Expl Agric. (2018), volume 54 (3), pp. 452–466 © *Cambridge University Press 2017*
doi:10.1017/S0014479717000163

NEMATODE MANAGEMENT IN RAIN-FED SMALLHOLDER MAIZE PRODUCTION SYSTEMS UNDER CONSERVATION AGRICULTURE IN ZIMBABWE

By SANDRA M. MADAMOMBE†‡¶, ISAIAH NYAGUMBO†, BRIGHTON M. MVUMI‡, PHILLIP NYAMUGAFATA‡, MENAS WUTA‡ *and* CLEOPAS C. CHINHEYA§

†*CIMMYT Southern Africa Regional Office, P.O. Box MP 163 Mt Pleasant, Harare, Zimbabwe,* ‡*Department of Soil Science and Agricultural Engineering, Faculty of Agriculture, University of Zimbabwe, P.O. Box MP167 Mt Pleasant Harare, Zimbabwe and* §*Nematology Department, Kutsaga Research Station, Airport Ring Road, P.O. Box 1909, Harare, Zimbabwe*

(*Accepted 23 March 2017*; *First published online 25 April 2017*)

SUMMARY

Nematode infestation in Sub-Saharan Africa's (SSA) cropping systems, worsened by poor crop rotations, is a major factor contributing to limited utilisation of applied nutrients and water, leading to low maize (*Zea mays* L.) yields particularly on sandy soils. The effects of nematode infestation on maize productivity were evaluated under conservation agriculture (CA) on granitic sandy soils in sub-humid smallholder farms of Goromonzi district of Zimbabwe. Four treatments were tested for three seasons on six smallholder farmers' fields in a randomised complete block design, each farm being a replicate: fenamiphos 40EC (a commercial synthetic nematicide), lime + fenamiphos 40EC, lime and an untreated control. Results of the study showed that independent application of fenamiphos 40EC and lime significantly reduced plant parasitic nematode infestations in maize roots by more than 10 times those present in the untreated plots while maize yield also increased significantly. Yield increase from fenamiphos and lime applications amounted to 53 and 42% respectively, compared to the untreated controls. Maize yield was negatively correlated with density of *Pratylenchus* spp. nematodes. Nematode management strategies involving fenamiphos 40EC or lime could significantly reduce maize yield losses in maize-based smallholder farming systems of SSA under CA. It was more economical to use fenamiphos than lime to control nematodes.

INTRODUCTION

Maize (*Zea mays* L.) is the most important cereal food crop and is a staple food for more than 300 million people in sub-Saharan Africa (SSA) (FAO, 2008). Maize is widely grown by smallholder farmers in Zimbabwe where average maize yield barely exceeds 0.8 t ha^{-1} (Kanonge *et al.*, 2009). About 70% of Zimbabwe's arable land is characterised by sandy soils derived from granite (Nyamapfene, 1991a). The sandy soils have a low nutrient status, low organic matter content and are generally acidic (FAO, 2006). The combination of inherent low soil fertility,

¶Corresponding author. Email: maka.madamombe@gmail.com

unaffordability of fertilizers, prevalence of soil pests such as nematodes, low and unreliable rainfall, result in low maize productivity in the smallholder farming sector.

Over the years, researchers and development agencies have focused more on addressing soil chemical fertility and the use of improved germplasm as the basis for sustainable intensification (Nezomba *et al.*, 2014; Vanlauwe *et al.*, 2011). However, soil health transcends several domains including physical and biological aspects. In maize-based farming systems which are dominant in Zimbabwe, nematodes have been reported as one of the major causes of low maize yield (Kagoda *et al.*, 2015; Nhamo, 2007), and then their sustainable control is needed to increase maize yield. More than 60 species of nematodes are associated with maize across the globe (Coyne *et al.*, 2007). *Pratylenchus* spp. (root lesion nematodes) and *Meloidogyne* spp. (root-knot nematodes) are species which attack maize and have the potential to cause economic yield losses (Kagoda *et al.*, 2011) by damaging, feeding on maize roots tissues and providing point of entry for root pathogens. In Zimbabwe, *Pratylenchus* spp. was found to be commonly associated with maize (Nhamo, 2007). The problem of nematodes in crop production in Zimbabwe is well-recognised in tobacco farming systems and relatively unknown in maize (Muzhandu *et al.*, 2013). In tobacco, *Meloidogyne* spp. is the most common nematode genus which is controlled by four year rotations with a non-susceptible crop as recommended for large-scale tobacco systems (Lipan *et al.*, 2014). Furthermore, the presence of nematodes in soil is influenced by the crop type, carbon source and soil physical properties (Muzhandu *et al.*, 2013).

Conservation agriculture (CA), a practice premised on reduced soil disturbance, provision of permanent soil cover and the use of crop rotations (Kassam and Friedrich, 2012), is a cropping system that mimics natural agro-ecosystems where higher density and diversity of crop damaging and beneficial organisms is high (Nana *et al.*, 2013). The balance between species is often determined by the rates of crop residue retention and the type of crop rotations practiced. However, despite their observed benefits (Nyagumbo *et al.*, 2016), rotations are hardly implemented under CA for various practical reasons and hence the need to understand the consequences of maize mono-cropping (Rusinamhodzi, 2015). Nematodes are some of the organisms that have been used as ecological bio-indicators reflecting environmental changes (Habig *et al.*, 2014). In addition, soil disturbance through tillage can cause redistribution of the plant parasitic nematode community structure. Thus CA, through reduced soil disturbance, is hypothesised to result in a more stable nematode community structure with long-term effects on crop health and sustainability (Djigal *et al.*, 2012; Stirling, 2014). Smallholder farmers practice continuous maize mono-cropping (Makwara, 2010; Mazvimavi and Twomlow, 2008) which potentially increases nematode infestations (Nie *et al.*, 2014) on nutrient deficient sandy soils found in most of the smallholder farming systems. The current study, therefore, sought to understand CA practice and different nematode management strategies on nematode infestation and maize productivity. The study was carried out on sandy soils in smallholder farming systems in a sub-humid region of Zimbabwe.

