major soil nutrients and BW infection substantially contribute to low potato yield. Sustainable solutions to the dual problem are found in building the soil's ability to provide nutrients as well as its biological resilience to suppress BW. This effort goes beyond mere application of chemicals because improvement of soil nutrients and management of BW incidence can be achieved through crop rotations, when N-fixing legumes are used in the rotation programs. Rotations also break disease cycles becoming one of the most important approaches to sustainable disease management. However, effective crop rotations patterns have been hindered because the small farm sizes farmers commonly practise monoculture practice and continuous cropping. This research therefore sought to identify suitable crop rotation patterns in potato cropping systems, with the potential to provide farmers with alternative methods of amending soil fertility and controlling BW, leading to improved yield and in effect improve potato farmers' livelihood and food security.

To address soil nutrient depletion constraint with respect to N and P and manage BW disease among small scale land holders and thus improve potato productivity in Njoro, it is necessary to introduce simple crop rotation pattern technology that suppress BW pathogen in the soil while enhancing soil nutrient contents. This is made possible when potatoes are rotated with non-solanaceous crops like legumes, *brassica* spp among others. Legumes in a rotation cycle would fix nitrogen from air, besides solubilizing P with the plant root exudates. The BW pathogen is also starved during the legume phase because the legumes are non-hosts. Residues of *brassica* spp/fresh biomass incorporated in the soil, bio-fumigates the soil. Bio-fumigation is based on incorporating soil amendment, fresh plant mass, manure into the soil, which release chemical substances, known as isothiocyanates (ITC's) suppress soil-borne pests and diseases. Plants from *cruciferous* family cabbage, radish, cauliflower release large amount of these toxic to soil-borne pests and diseases substances in the soil and are considered the best material for bio-fumigation. Soil organic matter from *Brassica* spp and other organic sources do enhance micro-biodiversity antagonistic to BW in the soil. In view of the above production constraint, the trial sought to identify; high value crops with BW suppressing potential and soil fertility enriching properties to manage soil bacterial wilt while improving soil fertility in the small scale farming community.

1.4 Objectives

1.4.1 Main Objective

To contribute towards enhanced potato production in the smallholder system of Rift Valley through sustainable crop rotation systems.

1.4.2 Specific Objectives

1. To determine the effect of crop rotation patterns on selected soil properties.
2. To determine the effect of crop rotation patterns on bacterial wilt population in soil and bacterial wilt incidence in potato crop.
3. To determine the effect of crop rotation patterns on potato growth and yield.

1.5 Hypotheses

1. Crop rotation pattern has no effect on selected soil properties.
2. Crop rotation pattern has no effect on soil bacterial wilt population in soils and bacterial wilt incidence in potato crop.
3. Crop rotation pattern has no effect on potato growth and yield.

1.6 Scope and Limitations

The study which was conducted in Egerton University research station, Njoro from (long rains of May 2012 to the long rains May 2014) covering four seasons. Pre-crop was grown during the “long rains” (April to August) and potato was grown in the “short rains” (October to December), except in the fourth season when potatoes were planted in long rains in 2014, because there was a prolonged drought during the 2013 short rains. Soil parameters studied to determine the effect of crop rotation sequence on soil properties, soil BW and potato yield were limited to plough layer (0-15 cm depth). The main limitation to this study were therefore the length of time taken to conduct crop rotation experiments; as the experiment needed an extended period of time to show clear effects of some of the parameters measured in the treatments. In addition, the trial was conducted only on a research station without on-farm trials to compare results of the study with real farm situations. The rotation systems adopted by this study tried to simulate the existing potato systems in Njoro, but it is worth noting that farmers do modify their rotation systems erratically, therefore limiting comparison between the field station results with those of farms.

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato Production in Kenya

Potato (*Solanum tuberosum* L.) is the second most important staple food crop in Kenya after maize. It is mainly grown in the Kenyan highlands including areas along the escarpments of the Rift Valley found North and West of Nairobi and on the north Eastern slopes of Mount Kenya. Potato matures in 3-4 months and is estimated to have yield of 40 t ha^{-1} and hence ideally suited to places where land is limited and labor is abundant (FAO, 2008). The crop is mainly grown at mid-elevation and highland areas (1,500 to 3,000 meters above sea level) in small holder farms. Nearly 75 % of Kenyan potato farmers cultivate on less than 0.2 hectares of land mainly two times a year (KARI, 2004). Globally, it is estimated that potato production will grow by 2.7% annually up to 2020. This exceeds the growth rate of all other major food crops, although the area under potato production in developing countries has grown by 38% while a decline of 15% over the same period in the developed world has been reported.

In Kenya, the registered average yearly growth in potato production was 5.5% from early 1990s to 2003 (FAO STAT, 2010). This growth is far less than the regional average of 38% though demand as a result of urbanization, general population increase and a shift in food consumption patterns particularly in urban centers is increasing. Increasing potato productivity with available production resources is a challenge in such areas because of population pressure. Low potato productivity has been found to be a result of declining soil fertility in many parts of Kenya because majority of small holder farmers cannot afford the recommended rate of fertilizers that is 90 kg N ha^{-1} + 230 kg P_2O_5 ha^{-1}(MoA, 2000). Some farmers use cattle manure to fertilize the potato crop but its quality is low mainly due to poor quality pastures and poor methods of handling and storage. Low productivity is also attributed to disease incidences especially Bacterial Wilt (BW) and poor quality potato seed (Ng'ang'a *et al*., 2003).

2.2 Soil Fertility under Potato Production

2.2.1 Organic Matter

Organic matter is a source of slow release nutrients and the site of water and nutrient holding capacity. Organic matter also provides the "glue" that holds soil aggregates together, which is important for good soil structure and facilitation of vigorous root exploration and adequate water, air, and nutrient movement in the soil. The primary component of organic matter is carbon, which is the source of energy for plants and microbes. As organic matter increases, microbial diversity and activity increases. The amount of organic matter being returned to the soil decreases as the number of low residue crops, such as potatoes, increases in the cropping system (Hopkin, 2004).

Promoting feasible management practices of crop residues, which can be integrated in the existing farming systems, socio-economic situations and climatic conditions, is thus very crucial. Crop residues left on soil surface as mulch have a slower decomposition rate and hence release nutrients over longer period of time, besides providing protection of soil against raindrop impact and runoff (Zeleke *et al.*, 2004). However there are several cases where leaving crop residue on soil surface (mulching) becomes a problem either due to climatic or socio-economic and farming systems. Erosion results in loss of valuable topsoil that contains important physical, chemical, and biological properties that are not as prevalent in subsoil materials (Mohr *et al.*, 2012). Research has shown that yield losses in potato occur if the layer of topsoil is less than 30.5 to 40.5 cm. Minimum tillage has been shown to work effectively in potato cropping systems to reduce water erosion, it is beneficial to plant green manure cover crop during and after potato production which greatly reduces erosion and increases the organic matter content of the soil. In addition to erosion benefits, organic matter is important for many reasons, such 'gluing' together soil particles and preserving soil moisture.

Crop diversification in terms of time and space is one of the major agronomic measures of integrated management to reduce risks of disease spread, to increase nutrient use efficiency in low-input systems and to minimize the dependence from external inputs such as synthetic nitrogen fertilizers by the integration of legume crops (Lemaga *et al.*, 2005). Potato yield and quality is strongly related to soil fertility. Closed systems for example those based on "zero-grazing" may offer specific opportunities for utilizing fodder crops as an appropriate rotation with potato.

In Kenya highland farmers tend to grow potatoes in very close rotations or even in some cases in mono-cropping as potatoes have developed to be both an important cash crop and food security crop due to lack of alternatives of other high value cash crops and inadequate knowledge of good agricultural practices. Therefore, due to the reliance on the performance of mono-cropping or poorly designed potato rotation, farmers are facing higher risks of complete crop failures by specific abiotic and biotic stress conditions, in particular due to the build–up of crop specific soil borne pest and diseases (Lemaga *et al*., 2005).

In potato based crop rotation system high value vegetables and *brassica* spp, which are non-host BW, may also be attractive rotation options for increasing yield in small holder farmers (Lemaga *et al*., 2005). Soil fertility is a result of pre-crop investment into legumes or organic residues from intercropping and animal or green manure. Improved crop rotations with leguminous crops or crops with a high production of organic matter would not only increase productivity but also activate microbiological processes in the soil affecting soil borne pathogens, having a beneficial effect on soil fertility and soil health.

2.2.2 Soil Nutrients

It is generally accepted that there are 17 essential elements required for plant growth (Havlin, 2008). The lack of any one of these essential plant nutrients can result in severe limitation of crop yield. Of the mineral elements, the primary macronutrients N, P, and K are needed in the greatest quantities from soil and are plant nutrients most likely to be in short supply in agricultural soils (Havlin, 2008). The balanced contributions of these components allow for adequate and optimum nutrients available of plant to plants.

Growing healthy potatoes for maximum yield and quality then requires that all the essential nutrients are supplied at the right rate, the right time, and the right place. Proper Nitrogen management is one of the most important factors required to obtain high yields of excellent quality potatoes. An adequate early season N supply is important to support vegetative growth, but excessive soil N later in the season will suppress tuber initiation, reduce yields. Excess soil N late in the season can delay maturity of the tubers and result in poor skin set, which harms the tuber quality and storage properties.

Phosphorus occurs in many forms, depending on factors including pH and chemical composition of the soil. While only a portion of the total soil P is available to the crop during a given growing season, the supply of available P is constantly replenished from reserves of less available P in the soil. Some of the available P may come from current year's fertilizer application, residual fertilizer, or from mineralization of organic residues. Potato plants require an adequate supply of P through-out the growing season to achieve optimum quality and yield. During the early growth stages, P stimulates the development of a vigorous root system and healthy tops. Plant demand for P peaks at tuber set and early bulking, and then slows during later bulking, when much of the nutrient demand of the developing tubers is met by translocation of P from the tops of the plants down to the roots (Hopkins, 2004).

