ASSESSMENT OF ROTATION CROPS AND COVER CROPS FOR MANAGEMENT OF ROOT-KNOT NEMATODES (*MELOIDOGYNE* SPP.) IN THE SOUTHEASTERN UNITED STATES

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ABSTRACT

McSorley, R., 2011. Assessment of rotation crops and cover crops for management of root-knot nematodes (*Meloidogyne* spp.) in the southeastern United States. Nematropica 41:200-214.

Studies that utilized rotation crops for management of root-knot nematodes in the southeastern United States were examined to evaluate the overall performance of rotation crops. In general, nematode-susceptible crops that followed effective rotation crops produced yields and supported nematode numbers similar to those obtained on crops treated with most standard nematicides. Fumigation with methyl bromide was an exception, and resulted in low nematode numbers up to the end of the susceptible target crop, whereas nematode numbers recovered following rotation crops. Performance of rotation crops was similar to clean fallow in most studies, and there was little evidence that rotation crops could suppress nematode numbers below levels obtained after clean fallow. Large reductions in nematode numbers often were achieved following rotation crops. In sites with relatively low initial population levels before rotation crops were used, effective rotation crops sometimes maintained relatively low nematode numbers through the following susceptible target crop, and nematode recovery was not observed until the second year of the rotation sequences. Where practical, very long rotations such as bahiagrass pastures were often effective in preventing increase in nematode numbers on subsequent susceptible crops. Rehabilitation of heavily infested sites is difficult, could require several years of rotation crops, and the benefit gained may last only through one susceptible crop.

Key words: Agronomic crops, cropping systems, nematode-antagonistic crops, nematicides, pest management, plant-parasitic nematodes, sustainable agriculture, vegetable crops.

RESUMEN

McSorley, R., 2011. Evaluación de cultivos de rotación y de cobertura para el manejo de *Meloidogyne* spp. en el sureste de Estados Unidos. Nematropica 41:200-214.

Se examinaron estudios que utilizaron cultivos de rotación para el manejo de *Meloidogyne* spp. en el sureste de Estados Unidos, con el fin de evaluar la efectividad de las rotaciones. En general, los cultivos susceptibles sembrados después de cultivos de rotación efectivos tuvieron productividad y densidades de nematodos similares a las obtenidas con cultivos tratados con nematicides convencionales. Una excepción fue la fumigación con bromuro de metilo, con la cual se alcanzan bajas densidades de nematodos hasta el final del cultivo. Con el uso de rotaciones, la densidad de población de los nematodos se recupera rápidamente después de la rotación. La efectividad de los cultivos de rotación fue similar al de tratamientos de barbecho limpio en la mayoría de los estudios, y existe poca evidencia que sustente la capacidad de los cultivos de rotación para suprimir las densidades de población de nematodos por debajo de los niveles obtenidos con barbecho limpio. Con frecuencia se obtuvieron grandes reducciones en densidades de nematodos después de cultivos de rotación. En lugares con poblaciones iniciales relativamente bajas, las rotaciones efectivas lograron mantener poblaciones bajas en el cultivo susceptible subsiguiente, y no se observó recuperación de las densidades sino hasta el segundo año. Rotaciones muy largas, como con pastizales, en los casos en los que son prácticas, pueden ser muy efectivas en prevenir el aumento de las poblaciones en los cultivos susceptibles subsiguientes. La rehabilitación de suelos altamente infestados es difícil, puede requerir varios años de rotación y los beneficios obtenidos pueden durar solo un año con cultivo susceptible.

Palabras claves: agricultura sostenible, cultivos agronómicos, cultivos antagonistas, hortalizas, manejo de plagas, nematodos fitoparásitos, , sistemas de cultivo.

