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Factors contributing to spread and population build-up of potato cyst nematodes in smallholder farms in Nyandarua County, Kenya

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The rate of spread and buildup of potato cyst nematodes (PCN) poses a significant threat to potato production in Kenya. A study was conducted to determine factors that could be contributing to the rapid spread and increase in population density of the nematodes in smallholder farms in three agro-ecological zones, namely Upper Highland-3 (UH3), Upper Highland-2 (UH2), and Lower Highland (LH4) of Nyandarua County. A stratified random sampling procedure was used to draw a sample of 65 farms for the study. A total of 62 (95.1%) samples out of 65 were infested with PCN. A significantly ($P \leq 0.05$) lower PCN count of 63.1 cysts was recorded in LH4 compared to 203.7 and 289.2 cysts/300cc of soil in UH2 and UH3, respectively. Sandy clay loam soil had a significantly ($P \leq 0.05$) higher number of cysts in LH4-229.6, UH2-460.1, and UH3-458.5 cysts/300cc compared to sandy clay soils, which had 2.0 cysts/300cc, and clay loam soils, which had 4.3 cysts/300cc soils in LH4. Nematode numbers were higher, up to 302 cysts, in farms growing more than one potato crop cycle in a year, compared to 197 cysts/300cc in farms where one potato crop cycle was practiced per year. The number of cysts recovered from soil adhering to farm tools, footwear, and potato tubers were 2.6-13.8, 1.8-8.8, and 2.8-12.9 cysts/50cc soil, respectively. Only 15% of the farmers used certified seed, while the rest used farm-saved tubers. A commonly grown variety, Shangi, had significantly ($P \leq 0.05$) the highest cyst counts of 463.1 cysts/300cc soil. Very few farmers showed any elements of IPM strategies, probably due to their limited knowledge of the pest and the available strategies. These findings reaffirm the need for an integrated approach incorporating crop rotation, planting of disease-free tubers, resistant varieties, and field sanitation, as well as enhancing farmers' knowledge on management of the pest, in an effort to reduce the spread and buildup of PCN.

Key words: *Globodera rostochiensis*, prevalence, *Solanum tuberosum*, site-specific factors.

INTRODUCTION

In Kenya, potato (*Solanum tuberosum* L.) is an important staple food crop after maize in terms of consumption and volumes produced (MoALF&C, 2021). It is estimated that the area under potato production is about 176,252 ha with

production volume of 1,859,7762 t (FAOSTAT, 2022) produced by just over a million farmers annually. However, productivity of the potato crop has been declining due to several factors that include both biotic and abiotic factors.

Potato cyst nematodes (PCN), *Globodera* species pose a potential or real threat wherever potatoes are grown.

They are specialised pathogens of solanaceous species (Sabeh et al., 2019) and the most economically important parasitic nematodes of potato. It is estimated that two of the species, *Globodera rostochiensis* and *Globodera pallida*, are responsible for the loss of 9% of the crop worldwide (Turner and Subbotin, 2013). Total losses of potato production can however occur when no control or containment strategies are employed. A potential third species was reported by Skantar et al. (2011) and has subsequently been described as *Globodera ellingtonae* (Handoo et al., 2012). However, its pathogenicity to potato is inconsistent (Zasada et al., 2019).

G. rostochiensis is one of the emerging pests in East Africa and was first detected in Kenya in 2014 (Mwangi et al., 2015) and in Uganda and Rwanda in 2018 (Niragire et al., 2019). Surveys carried out in Kenya have shown that the pest has a wide distribution particularly in the potato growing counties (Haukeland, 2016; Mburu et al., 2020). To date, PCN have been detected in 126 countries (79 for *G. rostochiensis* and 55 for *G. pallida*) (CABI, 2021 a,b).

Potato cyst nematodes are economically important pathogens of both ware and seed potato crops. Potato crops infested by PCN are often characterized by the crop turning yellow, slow growth, moisture stress and weak plants. Heavily infested soils can cause yield losses in potato crops of up to 70% (Mburu et al., 2020; Ozarslandan, 2019). Apart from the direct losses in potato, PCN damage is usually accompanied by secondary infections caused by other pests and diseases (Moxnes and Hausken, 2007). Potato cyst nematodes have short cycle and multiply rapidly, thus maintaining a high population threshold complicating its management.

A number of studies have previously been undertaken to determine relationships between abiotic soil parameters and plant-parasitic nematode populations. Factors such as soil characteristics, host crop and cropping practices have been shown to be important with regard to occurrence and density of nematodes (Simon, 2015; Fajardo et al., 2011). Soil characteristics are a major factor that affects the distribution and densities of PCN (Simon, 2015). Fajardo et al. (2011) reported that sandy soils presented a high population density of plant parasitic nematodes due to ease of mobility and infectivity as compared to clay soils in vineyards. Mburu et al. (2020) observed that the routine use of farm-saved tubers for seeding encourages and perpetuates the spread of PCN. Phillips (1989) reported that rotational gaps of 5 years or more are needed in the absence of other control measures to prevent undue yield losses due to PCN infections.

Gartner et al. (2021) noted that tolerant and susceptible cultivars, planted in infested land can lead to a very high

prevalence of PCN by increasing nematode population levels, while still giving acceptable yields, which thwarts PCN management programmes. A similar observation was made by Dandurand et al. (2019) who noted that if they are left uncontrolled, dramatic increases in nematode populations can occur in the presence of a susceptible host. Weed control is very important in potato production because some weeds not only serve as alternate hosts to nematodes, but they can also interfere with management of nematodes by providing protection from pesticides and adverse environmental conditions (Thomas et al., 2004, 2005). Good farm hygiene, including cleaning of equipment and machinery, will help minimize spread between fields (Price et al., 2021).

Trap cropping has been successfully used to reduce cyst nematode populations by more than 80% (Halford, et al., 1999). Growing of ware potato in monoculture and the use of short rotations has led to the increase of PCN populations in infested fields (Grubisic et al., 2007). Additionally, annual increase (148%) of potato cyst nematode was extensively studied in volunteer potato crops by Dewar et al. (2000).