Potato requires large amounts of soil K, since this nutrient is crucial to metabolic functions such as the movement of sugars from the leaves to the tubers and the transformation of sugar into potato starch. Potassium deficiencies reduce the yield, size, and quality of potato crop. Potassium deficiencies impair the crop's resistance to diseases and its ability to tolerate stresses such as drought and frost. Tubers adequately supplied with K are more resistant to black-spot bruising or after-cooking discoloration, while also experiencing less moisture loss and disease during storage (Hopkins, 2004).

Soil degradation and nutrient depletion due to continuous cultivation, removal or burning of crop residues, loss of nutrients through soil erosion, overgrazing between cropping seasons and inadequate use of inorganic fertilizers are the major causes of declining food production per capita in smallholder farms in Kenya. Nutrient balance studies carried out in western Kenya have shown that N and P balances were negative. On average 22 kg N, 2.5 kg P, and 15 kg K ha^{-1} are lost annually and losses can be as high as 112 kg N, 3 kg P, and 70 kg K ha^{-1} in the intensely cultivated highlands of western Kenya (Gildemacher *et al*., 2008). The losses are much higher than the estimated inorganic fertilizer use in Africa of 5 to10 kg per year emphasizing the need for soil fertility replenishment. Phosphorus limitations could partly be attributed to low native P and P-fixation by aluminum and iron oxides in the predominantly acid soils of some parts of Kenya, in addition to mining of P from the soil that is estimated at (1.5-13) kg ha^{-1} per year from small holder mixed farms. Potassium is the nutrient of greatest removal; with 55 -73 kg ha^{-1} K removed for a 45 ton ha^{-1} crop (Mohr *et al*., 2012). This nutrient removal can have a depleting effect as the frequency of potato crops increases in the rotation.

Countries with the highest levels of nutrient depletion are within the Eastern and Southern Africa, where the pattern mirrors human population pressure and its toll on natural resources. The steady fall in soil nutrients appears to be linked to poor soil fertility management driven by continuous cropping under an ever increasing population pressure; however, it has been demonstrated in Asia with a much higher population densities, where average grain yields are three times than those of Africa (Omamo *et al*., 2002). Other factors, such as mineral fixation, leaching, and decreasing mineral solubility complicate the availability of nutrients, which is one reason why soil testing needs to be the standard for fertilization rather than just basing it on removal rates. Shortening the rotation to a potato-cereal-potato-cereal cycle increases the removal to approximately 51 kg ha^{-1} P and 142 kg ha^{-1} K over the four years, most likely requiring an increase in the applied rate of both nutrients. In addition to nutritional effects, increasing the frequency of potatoes in rotation increases the erosion potential (Mohr *et al* 2012).

2.3 Bacterial Wilt (BW) and Potato Production

2.3.1 Biology and Ecology of BW

Bacterial wilt, caused by *Ralstonia solanacearum*, is the second most important potato disease in tropical and sub-tropical regions of the world after late blight (Champoiseau *et al*., 2010). In the early stages of the disease, foliage symptoms include rapid wilting of the youngest leaves at the end of the branches during the hottest time of the day. As the disease develops, all leaves may wilt quickly and desiccate although they remain green. This may be followed by yellowing of the foliage, and eventual plant death; other symptoms include epinasty, chlorosis, and stunting. Wilting is possibly a result of restricted water movement due to the formation of slime that surrounds the bacterial mass in the stem vascular bundles (Champoiseau *et al*., 2010).

Bacterial wilt is generally favored by temperatures between 25°C and 37°C. It usually does not cause problems in areas where mean soil temperature is below 15°C. Under conditions of optimum temperature, infection is favored by wetness of soil. However, once infection has occurred, severity of symptoms is increased with hot and dry conditions, which facilitate wilting of the potato plant.

2.3.2 Effect of BW on Potato Production

Bacterial wilt is, after late blight, the most important biotic constraint to potato production in Kenya. The disease was first observed in Kenya in 1940 and has spread from 1500 m to altitudes as high as 3440 m. Bacterial wilt has remained a major constraint to potato production because most of the traditional potato fields are contaminated by *R. Solanacearum* and good quality seed which is unavailable to most farmers in Kenya. Additionally, most potato growers hardly practice field sanitation or crop rotation procedures, perhaps due to limited land sizes and inadequate information to the farmers on the cause, spread, perpetuation and control options of bacterial wilt and other diseases. These factors have led to a general increase in incidence of various potato diseases leading to low potato yields (Janse and Wenneker, 2002).

2.3.3 Dissemination of BW Pathogen

The aggressiveness of the pathogen is influenced mainly by temperature and moisture; high temperature, and high soil moisture promote survival, reproduction, infectivity, and spread of the bacterium, and hence disease development. Temperature is the most important factor affecting the host-pathogen interaction as well as survival in soils. In general, increase in ambient temperature to between 30 and 35 ^{o}C increases the incidence and rate of onset of bacterial wilt on hosts such as potato. In potatoes, the bacteria is tuber borne, and is primarily disseminated through infected seed tubers (Champoiseau *et al.*, 2010). In cool conditions, such as tropical elevations above 2500 m, infected but symptomless plants may harbor the bacterium and then transmit the pathogen to progeny tubers as latent infection, leading to severe disease outbreaks when grown at warmer locations. The pathogen can also enter through stem wounds or stomata (EPPO, 2004). Wounds can occur due to cultivation activities, natural growth of secondary roots, attack by nematodes or other pests. Once introduced, the pathogen survives at soil depths of 1m or more, where microbial competition is low, or as slimy masses in the upper soil layers (Kinyua *et al*., 2001). The pathogen can survive in soil, mostly on plant debris and in the rooting system and rhizosphere of many hosts, weeds, other host crops, potato volunteers. Survival of the pathogen in the soil is reduced by extreme cold, and the presence of antagonistic microorganisms, while volunteer host plants enable bacterial survival across seasons. Race 3 also infects a number of non-solanaceous weeds asymptomatically (Pradhanang *et al*., 2000). This race has a long association with potatoes and has an optimum temperature of 27 - 28°C. Survival depends also on the race involved; race1 usually persists for many years in the soil because of its numerous hosts, while R3bv2A tends to persist for a few years due to limited hosts (Champoiseau *et al*., 2009).

2.3.4 Effect of Soil Properties on BW

Ralstonia solanacearum is one of the most important and widely distributed plant pathogenic bacteria in the tropical, sub-tropical and warm temperate climates of the world. It causes bacterial wilt disease on over 200 plant species in 50 families and remains the major biotic factor limiting growth and development of several important crops of family *Solanaceae*, including potato, tomato, eggplant, pepper and tobacco (Hayward, 1991). BW has a very wide host range and infects plants through roots. As the roots of wilted plants decay, the bacteria are released back into the soil increase the population. Infestation of potato plants by root-knot nematodes aggravates the disease. The bacterium is especially destructive in moist soils at temperatures above 24°C. It is less prevalent in high pH (alkaline soils), low soil temperature, low soil moisture and low fertility levels. Total control or eradication of BW still remains problematic to most farmers (Janse and Wenneker, 2002) with most extension messages being focusing on the use of disease resistant varieties. However, the use of resistant varieties has somehow assisted in transmission of the pathogen as most resistant varieties have latent infections (Lemay *et al*., 2003). This is probably a major reason why bacterial wilt problems have persisted in many potato growing areas. In addition cheap, effective and simple BW management options are not available to small-scale farmers.

2.3.5 Organic Compound and BW Prevalance

Soil-borne plant pathogens are frequently suppressed in organic compared to conventional farming systems (van Bruggen and Termorshuizen, 2003). This phenomenon has not been adequately investigated for *R. solanacearum*. The disease survival is found to be affected by soil type; temperature and moisture content (van Elsas *et al*., 2000). Despite reports on suppression of various pathogens in organically managed soils (van Bruggen and Termorshuizen, 2003), BW was found to survive least in loamy soil with relatively high organic matter content (4%) whilst survival was highest in soil with low organic matter content of below 2.0-2.5% (van Elsas *et al*., 2000), possibly because of the soil environment that favors diverse community of microorganism that are antagonistic to the BW pathogens.

Ammonium is known to reduce the growth of *R. solanacearum*, but was not found to be suppressive and its effect was found to be pH dependent. The mechanism of suppression of *R. solanacearum* is unknown but it was hypothesized that the effect is related to a shift in the soil microbial community towards a community with enhanced antagonism against *R. solanacearum*. The suppressive effect of soil amendment on the survival of *R. solanacearum* has also been shown to be dependent on soil type. Soil amendments with inorganic and organic mixtures reduce wilt incidence in some locations, however, more research is required to provide explicit and economically feasible types of material and doses for reliable disease management (Momol *et al*., 2000). Soils with high organic matter content like those amended with cattle manure, sun-hemp, and household compost and crop residues are reported to release chemicals that suppress BW populations. Traditional farmers' practice like adding chicken or other livestock manure which may reduce bacterial wilt under certain conditions. Phytosanitation and cultural practices are the most widely used practices for controlling bacterial wilt in the field (Champoiseau *et al*., 2010). These practices can be effective in regions where bacterial wilt is endemic, or in locations where it is present but not yet established (Champoiseau *et al*., 2010). Phytosanitation practices include planting disease-free tuber seeds, and quarantine measures, while cultural practices include crop rotation, intercropping, delayed planting, soil amendments, positive selection, and negative selection (Champoiseau *et al*., 2010). Although use of disease-free seed tubers is advocated in Kenya (Wakahiu *et al*., 2007), it is not effective as a control method because the quantities of disease-free certified seed tubers produced by the formal seed system are insufficient to meet the farmers' demands). This complicates the management of bacterial wilt as farmers rely heavily on seed tubers from informal sources, which often results in re-infection of fields (Muthoni *et al*., 2010).

