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Spatio-temporal distribution of banana weevil *Cosmopolites Sordidus* [Germar] and nematodes of various genera in Uganda: A case of smallholder banana orchards in Western Uganda

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Smallholder farmers' banana orchards in Western Uganda were used to study the spatio-temporal factors influencing the distribution of banana weevils and parasitic nematodes in tissue culture and non-tissue culture banana types using Nested case control design. Nematodes were extracted from randomly collected composite banana root samples from 20 banana orchards. The banana weevils were trapped in the rainy and dry seasons. A total of 1,280 banana genets were surveyed to determine weevil and nematode densities. Interactions between season and locations with high banana weevils and nematodes densities significantly negatively influenced the distribution of tissue culture and non-tissue culture banana in space and time. Both tissue culture and conventional bananas are prone to banana weevil and nematode infestations. Infestation with weevils and nematodes were higher for tissue culture banana in the dry season. Kiruhura district had a higher density for banana weevils (*Cosmopolites sordidus* [germar]) while Ibanda district had higher nematode densities. *Helicotylenchus multicinctus* and *Radopholus similis* were found most prevalent. This knowledge is not only important in shaping the adoption and sustenance of the adopted banana types, but also can form a basis for developing affordable strategies to lower the occurrence of banana weevil and nematodes below the threshold level in smallholder banana farms of Uganda.

Key words: Spatial, temporal, distribution, nematodes, weevil, tissue culture banana, nematodes, infestation.

INTRODUCTION

Banana production as an income generating practice in Uganda is steadfastly increasing and is likely to replace other traditional cash crops (Namanya, 2011). The crop has become an alternative to the unstable market for extremely perishable unprocessed animal products. Nonetheless, its production is constrained by pests and diseases. To address this nuisance Pest and Disease question, tissue culture banana production technology was introduced into the banana production industry in Uganda (Okech et al., 2004; Langat et al., 2013). The introduction was to enhance productivity, fill income gaps, (Nakato et al., 2017) and ultimately improve food security at smallholding farm level (Mbaka et al., 2008). The tendency to accept planting materials by the smallholder farmers are wedged to the choice of conventional suckers than the tissue culture plantlets. This tendency is partly animated by the socio-economic factors within the environs of the smallholder farmer, and the ability of the farmers to compare the survival time periods of the tissue culture banana versus the conventional banana plantations (Murongo et al., 2018). Smallholder banana farmers need to understand that environmental factors such as temperature, wind, light, and water supply, as well as erraticism of the soil physical and chemical structural composition vary both spatially and temporary. The spatial and temporal variability contributes to the distribution of biotic components in the farming system (Machado et al., 2014), especially effect on yield. The banana weevil and some genera of parasitic nematodes are some of the biotic factors that have led to the destruction of banana orchards (Wandui et al., 2013). Smallholder farming communities are largely not cognisant of some of the factors acting together or individually to distribute the pests in the banana orchards.

Bananas are susceptible to banana weevil and nematode attack under a wide range of conditions. The severity and occurrence of these biotic risk factors and plant damage depends on the prevailing environmental conditions, and specific banana cultivars. Such occurrences within the smallholder farms are prevented by farmers implementing cultural treatment practices, preceded by careful selection and handling of pest free and, where possible, resistant banana planting materials. Traditionally, farmers remove all leaves, outer leaf sheaths, roots, dead parts of the plant and pare the corm to eliminate weevils and weevil eggs. Ssebunya (2011) recommends that pared corms and suckers be soaked in soapy water over night to eliminate weevil eggs and nymphs. The suckers should be planted within one week after treatment to avoid re-infestation. Although less information is given on the control of nematodes, (Rwanda, 2013) recommends use of improved banana cultivars with high levels of resistance/tolerance, and proper management of the banana residues to offer a solution to banana weevil and nematode damage.

Traditional practices suggest that at planting time, the planting materials are treated for control of weevils and nematodes, but during the development process in real time across the seasons, the bananas are re-infested with the banana weevils and the parasitic nematodes. High prevalence rates of the banana weevil and the parasitic nematodes influence the survival, development and evolution of the crop under production (Ayuke, 2010). The biotic risk factors are also influential in the deterioration and degeneration of many other living organisms; the banana inclusive (Speijer, 2017). Banana varieties planted in Uganda are prone to detrimental biological interactions with the banana weevil and the parasitic nematode (Alou et al., 2014). The interactions lead to the collapse of the orchards (Ocan et al., 2008), damage the roots rapidly, provide space for the infection by pathogens, destroy the banana plant stability (Arinaitwe et al., 2014a), and result in serious yield losses (Grant, 2012). This study therefore sought to determine the distribution of banana weevils and parasitic nematodes as biotic risk factors in banana production, and how they relate to abiotic (spatio-temporal) factors within smallholder farming communities in western Uganda.

MATERIALS AND METHODS

Study design and conceptualization

Nested Case Control Design was adopted to retrospectively determine the exposure of the famers' banana orchards to the risk factors in space and time (Kuller et al., 2018). The design was deemed appropriate since the distribution of study units and observations were done on study points selected from a population of banana orchards that had been established over a period of time by smallholder farmers. The study design was mainly observational because no intervention was attempted and no attempt was made to alter the course of pest prevalence at that level. The "banana types" were conceptualised to denote the technology through which farmers' planting materials were developed. The type was considered non-tissue culture banana (NTCB) if the original planting materials were the traditional conventional suckers, but if the banana orchard was established from tissue cultured plantlets, the type was considered tissue culture banana (TCB). Nematodes and Banana weevils prevail as risk factors in the smallholder banana orchards, and the banana types are therefore, naturally exposed to these risk factors. Upon exposer to the risk factor, over a period of time under natural conditions, the banana types have an equal chance of getting infested or resisting infestation. The plants within a type that are not infested under similar orchard conditions after a period of time are the "controls" while those that are infested regardless of the degree of infestation are the "cases". The study assumed that there was a uniform inherent nature of the banana cultivars regardless of the type, conferred by their genetic stature to resist attack by the risk factors. The districts formed the major block. The seasons, and banana types were nested within the districts. The districts were conceptualized to represent the spatial aspect since they represent varying aspects. The dry season and rainy seasons epitomize the temporal aspect. The selected methods of capturing weevils were nested with the seasons and applied to the banana type in different districts. The total nematode counts were nested with nematode genera, within a banana type in and a district (Figure 1).