MATERIALS AND METHODS

Study site

The study was carried out in Chinhamhora communal area, sub-humid Goromonzi district (31°13′E; 17°30′S, altitude: 1420 to1560 m) over three consecutive cropping seasons. The experiment was established between November and December of the 2011/2012 season while field measurements on nematodes were only carried out during the 2012/2013 and 2013/2014 cropping seasons. Chinhamhora smallholder farming area lies in Zimbabwe's agro-ecological region IIa, which experiences daily air temperatures ranging between 21 and 31 °C during the cropping season, typically extending from mid-October to end of April and receives 750 to 1000 mm of rainfall per year.

Farming in Chinhamhora is dominated by horticultural production of tomatoes (*Solanum lycopersicum*) and leafy vegetables such as kale/Covo (*Tronchuda portuguesa*), Indian Kale (*Brassica juncea*) and rape (*Brassica napus*). Soils in the upper slope are well-drained, moderately shallow to deep and are classified as *Typic Kandiustalfs* according to the USDA taxonomy soil classification (Nyamapfene, 1991b). The shallow soils limited to mid and upper slope positions, are classified as *Lithic Ustorthents* based on the USDA system (Nyamapfene, 1991b). The soils are generally acidic, with soil pH ($CaCl_2$) ranging from 3.9 to 4.5 (Nyamangara *et al.*, 2000). Average farm size per household in Chinhamhora is 1–1.5 ha with the largest proportion being allocated to the staple maize crop in summer (Mutenje *et al.*, 2014). The farming area is characterised by urbanisation, which progressively continues to result in fragmentation of farms. Use of improved hybrid maize varieties among the farmers is high and estimated at 80–90% (Mutenje *et al.*, 2014).

Experimental design and treatments

Ten farmers were initially selected for the purposes of this experiment and prior to setting-up the experiment, soil samples were collected from a depth of 0–15 cm from each of the 10 farms for laboratory analyses of soil characteristics. The ten farms were screened down to six farms with closely matching soil characteristics. Four treatments on plots 15 × 15 m each were imposed on each farm: fenamiphos 40 EC (a commercial synthetic nematicide ethyl 4-methylthio-m-tolyl isopropylphosphoramidite sprayed around each planting station in the soil 7 days before planting at label rate of 25 Lha^{-1}.), lime + fenamiphos 40EC, lime (Calcitic ($CaCO_3$) applied 30 g/planting station which translates to 660 kg ha^{-1} two weeks before planting) and an untreated control with no lime and no nematicide. Calcitic lime, ground limestone composed of calcium carbonate ($CaCO_3$) was used in the experiment. Each farm was considered a replicate in a completely randomised block design.

From the collected soil samples, soil organic carbon was measured using the modified Walkley Black method (Okalebo *et al.*, 2002), soil texture was determined using the hydrometer method (Okalebo *et al.*, 2002) while soil pH was measured using Hanna HI 8314 membrane pH meter in a 1:5 soil:0.1 M $CaCl_2$ suspension. The soils were generally characterised as low in soil organic carbon (3.1 ± 0.3 g kg^{-1}), sandy in texture (Clay 9.3 ± 2.8%, Silt 7.3 ± 2.7%, Sand 84 ± 3.4%) and as stated earlier, acidic in pH ($CaCl_2$), ranging from 3.8 to 5.2 giving an average of 4.3 ± 0.5. Exchangeable bases were on average as follows; magnesium (Mg^{2+}) (1.8 ± 0.5 mg L^{-1}), calcium (Ca^{2+}) (5.7 ± 3.5 mg L^{-1}), potassium (K^+) (2.4 ± 0.5 mg L^{-1}), sodium (Na^+) (1.6 ± 0.3 mg L^{-1}).

At the start of each season in November or early December, maize SC513, a medium maturity variety, was planted in CA basins of 15 cm diameter and 15 cm depth after receiving at least 30 mm rainfall within three consecutive days. The planting basins were spaced at 90 cm inter-row and 50 cm in-row with two plants per station giving an average plant population of 44,000 plants per hectare.

Basal fertilizer (compound D; 7% N, 14% P_2O_5, 7% K_2O) was applied in basins at planting at a rate of 300 kg ha^{-1}. Top dressing with ammonium nitrate (34.5% N) at a rate of 200 kg ha^{-1} was split applied at four weeks after emergence (WAE) and eight WAE (AGRITEX, 2008). Manual weeding was done two to three times per season using hand hoes or when weeds grew to more than 10 cm in height.

Nematode sampling

Sampling for nematodes was done at 6 and 12 WAE, in both soil and maize roots (Coyne *et al.*, 2007) in 2012/2013 and 2013/2014 season. The same sampling intervals were maintained in 2013/2014 season except that only maize root samples were collected at six WAE. Composite soil samples were collected from rhizosphere of 10 randomly selected plants from each treatment plot on each farm using an auger. Similarly, root samples were collected by destructive excavation of five randomly selected plants using a hoe and carefully placed in khaki paper bags. All the soil and root samples were taken for extraction within the same day of collection.

Sample processing and nematode extraction from soil and root samples

Samples were processed at Kutsaga Research Station, Harare, Zimbabwe. The samples were stored in a cold room at 10 °C whilst they waited processing. From the composite samples, 200 g soil and 10 g root sub-samples were processed for nematode counts. Nematode density or populations in soil were expressed as numbers/200 g of soil and numbers/10 g of roots (Coyne *et al.*, 2007). Nematodes in soil were extracted using the Seinhost two-Erlenmeyer flask technique and the modified Bearmann filter method (Van Bezooijen, 2006) as it offers relatively high extraction efficiency which can be obtained with simple equipment and small amounts of water. However, the method is labour intensive and, when one set of bottles is used, it is very time consuming. As the method does not require running tap water, it can be carried out outside the laboratory (Van Bezooijen, 2006). Roots were washed thoroughly in water and were chopped into small pieces of approximately 1 cm length. About 10 g were weighed from each root sample macerated in a blender for 10 seconds in 0.5% NaOCl solution before the sample was poured into a Bearman tray and left for 48 h (Hooper *et al.*, 2005). The nematodes were identified using a compound microscope

https://doi.org/10.1017/S0014479717000163 Published online by Cambridge University Press

and identification was up to the genus level. A nematode identification key was used as a guide for differentiating nematode genus and species.