Amending infested soils with Stable Bleaching Powder (SBP) at 25 kg ha^{-1} has been effective and suitable for control of bacterial wilt under green-house and field condition. Phosphorous acid salts (PAS), Phosphorous acid and its ammonium, sodium, and potassium salts and mono- and di-potassium salts are categorized as biopesticides. (Norman *et al*., 2006) reported that drenching with PAS solution could protect geranium plants from infection by *R. solanacearum*. The control mechanisms against diseases have been shown by direct actions, including the inhibition of mycelial growth, alteration or reduction of membrane metabolism, and phosphorylation reactions in the pathogen, and by indirect actions, including the stimulation of plant defensive responses.

2.3.6 Effect of Potato Cropping System on BW Population

Crop rotation with non-host plants has been reported to reduce the *Ralstonia solanacearum* concentration in the soil. Crop rotation of 5 to7 years excluding host plants has been recommended to control the bacteria in the soil (EPPO, 2004). In Kenya, crop rotation of potato with maize led to higher potato yields than continuous potato cropping in areas with high bacterial wilt incidence. However, it has also been previously reported in Kenya that rotations of maize, cowpeas, and sweet potatoes did not reduce the soil inoculum concentration of R3bv2A inoculum concentration. In addition, R3bv2A may also survive by infecting plant roots of non-host crops grown in rotation. In Mauritius, R3bv2A was reported to survive on sugar cane roots during rotation even though sugar cane is not a host plant. In Kenya, crop rotation may not be very effective because of small farm sizes in potato producing zones leading to continuous cultivation of potato on the same pieces of land or very short rotations that are inadequate to reduce the disease (Kaguongo *et al*., 2008).

2.4 Importance of Minimum Tillage in Potato based Cropping System

Cropping sequence and rotation impacts soil chemical, physical, and biological properties, such as nutrient cycling, erosion potential, organic matter, and biological diversity. Potato takes up relatively high rates of nutrients and harvested tubers remove some of these nutrients in large quantities (Mohr, 2012). The speed at which the reserve nutrients enter the biologically active pool of nutrients also varies and can be inhibited as the number of high demand crops is increased in the rotation. Plant residues are chemically complex organic substrates that upon getting to the soil play an important role in maintaining soil productivity by providing a source of nutrients and inputs to organic matter. The plant residues are also known to affect soil physical properties such as tilth (Zeleke *et al*., 2004) and water retention and availability (Sharma and Bhushan, 2001). Decomposition is essentially a biological process but is affected by abiotic factors through their effects on soil organisms. Upon incorporation into the soil, plant residues are decomposed by the soil organisms to release soluble nutrients for plant uptake.

Potatoes typically are clean-tilled both before and after the season. Most other crops are more conducive to minimum tillage practices that leave a higher percentage of erosion preventing residues on the soil surface. Pre-season tillage is common to potato planting in order to reduce disease inoculum and to hasten decomposition. Furthermore, at the end of the season the potato plant leaves little residue on the soil surface and harvesting this tuber crop is the equivalent of a thorough tillage operation (Mohr *et al*., 2012). Therefore, it is typical for the soil to be exposed to a high wind and water erosion risk from after potato production. As a result, erosion increases as the frequency of potatoes in the rotation increases. Inclusion of other low-residue crops, such as onions, carrots and beans, has a similar effect on erosion rates, which is compounded if they are root crops. It is worth noting, diversity of crops in rotation leads to a diverse soil flora and fauna, as the roots excrete different exudates that attract different types of bacteria and fungi, which in turn, play an important role in the transformation of these substances into plant available nutrients. Crop rotation therefore hinders the development of weeds, arthropod pests and short-persistent soil-borne diseases by reducing their population levels in the soil.

2.4.1 Soil Fertility Management in Potato Cropping Systems

Nitrogen and phosphorus limit crop production while soil carbon does so through limitation of the biological activity in the soil. Although judicious application of inorganic fertilizers is recognized as the most effective amendments for overcoming soil fertility decline or alleviating nutrient deficiencies, their high cost, inaccessibility, and generalized recommendations result in low, erratic and unprofitable crop responses, and limit their use, particularly on smallholder farms in eastern Africa. A fertile soil provides a sound basis for flexible food production systems within the constraints of soil and climate, which can grow a wide range of crops to meet changing needs. Balanced fertilization is a prerequisite for getting optimum yield potential of potato (Kushwah *et al*., 2005). Sustainable production of crops cannot be maintained by using chemical fertilizers alone because of deterioration in soil physical and biological environments

(Khan *et al*., 2008). However, integrated use of both organic manure and chemical fertilizers has been suggested as the best approach in providing greater stability in production and improving soil fertility status. Application of organic manures in conjunction with fertilizers improves physical, chemical and biological properties of the soil besides improving fertilizer use efficiency and crop yield.

Harvesting crops with heavy stover will reduce the amount of organic matter added to the soil, but these scenarios still result in more organic matter addition as compared to a potato crop. In potato cropping typically there is high levels of tillage. Tillage warms and dries the soil, resulting in an increase in chemical oxidation and microbial decomposition of organic matter. The net effect of tillage is a significant loss of soil organic matter (Mohr *et al*., 2012). Although soil organic matter helps sustain soil fertility by improving retention of mineral nutrients, increase the water holding capacity of soils, and increase the amount of soil flora and fauna, continuous cropping and erosion reduce the level of soil organic matter. Therefore the proportion of textural components and the amount of organic carbon content present in the soil (Rawls *et al*. 2003), affect changes in organic carbon content and soil water retention capacity.

2.4.2 Disease Management in Potato based Cropping System

Research has shown that, use of Integrated Disease Management (IDM) protocols can reduce the disease impact on crop productivity. However, information on the nutritional requirements of potato plant and on the management of soil nutrients to reduce BW Incidence is scanty (Mureithi, 2000). Combination of N and P fertilizer each at 50 kg ha^{-1} with farmyard manure at (5×10^{3}) kg ha^{-1}increased market yields significantly ranging from 216% to 400%. (Lemaga, 2005). The goal of the small-holder farmers, therefore, is to provide as much soil nutrients as possible through organic inputs and meet the short fall of the limiting nutrients through inorganic fertilizers (FAO 2008).

Improvement in soil fertility management is a major factor that may increase productivity in potato production of small holder farmers in Kenya (Gildemacher *et al*., 2010). Studies in western Kenya show that there is inadequate utilization of fertilizers even in areas where fertilizer supply is not a problem. This underlines the need for awareness and knowledge about maintaining soil fertility and the need to replace farm-exported nutrients. For example in soils like Nitisols, where the soil are inherently acidic, farmers still apply the acidic Diammonium Phosphate (DAP) , rendering the soil even more acidic. Organic manures are also not applied in sufficient quantities and are usually of low quality and subjected to nutrient loss due to poor storage. For these reasons, potato yields are far below lower than the potential yields achieved in field trials despite the abundant presence of organic fertilizers. Maintaining a high yielding potential in potatoes requires soil health and fertility management. Soil health depends on physical and chemical properties and functions, organic matter and biological activity, which are fundamental to productivity soil fertility management.

The control of *R. solanacearum* is a soil borne pathogen, has wide host range, long survival in the soil, and has wide biological variation. Some level of bacterial wilt control has been possible through use of a combination of diverse methods (EPPO, 2004; Champoiseau *et al*., 2010). These include phytosanitation and cultural practices, chemical control, biological control, and host resistance (Champoiseau *et al*., 2010). Management of bacterial wilt in potatoes calls for an integrated approach. Plant resistance is an important component of the integrated disease management. However, although many potato varieties have been found to have some degree of resistance to the disease, they still transmit latent infection. Introgression of resistance from various sources may result in high resistant varieties.

CHARPTER THREE

3.0 Effect of Crop rotation Sequence on Selected Soil properties in Potato (*Solanum tuberusum* L.) based Cropping System

Abstract

Potato yields in rain-fed areas such as Njoro, could be enhanced by crop rotation in the face of rapidly declining soil nutrients particularly Nitrogen and Phosphorus as higher cost of inorganic fertilizer contribute to their non-use. A trial on the effect of crop rotation sequence of different vegetables on selected soil properties in a potato based cropping system was conducted in Egerton University Field Station for four growing seasons from May long-rain season of 2012 to short-rain season of December 2014. The crop rotation sequence included cabbage-potato-kale-potato (CB-P-K-P), kale-potato-cabbage-potato (K-P-CB-P), carrot-potato-carrot-potato (C-P-C-P), garden pea-potato-garden pea-potato (GP-P-GP-P), kale-potato-kale-potato (K-P-K-P) and potato monoculture (P-P-P-P). Soil samples from 0-15 cm depth were taken in the beginning and after harvest of the fourth season crop. The experiment was laid out down in a Randomized Complete Block Design (RCBD) with four replications. The selected soil properties measured was soil pH, OM, total N, extractable K and available P. The data was subjected to analysis of variance (ANOVA) using SAS 9.1.3. The differences between means were separated using LSD at ($p < 0.05$) confidence level. Results showed that there was a significant legumes/vegetable effect of vegetable crop rotation sequence on some of the selected soil chemical properties measured. Crop rotation increased soil pH and available P.

Keywords: Crop rotation sequence, Soil sample, Monoculture, Seasons.

