Cover Crops with Biofumigation Properties for the Suppression of Plant-Parasitic Nematodes: A Review

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Plant-parasitic nematodes are a problem in vineyards worldwide, with some species acting as vectors of grapevine soil-transmitted viruses. Global pressure on the use of soil-applied chemical nematicides has led to a search for new control options, or for alternative methods to suppress plant-parasitic nematodes as part of integrated pest management. This paper gives valuable background information on the use of cover crops with biofumigation properties for the suppression of plant-parasitic nematodes in vineyards.

INTRODUCTION

High population densities of plant-parasitic nematodes cause economically significant crop reductions in most agricultural crops, including in grapevine production in South Africa. In Australia, it is estimated that nematodes might cause a 7% production loss in the grapevine industry (Stirling *et al.*, 1992), and in California the grape production losses as a result of damage by *Meloidogyne* spp. (root-knot nematode) alone are estimated to be approximately 20% (Raski, 1986). In South Africa, plant-parasitic nematodes have a negative impact on the production of good quality and economically viable grapes.

There are 162 species of plant-parasitic nematodes from 35 different genera that have been identified from root and soil samples collected in vineyards (Lamberti, 1988). Plant-parasitic nematodes found in South African vineyards include *Criconemoides xenoplax* (Raski, 1952) Loof & De Grisse, 1989 (ring nematode), *Longidorus* spp. (needle nematode), *Meloidogyne* spp. (root-knot nematode), *Paratrichodorus* spp. (stubby root nematode), *Pratylenchus* spp. (root lesion nematode), spiral nematodes from different genera, *Tylenchulus semipenetrans* Cobb 1913 (citrus nematode) and *Xiphinema* spp. (dagger nematode) (Addison & Fourie, 2007; Storey, 2007).

Over the past few decades, producers relied heavily on chemical fumigation for the control of soil-borne pathogens (Gamliel *et al.*, 2000), using products such as dichlorodiphenyltrichloroethane (DDT), which has been withdrawn from the market, and methyl bromide, which is still used, but is in the process of being withdrawn. Currently, the global focus on sustainability in the agricultural environment is increasing in order to produce healthy, safe and good-quality crops and food. This focus includes the implementation of 'integrated pest (including disease and weed) management' (IPM), 'integrated production of wine', 'sustainable farming', 'farming for the future' (Woolworths) and 'from field to fork' (European Food Safety Commission), to name a few.

Multinational agricultural companies seem to have a bigger drive towards the development and funding of alternative management tools that are more target specific, have a lower impact on natural predators and the environment, and have a favourable toxicological profile. The focus is not limited to one specific crop or disease, but includes all the different crops, diseases, pests, weeds and nematodes. Research is also focusing on the development of alternative management practices, including cultural and biological control options (Akhtar & Mahmood, 1996).

In the process of identifying alternative, more environmentally friendly control options for the control of soil-borne plant pests and diseases, the interest in biofumigation has increased (Lazzeri *et al.*, 2004). The purpose of this review was to investigate the potential of cover crops with biofumigation properties for the suppression and control of plant-parasitic nematodes in South African vineyards.

Principles of chemical soil fumigation

The primary aim of soil fumigation is to suppress soil-borne problems such as diseases, nematodes and weeds that might otherwise have a negative economic impact on the production of crops (Louvet, 1979). The first application

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of fumigation for the control of nematodes was recorded as early as in the 1870s (Van Berkum & Hoestra, 1979). In the years after the Second World War, several soil fumigants reached the market, including products such as chloropicrin, methyl bromide, 1,3-dichloropropene, ethylenedibromide, 1,2-dibromo-3-chloropropane and methyl isothiocyanate (ITC) (Lembright, 1990).

However, for soil fumigation to be effective in the control of soil-borne pest and diseases, intensive research on the application rate and a sound knowledge of the soil and of the environmental conditions involved are required. It is also necessary to bear in mind the secondary, negative impacts of the use of this method on the soil (Louvet, 1979). Soil fumigation should be used as part of a holistic programme that follows a long-term approach (Louvet, 1979). Products such as methyl bromide, chloropicrin and combinations of chloropicrin and 1,3-dichloropropene must be applied by trained pest control operators to lower the risks involved when using fumigation products.

Fumigation of the soil is done before the planting or transplanting of seedlings to prevent a negative impact of the product on the crops planted. To increase the efficacy of soil fumigation, factors such as a knowledge of the crop involved, its correct seeding or planting date, the presence of soil-borne pests and diseases that might pose a problem to the specific crop, the availability of cultivars with resistance to certain soil-borne pest and diseases, and soil preparation should be taken into consideration before applying the product. Furthermore, knowledge of the pest or disease and its survival in the soil is also imperative for successful fumigation (Louvet, 1979).

Principles of soil biofumigation

Biofumigation takes place when certain soil-borne pests and diseases are suppressed as a result of the biocidal activity of glucosinolate-containing plants when they are incorporated into the soil (Kirkegaard *et al*., 1993, 1998). The fumigant action of the volatile compounds that are released during the biodegradation of organic matter suppresses plant pathogens (Piedra Buena *et al*., 2007).

Glucosinolates (GSLs) (glucose- and sulphur-containing organic anions) and ITCs are the main active compounds involved in biofumigation. The first observations of the unique properties of GSLs and ITCs were recorded at the beginning of the 17th century during efforts that were made to understand the reason for the sharp taste of mustard seeds (Challenger, 1959). GSLs are sulphur-containing secondary metabolites produced by certain crops that are hydrolysed by the enzyme myrosinase (MYR) to form ITCs, in a process that is known as the GL-MYR system (Wathelet *et al*., 2004). ITCs have a toxic effect on many soil-borne pathogens (Sarwar *et al*., 1998). Breakdown products, including the active compound ITC, are released when the plant cell walls are damaged or broken during maceration of the plant biomass (Sarwar *et al*., 1998; Wathelet *et al*., 2004).