Yield assessment

Maize biomass and grain yield were measured from each treatment plot per farm and from check plots measuring 5 m long × 2 rows wide randomly placed in each treatment. The width of the two rows was measured three times along the check plot to obtain the average width of the two rows. All freshly harvested maize cobs and biomass from each check plot were weighed using a digital hanging balance after counting the number of plants and cobs. One sub-sample containing 10 maize cobs was collected from each plot and immediately weighed before air drying. Approximately, 500 g of biomass sub-sample was taken from each plot. Maize cobs and biomass sub-samples were then air-dried and re-weighed after two to three weeks. The maize cobs were shelled and the maize grain yield was adjusted to 12.5% moisture content. Percentage yield loss and gain was calculated using equation (1) and (2) respectively,

$$\text{percentage yield loss} = \left[\frac{\left(Y \text{ in nematicide treated plot } \left(\frac{kg}{ha}\right) - Y \text{ in untreated plot} \left(\frac{kg}{ha}\right)\right)}{Y \text{ in nematicide treated plots } \left(\frac{kg}{ha}\right)}\right] \times 100\ \% \qquad (1)$$

where, Y = maize grain yield; A = harvested area; MC = grain moisture content; and GW = weight of grain after cobs air drying and shelling (Kagoda *et al.*, 2011).

$$\text{percentage yield gain} = \left[\frac{Y \text{ in treated plot } \left(\frac{kg}{ha}\right) - Y \text{ in untreated plot } \left(\frac{kg}{ha}\right)}{Y \text{ in untreated plot} \left(\frac{kg}{ha}\right)}\right] \times 100\ \% \qquad (2)$$

Data analysis

Nematode density data were transformed using *log (x+0.5)* to normalize the data. The transformed nematode data from both the soil and root extracts and the maize yield data were subjected to analysis of variance using GENSTAT 14. Where no significant differences were found between the interaction of years and treatments, the data were pooled for a combined analysis over the two years. Correlations and linear regressions between yield and nematode densities were done in Statistics 9. The least significant difference (LSD) at 5% significance level was used for mean separation where there were significant treatment effects.

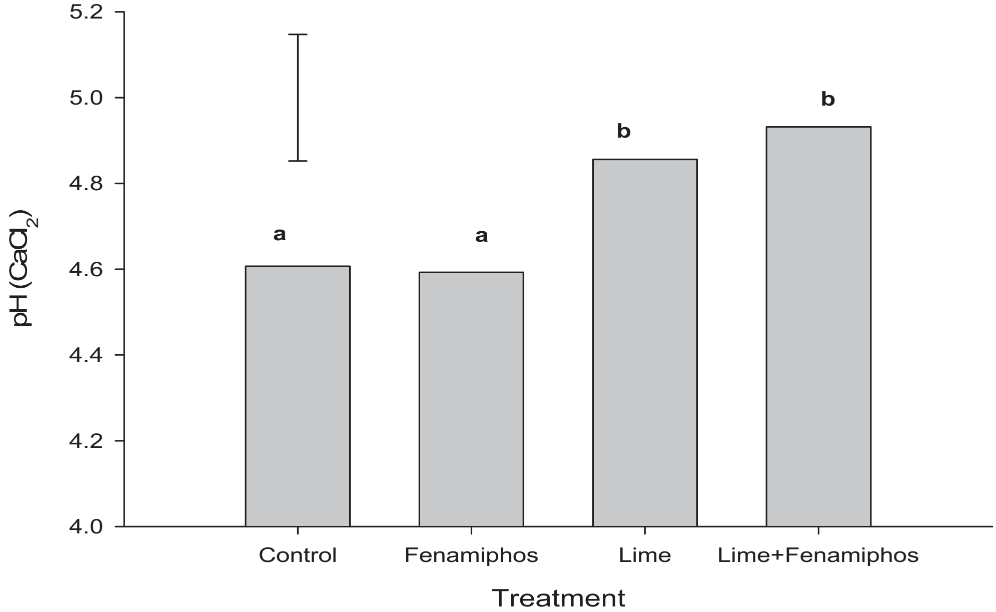

Figure 1. Soil pH response to the application of lime and fenamiphos for seasons 2012/2013 to 2013/2014 at Chinhamhora. Error bar denotes LSD(0.05) = 0.3. Different letters above each bar denote significant differences between treatments at $p < 0.05$.

RESULTS

Analyses of the soil samples collected after applying the treatments indicated that soil pH ($CaCl_2$) in the treated plots was significantly increased in the lime and combined lime plus fenamiphos-treated than in the untreated control and sole fenamiphos-treated plots (Figure 1).

Dominant species at genus level found at the site included *Meloidogyne* spp., *Pratylenchus* spp., *Criconema* spp., *Trichodorous* spp., *Helicotylenchus* spp., saprophytes and other less common nematodes such as *Tylenchulus* spp. and *Mononchus* spp. (Table 1). Due to their abundance, *Pratylenchus* spp. further classified to species level, included *Pratylenchus zeae*, *Pratylenchus penetrans* and *Pratylenchus brachyurus*. *Meloidogyne* spp. identified at the site was *Meloidogyne javanica*. The beneficial non-plant parasitic saprophytic nematodes were significantly higher in untreated soils at six WAE. Furthermore, *Pratylenchus* spp. infestation was significantly higher in untreated plots in both maize roots and surrounding soil during the first season of 2012/2013 at six WAE; while fenamiphos-treated plots had significantly lower infestations (Table 1). The nematode densities for the two years were thus significantly higher in untreated plots (Table 2). Consequently, *Pratylenchus* spp. density was significantly higher in control plots both at 6 and 12 WAE in both maize roots and soil samples. In contrast, the nematodes densities in fenamiphos treated plots were significantly lower than those found in the control even at 12 WAE. Because of its importance as one of the most damaging species to maize (Bridge and Starr, 2007; Coyne

Table 1. Nematode genera at six weeks after emergence (six WAE) in Chinhamhora for the season 2012/2013 ($n = 6$).