It was assumed that sustained production, rejection and /or fall

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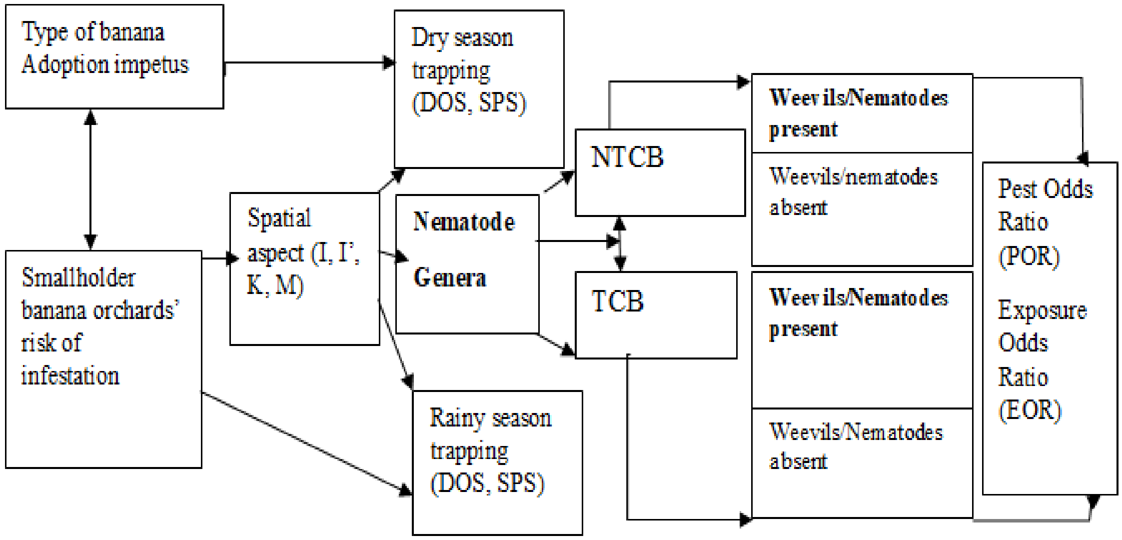

Figure 1. Summary conceptualization of the design for spatial and temporal banana weevil study in Uganda. The spatial aspect in this concept is the location representing I=Ibanda district, I'=Isingiro district, K=Kiruhura district and M=Mbarara district. Disc on Stamp (DOS) and Split Pseudo stem (SPS), respectively represent the method used to capture the banana weevils.

back into production of any cultivar of banana by the farmer is influenced by farmers' location and the season in which the practices on banana production are carried out. The study also assumed that the exposure of the banana orchards to the risk factors is enhanced by the season of the year as well as the location of the banana orchard. Non-Tissue Culture Banana (NTCB) and Tissue Culture Banana (TCB) types as previously adopted, were expected to show variations in pest incidences according to space (district) and time (season), following the two major methods of banana weevil pest traps that is, the Disc on Stamp [DOS] traps and Split Pseudo stem [SPS] traps.

Characterization of the location

The seasonal capture of the weevils was spread over four districts of Mbarara, Ibanda, Isingiro, and Kiruhura. A summary of the geographical aspects is shown in Table 1.

Table 1 summarizes the pertinent characteristics of the locations in the study area that have an effect on the practices, generally in agriculture and banana production in particular. The districts are characterized by a mixture of fairly rolling and sharp hills, fairly deep and shallow valleys flat lands. The proportions for water bodies, vis-à-vis the arable land vary from 2 to 6% of the total land covered with lakes, rivers, and gazetted swamps. The area is largely covered with savannah woodlands type of vegetation with a wider cover of thorny shrubs, which are gradually being replaced by banana orchards. The soils are loamy with proportions of sand and rocks in some districts. The soils are fertile due to manure deposits resulting from the historical pastoral activities that have characterized the area for a long time.

Sampling and selection criteria

The banana types were the major consideration in the selection criteria for the farmers' orchards to be included in the study. Records from Agricultural Productivity Enhancement Program (APEP), banana technology transfer program were used to identify smallholder banana farmers who benefited from the program during the 2005 to 2008 field demonstrations in western Uganda. At the end of the field demonstrations, approximated 320 farmers across the four districts received tissue culture banana plantlets, fertilisers, and information kits hence the current study considered these farmers for the field survey. Further selection depended on areas that have been under banana based cropping systems for a period not less than 15 years as well as the smallholder farmers' resource bequest (Murongo et al., 2018). Representative local orchards that had more than five genotypes and at least 150 genets sufficient to provide a required sample in a 30 × 30 m quadrat were further selected. The minimum average distance in kilometres between the individual farmers' orchards was approximated to 0.5 to 2 km. During the orientation survey with the Beneficiaries of APEP, it was established that a large number of the farmers who received tissue culture plantlets, developed banana plantations. However, these plantations have since been replaced by replanting conventional suckers from the neighbourhoods. Some of the reasons for this fall back were identified in a study by (Murongo et al., 2018). The banana farmers were actively involved in the identification of the banana type and occurrence of the types of banana. During the identification process, emphasis was placed on the origin of planting material of the banana orchard under observation other than the use of the banana cultivars within the orchard. The distribution of the banana type was estimated as a percentage of total farmers who reported to have received planting materials. About 19% of farmers were still able to trace the locations where the plantlets were planted and indicate that there have been no major replacements of the original sources of the planting materials. However, furtherance of the banana plantations was sustained with the use of internally generated suckers.

Assessment of biotic factors

The biological components of economic importance to this study were banana weevils and nematodes. Twenty orchards were

Table 1. Location specific aspects of Ibanda, Isingiro, Kiruhura and Mbarara districts.

District	Ibanda	Isingiro	Kiruhura	Mbarara
Total Area (km^2)	964.8	2,655.6	4,605	1,846.4
Arable Land (km^2)	771.8	2,496.3	4,516	1,778.4
Elevation (ft.)	5,900	5,900	5,900	5,900
Temp. Range (˚C)	14-28	14-27	13-30	17-30
Coordinates	00˚07′S 30˚30′E	00˚50′S 30˚50′E	00˚12′S 31˚00′E	00˚36′S 30˚36′E
Rainfall (mm)	1000-1250	800-1200	700-900	900-1200

Source: Summarised from Various Higher Local Government statistical abstracts for Uganda: for Ibanda district local government (2009), for Isingiro district local government (2009) for Kiruhura district local government, (2012) and for Mbarara district local government (2009).

randomly selected by taking five farmers from Ibanda, Isingiro, Kiruhura and Mbarara districts as sites for the determination of the banana weevil and nematode population densities. On each orchard, a quadrat of 30 × 30 m corresponding to approximated 25 to 50 genets of the banana type under study was used. Five traps for Disc on Stamp and Split Pseudo Stem, respectively were laid per orchard. The genets where weevils were trapped and nematodes extracted were randomly selected from genets within the quadrat. Hence, the population density for banana weevils and or nematodes was the total number of the organisms per quadrat, per orchard, obtained from the trapping the banana weevils, and extracting nematodes from the composite root samples from different districts. The densities were used to determine the spatial and seasonal distribution within the farmers' orchards.