The role played by biofumigation in integrated pest management (IPM)

The positive biological activity of the GSL degradation products used for the suppression of some pathogenic fungi (Manici *et al*., 1997) and nematodes (Lazzeri *et al*., 1993) serves to open up new perspectives on IPM (Lazzeri *et al*., 2004), because it has been proven to be effective against weeds, plant diseases and nematodes (Van Dam *et al.,* 2009). Numerous studies in the literature confirmed the ability of certain plants to suppress nematodes through the nematicidal activity of the secondary metabolites (Chitwood, 2002; Zasada & Ferris, 2004). Research has furthermore proved that many *Brassica* spp. show nematicidal activity on plant-parasitic nematode species such as *M. incognita, M. javanica, Heterodera schachtii* and *Pratylenchus neglectus* (Thierfelder & Friedt, 1995; Potter *et al*., 1998; Monfort *et al*., 2007).

Plants containing GSL

The Family Brassicacea (brassicas) contains more than 350 genera with 3 000 species, of which many are known to contain GSL. However, GSLs are not confined to brassicas alone. At least 500 species of non-brassica dicotyledonous angiosperms have also been reported to contain one or more of the over 120 known GSLs (Fahey *et al*., 2001). Each of the GSLs has its own chemical properties and can be placed in one of three different classes, namely aliphatic, aromatic or indole forms (Zasada & Ferris, 2004; Padilla *et al*., 2007).

Most GSL-containing genera, however, are clustered within the Brassicaceae, Capparaceae and Caricaceae families (Rodman, 1981). The GSL concentration in the cells of the various plants in the families differs substantially. Therefore, it is crucial to identify species that will be effective in supressing soil-borne pests and diseases, including nematodes. Rotation crops tested for the presence of GSLs are provided in Table 1, which shows that it is mostly the brassicas that contain GSLs and that different levels of GSL exist within different genera (Larkin & Griffin, 2007). Therefore the plant species that generally are considered for biofumigation are found mostly in the family Brassicaceae, and include B*rassica oleracea* (broccoli, cabbage, cauliflower, kale), *Brassica rapa* (turnip), *Raphanus sativus* (radish), *Brassica napus* (canola, rapeseed) and various mustards, such as *Sinapis alba* (white mustard) and *Brassica juncea* (Indian mustard) (Sarwar *et al.*, 1998; Ploeg, 2007).

Four cultivars with biofumigation potential are currently available commercially in South Africa, namely *Eruca sativa* cv. Nemat, *S. alba* cv. Braco, *B. juncea* cv. Caliente 199, and *B. napus* cv. AV Jade (canola) (Fig. 1). For the purpose of this paper, the agronomical aspects of these so-called 'biofumigation crops' will be discussed.

Eruca sativa cv. Nemat (salad rocket)

Nemat reduce plant-parasitic nematode populations and therefore can be included in a crop rotation programme. Nemat is a fast-growing, year-round crop, with leaves that have a distinct spicy, pungent flavour. Nemat is more drought tolerant than mustard, and hence can be grown in dry land conditions. It is unique in its mode of action of suppressing certain nematodes by functioning as a trap crop that also has the ability to form ITC when it is applied as a green manure (Riga & Collins, 2004; Riga *et al*., 2004; Curto *et al.,* 2005; Melakeberhan *et al.,* 2006).

Sinapis alba cv. Braco (white mustard)
White mustard shows potential as a cover crop in vineyards and as a rotation crop in rotation programmes that include annual crops. Nematodes are suppressed by this crop when the active compound is released during the incorporation process 60 to 75 days after planting. It also has an effect on the life cycle of certain nematodes by slowing down or preventing the completion of their life cycle in the roots (DLF International Seed, s.d.).

Brassica juncea cv. Caliente 199 (Indian mustard)
Caliente 199 is an annual, cool-season herb that requires a short growing season. Initial germination is quick, but then plant growth slows down for three to five weeks before 'exploding' with very rapid growth and biomass production. To maximise biomass production, adequate soil moisture and sufficient nutrient levels should be maintained throughout the growing season (Gies, 2004).

Caliente 199 is primarily included in a crop rotation programme during the season just before the planting of the cash crop, and is planted mainly to suppress certain soil-borne diseases and weeds, but can also have a suppressive effect on certain nematodes. It is specifically efficient when combined with *E. sativa* (L. Lazerri, personal communication).

Brassica napus cv. AV Jade (canola)
Canola is planted primarily in a crop rotation system that includes wheat (*Triticum aestivum*) in the winter rainfall areas of South Africa. The inclusion of canola as a rotation crop has economic benefits, since it has a positive impact on the alternating wheat (Le Roux, 2012). Depending on cultivar and planting date, canola flowers within 70 to 120 days after planting. Canola is a cool-season crop and performs best under climatic conditions of approximately 21°C and rainfall of approximately 300 mm. The species should preferably be established on clay-loam soils with pH levels of between 5.5 and 7.

Canola should be planted at a density of between 4 and 6 kg per ha. Similar to the other *Brassica* spp., canola is also a heavy nitrogen feeder and requires approximately 55 kg of nitrogen for every ton of seed produced. Sulphur is also a very important nutrient, with between 15 and 20 kg per

TABLE 1
Relative glucosinolate content of selected rotation crops used for potatoes.