Soil fumigants have long been used effectively to reduce PCN populations below the economic threshold level (Luc et al., 2005; Zasada et al., 2010). However, many of them have been phased out of general use due to their toxic effects on the environment. Although it has been established that PCN is widespread in the major potato-growing areas in Kenya, information on factors contributing to the rapid spread and buildup of population density is scarce. A study was conducted to investigate the relationship between the spread, population buildup of PCN, and site-specific factors that may have influenced the incidence and population densities of PCNs in Nyandarua County, Kenya.

MATERIALS AND METHODS

Study area

The study was carried out in Nyandarua County, Kenya, located at longitude 00° 55' East and latitude 03° 60' 62" South. The county was purposively selected for the study due to: (i) its importance in potato production, (ii) its long history of growing potatoes, (iii) its diverse cropping systems, (iv) reported incidence of PCN, and (v) the presence of various agro-ecological zones where potatoes are grown. Three main agro-ecological zones (AEZs) formed the focus of the study: Upper Highland (UH3), represented by Kinangop sub-county; Upper Highland (UH2), represented by Ol Jororok sub-county; and Lower Highland (LH4), represented by Kipipiri sub-county.

The study sites had average annual rainfall ranging from 1000 to 1250 mm in UH2 and 800 to 1000 mm in LH4. The temperatures ranged from 11-20°C in UH3 and UH2 and 15-25°C in LH4. The

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altitude of the three AEZs ranged from 2190 to 3000 m above sea level (masl). Specifically, the altitude in UH3 was 2330 to 2370 masl, in UH2 it ranged from 2400 to 3000 masl, and in LH4 it varied from 2190 to 2280 masl.

Data collection tool

Data on site-specific factors and PCN population density, source of planting material, farmers' knowledge of PCN, potato varieties grown, disease incidence, cropping systems, and potato cycles per year were collected using a questionnaire. The questionnaire was pretested on 10 farmers in UH3, Nyandarua County, and subsequently revised. The final version included both open-ended and closed questions.

Sampling procedures

Farmers were selected using stratified random sampling techniques. Three major potato-growing agro-ecological zones (AEZs) were chosen, and within each AEZ, farmers were randomly selected from a list of potato growers obtained from local agricultural extension offices across all AEZs. The required soil sample size was determined using the formula (Cochran, 1977):

$$n = Z^2 PQ / E^2$$

where n is the sample size, Z is 95% confidence level (standard deviation of 1.96), P is the prevalence of PCN reported in the area which is 90% (Haukeland, 2016), Q is $P-1$ and E is margin of error 8%.

Field survey

Interviews were conducted in farmers' potato fields to permit cross-checking of their answers with field observations. A total of 65 farmers, comprising 25 from UH3, 20 from UH2, and 20 from LH4, were interviewed. The occurrence of bacterial wilt (*Ralstonia solanacearum*), viruses, and late blight in farmers' fields was recorded as either present or absent during the farm interviews.

Soil samples collection

Soil samples were collected from 65 farms where the field survey was conducted in the three AEZs (25 from UH3, 20 from UH2, and 20 from LH4) using a soil auger. Although UH3 had more samples, this was due to its larger area. The soil samples were collected from the potato rhizosphere at a depth of 0-30 cm from 10 plants at the maturity stage, selected randomly. The subsamples from each farm were pooled to create a composite sample of 600 g. Additionally, 10 soil samples per farm were collected from agricultural tools (jembes), seed potatoes, and footwear (gumboots and shoes) from stores in each AEZ. Global Positioning System (GPS) readings were recorded at the sampling locations and used as a geo-reference point for the sample collection and interview sites. Geographical coordinates for each field were mapped using ArcGIS 10.2.2 computer software.

Quantification of PCN levels

Soil samples were analyzed for PCN by thoroughly mixing the composite sample from each farm. A 300 cc subsample was then

collected, and the presence of cysts was determined using the Fenwick can method (Fenwick, 1940). The extracted cysts, if present, were picked and counted under a dissecting microscope (Leica microscope M 275 with KL 1500 illuminator) at 10× magnification. To determine egg viability, three cysts were crushed, and the eggs were counted under the same microscope at 10 and 40× magnification using a counting dish. Cyst counts were expressed as numbers per 300 cc of soil, while egg counts were recorded as eggs per cyst or eggs per gram of soil.

Soil chemical and physical analysis

Two hundred grams of soil samples were collected from each of the 65 farms and analyzed for their physical and chemical characteristics at the University of Nairobi's (UoN) Department of Land Resource Management and Agricultural Technology (LARMAT) Soil Fertility Laboratory.

Chemical analysis

Soil samples were subjected to chemical characterization using the following protocols: Soil organic carbon (SOC) was determined using the Walkley-Black method (Nelson and Sommers, 2018). Total nitrogen (N) was analyzed using the micro-Kjeldahl digestion-distillation method (Black, 1965). Available phosphorus was determined using the molybdenum blue colorimetric method with a $\text{HClO}_4\text{-H}_2\text{SO}_4$ solution for digestion (Qaswar et al., 2019). Available soil elements, including sodium (Na), calcium (Ca), potassium (K), magnesium (Mg), and manganese (Mn), were determined using absorption spectrometry (Sims, 1991). Soil trace elements, including iron (Fe), zinc (Zn), and copper (Cu), were determined using the colorimetric method. Soil pH was determined using a glass electrode on a Hanna pH meter (Conkling and Blanchar, 1988). Electrical conductivity (EC) was measured in dS m^{-1} as described by Oztan and Ulgen (1961).

Physical analysis

A subset of the 65 samples was used to evaluate the relationship between soil texture and PCN population densities. Soil particle size analysis was conducted from each of the samples from the three agro-ecological zones using the modified hydrometer method (Gee and Bauder, 1986). The proportion of clay (0–2 μm), silt (2–50 μm) and sand (50 to >200 μm) was determined by the Bouyoucos method (Phogat et al., 2015).

Data analysis

Potato cyst nematode cysts and egg infestation levels were classified according to Jones (1970) as follows: absent (0 cysts/100g soil and 0 eggs/g soil), low (1-9 cysts/100g soil, 1-14 eggs/g soil), moderate (10-19 cysts/100g soil, 15-30 eggs/g soil), fair (20-39 cysts/100 g soil, 31-60 eggs/g soil), fairly high (40-80 cysts/100g soil, 61-120 eggs/g soil), and severe (over 81 cysts/100g soil, over 121 eggs/g soil). Potato cyst nematode egg and cyst infestation levels were mapped using GIS mapping software (Arc-GIS). A 5-color scheme was used to project corresponding cyst and egg density levels onto sampling sites.