The study considered the districts as a representation of the spatial characteristics. The study points were geo-referenced (Figure 6A). Geo-referenced smallholder farmers' orchards were used to set up traps to capture the weevils. Similar geo-points were used to obtain the root samples for nematode density determination.

Banana weevil population density determination

Two basic approaches were used to quantify the weevils in the farmers' fields; the Disc on Stump (DOS), and the Split Pseudo Stem (SPS) traps. The DOS was made by cutting a harvested stump, 5 to 10 cm above ground, and placing a 5 to 10 cm thick pseudo stem disc on top of the stump. The SPS was made from pseudo stem pieces of 5 to 10 cm split longitudinally and placed near a target plant with the split surface facing the ground. Although DOS method is inflexible and limited only to harvested, broken or damaged plants (Nankinga and Moore, 2000), it captures more weevils than the SPS (Ocan et al., 2008). The DOS method was restricted to old plantations that had the required number of harvested stumps. Five traps for each of the two trap methods were randomly laid in each of the five selected plantations per district.

Young and newly established orchards as well as the young proportions of the old orchards were appropriate for use of the SPS approach (Jallow and Achiri, 2016). The young plantations have not had much harvesting to create many stumps to sufficiently support the use of DOS. The method is easy to set under the widest range of conditions and trap materials are readily available. The background of the approach was informed by Ogenga-Latigo and Bakyalire (1993) and Ocan et al. (2008), that the variation in trapping conditions such as trap lengths, placement, duration of trapping and soil moisture conditions may significantly influence the catches in split pseudo stem traps. Therefore, the traps' lengths were limited to 30 cm, placed horizontally onto the surface and weevils checked after 24, 36 and 48 h, respectively. The time schedules were used to maximise and increase the duration of trapping weevils. The traps have the ability to remain active for 1 to 2 weeks. The first collection of the weevils was done after 24 h opening up the inverted traps and the adult weevils handpicked. The same trap materials were inverted again until the 36$^{th's}$ hour. A thin layer provided by a banana leaf in between the stump and the disc for DOS method, and between the ground and the split stem for the SPS was replaced after the 36th hour collection till the 48th collection. The total for the three collections was put together to form one single *genet* count. The weevil density was related to the type of banana on which the trap was set to determine the pest odds in the smallholder banana orchards. The density was based on the average number of weevils captured from the selected smallholder banana plantation. The pest populations were collected for two months in both the rainy dry seasons to give concrete variations of the weevils across the seasons of the year.

Only the banana weevils of the species *Cosmopolites sordidus* (germar) were identified. Since smallholder farm owners were involved in the identification, the study limited the identification to the immediate physical and morphological characteristics of the pest. The black and or dark brown beetles approximated to a body length of 7 to 10 mm were captured. The adult weevils were "light shy" and largely secretive upon opening the traps. Their ability to hook themselves firmly on the trap plant tissue due to the hook-like extensions on all its tibiae further segregated the weevils from other insects under the same trap.

Nematode population density determination

Extraction of nematodes was not done following the seasons per se, but the root samples were systematically collected on the same genets where banana weevil traps had randomly been placed. The systematic root sample collection following randomly selected genets was possible and representative since the farmers' orchards were small. Nematode population were determined by taking a composite root sample of 5 g obtained from collecting five roots per mat from five randomly selected genets per orchard. The samples were collected twice per month, for a period of four months. Nematodes were extracted from fresh banana roots following the modified Baermann's technique and protocol described by (Coyne et al., 2014). The nematode population densities were related to the banana type from which the composite root samples were obtained. This was important for establishing the pest odds in the smallholder banana orchards.

Sampling criteria involved pre-identification of the nematode genera understudy. The above ground and below ground symptoms were used to select the right root samples for the anticipated nematode genera. The genets where toppling over, was evident were given priority. Toppling over, extended root lesioning, root burrowing and necrosis are characteristic symptoms of *Radophorus similis* and the root burrowing nematode-*Platylenchus goodeyi* (Gowen et al., 2005). Root surface cracks, galls, deformed

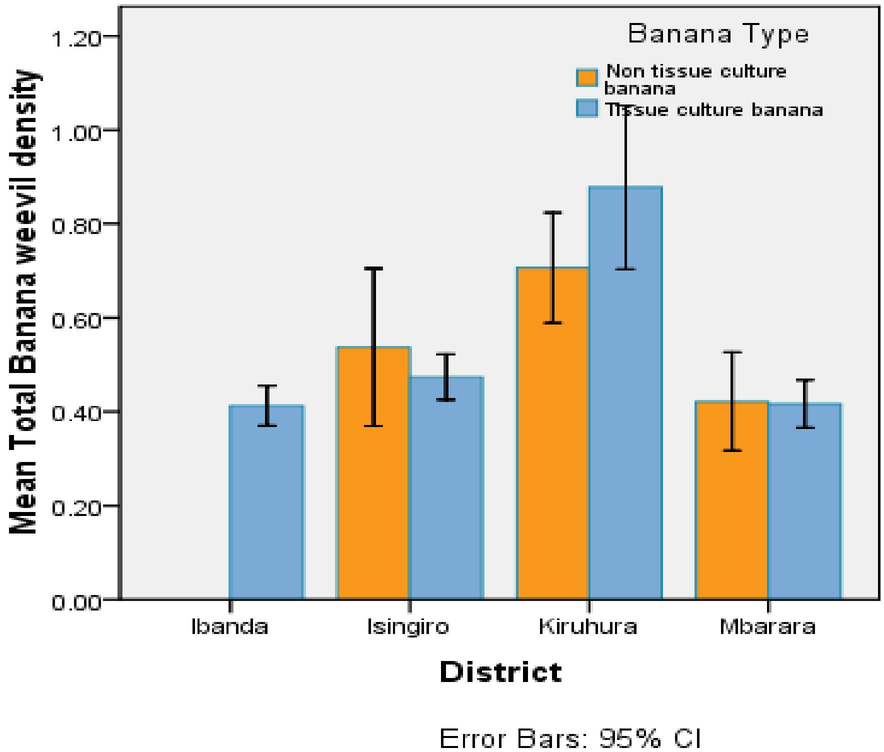

Figure 2. Total weevil population density distribution from total orchards per district, per banana type. Tissue culture banana was more infested in Kiruhura district compared to any other district. The overlaps in the error bars indicate significant infestation for both banana types in Isingiro, Kiruhura, and Mbarara.

roots, altered root architecture, and termination of root growths are characteristic symptoms of a combination of *Helicotylenchus multicinctus, P. goodeyi* and *Meloidogyne* species (Coyne et al., 2014). These symptoms were used to pre-qualify root samples before they were subjected to expert identification in the laboratory. Expert identification did not use chemical profiling, but used the morphological characteristics as defined by Coyne et al. (2014) to identify *H. multicinctus, P. goodeyi, R. similis* and *Meloidogyne* spp.