Crop/Cultivar	Scientific name	Glucosinolate content
Oats	*Avena sativa*	None
Ryegrass - 'Lemtal'	*Lolium multiflorum*	None
Barley	*Hordeum vulgare*	None
Canola - 'Hyola 401'	*Brassica napus*	Low
Rapeseed - 'Dwarf Essex'	*Brassica napus*	Moderate
Turnip - 'Purple top'	*Brassica rapa*	Moderate
Radish (oilseed)	*Raphanus sativa*	Moderate
Yellow mustard - 'Ida Gold'	*Sinapis alba*	Moderate
Indian mustard (unknown)	*Brassica juncea*	High

(Adapted from Larkin & Griffin, 2007)

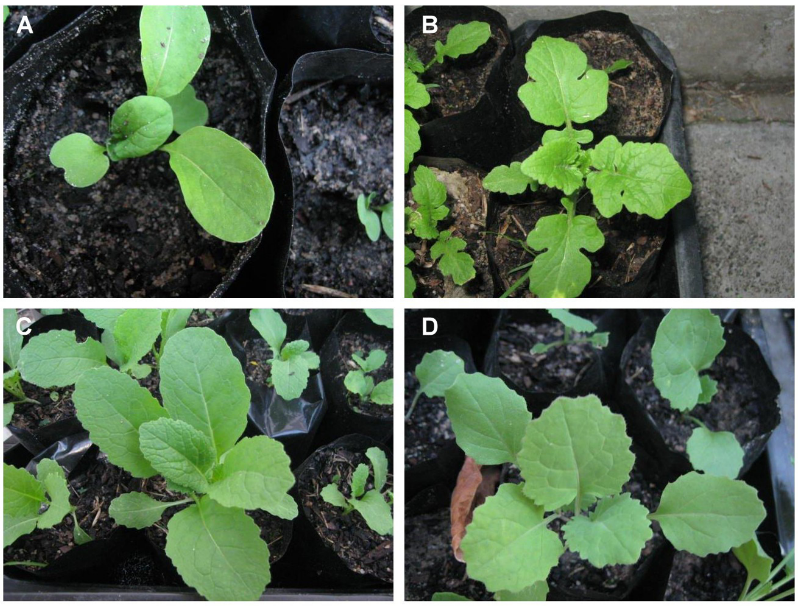

FIGURE 1
Seedlings of *Eruca sativa* cv. Nemat (A), *Sinapsis alba* cv. Braco (B), *Brassica juncea* cv. Caliente 199 (C) and *Brassica napus* cv. AV Jade (E) with biofumigation potential.

ha being required (Republic of South Africa, Department of Agriculture, Forestry and Fisheries, 2010). Root-knot nematode reproduction on 14 canola cultivars has been investigated and all cultivars were found to be poor hosts that maintain low root-knot nematode numbers (Mojtahedi *et al*., 1991).

Aspects that influence GSL release and ITC activity

Techniques that ensure the maximum rupturing/maceration of the cells involved, as well as effective incorporation, ensure the best release of ITC. This aspect, along with a variety that has a high GSL content and with enough water present for hydrolysis to take place, ensure optimum biofumigation (Brown *et al*., 1991; Poulton & Moller, 1993; Morra & Kirkegaard, 2002; Matthiessen *et al.*, 2004). One way to ensure the effective release of ITC is to slash the leaves with a slasher and then to plough the slashed residues into the soil as soon as possible, using a rotavator or disc harrow (Fig. 2). A flail chopper ensures the best maceration results and, consequently, a good GL-MYS interaction for the release of ITC (D. Gies, personal communication). The latter technique remains applicable particularly for the *Brassica* spp. such as mustards, which have a high GSL concentration in the above-ground parts of the plant.

The growth stage of the crop (emergence, rosette, flowering, seed filling, ripening), the amount of biomass produced and the correct incorporation into the soil all contribute towards the success of biofumigation (Bellostas *et al.*, 2004) (Fig. 3). The flowering stage of the plant maintains a higher GSL content than the vegetative plant parts. The GL-MYS interaction can be expected to take place more effectively later in the growing season, prior to seed set. In the root tissue, the concentration of GSL is higher in the earlier root growth stage, with decreasing concentrations during the root growth cycle.

Different types of GSLs are present in the roots and shoots of different plant species (Van Dam *et al*., 2009). Studies that were conducted by Van Dam *et al*. (2009), in which the root and shoot GSL of 29 plant species were evaluated for their GSL concentration and profiles, showed that the roots had a higher GSL concentration, as well as more diversity than the shoots. The root and shoot concentration of specific GSLs was found to differ from one another, with the most prominent indole GSL in the shoots being indol-3-yl GSL, and with the roots having higher concentrations of aromatic 2-phenylethyl GSL.

Low soil temperature slows down the enzymatic reaction during biofumigation, and therefore incorporation of green manure is not recommended at soil temperatures close to 0°C. The presence of organic matter seems to have an immobilising effect on the degradation products, thus preventing them from reaching the target pests (L. Lazzeri, personal communication).

The inclusion of sulphur fertilisers may improve the nutritional value of *Brassica* spp. Sulphur forms part of the process that takes place in the formation of secondary metabolites*, inter alia* GSLs. The level of GSLs is dependent on the genetic factors of the plant, but can also vary according to environmental conditions and the availability of soil sulphur (De Pascale *et al*., 2007).

Although the above-mentioned factors can be regarded as the most important, there are other parameters that also have an influence on the successful outcome of biofumigation. Fig. 3 illustrates the complex concept of biofumigation, with different variables that may have an influence on the expected effectivity. Knowing the effect of biofumigation on beneficial microorganisms is also of importance (Bellostas *et al*., 2004).

Control of plant-parasitic nematodes in vineyards

The three most important plant-parasitic nematode genera in South African vineyards, measured in terms of their presence and potential damage, are *Meloidogyne* spp. (root-knot nematode), *C. xenoplax* (ring nematode) and *Xiphinema* spp.

FIGURE 2
Slashing of crops with slasher (A). Texture of slashed crops (B). Slashed green material on the soil (C). Rotavating the green material into the soil (D).