Survey data was analyzed using descriptive statistics, data exploration, and cross-tabulations based on the Statistical Package for Social Sciences (IBM SPSS) version 26 computer software. Parameters on nematode frequency of occurrence, mean population density in 300 cc, relative density, and greatest density (maximum

value from the range of population density in 300 cc) were determined in relation to soil characteristics and farming practices.

Potato cyst nematode incidence was assessed using the formula: $\{(\text{Number of farms having PCN} \div \text{Total number of farms}) \times 100\}$. The relationship between PCN population density and soil characteristics was determined using correlation analysis.

RESULTS

Farmer's knowledge in relation to PCN population density

A total of 40 (61.5%) farmers out of 65 were not aware of PCN as a potential threat to potato production. Out of the 65 farmers interviewed, 25 had some knowledge on the pest (Figure 1). While none of the farmers had knowledge of IPM strategies against the pest.

Occurrence and population density of PCN infecting potato farms

Potato cyst nematodes were recovered from 62 farms (95.4%) of the 65 samples collected. A high incidence of 100% was observed in UH3 and LH4. The population density of PCN was not significantly different in UH3 and UH2 with each having 203.7 and 289.2 cysts/300 cc of soil, respectively but were significantly high compared to that of LH4 which had 63.1 cysts/300 cc soil (Table 1).

Distribution and population density of PCN in different AEZs

The geographic distribution of PCN infestation is presented in Figure 2a and b. The PCN infestation levels of the sampled farms varied, with 3.5% of farms having no infestation (0 cysts), 40.0% having low infestation (1-9 cysts), 6.2% having moderate infestation (10-19 cysts), 4.2% having fairly high infestation (20-39 cysts), 21.5% having high infestation (40-80 cysts), and 24.6% having severe infestation (≥ 80 cysts) per 100 g of soil. The detection of viable PCN eggs also varied, with 12.3% of farms having no eggs, 4.2% having moderate levels (1-30 eggs), 6.2% having fair levels (31-60 eggs), 18.5% having fairly high levels (61-120 eggs), 18.5% having high levels (121-240 eggs), and 40% having severe levels (≥ 240 eggs) per gram of soil. The most frequent population density was that with more than 240 eggs per gram of soil (40% of infested sites) and that with less than 9 cysts per 100 g of soil (40% of infested sites) across all three AEZs (Figure 2a and b).

Relationship between PCN densities with temperature, rainfall level and altitude

A significantly ($P \leq 0.05$) lower PCN count of 63.1 cysts/

300cc was recorded in LH4 where rainfall was less than 1000 mm and the temperature range was 18-25°C compared to 289.2 and 203.7 cysts/300cc in UH3 and UH2, respectively. The average annual rainfall was above 1000 mm and temperature was between 11-17°C (Table 2).

Effects of soil physical properties on potato cyst nematode population density

The study area soils were categorized into six textural classes namely clay loam, loam, sandy clay, sandy clay loam, sandy loam and clay (Table 3). The PCN population density differed significantly with the different soil textural classes. Sandy clay loam soil had a significantly higher number of cysts/300cc of soil in all the three AEZs compared to other soil textural classes. The lowest mean cysts (2.0 cysts /300cc soil) were registered in sandy clay soils in UH2 (Table 3).

Effects of soil chemical properties on potato cyst nematode population density

PCN population had a significant ($P \leq 0.05$) positive correlation coefficient = r with organic carbon in UH3- $r=0.265$, nitrogen UH3- $r=0.253$, phosphorous LH4- $r=0.205$, calcium UH3- $r=0.265$, zinc LH4- $r=0.223$ manganese UH3- $r=0.226$ (Table 4). A significant negative correlation coefficient = r was observed between PCN density with soil pH in UH3 - $r=0.399$, potassium UH3 - $r=0.416$, iron LH4 - $r=0.340$ calcium UH3 - $r=0.464$, copper UH3 - $r=0.286$, magnesium UH3 - $r=0.272$ at ($P \leq 0.05$) (Table 4).

Effect of cropping practices in relation to potato cyst nematodes population density

Number of potatoes cropping cycles in a year

Farms where four potato crop cycles were grown per year had significantly ($P \leq 0.05$) higher cyst counts of 302 cysts/300 cc of soil compared to the rest. Farms where only one potato crop was planted in a year had the least cyst count of 38.5 cyst/300 cc (Figure 3).

Intercropping, mono-cropping and relay cropping

Almost half (47.7%) of the potato farmers practiced mono-cropping; while 46.2%, intercropped and 4% relay cropped. Potato cyst nematodes cyst numbers were highest (344 cysts/ 300 g) in farms where potatorelay cropping was practiced in UH3. The lowest number of cysts nematode was recovered from intercropped potato farms having 185 cysts/300 cc (Table 5).

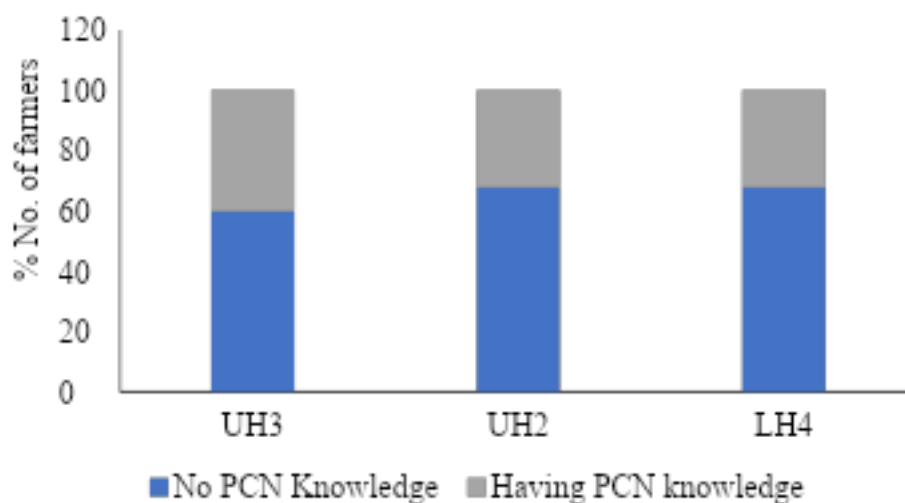


Figure 1. Farmer's knowledge of potato cyst nematode in the three agro-ecological zones, Nyandarua County in 2020.