3.1 Introduction

Cropping systems in Njoro region in Kenya are based on cereal-root crops alternating between the long (LRS) and short rain seasons (SRS) using di-ammonium phosphate and calcium ammonium nitrate fertilizers. For cereals, maize is usually sown at the beginning of the LRS as either monocrop or sole crop while wheat is planted as a monocrop. Potato crop is usually planted during the SRS as a sole crop when rain-fall is becoming increasingly unpredictable and with likelihood of prolonged drought periods. Where the soils have low organic matter, the risk of water stress during the SRS is high because these soils are characterized by low water holding capacity (Ooro *et al*., 2014). The farming communities are predominantly composed of small scale farmers who have access to various organic inputs but often insufficient quantities to provide the necessary soil nutrients required for improved production. On the other hand, many small scale farmers apply inorganic fertilizer at low doses, primarily for lack of low investments and exorbitant fertilizer prices. Use of soil amendments is mainly intended to improve crop yields. Improved yields results from improved nutrient status in soil and other soil properties such as soil organic matter (Mungai *et al*., 2009).

Nutrient deficiencies especially N and P are among the major constraints of crop production in Kenya. Although this problem could be addressed by use of fertilizers, this is not always the case because of their high cost which is often unaffordable to most resource constrained farmers. Cultivation of leguminous crops in rotation or mixture with other crops has been recognized as a cost effective way by which farmers can manage soil fertility. The legumes meet some of their N requirements through N fixation thus sparing some of the soil N for subsequent crops. Crop yield usually is affected by crop sequence applied, crop growth characteristics, type of harvested product, and management practices which influence physical and chemical properties of soil, availability of water, and incidence of diseases, weeds, and pests. Increased soil N availability, when legumes are included in the rotation and reduced incidence of diseases and pests are two of the most important benefits of crop rotations. A proper succession of crops is the basis of ecological production which ensures the preservation and improvement of both crop yield and soil fertility (Kirkegaard 2000).

The nutrients available to plant particularly N and P are important constituents of protein and phospholipids. P not only enhances the root growth but also promotes early plant maturity

Potassium (K) is often referred as the quality element for crop production due to its positive interaction with other nutrients especially with nitrogen and production practices. It promotes synthesis of photosynthates and transport to fruits and grains, and enhances their conversion into starch, protein, vitamins, oil. Researchers have also indicated that it is likely to increase P availability in soil through acidizing rock phosphate, mixing rock phosphate with sulfur and organic matter as well as using rock phosphate with microorganisms including P solubilizing bacteria. Sulphur oxidizing bacteria and Arbuscular Mycorrhiza (AM) are also other methods used for enhancing P availability (Vessey, 2003). Plant residues can be used as a source of C for soil fungi and heterotrophic bacteria, which produce organic acids enhancing P availability in the rock phosphate through protonation and chelating.

Soil organic matter (SOM) plays a number of essential roles in cropping systems and its dynamics merit special interest. SOM is therefore one of the important indicator of soil quality and its management is envisaged to maintain soil fertility and promote sustainable agriculture. The rate and extent of decay and release of N from litter will depend on its quality. Immediate net mineralization of inorganic N release into the soil occurs if the N content of the recently added plant litter is higher than the microbial requirements for their own growth. If the N content is lower a net immobilization occurs as microorganisms take up N for their growth and the release of N into the soil will depend on the microorganism' turnover rate. The carbon: nitrogen C: N of the recently added plant litter can be used as an indicator of whether immediate net mineralization or immobilization will occur. If the C: N ratio is large then net immobilization occurs, and if small then net mineralization is the result. The objective of the experiment was to evaluate effect of crop rotation sequence on selected soil properties including soil organic matter content which is a modifier of both soil physical and chemical properties.

3.2 Material and Methods

3.2.1 Site description

The experiment was conducted at Egerton University Field Station which is within the Lower Highland Zone III (LH 3) Agro-Ecological Zone (Jaetzold and Schmidt, 2007) Egerton University, Njoro campus is located at Latitude 0°23′S, Longitude 35° 35′E, and at an altitude of 2200 m (a.s.l). The area receives annual average precipitation of about 1000 mm and with a mean annual temperature of 15.9 °C. The rainfall distribution is bimodal, with the first rain season occurring from April to August while the second season occurs from October to December. Commonly grown crops are maize, wheat and potato depending on the farm scale. Most farmers produce their potatoes twice a year due to the bimodal rainfall patterns. The soils at the experimental site are well-drained, dark reddish clays classified as Mollic Andosols (Jaetzold and Schmidt, 2007)

3.2.2 Treatment and Cultural Practices

Potato (*Solanum tuberusum* L) *Sherekea* variety was rotated with cabbage (CB), kale (K), carrot (C) and garden pea (GP) in the following rotation sequences, which are also treatments: CB-P-K-P, K-P-CB-P, C-P-C-P, GP-P-GP-P, K-P-K-P, and monoculture P-P-P-P. Pre-crop was planted in the "long rains" (April to August) and potato was grown in the "short rains" (October to December), except in the fourth season when potatoes were planted in long rains in 2014, because there was a prolonged drought during the 2013 short rains. Certified potato seeds were spaced 75cm × 30cm and hilled at planting, while *brassica* spp and garden-pea were planted at spacing 50cm × 30cm and 60cm × 20cm respectively. Carrot seeds were hand drilled in furrow inter-spaced 30cm. Organic and mineral amendment were uniformly applied to supply NPK 126.79 N kg ha-^{1} and 71.19 P kg ha-^{1} in all the experiment plots except legume based plots where 74.06 P kg ha-^{1} was applied to increase use efficiency for symbiotic nitrogen fixation. *Dithane M45*®, 1.7 kg ha^{-1} and *Ridomil MZ*®, 2.5kg ha^{-1}was applied to control late blight at first appearance of the first symptom. The crop rotation sequence experiment was laid down as a randomized complete block design with four replications in 2012. The plots measured 4 m x 4.5 m.

Table 3.1: The cropping Pattern

2012		2013		2014
LRS	**SRS**	**LRS**	**SRS ***	**LRS**
CB-P-K-P	P-CB-P-K	K-P-CB-P		P-K-P-CB
K-P-CB-P	P-K-P-CB	CB-P-K-P		P-CB-P-K
C-P-C-P	P-C-P-C	C-P-C-P		P-C-P-C
GP-P-GP-P	P-GB-P-GP	GP-P-GP-P		P-GP-P-GP
K-P-K-P	P-K-P-K	K-P-K-P		P-K-P-K
P-P-P-P	P-P-P-P	P-P-P-P		P-P-P-P

* Crops in the rotation (CB) Cabbage, (P) Potato, (K) Kale, (C) Carrot, and (GP) Garden pea were in the treatment. Long Rain Season (LRS) and Short Rain Season (SRS). No cropping because drought.

3.2.3 Measurements of Soil Properties

Selected soil properties pH, organic carbon, N, K and P were measured before planting the crops and after harvesting the test crop at end of the fourth rotation as described by Okalebo *et al.*, (2007).

Nitrogen in the soil is determined by Kjeldahl method, which is essentially a wet oxidation process in which concentrated sulphiric acid converts soil-N to ammonium ion form, ammonium formed is distilled and collected in boric acid indicator and determined by distilling in 0.01N hydrochloric acid. Soil is extracted with a mixture of 0.1N hydrochloric acid and 0.025 sulphuric acid. The acid serves to replace the bulk of exchangeable metal cations and sulphate anions in exchange for phosphate. It is used to determine available phosphorus and extractable potassium. The metal cations were determined using A.A spectrometer. Organic carbon was measured using the Walkly-Black method by wet digestion method of potassium dichromate and heated with concentrated sulphuric acid under controlled condition. The excess chromic acid is used to oxidize organic carbon which is titrated against standard sulphate solution, using diphenylamine as indicator to determine organic carbon. Soil pH is measured using glass electrode at a soil to water ratio of 1:2.5 by dipping the electrodes in a suitable soil-water paste.

3.2.4 Data Collection

The data for soil chemical properties was taken at end of fourth season of the experiment. Composite soil samples from 0 -15 cm depth were obtained from each experimental plot, air dried in the laboratory, sieved through a 2 mm sieve and analysed using standard analytical procedures (Okalebo *et al.*, 2006) for soil pH, organic carbon, K, P and N.

3.2.5 Statistical Analysis

The experimental data was subjected to analysis of variance (ANOVA) and differences between means were separated using LSD at ($p < 0.05$) using SAS portable version.

3.3 Results and Discussion

3.3.1 Chemical Properties Soil before Treatment

The initial chemical properties of soil before the crop rotation treatment are as in Table 3.2.

Table 3.2: Selected physical and chemical properties of the soil in the study before treatment

Property	Value
pH	6.45
O C %	2.42
Total N (%)	0.37
K ppm	27.5
Available P ppm	31.0

There were significant differences in the pH, P, and organic C. at $P < 0.05$ (Table 3.3). Legume crop rotation sequence (GP-P-GP-P) had slightly higher levels P (41.4 ppm), and (C-P-C-P) pH (5.9). In the control (P-P-P-P) rotation pattern, unexpected available P (40 ppm) and pH (5.5) was measured at the end of fourth rotation, possibly because of micro-organism activity in the rhizosphere plus presence of hydrogen ions. In a trial conducted by (Hayat, 2010) high density of

Phosphate Solubilising Bacteria (PSB) were found in soil rhizosphere cropped with potato. While possibly loss of N in crop harvest or leaching in form of ammonium form which is normally compensated in the soil by hydrogen ions, may have lowered the soil pH (Havlin, 2008).