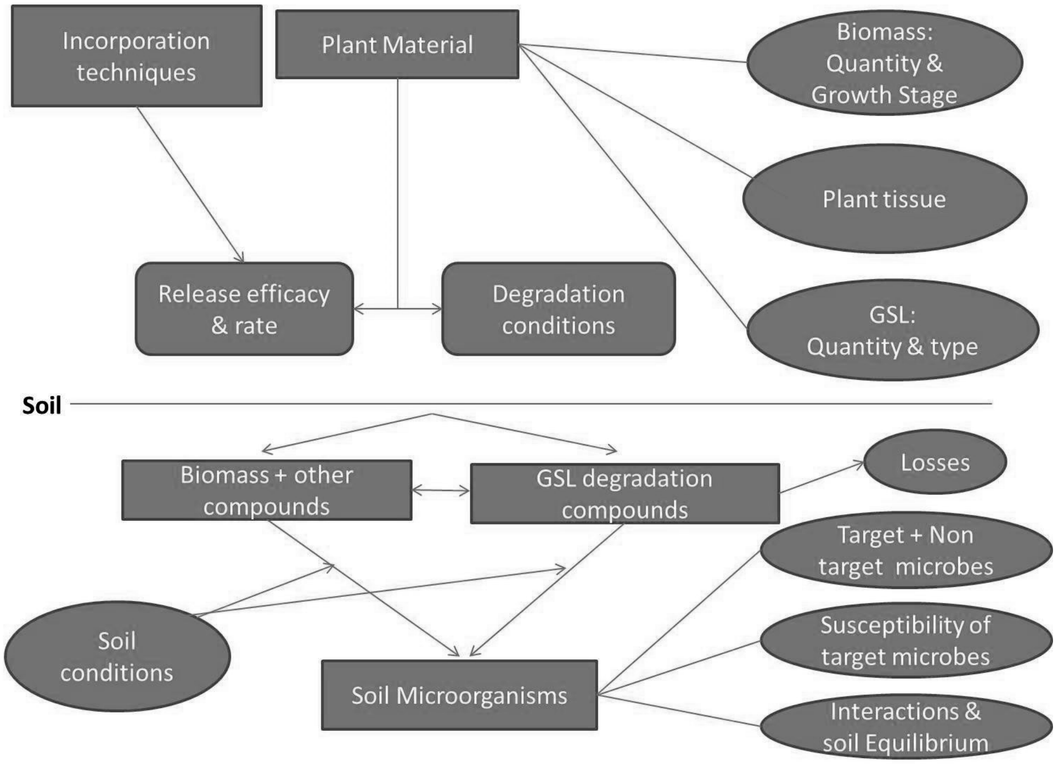

FIGURE 3
Interlinking of factors affecting the success of soil biofumigation (Bellostas *et al*., 2004).

(dagger nematode) (Storey, 2007).

Root-knot nematodes (Heteroderidae) have a wide host range, are widely distributed in agricultural soils, and can cause extensive loss in terms of the yield quality of numerous crops (Kleynhans *et al*., 1996). Damage symptoms on root-knot nematode-infested vines include stunted growth, poor vigour and substandard yields (Loubser & Meyer, 1987).

In terms of the ring nematodes (Criconematidae), only *C. xenoplax* is present in cultivated soil in South Africa. These ectoparasites are often found on woody perennials such as vines. They feed on the epidermal cells of the feeder roots, where they cause root stunting and collapsed roots, thereby influencing the uptake of nutrients and water through the root system (Kleynhans *et al*., 1996).

Dagger nematodes (Longidoridae) are ectoparasites that feed on the root tips of mostly woody perennials. Their feeding behaviour slows down the root development of susceptible cultivars (Malan & Meyer, 1993). For vines, *X. index* is the most economically important dagger nematode in South Africa, as they not only damage the roots of susceptible vine cultivars, but also are able to transmit grapevine viruses (Malan & Meyer, 1992; Kleynhans *et al*., 1996; Nicol *et al*., 1999; Malan & Hugo, 2003; Van Zyl *et al*., 2012).

Plant-parasitic nematodes can be present in the soil of the vine inter-row, or in the vine row, although most species are present in the vine row soil (Ferris & McKenry, 1976; Rahman *et al*., 2000), where they can infect the young, active feeder roots (Loubser & Meyer, 1986). Nematodes are controlled in South African vineyards using chemical control products such as fenamiphos, cadusafos and furfuraldehyde registered on grapevine, or by planting nematode-resistant rootstocks. The resistance of some of the rootstocks that are used in the South African grapevine industry is listed in Table 2. Inter-row cover cropping also has the potential to have a suppressing effect on the plant-parasitic nematode population and potentially can form part of a holistic IPM approach to control nematodes in vineyards (Rahman & Somers, 2005).

The use of cover crops, which is standard practice in South African vineyards, has many advantages, including the reduction of water run-off and erosion (Khan *et al*., 1986; Roth *et al*., 1988; Louw & Bennie, 1992), the preservation of soil moisture (Buckerfield & Webster, 1996), the reduction of evaporation from the soil (Myburgh, 1998), temperature regulation of the soil (Fourie & Freitag, 2010), the improvement of soil organic matter (Fourie *et al*., 2007; Fourie, 2012) and the suppression of weeds (Fourie *et al*., 2005, 2006; Fourie, 2010). The choice of cover crop is determined by the edaphic conditions that are prevalent in the different grapevine regions, as well as by the requirements of the grapevines concerned (Fourie *et al*., 2001). The inclusion of biofumigation crops as a cover crop in the cover crop management strategies employed in grapevines requires further research in South Africa, as the benefits thereof have to be determined.

Most of the scientific literature that has been cited focuses on the role that biofumigation can play in the suppression of root-knot nematode, although there are also indications of the effect that biofumigation can have on other nematode species such as *Paratrichodorus allius* (stubby root nematode) (Riga & Collins, 2004). The effect of biofumigation on plant-parasitic nematodes has been tested on different crops, including grapes (McLeod *et al*., 1995, 1998). ITC suppressed fungi, bacteria, nematodes and weeds in numerous *in vitro* experiments (Brown & Morra, 1997). The question arises whether biofumigation of green