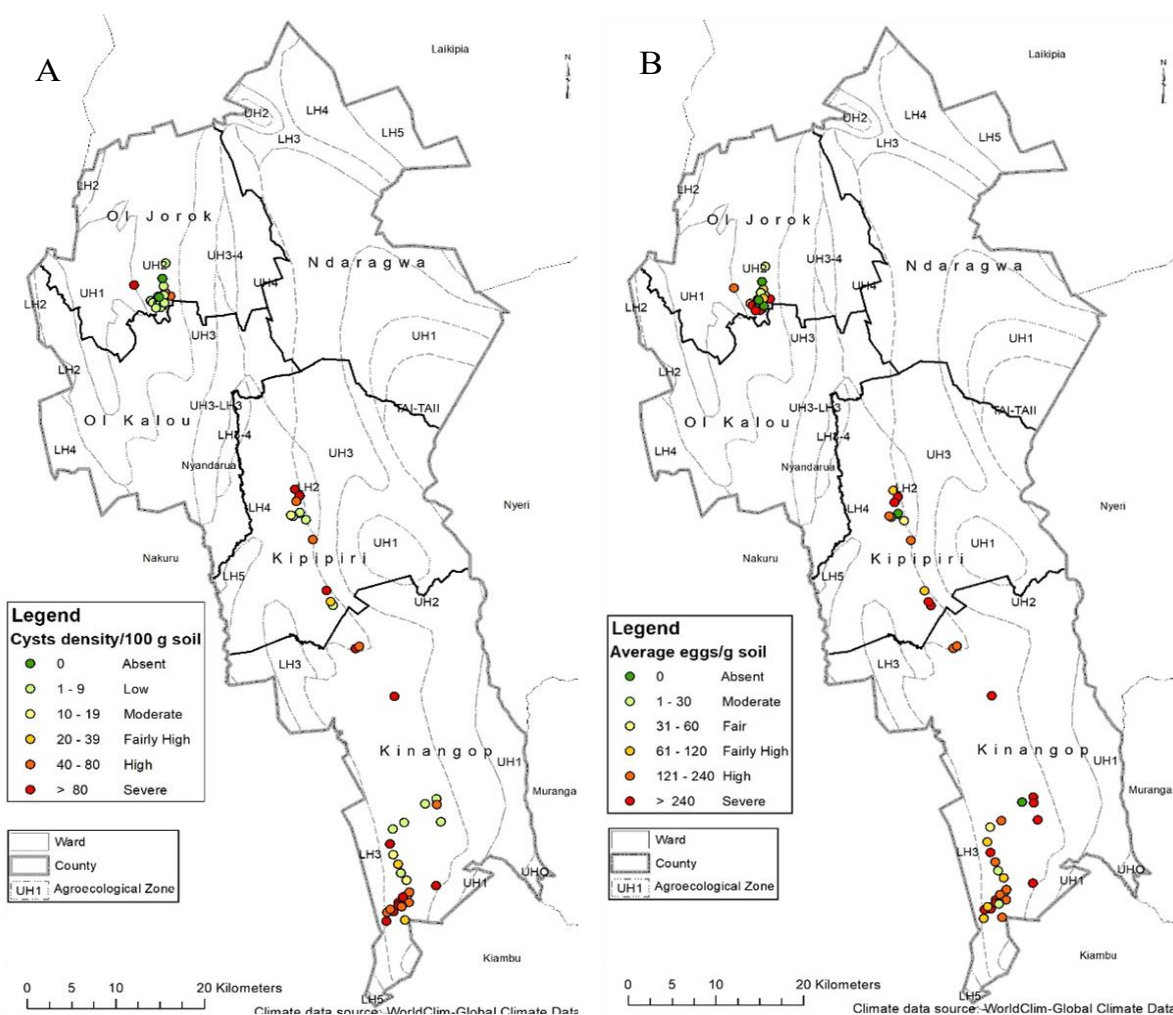


Figure 2. (A) The geographical distribution level of PCN cyst infestation in Nyandarua County; (B) The geographical distribution level of PCN eggs infestation in Nyandarua County.

Table 1. Percent infestation and population density of potato cyst nematodes infecting potato farms in three AEZs in Nyandarua County, Kenya.

AEZS	Samples analyzed	Number of samples infested	Percentage infestation	Average number of cyst/300 cc oil
Upper Highland 3	25	25	100	203.7 ^b
Upper Highland 2	20	17	85	289.2 ^b
Lower Highland 4	20	20	100	63.1 ^a
Total	65	62	95.4	186.7

Means followed by the same letter within columns are not significantly different $P < 0.05$.

Table 2. Altitude, annual rainfall, ambient temperature in relation to PCN population density in three agro-ecological zones in Nyandarua County, Kenya.

Sub-county	AEZs	Altitude (m.a.s.l)	Annual rainfall (mm)	Ambient temperature (°C)	Mean cysts/300 cc soil
Kinangop	UH3	2370-2400	1000-1500	11-17	289.2 ^b
Oljororok	UH2	2500-3000	1000-1250	11-17	203.7 ^b
Kipipiri	LH4	1299-2280	800-1000	18-25	63.1 ^a

Table 3. Soil particle size and classification of soil from three AEZs and the corresponding potato cyst nematode population densities in Nyandarua County, Kenya.

AEZ	Soil classification	Soil texture			Sample size	PCN population density at 300 cc soil			
		% Sand	% Silt	% Clay		Mean	Standard deviation	Minimum	Maximum
UH3	Clay	34	18	44	1	49.0	-	49.0	149.0
	Clay loam	42	25	33	10	194.5	253.8	0.5	776.5
	Loam	44	24	32	2	214.5	39.6	186.5	242.5
	Sandy clay	49	15	37	3	76.2	115.5	6.0	209.5
	Sandy clay loam	51	22	27	9	460.1	386.2	5.0	909.5
UH2	Clay loam	39	29	32	4	96.9	105.1	4.0	288.0
	Loam	46	33	22	4	154.3	190.5	5.5	404.5
	Sandy clay loam	50	22	28	10	458.5	415.2	5.5	1133.0
LH4	Clay loam	43	19	29	3	4.3	3.3	0.5	6.5
	Loam	45	32	23	10	107.2	202.4	2	615.5
	Sandy clay	48	16	36	1	2.0	-	2.0	2.0
	Sandy clay loam	54	21	26	5	229.6	361.2	1.0	839.0
	Sandy loam	51	28	18	1	177.0	-	177.0	177.0

Table 4. Correlation coefficients (r) between potato cyst nematode (PCN) population density and soil characteristics in three agro ecological zones in Nyandarua County.