Treatment	*Meloidogyne* (10 g roots)$^{-1}$	*Pratylenchus* (10 g roots)$^{-1}$	*Criconema* (200 g soil)$^{-1}$	*Pratylenchus* (200 g soil)$^{-1}$	*Meloidogyne* (200 g soil)$^{-1}$	Saprophytes (200 g soil)$^{-1}$	*Helicotylenchus* (200 g soil)$^{-1}$	*Trichodorous* (200 g soil)$^{-1}$	Others* (200 g soil)$^{-1}$
Untreated control	8 (0.27)	672 (1.97) ^{b}	0 (− 0.30)	54 (1.16)^{b}	38 (0.78)	1688 (3.14)^{c}	88 (1.78)	186 (0.71)	8 (0.27)
Lime	0 (− 0.30)	11 (0.28) ^{a}	0 (–0.30)	13(0.24)^{ab}	0 (–0.30)	338 (2.42)^{b}	38 (1.27)	0 (–0.30)	8 (0.03)
Lime + Fenamiphos	8 (− 0.03)	1 (–0.13)^{a}	4 (–0.02)	4(–0.02)^{a}	8 (0.03)	371 (2.49)^{b}	129 (1.61)	8 (0.27)	0 (–0.30)
Fenamiphos	0 (–0.30)	0 (–0.30)^{a}	0 (–0.30)	0 (–0.30)^{a}	0 (–0.30)	96 (1.94)^{a}	11 (0.53)	0 (–0.30)	0 (–0.30)
p value	NS	0.004	NS	0.031	NS	<0.001	NS	NS	NS
LSD	NS	(1.19)	NS	(0.97)	NS	(0.34)	NS	NS	NS
SED	(0.37)	(0.56)	(0.20)	(0.46)	(0.44)	(0.16)	(0.49)	(0.56)	(0.37)

NS = not significant. LSD = least significant difference at 5% level; SED = standard error of differences of means; Numbers in brackets denote transformed means of nematode density as *log (x+0.5)*; Means in the same column followed by the same letter are not significantly different at $p < 0.05$. *refers to nematodes that were not in abundance such as *Tylenchulus* spp and *Tylenchorynchus* spp.

Table 2. Mean nematode infestation in maize roots and soil at 6 and 12 weeks after emergence (6 and 12 WAE) in Chinhamhora ($n = 6$ replicates) for season 2012/2013 and 2013/2014.

	6 WAE	12 WAE				
Treatment	*Pratylenchus* (10 g roots)$^{-1}$	*Meloidogyne* (10 g roots)$^{-1}$	*Pratylenchus* (10 g roots)$^{-1}$	*Pratylenchus* (200 g soil)$^{-1}$	*Helicotylenchus* (200 g soil)$^{-1}$	Saprophytes (200 g soil)$^{-1}$
Control	623 (2.38)^{b}	262 (1.02)^{b}	516 (2.44)^{c}	670 (2.43)^{c}	178 (1.82)^{b}	1168 (3.04)^{b}
Lime	134 (1.11)^{a}	18 (0.16)^{a}	60 (1.15)^{ab}	105 (1.49)^{b}	90 (1.13)^{ab}	842 (2.72)^{b}
Lime + Fenamiphos	139 (1.15)^{a}	6 (–0.12)^{a}	138 (1.52)^{b}	292 (1.23)^{ab}	146 (1.42)^{ab}	775 (2.81)^{b}
Fenamiphos	28 (0.49)^{a}	4 (–0.14)^{a}	46 (0.57)^{a}	106 (0.67)^{a}	48 (0.74)^{a}	412 (2.40)^{a}
p value	<0.001	0.02	<0.001	<0.001	0.04	0.003
LSD	0.68	0.79	0.79	0.69	0.78	0.32
SED	0.34	0.39	0.39	0.34	0.38	0.16

NS = not significant, LSD = least significant difference at 5% significant level; SED = standard error of differences of means Numbers in brackets denote *log (x+0.5)* transformed means of nematode density as *log (x+0.5)*;
Means in the same column followed by with the same letter are not significantly different at $p < 0.05$.

Table 3. Mean two-year maize grain yield, biomass and grain yield loss in Chinhamhora.

Treatment	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Grain yield gain (%)	Grain yield loss (%)
Control	3074^{a}	6120^{a}	0	35
Lime	4369^{b}	7904^{b}	42	30
Lime + Fenamiphos	3371^{a}	7678^{b}	10	9
Fenamiphos	4704^{b}	8101^{b}	53	0
p value	<0.001	<0.05		
LSD	582	1499		
SED	273	703		

LSD = least significant difference at 5% level; SED = standard error of differences of means; Means in the same column followed by with the same letter are not significantly different at $p < 0.05$.

et al., 2013), special attention was given to the *Pratylenchus* spp., in subsequent analyses.

In terms of maize grain yield, the differences in treatments were also found to be significant (Table 3). The high nematode infestation in untreated control plots (no lime and no nematicide) resulted in much lower yield compared to fenamiphos (nematicide) treated plots which had the highest mean yield over the two years. This fenamiphos treatment gave a yield increase of 53% over the untreated control and had the lowest nematode density (Table 3). Relative to the fenamiphos treated plots, the grain yield loss due to nematode damage was equivalent to 35% in the control plots, 30% in lime and fenamiphos plots and lowest in lime treated plots at 9%. Biomass yield was also highest in fenamiphos-treated plots and lowest in the control with significant differences across the treatments over the two years (Table 3). Similarly, the percentage losses in biomass yield followed the same pattern as grain yields though somewhat lower in magnitude.