TABLE 2
Nematode resistance of certain grapevine rootstocks

Rootstock	Root-knot nematode	Ring nematode	Dagger nematode	Root lesion nematode	Citrus nematode
Ramsey	R	-	-	R	R
SO4	R	-	-	-	-
Dog Ridge	R	S	S	MR	MR
Freedom	R	S	S	MR	S
Harmony	R	S	S	S	S
Paulsen 775	R	-	-	-	-
Richter 99	MR	S	S	S	MR
101-14 Mgt	MR	-	-	-	-
143-B-Mgt	MR	-	-	-	-
Paulsen 1103	MR	-	-	-	-
Richter 110	MS	-	-	-	-
US 8-7	MS	-	-	-	-
Paulsen 1447	MS	-	-	-	-
Metallica	S	-	-	-	-
140 Ruggeri	S	-	-	-	-
Jacquez	S	-	-	-	-

Key: R - Resistant; MR - Mildly resistant; MS - Mildly susceptible; S - Susceptible, - unknown (Storey, 2007)

manures growing in the grapevine inter-row can have an effect on the nematode population in the vine row area after being incorporated into the soil mechanically. Rahman and Somers (2005) indicate that the application of *B. juncea* cv. Nemfix (Indian mustard) as a green manure is able to suppress *M. javanica* when it is incorporated into the inter-row or the vine row. The effect of the green manure on the root-knot nematode population was more pronounced when it was applied in the vine row area (Rahman *et al*., 2009).

According to Rahman *et al*. (2009), the use of *Brassica* species as cover crops planted in the grapevine inter-row reduced the root-knot nematode population over a period of three years. Biofumigation with the cover crops was observed to be as effective as mustard seed meal and fenamiphos applications over the three-year period.

Nematode biofumigation bioassays

Green manure

In vitro studies have shown that brassica green manures are more effective in suppressing nematodes than non-brassica green manures (Mojtahedi *et al*., 1991, 1993; Potter *et al*., 1998). The brassica green manures suppressed root-knot nematodes significantly in controlled environments (McLeod & Steel, 1999). Not only is the GSL content of the brassica green manures thought to cause the suppression, but other, secondary metabolites that are released during the biofumigation process might also play a role in the process. The effect of biofumigation on the biological activity of the soil is also indicated, as well as a possible increase in the population of antagonistic organisms, which could lead to the suppression of plant-parasitic nematodes in the soil (Piedra Buena *et al*., 2006).

Another possibility regarding the suppressing effect of biofumigation on plant-parasitic nematodes lies in the stimulation of competition for food sources that can occur after incorporating green manure into the soil. The main focus, however, is on the role that volatiles and non-volatiles play during the decomposition of plant residues in the soil (Piedra Buena *et al*., 2006). Research on the role of green manures has included *Capsicum* spp. (pepper), *Fragaria ananassa* (strawberry), *Solanum lycopersicum* (tomato), *Cucumis sativus* (cucumber) and *Citrus sinensis* (orange) residues. The treatments were evaluated using plastic bags that were infested with large numbers of the root-knot nematode, *M. incognita*. The biofumigation action was simulated by incorporating the crop by-products into the infested soil at a specific rate, in line with field dosages. Root galling was used as an indicator of the efficacy of the different crops as a biofumigant. In both bioassays there was a reduction in the amount of root galling caused by *M. incognita* in comparison to the amount that occurred in the untreated control (Piedra Buena *et al*., 2006).

Ploeg and Stapleton (2001) investigated the effect of time and temperature in combination with brassica soil residues on the suppression of *M. incognita* and *M. javanica*. Soil temperature and the length of exposure to such temperatures played an important role in the efficacy of soil solarisation treatments. The addition of broccoli residues to the soil at a temperature of 20°C was not effective in suppressing root galling on melon plants, but at a temperature of 30 to 35°C for a period of 10 days the amendment of broccoli to the soil almost eliminated the galling on the roots.

A pot trial with vines that was conducted by Rahman *et al*. (2011) compared the root-knot nematode suppression effect of fenamiphos and two *Brassica* spp. as green manure with that of Indian mustard seed meal. No statistical difference was found between the effects of the brassica green manures, the mustard seed meal or the fenamiphos treatments after their application over a period of three consecutive years. All of the treatments showed significantly different effects when compared with the untreated control.

Nematode host status of different biofumigation crops

The ideal cover crop to be applied in vineyards for nematode suppression should either be resistant or have a poor host status, in addition to having a biofumigation suppressing effect on the target nematode when applied to the soil as a green manure (Vianene & Abawi, 1998). The possibility exists that *Brassica* spp., if used as cover crops in vineyards, could also be susceptible to specific nematodes species that require suppressing. If the target pest manages to reproduce on the cover crop species before it is ploughed in as a green manure, these *Brassica* spp. cannot be recommended as a cover crop (McLeod & Warren, 1993).

Root-knot nematode species can complete their life cycle on several *Brassica* spp., but there are major differences in their susceptibility (McLeod & Steel, 1999). In a glasshouse study, Curto *et al*. (2005) evaluated the host status of different brassicas for *M. incognita*. Although all of the brassicas act as hosts, the life cycle of the nematode was in general much slower in comparison to tomato. These authors rated certain brassicas as poor or non-hosts (resistant), maintenance hosts (tolerant) or good host (susceptible). *Eruca sativa* cv. Nemat was evaluated for its potential as a trap crop for root-knot nematode. No eggs were produced in 80% of the plants, indicating that it has the potential to act as trap crop for *M. hapla* (Melakeberhan *et al*., 2006).

CONCLUSION

With the increasing pressure on chemical control options for nematode management in most crops, as well as the limited fumigation options that are available for use prior to the planting of crops, there is a growing need for more biological control options for nematodes as well as other soil-borne diseases. Biofumigation is a concept that has been studied for a long time that has definite potential and has shown good results where the method has been applied correctly for the management of nematodes, soil-borne diseases and weeds. The challenge is to understand the complex interactions during biofumigation, and to ensure that the different factors that play a role in optimal biofumigation are applied. The main factors concerned include the basic principles of fumigation, *Brassica* spp. selection and biomass production, GSL concentration and spectrum, ITC concentration and spectrum, and the maceration and incorporation process.