N and P contents did not change considerably in the test season as opposed to K which was depleted one half compared to content at the beginning of the experiment. It is estimated100-120kg K ha^{-1} is removed in potato cropping (Lester 2006). The frequency of potato cropping increases nutrient removal with a depleting effect on the soil which was evident in the fourth season of the experiment compared to the soil before cropping (Table 3.2 and 3.3). The amount of organic carbon being returned to soil decreases as the number of low residue crops, such as potato cropping frequency is increased in potato cropping system. Soil normally contains 0.1% to 0.15% nitrogen, but 1 to 4 percent of total N is available to plants. However the results showed that adequate N, P and low K soil content was in the soil. Adequate amount of N, P, and K in the soil are as follows: 1-4% of (N), 20-40 ppm of (P) and 150-250 ppm of (K) respectively (Havlin 2008).

In the experiment C: N ratio was recorded highest in (K-P-CB-P) at 20, and (GP-P-GP-P) at 19 rotations sequence. Micro-organisms try to maintain C: N ratio approximately 10 among crop residues which varies greatly. Legumes and *brassica spp* generally have C: N ratio lower but close to less than 20 (Hooman and Islam, 2010). Probably some management practices, such as, cultivation can reduce organic carbon inputs to the soil, increasing/and the decomposition of soil organic materials. It is important to note that organic manure was added equally applied to all the plots in the experiment for slow release of required nutrients. Therefore it is probable that organic carbon determined was affected.

Table 3.3 Effect of crop-rotation on selected soil chemical properties measured at Njoro.

Rotation sequence	**pH**	**P(ppm)**	**K(ppm)**	**C%**	**N%**	**C:N**
CB-P-K-P	5.7 $_{ab}$*	34 $_{b}$	17.4$_{a}$	2.3 $_{b}$	0.21$_{a}$	11.47$_{b}$
C-P-C-P	5.9 $_{a}$	35.2 $_{ab}$	17.4$_{a}$	2.3 $_{b}$	0.28$_{a}$	10.58$_{b}$
K-P-CB-P	5.7 $_{ab}$	33 $_{b}$	16.2$_{a}$	2.6 $_{ab}$	0.14$_{a}$	19.84$_{a}$
GP-P-GP-P	5.8 $_{a}$	41.4$_{a}$	19.0$_{a}$	2.6 $_{ab}$	0.21$_{a}$	12.35$_{a}$
K-P-K-P	5.65$_{ab}$	32 $_{b}$	13.8$_{a}$	2.8 $_{a}$	0.29$_{a}$	16.26$_{a}$
P-P-P-P	5.5 $_{b}$	40.3$_{a}$	13.6$_{a}$	2.7 $_{a}$	0.23$_{a}$	13.66$_{b}$

*Means of the same letters within a column are not significantly different at $P < 0.05$. Crops in the rotation (CB) Cabbage, (P) Potato, (K) Kale, (C) Carrot, and (GP) Garden pea were in the treatment.

3.4. Conclusion

Based on the above crop rotation study results, there is evidence that crop rotation has an effect on some soil properties. The experiment also confirmed that large amount of K was removed from the soil in potato cropping. The scientific investigation has important implication on cropping sequence and rotation with its multiple benefits in soil fertility improvement in potato growing areas in the study region.

CHAPTER FOUR

4.0 Effect of Crop Rotation Sequence on Soil Bacterial Wilt Population and Wilt Incidence

Abstract

Bacterial wilt caused by *Ralstonia solanacearum* is a big problem in potato industry in Kenya since it reduces productivity, quality and storability of harvested tubers. The high cost of fungicides which can be used to control it renders them prohibitive to the small scale farmers. Bacterial Wilt therefore lowers productivity among small size farming community in Njoro which results in high potato losses. In order to asses alternative BW control approach accessible to small scale farmers, a study was set to evaluate effect of crop rotation on soil bacterial wilt and bacterial wilt incidence on potato production. Crop rotation pattern treatment were cabbage-potato-kale-potato CB-P-K-P, kale-potato-cabbage-potato K-P-CB-P, carrot-potato-carrot-potato C-P-C-P, garden pea potato-garden-pea-potato GP-P-GP-P, kale-potato-kale-potato K-P-K-P and potato monoculture P-P-P-P. The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replications. Initial data on soil BW population was collected at first season and then in fourth season. BW incidence was collected in the long rain season of fourth rotation. Soil bacterial wilt pathogen count measured before the treatment was 11 cfu g^{-1} . Pathogen count was below infectious level of 30 cfu g^{-1} in all the treatments. Bacterial wilt incidence which was observed in test crop during fourth season, where potato monoculture had significantly high BW incidence than vegetable/legume based crop rotation pattern at $P < 0.05$. Which indicated that despite seemingly low soil BW counts in the soil, BW virulence was suppressed in all the crop rotation patterns except the no rotation pattern? The experiment proved that, BW was virulent in no crop rotation pattern. Therefore crop rotation is important practice in BW control and potato production.

Keyword: Bacterial pathogen count, Bacterial wilt virulence, Crop rotation pattern.

4.1. Introduction

Potato is affected by bacterial wilt which is the most destructive disease followed by common scab and soft rots. Bacterial wilt or brown rot is caused by *Ralstonia solanacearum* and has one of the most damaging pathogens in Central, Eastern and Rift Valley Provinces reported to be endemic at intermediate altitudes 1390-2790 m above sea level, being mainly spread by infected seed. With increase in global temperature, the disease is likely to spread to new areas and affect potato cultivation. The disease causes damage at two stages; killing the standing plants by causing wilt and, causing rot of infected tubers in storage and transit. Another indirect loss is spread of the disease through planting of healthy looking tubers harvested from infested fields.

The pathogen survives through infected seed tubers and in plant debris in soil. Symptom-less plants may harbor the bacterium and transmit it to progeny tubers as latent infection. This could lead to severe disease outbreaks when the tubers are grown at disease free sites. High soil moisture, temperature, oxygen stress and soil type affect the survival of the pathogen. The pathogen population decline gradually in soil devoid of host plants and their debris. Incidence of the disease in these areas was found to decrease with altitude. Soil temperature and moisture were major factors influencing the severity of the disease. Most plants inoculated at high altitudes had latent infection (Mureithi, 2000). Research has shown that, crop rotation is a popular and simple method to control bacterial wilt. Pirou *et al*., (2007) reported that, the disease cannot be eradicated from soil but can be kept far below economic thresholds (Pirou *et al*., 2007). Rotation crops that show good levels of reduction of the BW causing bacteria in the soil are cabbage, cauliflower, coriander, onion, leek, carrots, and food-security crops such as sweet potato and lupine. Rotations with these crops do not only control BW, it also increases potato yields by 230% to 370% (Pirou *et al*., 2007). Interest in biological control has increased due to concerns over the general use of chemicals. The benefits of BCAs are potentially self-sustaining, spread on their own after initial establishment, reduced input of non-renewable resources, and long-term disease suppression in an environmentally friendly manner (Quimby *et al.*, 2002). The mechanisms employed by BCAs are sustained by various interactions such as competition for nutrients and space, antibiosis, parasitism, and induced systemic resistance.

Organic amendments to soil have direct impacts on plant health and crop productivity. They are advantageous because they improve the physical, chemical, and biological properties of soil, which can have positive effects on plant growth. The degradation of organic matter in soil can directly affect the viability and survival of a pathogen by restricting available nutrients and releasing natural chemical substances with varying inhibitory properties (Bailey *et al*., 2003). Carbon released during the degradation of organic matter contributes to increasing soil microbial activity and thereby enhances the likelihood of competition effects in the soil. Organic amendments to soil have been shown to stimulate the activities of microorganisms that are antagonistic to pathogens. Organic matter originates from recently living organisms and decays or is the product of decay (Fujiwara *et al.*, 2012). It is categorized into plant or animal origins, and simple organic carbons. In the previous references to an *R. solanacearum* study, different organic matter, such as plant residue (80%), animal waste (10%), and simple organic matter (10%), were shown to control bacterial wilt disease. It was found that biological amendments were generally effective for delivering microorganisms to natural soil, resulting in a wide variety of effects on soil microbial communities depending on the particular types, numbers, and formulations of organisms added. A new approach is the suppression of bacterial wilt in an organic hydroponic system through a rhizosphere biofilm that only forms on roots in the organic system (Fujiwara *et al.*, 2012).

4.2 Material and Methods

The described information on site description, experimental designs, and cultural practices is as described in (chapter 3 section 3.3). The experiment was conducted at Egerton University Field Station which is within the Lower Highland Zone III (LH 3) Agro-Ecological Zone (Jaetzold and Schmidt, 2007) Egerton University; Njoro campus is located at an altitude of 2200 m (a.s.l).

Potato (*Solanum tuberusum* L) *Sherekea* variety was rotated with cabbage (CB), kale (K), carrot (C) and garden pea (GP) in the following rotation patterns; CB-P-K-P, K-P-CB-P, C-P-C-P, GP-P-GP-P, K-P-K-P, and monoculture P-P-P-P. Potato seeds were spaced 75cm × 30cm and hilled at planting, while *brassica* spp and garden-pea were planted at spacing 50cm × 30cm and 60cm × 20cm respectively. Carrot seeds were hand drilled in furrow inter-spaced 30cm. The crop rotation sequence experiment was laid down as a randomized complete block design with four replications in 2012. The plots measured 4 m x 4.5 m.