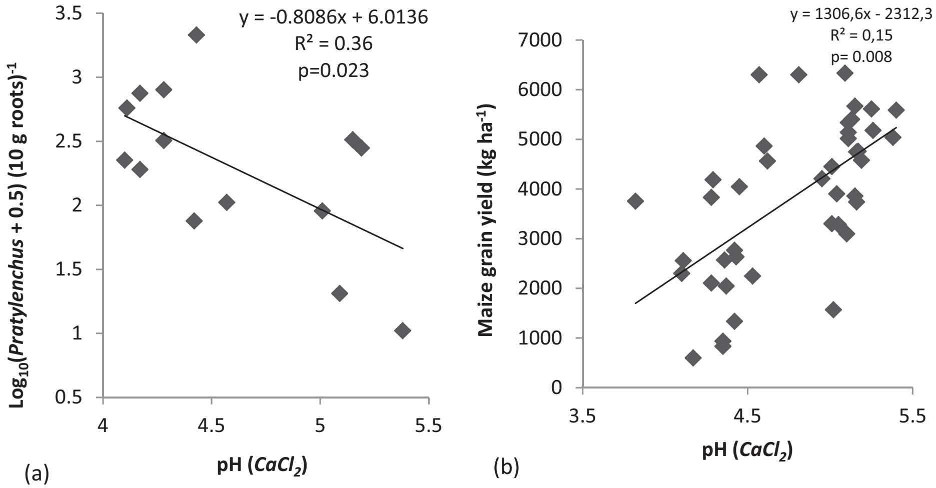

Figure 2. The relationship between Log density of *Pratylenchus* spp. infestation in maize roots and soil pH in untreated control systems (a), and the relationship between maize grain yield and pH ($CaCl_2$) based on yield results from 2012/2013 (b) in Chinhamhora, Goromonzi district, Zimbabwe. In (a), data are based on samplings at 12 WAE, taken in two seasons (polled data).

For the untreated controls, regression analysis showed a negative linear relation between *Pratylenchus* spp. and pH (Figure 2a). This regression between soil pH in untreated controls and log density of *Pratylenchus* spp. was significant at $p = 0.04$ (Figure 2a). However, for the fenamiphos-treated system the relationship between pH and *Pratylenchus* spp. was insignificant. Further regression analyses also showed a strong positive and significant ($p = 0.008$) linear relationship between maize grain yield and pH (Figure 2b).

Consequently, the relationship between nematode infestation by *Pratylenchus* spp. and maize grain yield was negatively correlated (Figure 3). The resulting regression between log density of *Pratylenchus* spp. and maize yield was thus significant at both 6 WAE (Figure 3a) and 12 WAE (Figure 3b) in maize roots. The same pattern was observed at 12 WAE in soil samples (Figure 3c) using pooled data from both seasons.

DISCUSSION

Application of lime and the nematicide fenamiphos generally reduced the nematode densities in soil. The non-plant parasitic nematodes such as the saprophytes were also reduced in numbers (Tables 1 and 2). The decrease in saprophytes in soil treated with lime and nematicide is a negative effect on soil health since the saprophytes are essential for organic matter decomposition and nutrient cycling (Massawe, 2010). Furthermore, parasitic nematodes such as *Helicotylenchus* spp., known to contribute positively to soil health, have been reported in agricultural lands but excessively large numbers potentially cause a significant reduction in maize yield (Kandji *et al.*, 2002). Thus, a certain balance for *Helicotylenchus* spp. is required in the soil. Differences in

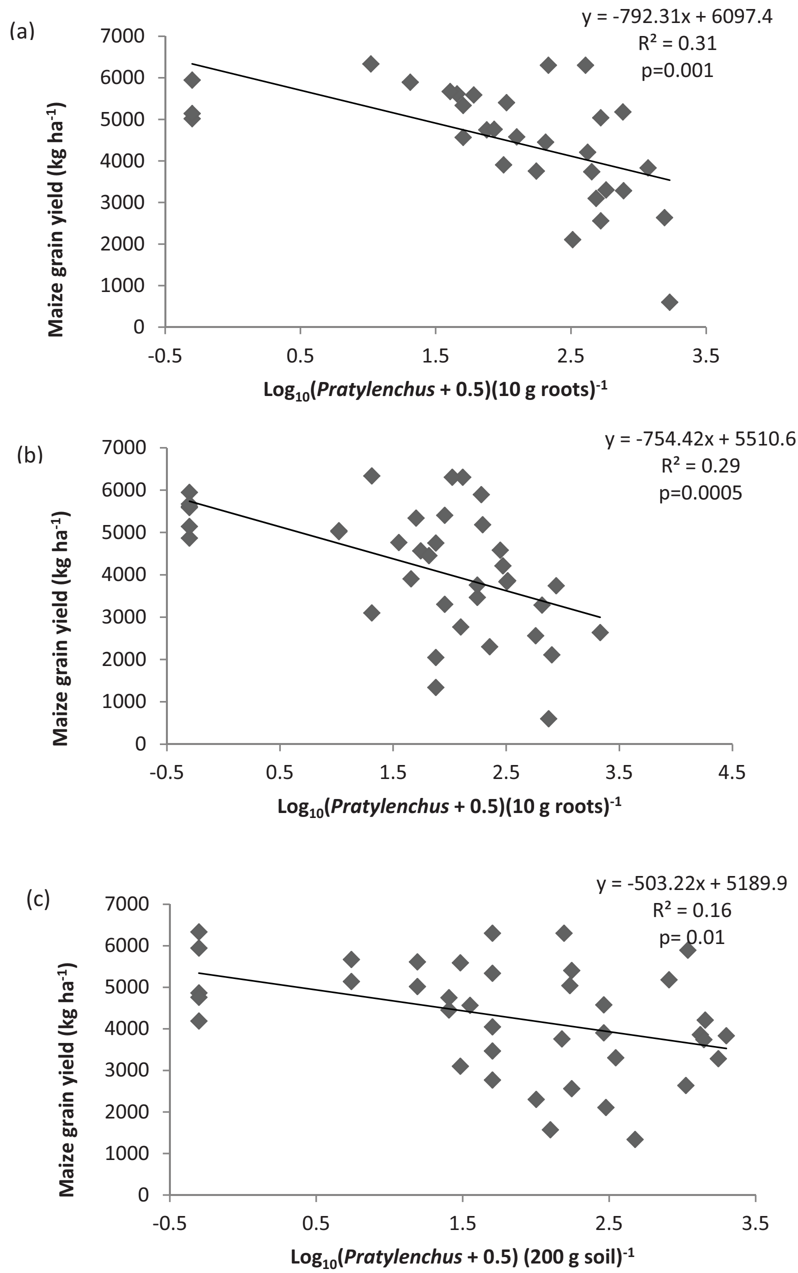

Figure 3. The relationship between maize grain yield and log density of *Pratylenchus* spp. infestation in maize roots at 6 weeks after emergence (a) and at 12 weeks after emergence (b) and in soil at 12 weeks after emergence (c) in Chinhamhora, Goromonzi district, Zimbabwe combined for 2012/2013 and 2013/2014.

https://doi.org/10.1017/S0014479717000163 Published online by Cambridge University Press

Pratylenchus spp. density in roots at 6 and 12 WAE was attributed to phenological development of the species feeding and reproducing in roots. The *Pratylenchus* spp. migrate in the roots as they feed, causing physical damage to the root system which depress the plant's ability to take up water and nutrients from the soil. Root openings by nematodes allow pathogens to access the damaged root tissues causing secondary root infections thereby further reducing yield potential. Therefore, regression of *Pratylenchus* spp. infestation in roots versus grain yield was more significant at 12 weeks (Figure 3b) than at 6 weeks (Figure 3a) because of increases in *Pratylenchus* spp. population with time (Massawe, 2010).