The potential for biofumigation as part of an IPM approach consists of the role of the active compounds, primarily ITC, in the direct suppression of soil-borne diseases, nematodes and weeds, and also the secondary effect that can be expected during the application of green manure in the soil. The secondary effect plays a very important role in promoting microbial and other microorganism diversity in the soil, and therefore can be expected to have a positive impact on the stimulation of competition among soil-borne diseases in the rhizosphere. Another important factor that can have a positive impact on the suppression of the nematode populations is the susceptibility or resistance of the brassica crops used. With good management practices and proper medium- to long-term planning, biofumigation, together with all the other beneficial aspects mentioned, could play an important role as part of a rotation/cover crop system for annual and perennial crops, and specifically as part of a cover crop rotation programme in vineyards.

LITERATURE CITED

Addison, P. & Fourie, J.C., 2007. Cover crop management in vineyards of the Lower Orange River region, South Africa: 2. Effect on plant-parasitic nematodes. S. Afr. J. Enol. Vitic. 29, 26-32.

Akhtar, M. & Mahmood, I., 1996. Control of plant-parasitic nematodes with organic and inorganic amendments in agricultural soil. App. Soil Ecol. 4, 243-247.

Bellostas, N., Sørensen, J.C. & Sørensen, H., 2004. Qualitative and quantitative evaluation of glucosinolates in cruciferous plants during their life cycles. Agroindustria 4, 267-272.

Brown, P.D. & Morra, M.J., 1997. Control of soil-borne plant pests using glucosinolate-containing plants. Adv. Agron. 61, 167-231.

Brown, P.D., Morra, M.J., McCaffrey, J.P., Auld, D.L. & Williams, L., 1991. Allelochemicals produced during glucosinolate degradation in soil. J. Chem. Ecol. 17, 2021-2034.

Buckerfield, J.C. & Webster, K.A., 1996. Earthworms, mulching, soil moisture and grape yields. Wine Indust. J. 11, 47-53.

Challenger, F., 1959. Aspects of the organic chemistry of sulphur. Butterworths, London.

Chitwood, D.J., 2002. Phytochemical based strategies for nematode control. Ann. Rev. Phytopath. 40, 221-249.

Curto, G., Dallavalle, E. & Lazzeri, L., 2005. Life cycle duration of *Meloidogyne incognita* and host status of Brassicaceae and Capparaceae selected for glucosinolate content. Nematol. 7, 203-212.

De Pascale, S., Maggio, A., Pernice, R., Fogliano, V. & Barbieri, G., 2007. Sulphur fertilization may improve the nutritional value of *Brassica rapa* L. subsp. *sylvestris*. *Eur. J. Agron.* 26, 418-424.

DLF International Seed, s.d. http://www.dlfis.com

Fahey, J.W., Zalcmann, A.T. & Talalay, P., 2001. The chemical diversity and distribution of glucosinolates and isothiocyanates among plants. Phytochem. 56, 5-51.

Ferris, H. & McKenry, M.V., 1976. Nematode community structure in a vineyard soil. J. Nematol. 8, 131-137.

Fourie, J.C., 2010. Soil management in the Breede River Valley wine grape region, South Africa. 1. Cover crop performance and weed control. S. Afr. J. Enol. Vitic. 31, 14-21.

Fourie, J.C., 2012. Soil management in the Breede River Valley wine grape region, South Africa. 4. Organic matter and macro-nutrient content of a medium textured soil. S. Afr. J. Enol. Vitic. 33, 105-114.

Fourie, J.C. & Freitag, K., 2010. Soil management in the Breede River Valley wine grape region, South Africa. 2. Soil temperature. S. Afr. J. Enol. Vitic. 31, 165-168.

Fourie, J.C., Agenbach, G.A. & Louw, P.J.E., 2007. Cover crop management in a Chardonnay/99 Richter vineyard in the Coastal Region, South Africa. 3. Effect of different cover crops and cover crop management practices on organic matter and macro-nutrient content of a medium textured soil. S. Afr. J. Enol. Vitic. 28, 61-68.

Fourie, J.C., Louw, P.J.E. & Agenbag, G.A., 2001. Effect of seeding date on the performance of grasses and broadleaf species evaluated for cover crop management in two wine grape regions of South Africa. S. Afr. J. Plant Soil 18, 118-127.

Fourie, J.C., Louw, P.J.E. & Agenbag, G.A., 2005. Cover crop management in a Sauvignon blanc/Ramsey vineyard in the semi-arid Olifants River Valley, South Africa. 1. Effect of management practices on selected grass and broadleaf species. S. Afr. J. Enol. Vitic. 26, 131-139.

Fourie, J.C., Louw, P.J.E. & Agenbag, G.A., 2006. Cover crop management in a Chardonnay/99 Richter vineyard in the Coastal Region, South Africa. 1. Effect of two management practices on selected grass and broadleaf species. S. Afr. J. Enol. Vitic. 27, 167-177.

Gamliel, A., Austerweil, M. & Kritzman, G., 2000. Non-chemical approach to soilborne pest management – organic amendments. Crop Prot. 19, 847-853.

Gies, D., 2004. Commercial use of mustards for green manure and biofumigation in the United States. Agroindustria 3, 403-405.

Khan, M.J., Monke, E.J. & Foster, G.R., 1986. Mulch cover and canopy effects on soil loss. Pap. ASAE no 86-253. Department of Agricultural Engineering, Purdue University, West Lafayette, IN.

Kirkegaard, J.A., Gardner, P.A., Desmarchelier, J.M. & Angus, J.F., 1993. Biofumigation using Brassica species to control pests and diseases in horticulture and agriculture. In: Wratten, N. & Mailer, R.J. (eds). Proc. 9th Australian Research Assembly on Brassicas. Agricultural Research Institute, Wagga Wagga. pp. 77–82.

Kirkegaard, J.A., Sarwar, M. & Matthiessen, J.N., 1998. Assessing the biofumigation potential of crucifers. Acta Hortic. 459, 105-111.

Kleynhans, K.P.N., Van den Berg, E., Swart, A., Marais, M. & Bucley, N.H., 1996. Plant nematodes in South Africa. Handbook no. 8. Pretoria, ARC-Plant Protection Research Institute.