Table 4.1: Experimental treatment and layout

Treatment	**Seasons**															
	Rep 1				**Rep 2**				**Rep 3**				**Rep 4**			
	LRS	SRS	LRS	LRS	LRS	SRS	LRS	LRS	LRS	SRS	LRS	LRS	LRS	SRS	LRS	LRS
1	*CB	P	K	P	P	P	P	P	CB	P	K	P	K	P	CB	P
2	K	P	CB	P	CB	P	K	P	K	P	K	P	CB	P	K	P
3	C	P	C	P	K	P	K	P	K	P	CB	P	P	P	P	P
4	GP	P	GP	P	K	P	CB	P	GP	P	GP	P	K	P	K	P
5	K	P	K	P	C	P	C	P	C	P	C	P	GP	P	GP	P
6	P	P	P	P	GP	P	GP	P	P	P	P	P	C	P	C	P

*****The treatment abbreviations represent the crops cabbage (CB), kale (K), carrot(C), garden pea (GP), and potato (P). Long Rain Season (LRS), Short Rain Season (SRS).

4.3 Measurements of Bacterial Wilt Pathogen population and Bacterial Wilt Incidence

4.3.1 Soil Sampling

Soil was sampled from column between guard rows at harvest from (0 -15 cm) soil depth to preserve natural soil environment condition. The soil samples were stored in a cooling box, and analyzed for soil BW within 24 hours.

4.3.2 Bacterial Wilt Pathogen Population

To ascertain soil bacterial wilt count, 1gram sample of the soil was serially diluted to 10 folds then inoculated on TZC (triphenyltetrazolium chloride) selective media agar and incubated at 28°C for 5-7 days for *R. solanacearum* determination. The Kelman's TZC agar is useful for distinguishing *R. solanacearum* among other bacteria during isolation. About 1 gm of 2, 3, 5 (TZC) was dissolved in 100 ml of distilled water, and then placed in a light-proof capped bottle autoclaved for only 8 minutes. The Basal medium composition was 10 g dextrose, 10 g peptone, 1 g casamino acids, 18 g Agar and 1000 ml of distilled water. To each liter of the melted, somewhat cooled agar basal medium, 5 ml of the TZC solution give a final concentration of 0.005% and 20 ml of the agar was poured in petri plate. The recommended BW pathogen count in the trial was 30 cfu g^{-1}. Total colony forming units (cfu's) were calculated per gram dry soil.

4.4. BW Incidence

Plots were assessed at weekly intervals to determine days to onset of first wilt symptoms. Subsequent counts of wilted plants were made at two-week intervals from the onset of the disease. At each assessment, all plants that showed either complete or partial wilting were considered wilted, these were staked to avoid double counting in subsequent assessments and also to avoid the possibility of missing those that died completely during the growth period. The counts of symptomatic plants were expressed as a percent of the total number of plants that emerged.

4.5. Statistical Analysis

The data for both BW pathogen count and incidence were subjected to analysis of variance (ANOVA). The data on BW incidence were first subjected to square root transformation to enhance interpretability of the data before analysis. The differences between means were separated using LSD whenever they were significant at 5% confidence level.

4.6. Results and Discussion

4.6.1 Effect of Crop Rotation Sequence on Soil BW Population

The no rotation pattern (P-P-P-P) had significant effect on BW population (27 cfu^{-1}) at ($p < 0.05$). BW pathogen count in the rotation patterns were significantly lower at $P > 0.05$ compared to potato monoculture pattern. In GP-P-GP-P pattern 13 cfu g^{-1} was recorded, which was 52% lower than the monoculture (cfu) in the pattern, followed by C-P-C-P at 15 cfu g^{-1} lower by 44%, K-P-CB-P at 16 cfu g^{-1} lower count by 41%, CB-P-K-P at 18 cfu g^{-1} was lower by 33% and K-P-K-P at 19 cfu g^{-1} was lower by 30% (Table 4.2). Notwithstanding, important soil factors such as warm temperature may have affected occurrence and persistence of the pathogen.

Table 4.2: Effect of crop-rotation sequence on soil BW population

Treatment	**BW population** (cfu)g^{-1}
CB-P-K-P	18_c*
K-P-CB-P	16_{cd}
C-P-C-P	15_c
GP-P-GP-P	13_d
K-P-K-P	19_b
P-P-P-P	27_a

*Means with the same letter are significantly different at $P < 0.05$. The treatments abbreviations represent the crops Cabbage (CB), Potato (P), Kale (K), Carrot(C) and Garden pea (GP).

From the experiment results, it can be deduced that vegetable/ legume-crop rotation pattern GP-P-GP-P had highest suppressive effect on BW pathogen in soil, followed by (C-P-C-P) a root-crop rotation pattern. Second least suppressive effect on BW pathogen was in patterns K-P-CB-P, CB-P-K-P combination of cabbage and kale (*brassica* spp) finally rotation pattern (K-P-K-P) *brassica* spp had the least suppressive effect on BW pathogen population.

Rotation after legume showed low BW pathogen count (13 cfu^{-1}) at $P < 0.05$, probably because there was presence of antagonistic microorganisms, attracted to legume plant roots. Similarly, in *brassica* spp crop rotation pattern there was low BW pathogen count probably beneficial microorganisms supported nutritionally from exudates of cabbage in the rotation crop. Hooman *et* *al.,* (2010) reported that, plant species have developed a defence strategy against soil borne pathogens that involves selective stimulation and support of populations of antagonistic rhizosphere microorganisms. Best example is the natural disease-suppressive soils which are the indigenous micro flora that protect plants against soil borne pathogens (Weller *et al*., 2002).

Results of the two *brassica* spp rotation sequence BW pathogen counts to no rotation pattern P-P-P-P, and CB-P-K-P showed lower pathogen count of 33% and K-P-CB-P had lower count of 41%, indicating cabbage rotation pattern suppressed BW pathogens more effectively than kale as a pre-crop to the test crop. The finding may be attributed to effect of antagonistic microorganism associated with the pre-crop favouring cabbage than kales. This may explain why K-P-K-P rotation sequence had low suppressive effect on BW pathogens, compared to cabbage because kale has lower suppressive effect on BW pathogens than cabbage.

Carrot, a shallow-rooted crop included in the crop rotation showed lower BW pathogen count than potato monoculture by 44%. Potato is apparently active at lower soil depths of 15-30 cm as opposed to carrot that is a shallow rooted crop. It is possible, low BW infestation may be a result of minimal interaction between the roots of rotation crops potato and carrot because the crops are active at different rhizosphere levels.

4.6.2 Effect of Crop Rotation Sequence on BW Incidence

The experimental plots showed mild soil BW infestation, although BW incidences were significantly high in the following crop rotation sequence indicated. The lowest incidence occurred after rotation with cabbage at 0.36% incidence in rotation sequence (K-P-CB-P), followed by rotation after garden pea at 0.64% incidence in the sequence (GP-P-GP-P). The second highest incidence to (P-P-P-P) monoculture sequence occurred in (K-P-K-P), rotation after kale at 5% incidence. Highest BW incidence occurred in P-P-P-P monoculture pattern. (Table 4.3).

Table 4.3: Effect of crop-rotation sequence on BW Incidence

Treatment	BW Incidence %	Square roots of BW Incidence %
CB-P-K-P	1.0*	1.0 c
K-P-CB-P	0.36	0.6 d
C-P-C-P	1.0	1.0 c
GP-P-GP-P	0.64	0.8 d
K-P-K-P	5.0	2.2 b
P-P-P-P	22.1	4.7a

*Means with the same letter are not significantly different at P < 0.05. The treatments abbreviations represent the crops Cabbage (CB), Potato (P), Kale (K), Carrot(C) and Garden pea (GP).

It was observed that, bacterial wilt incidence results seem to confirm the pattern of soil pathogen population in the rotation patterns. *R.solanacearum* a soil-borne pathogen which colonizes the xylem, causing bacterial wilt shows first sign of infection when wilting of individual leaves occurs on a single stem. However, the disease soon spreads down the runner and then infects the whole plant, causing it to shrivel and die. This shows the above ground wilting has its genesis in the soil where plant root system is anchored.

The suppressive capacity against BW in legume rotation is in line with a report by University of Minnesota Extension (2014), that crop rotation increases soil biodiversity and nutrient cycling capacity by supplying different residue types and food sources, reducing build-up and carry-over of soil-borne disease organisms and can help create favourable growing conditions for healthy, well-developed crop root systems. In contrast growing potato on same soil, year after year leads selectively to potato building toxicity to itself and enriching soil borne pathogens of the roots of potato. This was witnessed in the high level of BW incidence of 21% in potato monoculture P-P-P-P pattern.

However, the count below 30 cfu g^{-1} of soil BW pathogen in the experiment may be attributed to environmental condition in Njoro which might have been unfavourable for survival of *R. solanacearum* pathogen in the soil. (Pradhanang *et al.,* 2000) from India reported that, survival in-vitro and virulence of *R. solanacearum* are optimal at temperatures between 24°C and 35°C, suggesting that, lower temperatures decrease both survival and virulence of the pathogen. van Elsas *et al*., (2000) also note, that severe drought negatively affects *R. solanacearum* survival and its survival period positively correlates with wet and poorly drained soils. Reports by the above authors may support the observation that, average temperature in Njoro, which was below 24°C (Appendix 8), may have affected the optimal temperature for both survival and virulence of *R. solanacearum* as suggested by (Pradhanang *et al*., 2000), which probably explains the low soil pathogen count.

4.7. Conclusion

Results of the experiment showed that, crop-rotation reduced BW incidence in legume and *brassica spp* crop-rotation patterns. The result also showed that the no rotation pattern (P-P-P-P) increased BW of pathogen built-up in the soil and above ground. Therefore crop rotations pattern an alternative to manage BW.