Data analysis

The study retrospectively examined the effect of banana weevils and nematodes on the distribution of banana types in space and followed the banana types back in time to check for the prevalence of the banana weevils and nematodes. The study units were assumed to have been "pest free" at the time of planting and thus classified the planted materials based on the presence and or absence of the pest factors. As such, 1,280 samples were observed during the survey that spanned a period of 14 months, from September 2017 to December 2018. The measures of association between the risk factors and the type of banana were obtained by analysing the Pest Odds Ratio (POR), and the Exposure Odds Ratio (EOR). The POR would be the orchards that were exposed to risk factors' but were not actually infested. However, under natural conditions, it is rather unusual to have the pest odds. The EOR were the orchards that were exposed to the risk factors and were actually infested. The association between POR and EOR is the Risk Ratio (RR). Where the Risk Ratio was low and cumulative, the incidence of the pest infestation was concluded to be diminutive. The risk ratio was determined by;

$$(B/N1)\ /\ (C/No) \quad (1)$$

Or, $(B/C)\ /\ (N1/No)$ (2)

where B was the number of infested banana *genet*s, $N1$ was the total number of sampled banana *genet*s, C was the number of uninfested banana *genet*s, No was the total number of exposed banana *genet*s. Spatial data was arranged using arc-GIS, graphics developed with MS Excel 2013 and statistical analyses run with R version i386.3.3.1. Nested Analysis of Variance was run because distribution of banana types and the risk of exposure to pest infestation of the banana orchards both depend on the geographical aspect, and the various seasons through which the banana orchards develop.

RESULTS AND DISCUSSION

Mean banana weevil and nematode densities

Figure 2 shows the mean weevil densities in non-tissue culture and tissue culture banana types. It was observed that out of the 1,280 observations, all the banana *genet*s naturally exposed to the banana weevil infestation were

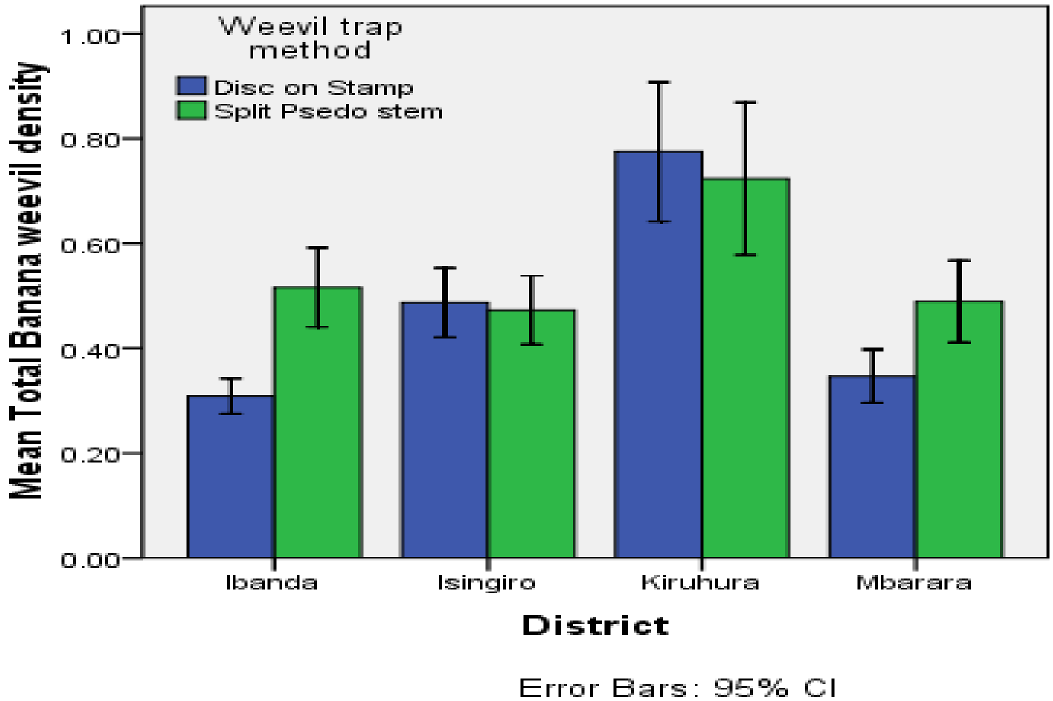

Figure 3. Total banana weevil population density for total orchards per district captured by Disc on Stamp and Split pseudo stem; The overlapping error bars indicate the significance of the methods in trapping the weevils in farmers' fields.

actually infested. Therefore, there were no Pest Odds Ration to recommend as case controls.

Figure 3 shows the methods used to determine the density of banana weevils in the study area. The disc on stamp method of trapping banana weevils captured a higher number of weevils compared to the Split pseudo stem. The split pseudo stem performed better in Ibanda and Mbarara districts.

The smallholder farmer orchards of the tissue culture banana origin were slightly more infested with the banana weevil, than the orchards developed from the conventional traditional suckers. Banana weevil problems appear to be more serious in the tissue culture originated highland cooking banana types in western Uganda. Tissue culture plantlets are fragile, and smallholder farmers must employ appropriate management practices to harness the potential of the TC technology most especially at the initial stages of growth after transplanting into the field. Usually, farmers transplant the plantlets into fields that are already burdened with the banana weevil pest pressure alongside other abiotic constraints. In a low input situation of the smallholder farmers, standards for quality management during the production process may not only be a serious limiting factor but also an enabling factor in the multiplication of banana weevil in smallholder fields.

Figure 4 shows the distribution nematodes within the banana type. There was a higher population density for nematodes in tissue culture originated banana plantations than the banana weevils in both plantations.

The distribution of nematodes in smallholder farmers' orchards by genera (Figure 5) for each district, indicate a higher prevalence of *H. multinctus* in Ibanda and Isingiro districts. *R. similis* densities are also high in the same districts. *P. goodeyi* was more prevalent in Kiruhura and Isingiro, while *Meloidogyne* spp. were mostly found in Isingiro.