Soil parameter	UH3		UH2		LH4	
	PCN population density (r)	Soil nutrient indices	PCN population density (r)	Soil nutrient indices	PCN population density (r)	Soil nutrient indices
pH	-0.399*	5.02	0.060	5.49	0.149*	5.2
Electric conductivity	-0.192*	0.393	-0.129*	0.282	0.116*	0.3
Organic carbon	0.265*	3.22	0.207*	3.2	-0.069	3.8
Nitrogen	0.253*	0.315	0.048	0.306	0.001	0.369
Phosphorous	0.148*	93.95	-0.196*	31.79	0.205*	69.1
Potassium	-0.416*	1.97	0.082	2.84	0.079	2.57
Sodium	-0.077	0.416	0.192*	0.39	-0.040	0.399
Calcium	-0.464*	5.077	0.108*	6.38	0.027	6.52
Magnesium	-0.272	2.486	0.019*	2.64	0.023	3.47
Exchangeable acidity	0.220*	1.788	-0.015	1.66	-0.085	1.85
Zinc	-0.205*	24.64	0.034	21.42	0.223*	18.97
Copper	-0.286*	1.74	-0.049	2.22	0.112*	2.05
Iron	0.148*	130.47	-0.259*	75.22	-0.340*	94.11
Manganese	0.226*	153.71	-0.240*	105.9	-0.277*	111.6

*Indicates that the correlations were significant at $P \leq 0.05$. r = Correlation co-efficient.

Table 5. Effect of cropping system on potato cyst nematode population density.

Cropping system	Agro ecological zone						Combined AEZs			
	UH3		UH2		LH4					
	Mean No. of PCN/300 cc soil	Standard deviation	Mean No. of PCN/300 cc soil	Standard deviation	Mean No. of PCN/300 cc soil	Standard deviation	No. of infested samples	Infested samples (%)	Mean No. of PCN/300 cc soil	Standard deviation
Intercrop	172	304.2	338	357.5	49	88.4	30	46.2	185	287.9
Mono crop	225	220.5	285	322.0	81	216.2	31	47.7	212	257.7
Relay crop	344	369.0	-	-	-	-	4	6.2	344	369.0

PCN: Potato cyst nematode.

Crop rotation

The frequency of farms where crop rotation was

practiced was 93.8%. Across the three AEZs, the PCN population density was significantly ($P \leq 0.05$) lower in farms where crop rotation was practiced,

with 92.1 cysts/300 cc in UH3 and 28.2 cysts/300 cc in LH4, compared to farms without crop rotation, which had 242.5 cysts/300 cc in UH3 and

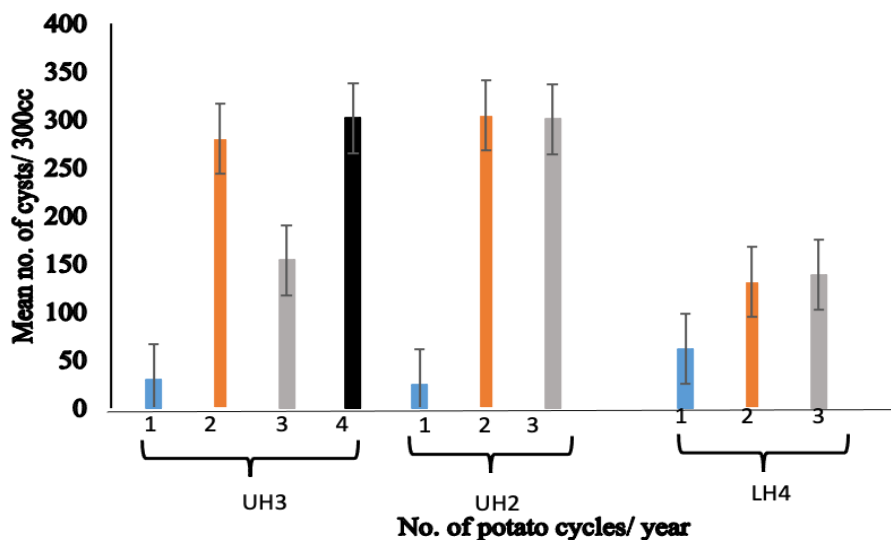


Figure 3. Number of potato crops grown in the same field per year in relation to mean population density (PCN cysts/300 cc soil) of potato cyst nematode detected in potato fields in three AEZs, Nyandarua County, Kenya.

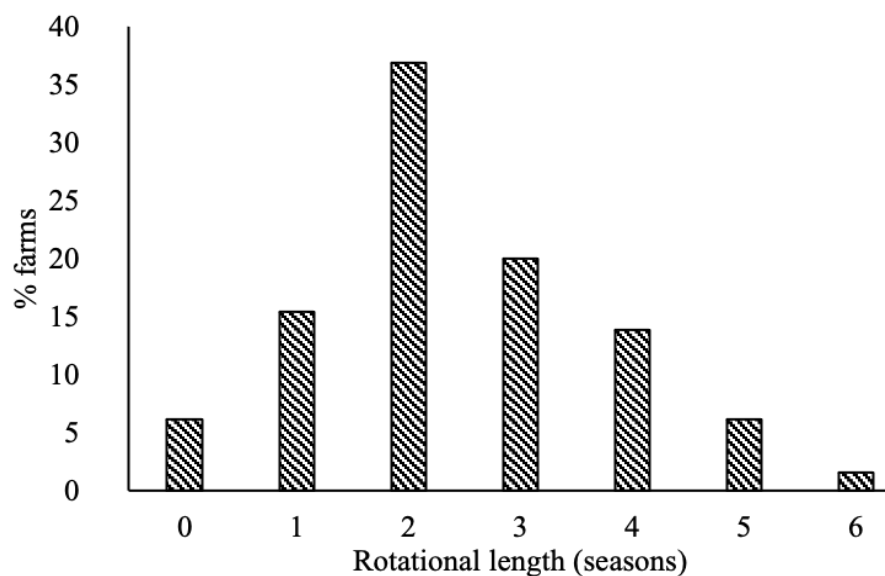


Figure 4. Rotational length, in seasons, between successive potato crops in the same plot in Nyandarua County.