Grain yield in fenamiphos-treated plots (Table 3) that had the lowest nematode infestation (Table 2) was higher (+53%) when compared to the untreated control. Clearly, this indicates that nematodes are associated with yield losses in maize (Thompson *et al.*, 2008). This also confirms other research findings suggesting that nematodes reduce maize yield (Kagoda *et al.*, 2011). Grain yield in lime treated plots was higher by 42% when compared to the control (Table 3). The mean grain yield obtained in the current study is above the average yield (0.8 t ha^{-1}) attainable by smallholder farmers in this region of Zimbabwe (Marongwe *et al.*, 2012). In the lime-treated plots, nematode densities were significantly lower than in control plots, indicating that lime indirectly induces changes in the microbial community affecting soil nematode communities and food webs (Wang *et al.*, 2015); thus soil pH is important in management of nematodes. By applying fenamiphos, a yield loss of 35% due to nematode infestation is avoided while a yield loss of 30% is avoided by application of lime. However, combining lime and fenamiphos had no significant reduction in grain yield loss from that of the untreated control compared to using lime alone, thereby suggesting that combining the two treatments does not give any extra benefit in controlling nematodes. Reactivity of both lime and fenamiphos is reduced when used in combination and this explains the compromised yield (Singh *et al.*, 2003). As fenamiphos degrades faster when lime is added, the combination of the two treatments should be avoided (Singh *et al.*, 2003). Although smallholder farmers usually and mostly rely on grain yield as a measure of productivity and a major reason for adoption of a technology, biomass yield is also of critical importance in CA; especially if livestock is an integral component of the farming system (Valbuena *et al.*, 2012).

In the current study, biomass yield in the untreated control plots was also significantly lower than the treated plots and biomass yield patterns were similar to grain yield. Biomass yield was highest in fenamiphos followed by lime and a combination of lime and fenamiphos. The results therefore suggest that nematode infestations equally affect both maize grain and biomass yield. Since CA requires retention and a buildup of organic material to give at least 30% soil cover by the time of planting (Kassam and Friedrich, 2012), mono-cropping by smallholder farmers and failure to control nematodes could result in a continual decline of biomass yield; resulting in major implications on CA performance. The negative response of yield to nematodes in the untreated control system reflects on the current management practices by smallholder farmers in Chinhamhora and other similar areas of Zimbabwe. The commonly practised maize mono-cropping promotes multiplication of nematodes in soil and increases the risk of nematode damage (Eche *et al.*, 2013). Yet, if farmers were to practice rotations as recommended for CA with non-host leguminous crops, then the buildup of nematodes would also be controlled. Current rotations mainly involve horticultural crops (Mutenje *et al.*, 2014) such as tomatoes which also favour proliferation of nematodes. Future studies thus need to further explore the nematode status on farms where rotations are being practised (Eche *et al.*, 2013) in order to evaluate the contribution of rotations to nematode control in this farming system.

Although application of lime may have resulted in improved nutrient availability in the soil since the soil was very acidic, the low nematode numbers in the infestation assessments suggest that the yield benefit obtained from application of lime was also due to its effectiveness in reducing the nematode population (Wang *et al.*, 2015). The results of the study show a reduction in the nematode population on application of lime (Tables 1 and 2) and generally with increase in pH (Figure 2a). Thus, yield response in fenamiphos-treated systems where pH remained low (Table 3) was similar to lime-treated systems, indicating that the yield increase response observed for lime is not only due to nutrient availability benefits related to pH management but rather to the control of *Pratylenchus* spp. activity. Fenamiphos effectively reduces the nematode population irrespective of pH levels in soil as found in this study, therefore nematode attack to plants is reduced as confirmed by the lack of a significant correlation between *Pratylenchus* spp. and pH in the fenamiphos-treated plots. This deactivation of *Pratylenchus* spp. through fenamiphos results in increased root growth for water and nutrient uptake hence the pronounced significant yield gain even when pH conditions were sub-optimal for maize. Furthermore, the nematode population declined as pH increased in untreated control plots thus providing further evidence for the influence of pH on nematode density (Figure 2a). Thus, liming is effective in altering and creating an unfavourable environment (Wang *et al.*, 2015) for the nematodes to thrive and consequently increasing yield.

The current study demonstrated that nematodes are contributing significantly to yield losses in maize cropping systems on sandy soils in smallholder systems. Low pH also results in yield losses due to aluminium toxicity to crops (Nyamangara *et al.*, 2000) thereby also resulting in yield losses. Therefore, lime could serve a dual purpose in such nematode-infested systems. The results also suggest that since both lime and fenamiphos are effective in nematode control when applied separately, yet the use of lime would be environmentally sustainable and a more preferred option for wider application since it also has positive benefits with regards to nutrient availability in the system. The lime requirements for this soil averaged 660 kg ha^{-1} and costs USD$ 6 per 50 kg bag, which equates to about USD$ 120 ha^{-1} inclusive of transport to smallholder communities around Harare located within 50 km radius. The bulkiness of lime impacts negatively on transport costs and ranks lower than other inputs thus hindering its use by smallholder famers (Musharo and Nyamangara, 2011). Unlike chemical fertilizers and other agricultural inputs, lime is not readily available from local agro-dealers shops that are within the farmers reach. In comparison, fenamiphos

40EC costs USD$ 24 a litre but only 1.7 litre of undiluted fenamiphos 40EC is required per hectare. A farmer thus needs approximately USD$ 60 ha^{-1} including transport if using the nematicide which is a much lower cost than if they have to use lime. Fenamiphos, therefore is much more attractive option cost wise than lime. However, lime is more sustainable than fenamiphos and lime is easier to handle than a hazardous nematicide. Lime may however have the set back that it reacts slowly with the soil and in situations where the nematode problem has become pandemic; the use of lime may not bring about immediate results unless the lime is applied prior to the start of the season. This means the choice of a nematode control method also depends on timing; let alone cost. The use of fenamiphos is limited due to its persistence in the environment and its effect on non-target organisms. Continuous use of fenamiphos reduces its efficacy against targeted nematodes due to its biodegradability hence; it is recommended to change to other commercially available nematicides after every three years (Hugo *et al.*, 2014).