Factors summarised in Table 2 including but not limited to type of soil, moisture and temperature have a bearing on the distribution of the nematode genera. These factors have a direct effect on the growth of banana types that are hosts to different nematodes. In South and Central Africa, *Meloidogyne* spp. and *P. goodeyi* have been found most prevalent. The current results contravene an earlier study by (Daneel et al. 2015), which established that *Meloidogyne* and *Pratylenchus* were the most widespread genera in South Africa. Nonetheless, the study results corroborate Gowen et al. (2005), that the root system of banana is attacked by several nematode species triggering coincident infections. In this present survey, *R. similis* and *H. multicinctus* were the most frequent and widely distributed in all sampled locations and on all surveyed *genets*. The current study results agree with Daneel et al. (2002), where, for Swaziland, the mean population densities for *H. multicinctus* and *P. goodeyi* were higher than *R. similis*, with nearly 90% of

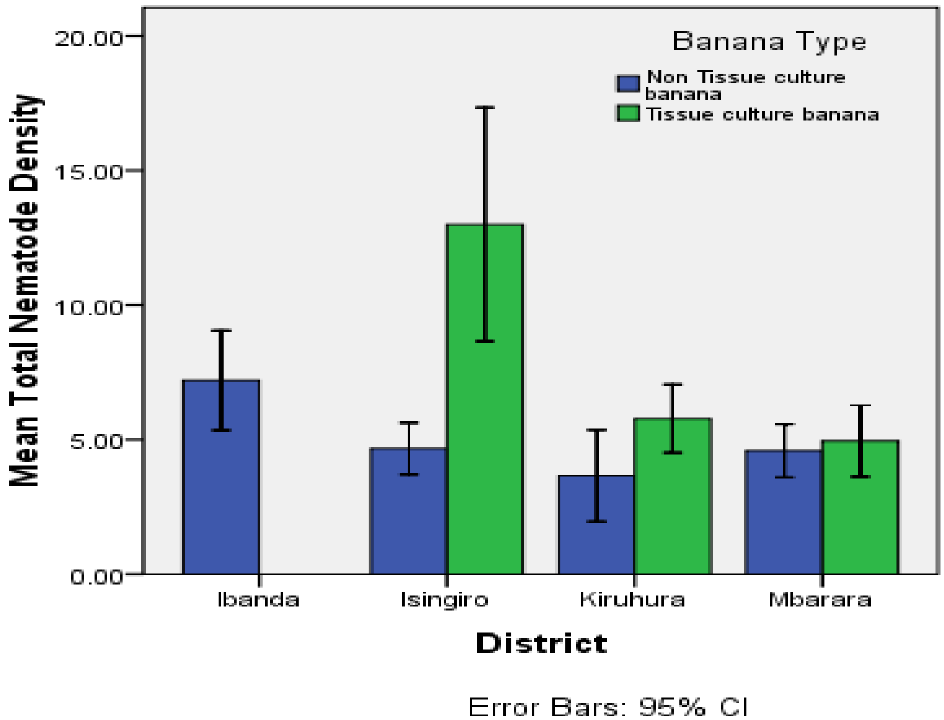

Figure 4. Total Nematode population density distribution for total banana orchards per district per banana type. Tissue culture banana was more infested with Nematodes in Isingiro district compared to any other district. The overlaps in the error bars indicate significant nematode infestation for both banana types in Isingiro, Kiruhura, and Mbarara.

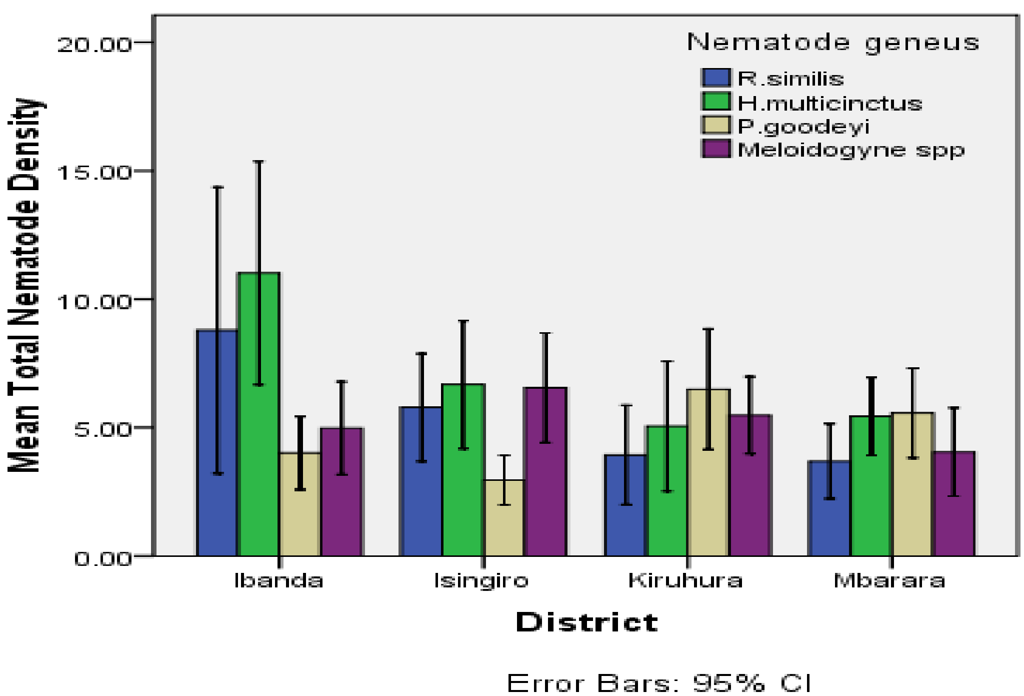

Figure 5. Total nematode population density distribution for total banana orchards per district per nematode genera. The overlaps in the error bars indicate significant nematode genera variations for Ibanda, Isingiro, Kiruhura, and Mbarara districts.