377.3 cysts/300 cc in LH4. However, in UH2, farms without crop rotation had the highest cyst density, with 1073 cysts/300 cc, whereas farms with crop rotation had 249.8 cysts/300 cc (Table 6).

The rotation lengths of the 65 sampled sites were determined, and the most common rotation length was one potato crop after two seasons, which was practiced by 36.9% of farms (Figure 4). Only 6.2% of farms did not practice crop rotation. The longest rotational period was

after six seasons, which was practiced by only one farm (Figure 4).

Eight crops (maize, peas, cabbages, beans, carrots, snow peas, kales, and oats) were grown in rotation with potatoes across the three AEZs (Figure 4). In UH3 and UH2, maize was the most commonly used rotational crop, practiced by 36.9% and 37% of farms, respectively. In LH4, the majority of farmers (31.5%) used peas as their rotational crop (Figure 4).

Table 6. Association between the potato cyst nematode mean population density and the crop rotation practice in three agro-ecological zones, Nyandarua County, Kenya.

Practicing crop rotation	No. of farmers	Farmers %	Agro ecological zone						Combined AEZs	
			UH3		UH2		LH4			
			Mean PCN/300 cc soil	Standard deviation	Mean PCN/300 cc soil	Standard deviation	Mean PCN/300 cc soil	Standard deviation	Mean PCN/300 cc soil	Standard deviation
No	4	6.2	242.5		1037	-	377.3	336.9	508.5	407.5
Yes	61	93.8	92.1	241.7	249.8	308	28.2	73.2	15.5.6	246.6
Total	65	100	203.7	236.7	289.2	347.7	63.1	149.4	186.7	267.8

Table 7. Effect of seed source on the mean population density (cysts/300cc) of potato cyst nematode.

Seed source	No. of farms	No. of farms (%)	Agro ecological zone									Total		
			UH3			UH2			LH4					
			No. of farms	Mean number of cysts/ 300 cc soil	Standard deviation	No. of farms	Mean of cysts/ 300 cc soil	Standard deviation	No. of farms	Mean number of cysts/ 300 cc soil	Standard deviation	No of farms	Mean number of cysts/ 300 cc soil	Standard deviation
Non certified seed	60	92.31	22	69.6	251.7	20	303.41	356.6	18	247.3	156.5	60	200.7	280.7
Certified seed	5	7.69	3	4.3	80.5	1	26.2	46.2	2	29.7	2.5	5	60.2	83.0

Relationship between seed source and PCN population density

The study revealed that 92.3% of the farmers used non-certified seeds, while 7.7% used certified seeds (Table 7). The cyst count per 300 cc of soil was significantly ($P \leq 0.05$) higher in farms where non-certified seeds were used, with an average of 203.6 cysts/300 cc, compared to farms where certified seeds were used, which had an average of 90.2 cysts/300 cc (Table 7).

Potato diseases in relation to population density of PCN

Among the diseases and pests observed, late blight was the most common in all the AEZs

followed by potato cyst nematode (Table 8). The results showed that 96.9% of potato farms had late blight followed by PCN (95.4%), bacterial wilt (76.9%) and viral diseases (18.5 %). Across sites, the highest number of potato cyst nematodes (264.4) occurred in fields which had viruses.

Farm equipment and seed potato in relation to PCN population density

Potato cyst nematodes (PCN) cysts recovered from soil adhering to jembes, seeds, and footwear in UH3 and LH4 were significantly ($P \leq 0.05$) higher than those in the UH2 agro-ecological zone (Figure 5). The number of cysts adhering to jembes, footwear, and seeds ranged from 2.6 to 13.7, 1.8 to 8.8, and 2.8 to 12.9 cysts/50 cc soil,

respectively. A significantly ($P \leq 0.05$) low number of cysts were recovered from UH2 soils, with 1.8, 2.6, and 2.8 cysts/50 cc from footwear, farm tools, and seeds, respectively (Figures 5 and 6).

A significantly ($P \leq 0.05$) high number of viable eggs (120.4/cyst) were recovered from soil adhering to seeds in UH3. In contrast, UH2 had a significantly low number of PCN eggs recovered from footwear, farm tools, and seeds, with 38.2, 39.4, and 54.9 viable eggs/cyst, respectively (Figure 7). The PCN cyst count significantly varied across the sites. Non-disinfected tools had a significantly higher number of cysts compared to disinfected tools (Figure 8).

Approximately 10% of the farmers reported that they sometimes cleaned their footwear after use but did not disinfect them. None of the farmers were aware that cleaning and disinfecting jembes,

Table 8. Association between the potato cyst nematode population density and the potato diseases in three agro-ecological zones, Nyandarua County, Kenya.

Pest and diseases	UH3			UH2			LH4			Combined AEZs		
	No. of infected (farms) by disease/pests	% Infestation	PCN population density at 300 cc	No. of infested samples (farms)	% infestation	PCN population density at 300 cc	No. of infested samples (farms)	% infestation	PCN population density at 300 cc	No. of infested samples (farms)	% Infestation	PCN population density at 300 cc
Bacterial wilt	21	84	44.9	14	70	150.6	15	75	302.0	50	76.9	151.7
Rhizoctonia	7	35	4.7	-	-	14.0	8	40	165.3	-	-	77.4
Late blight	23	92	63.1	20	100	289.2	20	100	163.9	63	96.9	172.1
Viruses	4	16	3.3	5	25	402.7	3	15	277.9	12	18.5	264.4
*PCN	25	100	66.4	17	68	289.2	20	100	254.4	62	95.4	202.1

*This was established after cysts extraction from samples collected. The other diseases were observed during the farm interview.