CHAPTER FIVE

5.0. Effect of Crop Rotation Sequence on Potato Growth and Yield

Abstract

The constraint of low potato yields in Njoro due to BW disease and low soil fertility can be managed by appropriate crop rotations. Against this back ground, a trial using selected legume/vegetables currently used by small scale farmers in Njoro with potato crop was set up and run for four seasons, in order to evaluate the effects of crop rotation patterns on plant vigour and potato yield. The potato seed variety *Sherekea* were alternatively grown with the rotation crops (CB) cabbage,(K) kales, (C) carrot, (GP) garden pea in experiment design Randomized Complete Block (RCBD) with six crop rotation regimes replicated four times. Data was collected on plant growth vigour and potato tuber yield at end of study period. The data was subjected to analysis of variance (ANOVA) and where the effects were significantly different where the means were separated using LSD at $P < 0.05$. Result of the experiment showed that plant vigour and potato yield were significantly higher at $p < 0.05$ in rotation GP-P-GP-P followed by K-P-CB-P, and K-P-K-P compared to potato monoculture P-P-P-P rotation. The result of the trial is evidenced that the improved potato yield and plant vigour were rotation effect caused in the crop rotation patterns.

Keywords: Rotation effect, Plant vigour, Potato yield, Monoculture.

5.1 Introduction

Potato is an important crop in the Rift Valley. Small-holder Farmers with less than one hectare who grow potatoes have land holdings of less than one hectare. The crop is planted during the short rain as a sole crop and intercropped in long rain season. High cost of inputs especially seed, fungicides and fertilizers greatly limit the production of potatoes in Kenya (Kaguongo *et al*., 2008)**.** In the long run, the current potato production practices in Kenya are not sustainable due to ineffective soil-borne disease and pest management, as well as soil structure and fertility management.

A number of technical innovations including rotation could offer possibilities for improving productivity and biophysical sustainability of the cropping systems. Rotation breaks soil pathogen and pest cycles, reduces pesticide use, and soil erosion, facilitates weed control, enhances crop yield and productivity, and restores soil fertility (Carter *et al*., 2002, Edwards *et al*., 2000). Different cropping systems that reduce potential soil erosion also reduce losses of soil organic carbon and other nutrients from the system. A proper succession of crops is therefore the basis of ecological production which ensures the preservation and improvement of both crop yield and soil fertility.

Legumes have received considerable attention as an important component of sustainable cropping systems because; they can supply biologically fixed N to subsequent crops. Therefore, the potential benefits of growing legumes prior to potatoes include contributions of biologically fixed N to the cropping system, improved yield and quality, improved soil physical properties, suppression of soil-borne potato diseases, and N contributions to subsequent crops. In crop rotation experiments, monoculture is generally compared to various crop sequences. The fact that in most cases yields of cultivated crops are higher in crop rotation, compared to a monoculture under identical conditions, is explained by what has been termed as the “rotation effect”. Rotation effect is the increase in yield that crops grown in rotation show compared with crops grown in monoculture (Berzsenyi *et al*., 2000).

Crops in rotation sequence affect availability and use of water and nutrients consequently increasing or lowering crop yields. The benefits of crop rotation for land and resource protection and productivity have been identified (Berzsenyi *et al*., 2000), but many of the rotation factors, processes and mechanisms responsible for increased yield and other benefits need to be better understood. Increased nitrogen supply is sometimes responsible, but improvements in soil water and other nutrient availability, soil structure, and microbial activity and weed control, decreased insect pressure and disease incidence and the presence of phytotoxic compounds and/or growth-promoting substances originating from crop residues have also been identified as contributing factors. The purpose of the study was to investigate effect of different crop rotation sequences on plant growth and yield of potato under rain-fed conditions in Njoro and evaluate the best crop rotation sequence to improve potato yield.

5.2 Material and Methods

5.2.1 Site description

The described information on site description, treatment and cultural practices is as described in section 3.3. The treatments were designed by rotating Cabbage (CB), Kales (K), Carrot (C), Garden Pea (GP) and Potatoes (P) in six different rotation sequences namely; CB-P-K -P, K-P-CB-P, C-P-C-P, GP-P-GP-P, K-P-K-P, and monoculture P-P-P-P (Table 5.1). The treatments were laid down as a randomized complete block design with four replications. The plots measured 4m x 4.5m as explained in earlier chapter three.

Table 5.1 Experimental design

Rotation Pattern	Treatments															
	Rep 1				Rep 2				Rep 3				Rep 4			
1	*CB	P	K	P	P	P	P	P	CB	P	K	P	K	P	CB	P
2	K	P	CB	P	CB	P	K	P	K	P	K	P	CB	P	K	P
3	C	P	C	P	K	P	K	P	K	P	CB	P	P	P	P	P
4	GP	P	GP	P	K	P	CB	P	GP	P	GP	P	K	P	K	P
5	K	P	K	P	C	P	C	P	C	P	C	P	GP	P	GP	P
6	P	P	P	P	GP	P	GP	P	P	P	P	P	C	P	C	P

*****The treatment abbreviations represent the crops cabbage (CB), kale (K), carrot(C), garden pea (GP), and potato (P).

5.2.2 Data Collection

Plant characteristics measured to assess plant growth performance were plant height (terminal stem length) of the selected 55 plants were measured at bulking stage when plant has 50% flowered. Total number of 55 plants were selected per plot for measurement from the middle 5 rows the weights measured at harvest were averaged then converted to t ha^{-1}.

In determining the fresh tuber yield, all the plants in the inner five rows were harvested by uprooting the potato plant and sorting the tubers into the three grades. The grades were separated into the following category: ware measuring more than 30 mm, seed less than 30 mm and chat less than 10 mm.

5.2.3. Statistical Analysis

The experimental data was subjected to analysis of variance (ANOVA) and differences between means of plant growth and yield were separated using LSD test 5 at $p < 0.05$.

5.3. Results and Discussion

5.3.1 Plant Vigor

The experiment results showed that there was significant difference in the effect of crop-rotation pattern on plant growth and number of tubers at $P < 0.05$ in all the rotation patterns compared to potato monoculture P-P-P-P (Table 5.2). As observed earlier, BW proliferation was in P-P-P-P rotation pattern, it may have contributed to reduced plant vigour in the no rotation.

Table 5.2: Effect of crop-rotations on plant height (cm) and yield of potato yield ton ha^{-1}.

Treatment	Plant height (cm)
CB-P-K-P	27.8_a*
K-P-CB-P	27.8_a
C-P-C-P	28.0_a
GP-P-GP-P	29.5_a
K-P-K-P	29.0_a
P-P-P-P	23.5_b

*Means with different letters within a column are significantly different based on $P < 0.05$. CB, GP, K, C, and P are cabbage, garden pea, kale, carrot and potato, respectively, in the rotation sequence

5.3.2 Potato Yield

The potato yield in rotation patterns GP-P-GP-P measuring 15.7 ton ha^{-1} and CB-P-K-P with 12.3 ton ha^{-1} were pronounced against potato monoculture P-P-P-P with 8.1 ton ha^{-1} (Table 5.3). The potato yield may be attributed to effect of rotation patterns on potato. The reason for increased yields is not always clear, and in most cases it is probably not due to a single cause, but growing a variety of crops in sequence has many positive effects on soil fertility.

Ware and seed tubers were less in number in no rotation pattern compared to the other treatments. It is further observed that, the number of chat is higher at $P < 0.05$ in rotation pattern P-P-P-P. Whereas in no-rotation pattern P-P-P-P, ware and seed were less than in the rest of the rotation patterns. Possibly the low yield in P-P-P-P pattern could be explained by insufficient nutrients to the plant in the growth process.

Table 5.3: Effect of crop-rotations on yield of potato yield

Treatment	% numbers of tubers per plot			Yield ton ha^{-1}
	Ware (diameter above 30 mm)	Seed (diameter below 30 mm)	Chat (diameter below 10 mm)	
CB-P-K-P	41_a	40_a	18_a	12.3_b
K-P-CB-P	42_a	39_a	19_a	13.8_{ab}
C-P-C-P	44_a	33_a	23_a	13.6_{ab}
GP-P-GP-P	40_a	36_a	24_a	15.7_a
K-P-K-P	45_a	40_a	14_a	13.6_{ab}
P-P-P-P	41_b	24_b	35_a	8.1_c

*Means with different letters within a column are significantly different based on $P< 0.05$. CB, GP, K, C, and P are cabbage, garden pea, kale, carrot and potato, respectively, in the rotation sequence

In a diverse rotation, deep-rooted crops alternate with shallower, fibrous-rooted species to bring up nutrients from deeper in the soil which captures nutrients that might otherwise be lost from the system. Legumes fall under this grouping. Differences in plant rooting patterns including root density and root branching at different soil depths also results in more efficient extraction of nutrients from all soil layers when a series of different crops is grown. *Brassica* spp have deep roots, able to extract nutrients from deep the soil.

It is possible P was solubilized by (PSB) that colonized the potato root system. The significance of the study may be attributed to high yield under rotation pattern GP-P-GP-P to potato and garden pea a legume crop which research has confirmed to fix atmospheric N to the system. It has fibrous root network that captures nutrients including phosphorus (Vance *et al*., 2003). Legumes are of special interest in crop rotations because of their ability to fix nitrogen to soil. Notwithstanding monoculture rotation pattern contributes to proliferation of diseases with adverse effects on crop yields. Acosta-Martinez *et al.,* (2008) reported that, potato yield which declined substantially after 2 years of monoculture pattern, was accompanied by increase in disease incidence. Changes of soil organic carbon, and Total N and electrical conductivity were responsible for *fusarium* enrichment. The disease incidence resulted in low plant vigor and decline in potato yield as confirmed by the current trial in the monoculture rotation pattern.