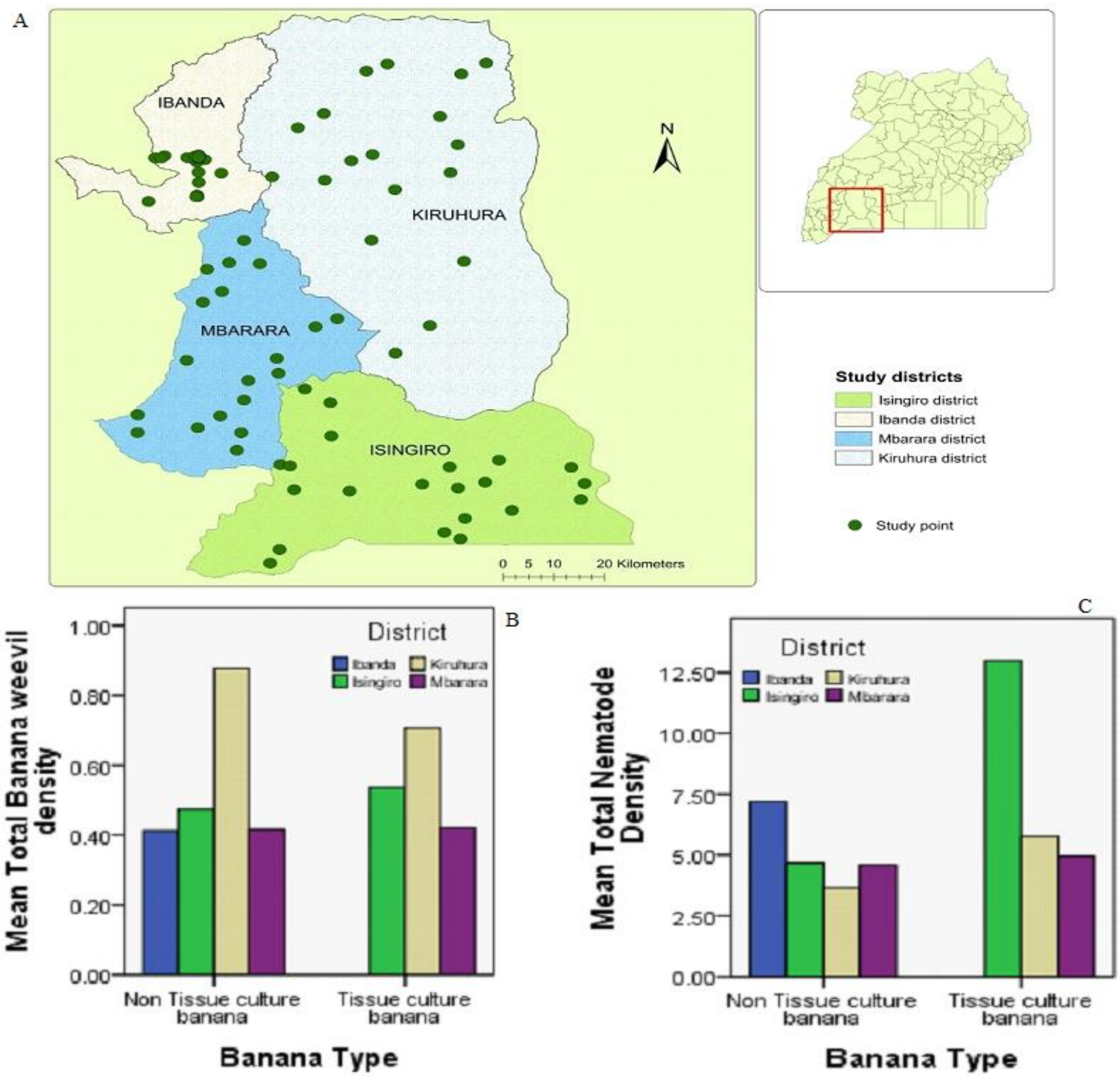

Figure 6. Spatial distribution of weevil and nematode densities within non–tissue culture and Tissue culture banana in the western region of Uganda. The districts are a common denominator characterising the spatial aspect. A shows the geo referenced study points, B shows the weevil density established from the geo referenced orchards, and C shows the nematode density established from the geo referenced orchards.

the root samples infested with *H. multicinctus.* In the neighborhoods of the study area, a survey conducted in the Democratic Republic of Congo by Kamira et al. (2013), showed that *H. multicinctus* was present in 89% of the samples whereas *Meloidogyne* was found in 54% of the samples. On the other hand, *R. similis*, was present in 30% of the samples which appears considerably higher than compared to the Western region of Uganda.

Spatial distribution of banana weevil and nematodes

The results of the survey explicitly show that all the geo-referenced study points indicated the infestation of both non-tissue culture and tissue culture banana types with both banana weevils (Figure 6B) and the nematodes (Figure 6C). Spatially, there was higher nematode density in all the districts than the densities for banana weevils. Isingiro district returned the highest density for banana weevil. Ibanda district returned the highest degree of infestation with the nematodes.

The elevations, temperature and rainfall ranges for the study area do not differ significantly from one spatial location to the other. The relatively similar characteristics provide similar conditions for the distribution of studied biotic components within the districts. The current spatial distribution of the banana weevil and the nematodes

Table 2. Variance for spatial-temporal banana weevil interactions with banana type.

Parameter	Df	Sum Sq.	Mean Sq.	F value	Pr (>F)
Weevil density	1	5.13	5.13	29.706	6.04e-08 ***
Season(Dry/Rainy)	1	1.04	1.04	6.020	0.0143 *
Location(District)	1	35.51	35.51	205.701	< 2e-16 ***
Season: Method(DOS/SPS)	1	0.00	0.00	0.014	0.9051
Weevil Density: Season	1	0.56	0.56	3.225	0.0728 .
Weevil Density: Season: Location	1	0.78	0.78	4.490	0.0343 *
season: Location	1	0.04	0.04	0.255	0.6138
Weevil Density:Season:Season:Method	1	0.24	0.24	1.368	0.2425
Season: Method: Location	1	0.00	0.00	0.009	0.9239
Weevil Density:Season:Season:Location	1	0.01	0.01	0.070	0.7909
Season:Method:Location	1	0.00	0.00	0.004	0.9471
Residuals	1268	218.89	0.17	-	-

Source: primary data; [***], [**], [*], [.] show significance at "0", "0.1", "1" and "5" critical values, respectively.

ought to be considered in line with Okech et al. (2004), who postulated that above 1400 masl, certain insect pest incidences are not a serious problem. The study area lies within altitudes that are above 1400 masl, which suggests that the insect pests problem including the banana weevil should be less of a risk (Okech et al., 2004; Arinaitwe et al., 2014b). For this study, it could be argued that at altitudes above 1400 masl, the associated spatial characteristics support banana crops to subsist with the observed densities for banana weevils and nematodes. In such cases, Queiroz et al. (2017) suggests that the general pest problem can be managed by improving the cultural practices. Studies have indicated that the banana weevils are largely less immobile and their genetic mobility is generally slow (Twesigye et al., 2018b). Likewise, nematode mobility is quite slow. Therefore, self-mobility by the weevils and the nematodes cannot be a factor to explain satisfactorily the current spatial distribution observed in the study. Chitamba et al. (2016) identified long-term monoculture practices as a contributing factor towards such spatial distributions, while Daneel et al. (2015) suggested the use of tissue-culture banana plants as mitigating factor for the spread of the nematode and the banana weevil. Murongo et al. (2018), established that 83% of the smallholder farmers in the current study area use conventional suckers as planting material. This is done without any intensive or effective quarantine system to prohibit infected materials dispersing within the region. Therefore, the current spatial distribution of the two biotic components is due movement of banana plant materials and residues from smallholder farm to the next.