Lamberti, F., 1988. Nematode parasites of grapevine and their control. In: Proc. Int. Symp. on Plant-Protection Problems and Prospects of Integrated Control in Viticulture. Report EUR 111548 Commission of the European Communities, International Organisation for Biological and Integrated Control, Zurich. pp. 163–172.

Larkin, R.P. & Griffin, T.S., 2007. Control of soilborne potato diseases using brassica green manures. Crop Prot. 26, 1067-1077.

Lazzeri, L., Leoni, O. & Manici, L.M., 2004. Biocidal plant dried pellets for biofumigation. Ind. Crops Prod. 20, 59-65.

Lazzeri, L., Tacconi, R. & Palmieri, S., 1993. *In vitro* activity of some glucosinolates and their reaction products toward a population of nematode *Heterodera schachtii*. J. Agric. Food Chem. 41, 825-829.

Lembright, H.W., 1990. Soil fumigation: Principles and application technology. J. Nematol. 22, 632-644.

Le Roux, F., 2012. Kanola juis puik wisselbougewas. Landbouweekblad 1764, 27 Julie, 4.

Loubser, J.T. & Meyer, A.J., 1986. Strategies for chemical control of root-knot nematodes (*Meloidogyne* sp.) in established vineyard. S. Afr. J. Enol. Vitic. 7, 84-89.

Loubser, J.T. & Meyer, A.J., 1987. Population dynamics of the root-knot nematodes *Meloidogyne incognita* Chitwood and *Meloidogyne javanica* Chitwood on grapevines in two different regions of South Africa. S. Afr. J. Enol. Vitic. 8, 36-40.

Louvet, J., 1979. Aims of soil disinfestation. In: Mulder, D. (ed). Soil disinfestation. Elsevier Scientific, Amsterdam. pp. 1–15.

Louw, P.J.E. & Bennie, A.T.P., 1992. Water runoff and soil erosion in vineyard soils. Austr. Grapegrower & Winemaker Ann. Tech. Iss. 100-113.

Malan, A.P. & Hugo, H.J., 2003. Present status of grapevine nepoviruses and their nematode vectors in South Africa. Wineland 14, 120-123.

Malan, A.P. & Meyer, A.J., 1992. Transmission of grapevine fanleaf virus by a South African population of *Xiphinema index*. Phytophylactica 24, 217-219.

Malan, A.P. & Meyer, A.J., 1993. Interaction between a South African population of *Xiphinema index* and different grapevine rootstocks. S. Afr. J. Enol. Vitic. 14, 11-15.

Manici, L.M., Lazzeri, L. & Palmieri, S., 1997. *In vitro* fungitoxic activity of some glucosinolates and their enzyme-derived products toward plant pathogenic fungi. J. Agric. Food Chem. 45, 2768-2773.

Matthiessen, J.N., Warton, B. & Schackleton, M.A., 2004. The importance of plant maceration and water addition in achieving high brassica-derived isothiocyanate levels in soil. Agroindustria 3, 277-280.

McLeod, R.W. & Steel, C.C., 1999. Effects of brassica-leaf green manures and crops on the activity and reproduction of *Meloidogyne javanica*. Nematol. 1, 613-624.

McLeod, R.W. & Warren, M., 1993. Effects of cover crops of inter-row nematode infestation in vineyards. 1. Relative increase of root-knot nematode *Meloidogyne incognita* and *M. javanica* on legume, cereal and brassica crops. Aust. Grapegrow. Winemak. 357, 28-30.

McLeod, R.W., Gendy, M.Y. & Steel, C.C., 1998. Observations on brassicas as cover crops and testing of biofumigation in vineyards. Aust. Grapegrow. Winemak. 414a, 83-86.

McLeod, R.W., Somers, M.Y. & Gendy, M., 1995. Cover crops and nematodes – some field observations. Aust. Grapegrow. Winemak. 381, 53-57.

Melakeberhan, H., Xu, A., Kravchenko, A., Mennan, S. & Riga, E., 2006. Potential use of aragula (*Eruca sativa*) as a trap crop for *Meloidogyne hapla*. Nematol. 8, 793-799.

Mojtahedi, H., Santo, G.S., Hang, A.N. & Wilson, J.H., 1991. Suppression of root-knot nematode populations with selected rapeseed cultivars as green manure. J. Nematol. 23, 170-174.

Mojtahedi, H., Santo, G.S., Wilson, J.H. & Hang, A.N., 1993. Managing *Meloidogyne chitwoodi* on potato with rapeseed as green manure. Plant Dis. 77, 42-46.

Monfort, W.S., Csinos, A.S., Desaeger, J., Seebold, K., Webster, T.M. & Diaz-Perez, J.C., 2007. Evaluating brassica species as an alternative control measure for root-knot nematode (*M. incognita*) in Georgia vegetable plasticulture. Crop Prot. 26, 1359-1368.

Morra, M.J. & Kirkegaard, J.A., 2002. Isothiocyanate release from soil-incorporated Brassica tissues. Soil Biol. Biochem. 34, 1683-1690.

Myburgh, P.A., 1998. Water consumption in South African vineyards: A modeling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. Dissertation, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Nicol, J.M., Stirling, J.R., Rose, B.J., May, P. & Van Heeswijck, R., 1999. Impact of nematodes on grapevine growth and productivity: Current knowledge and future directions, with special reference to Australian viticulture. Aust. J. Grape Wine Res. 5, 109-127.

Padilla, G., Cartea, M.E., Velasco, P., De Haro, A. & Ordas, A., 2007. Variation of glucosinolates in vegetable crops of *Brassica rapa*. Phytochem. 68, 536-545.

Piedra Buena, A., Garcia-Alvarez, A., Diez-Rojo, M.A. & Bello, A., 2006. Use of cover crop residues for the control of *Meloidogyne incognita* under laboratory conditions. Pest Manag. Sci. 62, 919-926.