It was observed that, the rotation patterns K-P-CB-P and K-P-K-P had the highest yields 13.8 ton ha^{-1} and 13.6 ton ha^{-1}, respectively. The high yields may be explained by action of (PSB) Phosphorus Solubilising Bacteria that contributes P by colonizing deep-rooted *brassica spp* rotation crops. Because P is a vital for development and growth of potato which subsequently results improved yields. Although shallow-rooted crop such as carrots had high yields in the trial it could however be attributed to findings that high yields after carrot cropping maybe as a result of little exploitation of soil nutrients by carrots at lower soil depths of 15-30 (cm), where the potato is apparently active. A study done in Mansehra (Pakistan), to ascertain soil characters for agricultural significance with main focus on their phosphate solubilizing ability/capacity had this result. Population density of (PSB) Phosphate Solubilizing Bacteria from vegetable fields was found highest in the rhizosphere soil of vegetable *Brassica rapa* ($5.33x10^9$) followed by *Solanum tubersum* L ($2.31x10^9$), (Hayat, 2010).

5.4. Conclusion

The study findings demonstrate importance of vegetable/legumes in crop rotation. It further confirms that potato monoculture leads to low potato yields. Therefore potato yields among small-scale farmers in Njoro can improve when findings of the study is adopted in their potato production practice.

CHAPTER SIX

General Discussion, Conclusion and Recommendation

6.1 General Discussion

This study evaluated the effect of crop rotation sequence on soil properties and BW population in potato cropping system. It was set to specifically assess the effect of crop rotation sequencing of vegetables commonly grown by Njoro small-holder farms on their effectiveness on control of BW and BW Incidence. Finally, the study determined the effectiveness in improving soil fertility, managing BW and improving potato yield. The study has further shown that despite the short term crop rotation period, legume and carrot crop rotation sequence had higher level soil pH compared to potato monoculture sequence. While majority of crop rotation sequences showed slight increase in N and P soil properties.

This study further showed that, BW incidences were significantly higher at $P < 0.05$ by 22% in P-P-P-P monoculture sequence compared to rotation sequence K-P-K-P kales at 5% then garden pea GP-P-GP-P at 0.64% and the least occurred in rotation after cabbage K-P-CB-P at 0.36%. Finally the study has shown that, effect of crop-rotation pattern on plant growth was highest with crop rotation sequence garden pea GP-P -GP-P by 26% compared to potato monoculture P-P-P-P heights. The grading of the tubers in rotation pattern with garden pea was significantly high ($P< 0.05$) GP-P-GP-P by 45% compared to the monoculture rotation pattern. The potato yields were significantly higher in rotation patterns GP-P-GP-P with 15.7 ton ha^{-1} and CB-P-K-P with 12.3 ton ha^{-1} against potato monoculture P-P-P-P with 8.1 ton ha^{-1}. With relatively improved N conditions there was significant increment in nitrogen fixation (using shoot growth as reliable proxy). This indicates that N and P were necessary for optimum potato production.

6.2 Conclusion

1. It can then be deduced from the study that, despite the short term rotation trial, pH and P was improved in the soil, as result of crop rotation.
2. Soil BW and BW Incidence was significantly suppressed in all crop rotation patterns except in the no rotation pattern, proving that crop rotation enhanced soil property, which controlled built-up of BW disease in soil and above ground.

3. The improved yields in crop rotation pattern is a demonstration of potential in crop rotation as opposed to no rotation pattern, as continuous cropping has been commonly practised by small scale farmers.

6.3 Recommendations

1. Crop rotation effects are additive and usually tend to have impact after longer duration. The experiment was conducted for four seasons; I would recommend that the experiment should be run for a longer duration in order to obtain measurable results or trends.
2. The improved yields in all the rotation patterns are a benchmark to discourage continuous mono-cropping among the small-scale farmers in Njoro. In the present scenario, vegetable/legumes rotation (GP-P-GP-P and *Brassica* spp (K-P-CB-P) rotation patterns should be encouraged for adoption to small scale farmers.
3. The experiment was on station, therefore for better comparison a similar trial should be conducted in real small-scale on-farm setting.

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APPENDICES

Appendix 1: Analysis of variance for soil pH

Source	DF	S/Squares	Mean Square	F Value	Pr> F
Model	17	27.41111111	1.61241830	13.40	<.0001*
Error	54	6.50000000	0.12037037		
Corrected Total	71	33.91111111			

***** Significant at 1% level.

Appendix 2: Analysis of variance for Carbon %

Source	DF	S/Squares	Mean Square	F Value	Pr> F
Model	17	11.02277778	0.64839869	3.57	0.0002*
Error	54	9.81000000	0.18166667		
Corrected Total	71	20.83277778			

***** Significant 5% level.

Appendix 3: Analysis of variance for Nitrogen %

Source	DF	Squares	Mean Square	F Value	Pr> F
Model	17	34.75902778	2.04464869	9.35	<.0001*
Error	54	11.80750000	0.21865741		
Corrected Total	71	46.56652778			

***** Significant at 1 % level.

Appendix 4: Analysis of variance of Phosphorus

Source	DF	S/Squares	Mean Square	F Value	Pr> F
Model	17	1719.836111	101.166830	1.99	0.0292*
Error	54	2751.275000	50.949537		
Corrected Total	71	4471.111111			

***** Significant at 5% level

Appendix 5: Analysis of variance of Potassium

Source	DF	S/Squares	Mean Square	F Value	Pr> F
Model	17	5677.46403	333.96847	3.87	<.0001
Error	54	4656.87250	86.23838		
Corrected Total	71	10334.33653			

***** Significant at 1 % level.

Appendix 6: Analysis variance of Bacterial wilt Incidence %

Source	DF	Sum of Squares	Mean Square	F Value	Pr> F
Model	8	1692.368333	211.546042	3.71	0.0138
Error	15	854.585000	56.972333		
Corrected Total	23	2546.953333			

* Significant at 5 % level

Appendix 7: Analysis of variance of crop yield

Source	DF	Sum of Squares	Mean Square	F Value	Pr> F
Model	11	274.2316667	24.9301515	2.21	0.036
Error	36	405.5850000	11.2662500		
Corrected Total	47	679.8166667			

* Significant at 5 % level

Appendix 8: Annual rainfall and temperature for Njoro, period between 2012 and September 2014

Month	**Rainfall in (mm)**			**Temperature**		
	2012	**2013**	**2014**	**2012**	**2013**	**2014**
January	0	42.7	7.1	21.1	20.6	21.5
February	16.3	2.5	23.5	21.3	21.9	21.5
March	31.6	85.7	122.8	22.5	21.3	21.3
April	387	239.7	48.7	20	20.3	21.0
May	181.8	70.7	143.7	19.7	20.7	21.1
June	166.2	137.7	95.1	18.7	18.9	20.3
July	87.2	169.3	70.0	17.6	18.8	19.2
August	220.3	99.4	143.2	18.7	18.5	19.3
September	192.4	154.2	82.7	19.4	20.3	20.2
October	94.3	68.5	-	20	20.7	-
November	26.6	78.6	-	19.7	19.8	-
December	152.1	185.4	-	19.3	19.3	-
	Total			**Mean**		
	1555.8	**1334.1**	**736.8**	**19.8**	**20.1**	**20.6**

Source: Egerton University, station 9035092

Appendix 9: Comparison of rotations for performance in yield and vigor

Comparisons significant at the 0.05 level are indicated by ***.

Treatment Comparison	Difference Between Means	95% Confidence Limits		
5 - 6	1.1075	-1.1545	3.3695	
5 - 1	2.1625	-0.7577	5.0827	
5 - 3	2.1925	-0.7277	5.1127	
5 - 4	3.0825	0.8205	5.3445	***
5 - 2	3.0825	0.1623	6.0027	***
6 - 5	-1.1075	-3.3695	1.1545	
6 - 1	1.0550	-2.1440	4.2540	
6 - 3	1.0850	-2.1140	4.2840	
6 - 4	1.9750	-0.6370	4.5870	
6 - 2	1.9750	-1.2240	5.1740	
1 - 5	-2.1625	-5.0827	0.7577	
1 - 6	-1.0550	-4.2540	2.1440	
1 - 3	0.0300	-3.6639	3.7239	
1 - 4	0.9200	-2.2790	4.1190	
1 - 2	0.9200	-2.7739	4.6139	
3 - 5	-2.1925	-5.1127	0.7277	
3 - 6	-1.0850	-4.2840	2.1140	
3 - 1	-0.0300	-3.7239	3.6639	
3 - 4	0.8900	-2.3090	4.0890	
3 - 2	0.8900	-2.8039	4.5839	
4 - 5	-3.0825	-5.3445	-0.8205	***
4 - 6	-1.9750	-4.5870	0.6370	
4 - 1	-0.9200	-4.1190	2.2790	
4 - 3	-0.8900	-4.0890	2.3090	
4 - 2	0.0000	-3.1990	3.1990	
2 - 5	-3.0825	-6.0027	-0.1623	***
2 - 6	-1.9750	-5.1740	1.2240	
2 - 1	-0.9200	-4.6139	2.7739	
2 - 3	-0.8900	-4.5839	2.8039	
2 - 4	0.0000	-3.1990	3.1990	

Means with the same letter are not significantly different.

Grouping		Mean	N	rotation
	A	15.738	8	4
B	A	13.813	8	2
B	A	13.563	8	6
B	A	13.550	8	3
B		12.288	8	1
	C	8.100	8	5

Tests (LSD) for height

Alpha	0.05
Error Degrees of Freedom	36
Error Mean Square	17.68597
Critical Value of t	2.02809
Least Significant Difference	4.2645

Means with the same letter are not significantly different.

Grouping	Mean	N	rotation
A	28.975	8	4
A	28.738	8	6
A	27.525	8	1
A	27.363	8	3
A	27.175	8	2
B	22.800	8	5