Temporal distribution of the banana weevil

Infestation of the banana *genets* by the banana weevil was high during the dry season for Isingiro and Kiruhura districts, respectively (Figure 7A). The infestation was higher in tissue culture banana in the dry season compared to the same season in non-tissue culture banana (Figure 7B). Finally, both the DOS and SPS trap methods effectively captured a significant high number of weevils in both seasons; however, the SPS returned a higher density during the dry season capture (Figure 7C).

The banana weevil mean densities during the dry season were significantly higher than those for the rainy season for the method of capture, within the banana type, and for locations of the banana orchards (Figure 7). This phenomenon can be understood from point of view of the orchard management practices by the smallholder farmers. Towards the end the rainy season the farmers de-leaf the old and dry leaves of *ramets* of each genet. The leaves, in addition to other external materials such as lemon grass, are used to mulch the plantations in the dry season. According to the findings by Gold et al. (2006), mulched banana plantations whether on research stations farmers' fields have high banana weevil infestation. The practice of mulching varies with the location of the farmer.

Temporal factors affect the distribution of banana weevil and the banana weevil has an effect on the distribution of different banana types. The weevil incidences between 20 and 90%, are capable of destroying a banana orchard in the shortest time of its existence (Katungi et al., 2006; Njau et al., 2011; Speijer, 2017). Although the current study did not correlate the mean banana weevil densities with banana orchard damage, the results place the smallholder farmers' fields within the banana weevil destructive bracket. Persistent seasonal shifts in temperature and rainfall have led to the general decline (27%) in plantain production in Uganda. According to Sabiiti et al. (2016), such variations in weather and climate have had a significant impact on

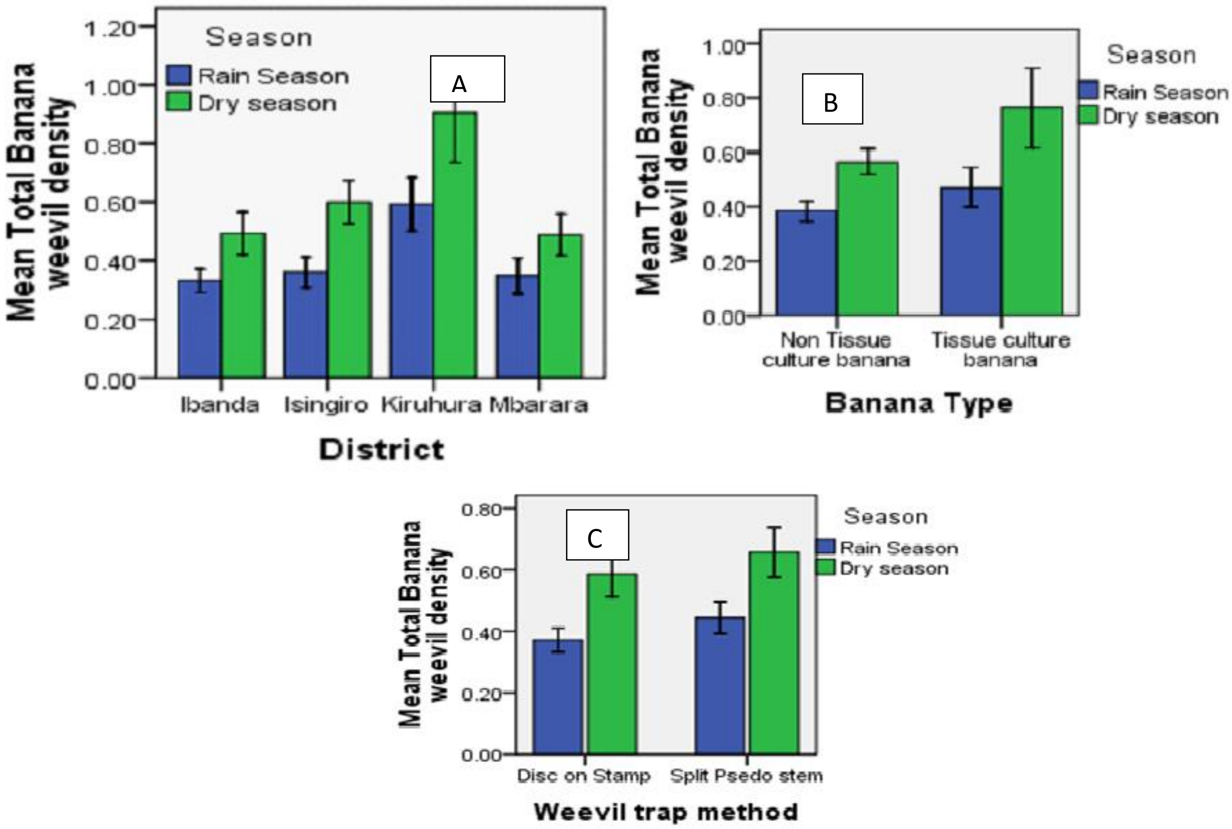

Figure 7. Temporal (seasonal) distribution of banana weevil within Non Tissue culture and Tissue culture banana in different location (districts) of western region of Uganda. A shows the seasonal weevil distribution following the location (Districts), B shows the weevil density established in the banana types following the season, and C shows the weevil captured by different traps in the seasons.

rain-fed banana yields in East Africa. Mean banana weevil densities need to be monitored alongside the seasonal variations to understand a relationship between the seasonal pest variations and the total banana production yield. What appears paradoxical is that despite the high mean weevil densities established by the study, the National Statistics (UBOS, 2010, 2016, 2017) consecutively identified the same regional districts as the largest producers of banana (2,883,648 tonnes) in the whole country.

Effect of interaction between banana weevil, nematodes and the abiotic factor on banana distribution

Interaction with banana weevil

The distribution of the banana type, that is, whether smallholder farmers chose to sustain the production of banana either from tissue culture products, or conventional plantations was significantly determined by the spatial characteristics ($P < 0.0001$) and the prevalence of the banana weevils ($P < 0.001$). The temporal aspect as represented by the season and the interactions that exist between the banana weevil densities, the season and the location significantly determined the distribution of different types of banana ($P < 0.01$). Interactions between the mean banana weevil density and the seasons were significant in the distribution of the type of banana at ($P < 0.05$) (Table 3). The proportions of the variance in the distribution of banana type and the risk of infestation of the farmers' banana orchards that could not be explained by other effects other than the location, mean weevil density and season were very low.