CONCLUSION

The study showed that *Pratylenchus* spp. reduces maize grain yield. The use of fenamiphos, results in significantly lower nematode infestations and consequently higher maize grain yield. These findings suggest that failure to control nematodes results in maize grain yield loss of at least 35%. Then, maize grain yield can improve by over 1.5 t ha^{-1} when a nematicide is applied. The study also demonstrated that lime is as effective as the nematicide in *Pratylenchus* spp. control and other nematodes and can result in maize grain yields improving by 1 t ha^{-1}. Yield gain due to the use of lime for nematode control amounted to 42% compared to the untreated control. The study therefore highlights the need for nematode control, especially the *Pratylenchus* spp. in maize produced on granitic sandy soils since yield loss can amount to more than 30%. Farmers may be recommended to use lime also as a nematode control strategy in sandy soils of Zimbabwe under maize production because of its extra positive established effects on pH and nutrient availability. However, in situations where quick results are required to control the nematodes, the use of a nematicide could be more appropriate and the usual precautions in handling pesticides are then needed. Further, long-term studies are required to understand nematode dynamics and management in smallholder CA systems, especially in granitic sands.

Acknowledgements. The authors would like to acknowledge the International Maize and Wheat Improvement Centre (CIMMYT) for funding this study and the extra logistical support facilitated through the ACIAR-funded project ‘Integrating crop and livestock production for improved food security and livelihoods in rural Zimbabwe (ZimCLIFS)’. We extend our gratitude to Kutsaga Research Station for the technical assistance in the nematology laboratory. We also want to acknowledge the farmers in Chinhamhora for hosting the trials. Last but not least we thank the Agricultural Technical and Extension Services (AGRITEX) extension staff especially Mr. Evans Magama, for his role in supervising and monitoring the trials.

REFERENCES

AGRITEX. (2008). Section C: Crop production. In *Farm Management Handbook*. (Eds F. Gamu and S. Mangena. Zimbabwe: Department of Agricultural technical and extension (AGRITEX).

Bridge, J. and Starr, J. L. (2007). *Plant Nematodes of Agricultural Importance: A Color Handbook*. Academic Press, An imprint of Elsevier. London: Manson publishing.

Coyne, D. L., Fourie, H. H. and Moens, M. (2013). Current and future management strategies in resource poor farming. In *Plant Nematology* (Eds R. N. Perry and M. Moens). London, UK: MPG Books group.

Coyne, D. L., Nicol, J. M. and Claudius-Cole, B. (2007). *Practical plant nematology: A field and laboratory guide*. Mexico: CIMMYT [u.a.].

Djigal, D., Saj, S., Rabary, B., Blanchart, E. and Villenave, C. (2012). Mulch type affects soil biological functioning and crop yield of conservation agriculture systems in a long-term experiment in Madagascar. *Soil Tillage Research* 118:11–21.

Eche, M. N., Iwuafor, O. E. N., Amapu, Y. I. and Bruns, V. M. (2013). Effect of fertility management on plant parasitic nematodes and maize yield under long-term continuous cropping in Northen Guinea Savanna of Nigeria. *ESci Journal of Crop Production* 02:49–54.

FAO (2006). *Fertiliser Use by Crop in Zimbabwe*. Rome, Italy: Food and Agriculture organization of the United Nations.

FAO (2008). *The State of Food Insecurity in the World*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Habig, J., Hassen, A. J. and Swart, A. (2014). Application of microbiology in conservation agriculture. In *Conservation Agriculture*, 537–540 (Eds M. Farooq, and K. Siddique). Switzerland: Springer International Publishing.

Hooper, D. J., Hallman, J. and Subbotin, S. (2005). Methods for extraction,processing and detection of plant and soil nematodes. In *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture*, 53–86 (Eds M. Luc, R. M. Sikora and J. Bridge). Wallingford, UK: CAB International.

Hugo, H. J., Mouton, C. and Malan, A. P. (2014). Accelerated microbial degradation of nematicides in vineyard. *South African Journal of Enology and Viticulture* 35:157–167.

Kagoda, F., Derera, J., Tongoona, P., Coyne, D. and Talwana, H. (2011). Grain yield and heterosis of maize hyabrids under nematode infestested and nematicide treated conditions. *Journal of Nematology* 43:209–219.

Kagoda, F., Hearns, S., Adewuyi, O. and Coyne, D. L. (2015). Response of drought tolerant maize inbreds to water stress under nematode infested conditions. *Euphytica* 206:77–87.

Kandji, S. T., Ogol, C. K. P. O. and Albrecht, A. (2002). Diversity of plant-parasitic nematodes and their relationships with some soil physico-chemical characteristics in improved fallows in western Kenya. *Applied Soil Ecology* 18:143–157.

Kanonge, G., Nezomba, H., Chikowo, R., Mtambanengwe, F. and Mapfumo, P. (2009). Assessing the potential benefits of organic and mineral fertiliser combinations on maize and legume productivity under smallholder management in Zimbabwe, in: African Crop Science Conference Proceedings. African crop science society, Uganda, pp. 63–79.

Kassam, A. and Friedrich, T. (2012). An ecologically sustainable approach to agricultural production intensification: Global perspectives and developments. *Field Actions Science Report* 6:1–6.