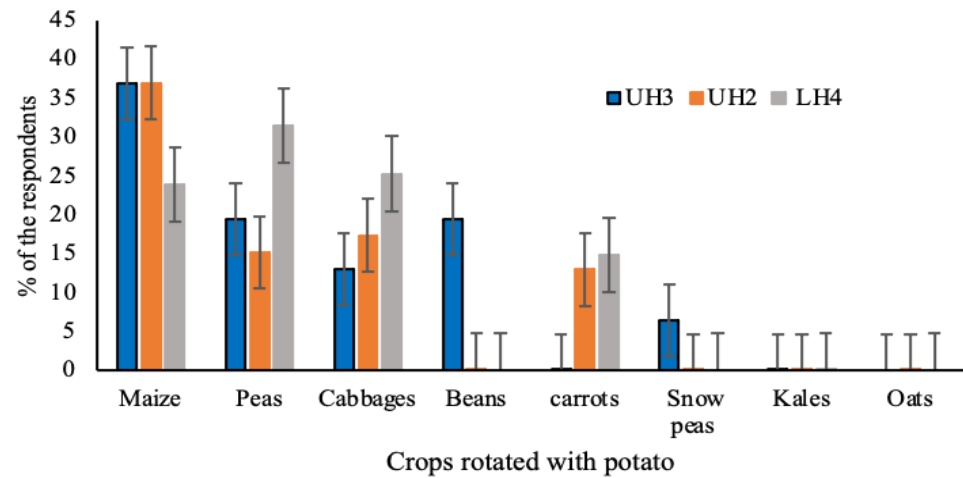


Figure 5. Crops commonly rotated with potato by farmers (% respondents) in three agro ecological zones in Nyandarua, County.

footwear, and seed potatoes could minimize the spread of PCN.

DISCUSSION

This study has revealed that potato cyst

nematodes are widespread in Nyandarua County, with over 95% of the farms being infested. The high prevalence of PCN gives an indication of the rapid spread of the pest, given that the pest was first reported in Kenya about five years ago. Findings from this study are consistent with previous studies that reported high incidence (90%) and

high levels of infestation of PCN above economic thresholds in the potato-growing areas in Kenya (Haukeland, 2016; Mburu et al., 2020).

The results of this study showed that the surveyed sites had temperatures ranging from 11-25°C. Such temperatures are suitable for reproduction of PCN because they prevent

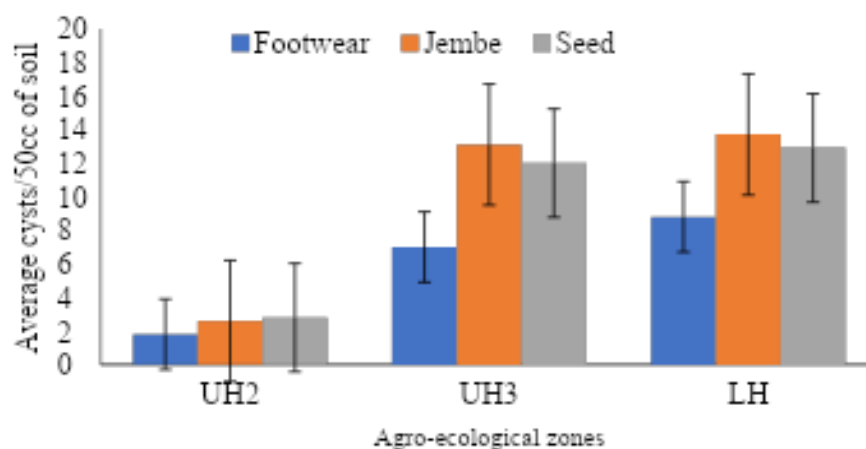


Figure 6. Mean number of PCN cysts recovered from farm equipment and seed potato used in soil infested with PCN in the three agro-ecological zone in Nyandarua County.

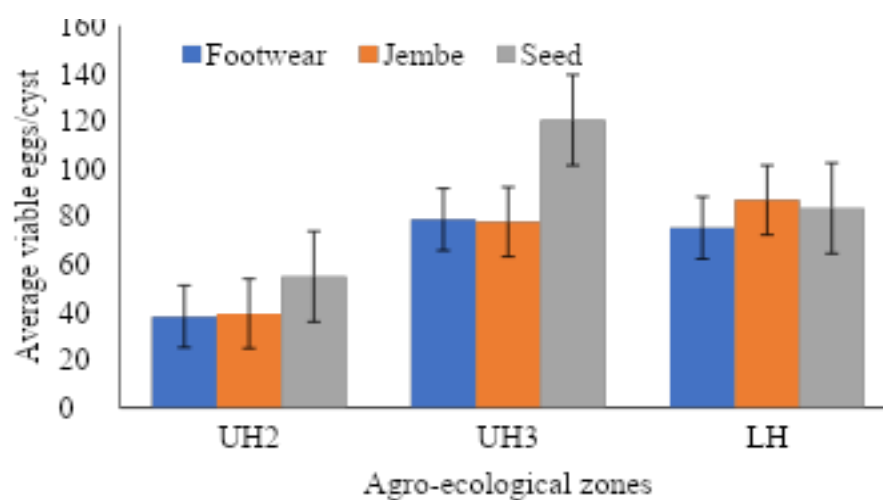


Figure 7. Mean number of viable eggs recovered from Jembes and seed potato used in soil infested with PCN in the three agro ecological zone in Nyandarua County.

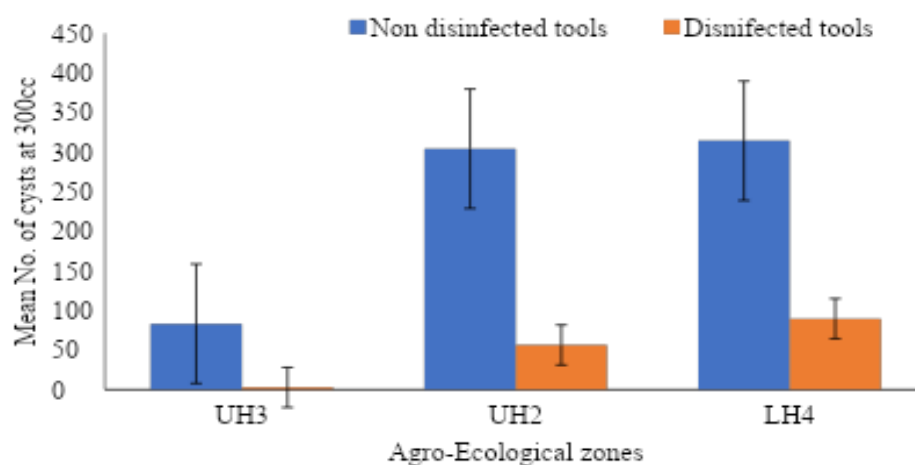


Figure 8. Number of PCN cysts from farms where Tools were disinfected and where they were not.

desiccation and dryness in the soil.