Piedra Buena, A., Garcia-Alvarez, A., Diez-Rojo, M.A., Ros, C., Fernadez, P., Lacasa, A. & Bello, A., 2007. Use of pepper crop residues for the control of root-knot nematodes. Bioresource Technol. 98, 2846-2851.

Ploeg, A.T. 2007. Biofumigation to manage plant-parasitic nematodes. In: Ciancio, A. & Mukerji, K.G. (eds). Integrated management and biocontrol of vegetable and grain crops nematodes. Springer-Verlag, Berlin. pp. 239–248.

Ploeg, A.T. & Stapleton, J.J., 2001. Glasshouse studies on the effect of time, temperature and amendment of soil with broccoli plant residues on the infestation of melon plants by *Meloidogyne incognita* and *M. javanica*. Nematol. 3, 855-861.

Potter, M.J., Davies, K. & Rathjen, A.J., 1998. Supressive impact of glucosinolates in Brassica vegetative tissues on root lesion nematode, *Pratylenchus neglectus*. J. Chem. Ecol. 24, 67-80.

Poulton, J.E. & Moller, B.L., 1993. Glucosinolates. In: Lea, P.J. (ed). Methods in plant biochemistry, vol. 9. PJ Academic Press, London. pp. 209–237.

Rahman, L. & Somers, T., 2005. Suppression of root knot nematode (*Meloidogyne javanica*) after incorporation of Indian mustard cv. Nemfix as green manure and seed meal in vineyards. Aust. Pl. Pathol. 34, 77-83.

Rahman, L., Somers, T. & Creecy, H., 2000. Distribution of nematodes in vineyards and relationship of root knot nematode (*Meloidogyne* spp.) to vine growth and yield. Aust. Grapegrow. Winemak. 438a, 53-57.

Rahman, L., Weckert, M. & Orchard, B., 2009. Effect of three consecutive annual applications of brassica green manures on root-knot nematode suppression in soil. Austr. N.Z. Grapegrow. Winemak. 37, 10-12.

Rahman, L., Whitlaw-Weckert, M.A. & Orchards, B., 2011. Consecutive applications of brassica green manures and seed meal enhances suppression of *Meloidogyne javanica* and increases yield of *Vitis vinifera* cv. Semillon. Appl. Soil Ecol. 47, 95-203.

Raski, D.J., 1986. Grapes. In: Union Carbide Agricultural Products Company Inc. (ed). Plant parasitic nematodes of bananas, citrus, coffee, grapes and tobacco. Union Carbide Agricultural Products Company Inc., Research Triangle Park, NC, 70 pp.

Republic of South Africa, Department of Agriculture, Forestry and Fisheries, 2010. Canola: Production guideline. http://www.nda.agric.za/docs/Brochures/prodGuideCanola.pdf

Riga, E. & Collins, H., 2004. Green manure effects on *Meloidogyne chitwoodi* and *Paratrichodorus allius*, economically important nematodes in the Pacific Northwest of the USA. Agroindustria 3, 321-322.

Riga, E., Mojtahedi, H., Ingram, R., & McGuire, A.M., 2004 (2nd ed). Green manure amendments and management of root knot nematodes on potato in the Pacific Northwest of USA. In: Cook, R.C. & Hunt, D.J. (eds). Nematology monographs and perspectives. Proc. 4th Cong. of Nematol. pp. 151–158.

Rodman, J.E., 1981. Divergence, convergence and parallelism in phytochemical characters: the glucosinolate–myrosinase system. In: Young, D.A. & Seigler, D.S. (eds). Phytochemistry and angiosperm phylogeny. Praeger, New York. pp. 43–79.

Roth, C.H., Meyer, B., Frede, G. & Derpsch, R., 1988. Effect of mulch rates and tillage systems on infiltrability and other soil physical properties of an oxisol in Parana, Brazil. Soil Tillage Res. 11, 81-91.

Sarwar, M., Kirkegaard, J.A., Wong, P.T.W. & Desmarchelier, J.M., 1998. Biofumigation potential of brassicas. III. *In vitro* toxicity of isothiocyanates to soil-borne fungal pathogens. Plant Soil 201, 103-112.

Stirling, G.R., Stanton, J.M. & Marchall, J., 1992. The importance of plant-parasitic nematodes to Australian and New Zealand agriculture. Aust. Pl. Pathol. 24, 104-115.

Storey, S., 2007. Nematodes in vines: Practical guidelines for the short- and long-term control of nematodes. Wineland 60-63.

Thierfelder, A. & Friedt, W., 1995. Development of novel rapeseed varieties (*Brassica napus*) resistant against beet cyst nematodes (*Heterodera schachtii*). In: Organising Committee of the Ninth International Rapeseed Conference Cambridge (ed). Ninth Int. Rapeseed Cong. (GCIRC), Cambridge, UK, pp. 1208–1210.

Van Berkum, J.A. & Hoestra, H., 1979. Practical aspects of chemical control of nematodes in soil. In: Mulder, D. (ed). Soil disinfestation. Elsevier Scientific, Amsterdam. pp. 53–120.

Van Dam, N.M., Tytgat, T.O.G. & Kirkegaard, J.A., 2009. Root and shoot glucosinolates: A comparison of their diversity, function and interactions in natural and managed ecosystems. Phytochem. Rev. 8, 171-186.

Van Zyl, S., Vivier, M.A. & Walker, M.A. 2012. *Xiphinema index* and its relationship to grapevine: A review. S. Afr. J. Enol. Vitic. 33, 21-32.

Viaene, N.M & Abawi, G.S., 1998. Management of *Meloidogyne hapla* on lettuce in organic soil. Plant Dis. 82, 945-952.

Wathelet, J., Lori, R., Leoni, O., Rollin, P., Quinsac, A. & Palmieri, S., 2004. Guidelines for glucosinolate analysis in green tissues used for biofumigation. Agroindustria 3, 257-266.

Zasada, I.A. & Ferris, H., 2004. Nematode suppression with brassicaceous amendments. Soil Biol. Biochem. 36, 1017-1024.