Leppan, W., Lecours, N. and Buckles, D. (Eds.) (2014). *Tobacco Control and Tobacco Farming: Separating Myth from Reality*. New York, NY: Anthem Press.

Makwara, E. C. (2010). Sustainable and profitable farming through conservation agriculture in Zimbabwe: Prospects, opportunities and constraints. *Journal of Sustainable Development in Africa* 12:181–190.

Marongwe, L. S., Nyagumbo, I., Kwazira, K., Kassam, A. and Friedrich, T. (2012). Conservation Agriculture and Sustainable Crop Intensification: A Zimbabwe Case Study, Integrated Crop Management. Plant Productionand Protection Division, Food and Agriculture Organization of the United Nations; Rome, 2012.

Massawe, C. R. S. (2010). Impact of nematode pest management strategies on nematode communities in tomato production systems in Zimbabwe (phd). University of Zimbabwe, Harare, Zimbabwe.

Mazvimavi, K. and Twomlow, S. (2008). Conservation farming for agricultural relief and development in Zimbabwe. In *No-Till Farming Systems*, Special Publications, 169–178 (Eds T. Goddard, M. Zoebisch, Y. Gan, W. Ellis, A. Watson and S. Sombatpaint). Bangkok: World Association of Soil and Water Conservation.

Musharo, C. and Nyamangara, J. (2011). Effect of Al concentration and Liming acid soils on growth of selected maize cultivars grown on sandy soils in Southern Africa. In *Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts, SpringerLink : Bücher*, 491–499 (Eds A. Bationo, B. Waswa, J. M. Okeyo, F. Maina and J. M. Kihara). Heidelberg, London: Springer science & Business Media.

Mutenje, M. J., Kassie, G. T., Gwara, S. and Mujeyi, A. (2014). Integrating crops and livestock for improved food security and livelihoods in rural Zimbabwe (ZIMCLIFS). (Baseline report). International Maize and Wheat Improvement Center CIMMYT, Southern Africa Regional office, Harare, Zimbabwe.

Muzhandu, R. T., Chinheya, C. C., Manjeru, P. and Dimbi, S. (2013). Use of edaphic factors to map the spatial distribution of root knot nematodes in tobacco plantations. *African Journal of Agricultural Research* 8:3946–3949.

Nana, P. D., Degué, P., Mkomwa, S., Da Sansan, J. B., Essecofy, G., Bougoum, H., Zerbo, I., Ganou, S., Andrieu, S. and Douzet, J. M. (2013). Conservation Agriculture in west and central Africa. In *Conservation Agriculture: Global Prospects and Challenges* (Eds. R. A. Jat, K. L. Sahrawat and A. H. Kassam). Croydon, UK: CABI.

Nezomba, H., Mtambanengwe, F., Chikowo, R. and Mapfumo, P. (2014). Sequencing integrated soil fertility management options for sustainable crop intensification by different categories of smallholder farmers in Zimbabwe. *Experimental Agriculture* 51:17–41.

Nhamo, N. (2007). *The Contribution of Different Fauna Communities to Improved Soil Health: A Case of Zimbabwean Soils Under Conservation Agriculture.* zu Bonn: Rheinischen Friedrich-Wilhelms-Universität.

Nie, L., Fahad, S., Peng, S., Huang, J. and Cui, K. (2014). Causes of soil sickness associated with aerobic rice continuous monocropping. *International Journal of Agriculture and Biology* 16:431–434.

Nyagumbo, I., Mkuhlani, S., Pisa, C., Kamalongo, D., Dias, D. and Mekuria, M. (2016). Maize yield effects of conservation agriculture based maize–legume cropping systems in contrasting agro-ecologies of Malawi and Mozambique. *Nutrient Cycling in Agroecosystems* 105:275–290.

Nyamangara, J., Mugwira, L. M. and Mpofu, S. (2000). Soil fertility status in the communal areas of zimbabwe in relation to sustainable crop production. *Journal of Sustainable Agriculture* 16:15–29.

Nyamapfene, K. (1991a). *Soils of Zimbabwe*. Harare, Zimbabwe: Nehanda Publishers.

Nyamapfene, K. (1991b). *Soils of Zimbabwe*, 1st edn. Harare: Nehanda Publishers (Pvt) Ltd..

Okalebo, J. R., Gathua, K. W. and Woomer, P. L. (2002). Laboratory methods of soil and plant analysis. *A Working Manual*, 2nd edn. Nairobi, Kenya: TSBF-CIAT and SACRED Africa.

Rusinamhodzi, L. (2015). Crop rotations and residue management in conservation agriculture. In *Conservation Agriculture*, 21–37 (Eds M. Farooq and K. H. Siddique). Switzerland: Springer International Publishing.

Singh, B. K., Walker, A., Morgan, J. A. W. and Wright, D. J. (2003). Role of soil pH in the development of enhanced biodegradation of fenamiphos. *Applied And Environmental Microbiology* 69:7035–7043.

Stirling, G. R. (2014). *Biological Control of Plant-parasitic Nematodes*, 2nd edn. CABI, Croydon, UK: Soil Ecosystem Management in Sustainable Agriculture.

Thompson, J. P., Stirling, G. R. and Bell, M. J. (2008). Root-lesion nematodes (Pratylenchus thornei and Pratylenchus neglectus): A review of recent progress in managing a significant pest of grain crops in northern Australia. *Australiasian Plant Pathology.* 37:235–242.

Valbuena, D., Erenstein, O., Tui, S. H.-K., Abdoulaye, T., Claessens, L., Duncan, A. J., Gerard, B., Rufino, M. C., Teufel, N., van Rooyen, A. A. and van Wijk, M. T. (2012). Conservation agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in sub-saharan Africa and South Asia. *Field Crops Research* 132:175–184.

Van Bezooijen, J. (2006). *Methods and Techniques for Nematology*. Wagenigen: Wagenigen University.

Vanlauwe, B., Kihara, J., Chivenge, P., Pyper, P., Coe, R. and Six, J. (2011). Agronomic use of N fertilizer in maize-based systems in Sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339:35–50.

Wang, X., Zhao, J., Fu, S., Zhao, C., Wan, S. and Zhou, L. (2015). Soil nematode assemblages in an acid soil as affected by lime application. *Nematology* 17:179–191.