The smallholder farmers' orchards are represented by the banana types. Once the banana types are exposed to the risk of infestation by the weevils under natural conditions, then the orchards within which the banana types are found are assumed to be infested. Both conventional plantations and tissue culture banana plantations are equally affected by banana weevil across the locations and seasons. High banana weevil densities degenerate the banana orchards regardless of the type grown in the orchards (Alou et al., 2014). The current study indicates that interactions between banana types and high banana weevil population densities result in destruction of the banana types (Table 2). Therefore, the response of the type of banana towards banana weevil densities in smallholder farmers' fields cannot be dissociated from the effect attributed to the mean high population density of the banana weevils. Interactions that exist between the banana type and the spatio-temporal aspects, significantly affect the distribution of banana type. This result corroborates Wairegi et al. (2010) and Sabiiti et al. (2016) who argued that smallholder farmers' choices for plantain production are enhanced by the prevailing climatic conditions such as a stable balance between the rainy and dry seasons that characterise the environment of the smallholder farmers. The current study assumed that the banana types have inherent genetic abilities to resist harmful interactions with the biotic factors. In such cases, plant-based secondary metabolites exuded by the different types of banana with respect to the spatial and temporal prevailing conditions may indirectly contribute to significant mean weevil densities. For instance, spatial and temporal conditions that stimulate the banana plant [whether tissue culture or conventional] to exude terpenoids, may cause a high banana weevil infestation. According to Ndiege et al. (1991) and Gunawardena and Dissanayake (2000), terpenoids are secondary metabolites that are weevil attractants. Whereas it may be possible that the two banana types are exuding similar weevil attractants, the exudates may vary according to season, and perhaps the location of the orchards. The accumulated mean banana weevil density in turn exerts a negative effect on the banana type in question thus impacting on the general distribution.

Interaction with the parasitic nematodes

Location and the mean nematode density significantly determined the distribution of banana types ($P < 0.0001$, 0.001, respectively). The temporal aspect as represented by the season, the interactions that exist between the mean nematode densities and the location significantly determined the distribution of different types of banana ($P < 0.01$) (Table 3). The proportions of the variance in the distribution of banana type and the risk of infestation by the nematodes in the farmers' banana orchards that could not be explained by other interactions apart from the location and mean nematode density were very low.

The study has established that both conventional and tissue culture banana plantations are similarly negatively affected by the parasitic nematodes regardless of the location and season, although the degree of infestation varies across spatial and/or temporal scales. Even though various surveys have confirmed the presence of nematodes on bananas, abundance and frequency differ between genera (Daneel et al., 2015). The current study has shown that interactions between banana types and high nematode population densities are detrimental to the survival of the banana (Table 3). Hence, the response of the type of banana towards banana nematode prevalence in smallholder farmers' fields cannot be dissociated from the negative effect attributed to the high nematode population density of the banana weevils. Interactions that exist between the banana type and the spatio-temporal aspects, significantly affect the distribution of banana type. This result corroborates the inherent genetic capabilities of the plant which may exude secondary metabolites by the different types of banana hence their inherent ability to resist nematode destruction. For instance, Ndiege et al. (1991) established that *1, 8-cineole* exudates are nematode repellents. Such exudates may also vary with respect to the spatial and temporal prevailing conditions, and like in the case of banana weevil, they may indirectly contribute to significantly higher mean parasitic nematode densities if the concentration of the metabolite is low. . The variations in mean nematodes' density would negatively impact on the distribution of the banana type in question. For instance, the presence of the nematodes may have no effect on the distribution of banana weevil but the effect of the weevil on the banana may be associated with the prevalence of the nematodes. Speijer (2017) earlier established that the banana weevil damage to the roots can be high in nematode infested areas in mulched plots. Other than mulching, Speijer (2017) also identified the cycle of production as an enabler, where, nematode infested mulched banana plots suffer grave banana weevil damage after the fourth cycle. The current study did not consider the degree of damage of either the roots and or corms by the two pests but the implied argument is that, nematodes and banana weevil independently damage banana crops under homogenous field conditions unless variations occur within field conditions.

CONCLUSION AND POLICY RECOMMENDATIONS

This study has shown that under natural conditions, when smallholder banana farms are exposed to weevil and nematode pests both tissue culture banana and those developed from conventional suckers are prone to banana weevil and nematode infestation. The interactions between the season and locations as abiotic factors with banana weevils and nematodes significantly negatively influences the distribution of tissue culture and non-tissue culture banana in space and time. The location and season within which the banana orchard is found, enhance the variations in the levels of infestation. The study further established that tissue culture banana is infested with both weevils and nematodes of various genera. *H. multicinctus* and *R. similis* have been found most prevalent in Western Uganda. The incidences of the weevil and nematode pests, and an understanding of their seasonal and spatial distribution, should form a

Table 3. Variance for spatial-temporal Nematodeinteractions with banana type.

Parameter	Df	Sum Sq.	Mean Sq.	F value	Pr (>F)
Nematode density	1	1.69	1.69	9.652	0.00193 **
Season(Dry/Rainy)	1	0.00	0.00	0.000	1.00000
Location(District)	1	37.82	37.82	216.119	<2e-16 ***
Season: Method(DOS/SPS)	1	0.00	0.00	0.000	1.00000
Nematode: Season	1	0.000	0.000	0.000	0.000
Nematode: Season: Location	1	0.83	0.83	4.722	0.02997 *
season: Location	1	0.000	0.000	0.000	1.00000
Nematode Density: Season:Season:Method	1	0.000	0.000	0.000	1.00000
Season: Method: Location	1	0.000	0.000	0.000	1.00000
Nematode Density: Season:Season:Location	1	0.000	0.000	0.000	1.00000
Season:Method:Location	1	0.000	0.000	0.000	1.00000
Residuals	1268	221.87	0.17	-	-

Source: Primary data; [***], [**], [*], show significance at "0", "0.1", and "1%"critical values, respectively.

basis for developing strategic and affordable treatments meant to lower the occurrence of banana weevil and nematodes below the threshold level in smallholder banana farms of Uganda. In fact, farmers are most likely to accept the type of banana that co-exists with pest infestation in those management practices that are affordable by the smallholder farmers. Hence, regional and season-specific control strategies should be developed for sustainable traditional production systems for conventional banana orchard management and adoption of the tissue culture banana technologies.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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