They are also suitable for maintaining a thin film of water around the juveniles for ease of mobility and therefore access to food (Skelsey et al., 2018). This finding is consistent with a previous study where a high percentage hatch of *G. rostochiensis* occurred at 10 to 25°C (Kaczmarek et al., 2014). The ambient temperatures recorded in this study may have favored *G. rostochiensis* reproduction as they are within the reproductive range for the species.

The high altitude of the study sites positively influenced the PCN population density. Findings from this study agree with those of Yusianto and Hardjomidjojo (2020), who observed that at an altitude of 2000 masl, PCN had the most dominant attack and high density.

This study shows that annual rainfall >1000 mm is more conducive to high PCN densities compared to annual rainfall of <1000 mm. This could be attributable to runoff, which is a source of PCN spread and occurs with high rainfall. This speculation is supported by the work of Yusianto and Hardjomidjojo (2020), who observed that spread of PCN occurred in many ways, including rainfall runoff. Effects of rainfall have also been reported to play a significant role in the population densities of PCN and also in the safety of their soft bodies by preventing desiccation (Nisa et al., 2021).

Soil texture is associated with aspects such as aeration, water holding capacity, root system, and distribution of species in the soil (Quist et al., 2019). This could explain the high spread and population density of PCN observed in sandy, clay loam and loam soils in this study. Prot and Van Gundy (1981) demonstrated soil type as an important factor influencing nematode spread and density, where *Meloidogyne incognita* mobility was inhibited in clay soils and silt since they inhibited migration of *Meloidogyne incognita* thus reducing their population.

Among the surveyed farms, no potato grower was found to be using nematicides or practicing any control measures, thereby increasing the PCN buildup. Additionally, during interviews with farmers about their awareness of PCN, the majority stated that they were unaware of PCN in potatoes and were more concerned with late blight and bacterial wilt. This lack of awareness could be attributed to the failure to recognize visual symptoms. Mburu et al. (2020) noted that PCN symptoms are unclear, making the pest overlooked by most potato growers in Kenya. Many farmers were also unaware of integrated approaches for managing the pest, indicating a knowledge gap among farmers.

The current study shows that cysts were recovered from seeds, footwear, and farm tools. Few cysts could potentially form an invasive population. According to Banks et al. (2012), one cyst from a gram of soil can reproduce 30 cysts in a season. Furthermore, during the study, it was observed that the majority of farmers in Nyandarua rely on non-certified seed sources, including own farm-saved seeds, open markets, and neighbors. The

use of non-certified seeds leads to the use of seeds infested with pests and diseases, which accelerates the spread of seed-borne diseases and pests (Kinyua et al., 2001). Seeds, jembes, and footwear could be the primary sources of PCN spread. Moreover, nematodes do not move long distances on their own and are therefore unable to spread from one field to another on their own.

In previous studies, seeds and farm equipment have been blamed for the rapid spread of PCN through soil attached to seed potatoes and farm equipment from infested fields (Briar et al., 2016; Mburu et al., 2020). Many farmers commonly hire casual labor during certain parts of the production season. Often, the hired laborers come with their tools, which are not disinfected before use. This practice is also likely to have contributed to the rapid spread of PCN.

It was noted that variety Shangi was grown by almost all farmers. According to Mburu et al. (2020), variety Shangi is moderately susceptible to PCN. It is possible to infer that the widespread planting of the susceptible variety Shangi in Kenya has accelerated PCN infestation in potato production fields, accelerated by relay cultivation of the variety. Previous studies indicate that there is a significant relationship between PCN and the use of resistant and non-resistant cultivars, whereby cultivars resistant to PCN would possibly reduce PCN density (Grubisic et al., 2007).

However, deploying resistance to PCN is challenging in Kenya due to market choice. Additionally, potato cultivars in Kenya are of unknown PCN resistance, and varieties with partial resistance to PCN (KEPHIS, 2020) are limited since they have breeders' rights. This presents a serious problem in subsequent years due to intensive cultivation of a susceptible variety (Shangi) and the lack of partially resistant or resistant varieties in the Kenyan market.

The findings of this study showed that farms that intercropped and rotated their potato crops recorded a lower PCN population density compared to farms that mono and relay cropped potato crops. The lower PCN population densities in the intercrop and rotational potato production systems could be attributed to the crops used, which were non-hosts. These included peas, cabbages, beans, carrots, snow peas, kales, and oats.

According to Briar et al. (2016), planting non-host crops in rotation would remove the food source for plant-parasitic nematodes, thus preventing colonization and establishment of PCN, consequently leading to a decline in their population below damaging levels. Moreover, different crop species planted as intercrop or rotational crops give antagonistic action on nematode populations as well as enhancing crop yield by lowering crop pests or through other agronomical benefits, such as maintaining soil fertility, resulting in increased crop yield (Bairwa et al., 2017).

This study found that the majority of farmers had a short rotational length of one in two seasons or lower. The high number of PCN reported in this study could be attributed to the short rotation cycle. This finding agrees with

Trudgill et al. (2014), who observed that rotation caused a decline of 26.2% per year in eggs per gram of soil of *G. pallida* in commercial potato crops.

According to Skelsey et al. (2018), a rotation with a non-host crop is recommended for PCN, while for seed, a minimum of one crop every 6 years for potato production in Scotland is an effective control measure to slow the increase in PCN risk.

Conclusion

The results of this study suggest that site-specific factors, such as soil characteristics, farming, and cropping practices, interact to determine the incidence and population density of PCN. Understanding the interacting relationships is essential for predicting yield reductions from estimates of pre-planting densities. Our findings emphasize the need to promote integrated management of the pest, incorporating approaches such as crop rotation, planting disease-free tubers, resistant varieties, and field sanitation, as strategies to reduce the spread and buildup of PCN. Furthermore, considering soil factors during the development of integrated management strategies for the pest is crucial.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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