Crop rotation has long been recognized as an important tool for managing plant-parasitic nematodes (Duncan, 1991; Good, 1968; Halbrendt and LaMondia, 2004; Johnson, 1982; McSorley, 2001; Trivedi and Barker, 1986). However, management of root-knot nematodes (*Meloidogyne* spp.) by crop rotation or other means can be especially challenging due to their unusually wide host ranges and high fecundity levels (e.g., averaging 292 to 845 eggs/female, Ferris *et al*., 1984) and their ability to recover and build population levels quickly once a favorable host crop is grown. Exponential growth of *M. arenaria* (Neal) Chitwood juveniles (J2) has been documented in the field on susceptible peanut (*Arachis hypogaea* L.) (Rodriguez-Kabana *et al*., 1986). In another field study, a multiplication rate of Pf/Pi = 329 was observed, where Pi = initial population level of *M. incognita* (Kofoid & White) Chitwood and Pf = final population level on a 2-month maturity date bean (*Phaseolus vulgaris* L.) crop (Wang *et al*., 2003).

Rotation crops used to manage root-knot nematodes have included common agricultural crops in alternating years, such as corn (*Zea mays* L.) in rotation with soybean (Glycine max (L.) Merr.) for management of *M. incognita* (Kinloch, 1986), or annual rotations of peanut and cotton (*Gossypium hirsutum* L.) for management of *M. arenaria* race 1 in peanut and *M. incognita* race 3 in cotton (Johnson *et al*., 1998; Rodriguez-Kabana *et al*., 1987). Depending on local conditions, summer or winter cover crops could be used in rotations prior to the planting of cash crops. This has allowed exotic or unusual crops to be introduced into cropping systems, especially during summer months (Rodriguez-Kabana *et al*., 1988a; 1989). Information on effective rotation crops against root-knot nematodes and relative comparisons of crops with one another are available from a variety of sources (Araya and Caswell-Chen, 1994; McSorley, 1999; 2001; McSorley *et al*., 1994a,b; Rodriguez-Kabana *et al*., 1988a; 1989; Sipes and Arakaki, 1997; Wang *et al*., 2004).

Of course, results with cover crops and rotation crops depend on the crop cultivar used and the species and races of root-knot nematodes present. Some of the more useful summer cover crops used against root-knot nematodes are: cowpea (*Vigna unguiculata* (L.) Walp.) (Gallaher and McSorley, 1993; Kirkpatrick and Morelock, 1987; Roberts *et al*., 2005); sorghum (*Sorghum bicolor* (L.) Moench) or sorghum-sudangrass (*S. bicolor* x *S. sudanense* (piper) Stapf) (McSorley *et al*., 1987; McSorley and Gallaher, 1991); marigolds (*Tagetes* spp.) (Ferraz and de Freitas, 2004; Hooks *et al*., 2010; Ploeg, 2002); sunn hemp (*Crotalaria juncea* L.) (Wang *et al*., 2002); sesame (*Sesamum indicum* L.) (Starr and Black, 1995); pearl millet (*Pennisetum glaucum* L.) (Johnson *et al*., 1995; Timper *et al*., 2002); velvetbeans (*Mucuna* spp.) (Queneherve *et al*., 1998; Rodriguez-Kabana *et al*., 1992); and American jointvetch (*Aeschynomene americana* L.) (Rhoades, 1980). Weeds such as hairy indigo (*Indigofera hirsuta* L.), castor (*Ricinus communis* L.), partridge pea (*Cassia fasiculata* Michx.), and showy crotalaria (*Crotalaria spectabilis* L.) have also been investigated as potential summer cover crops (McSorley *et al*., 1994a; Rodriguez-Kabana *et al*., 1988; 1991a; 1995).

Useful winter cover crops include small grains like rye (*Secale cereale* L.), oat (*Avena sativa* L.), and wheat (*Triticum aestivum* L.), although results may be quite variable and highly dependent on cultivar and nematode species (Ibrahim *et al*., 1993; Johnson and Motsinger, 1989; Minton and Bondari, 1994; Opperman *et al*., 1988). Winter legumes like hairy vetch (*Vicia villosa* Roth), crimson clover (*Trifolium incarnatum* L.) and other clovers (*Trifolium* spp.), and lupine (*Lupinus angustifolius* L.) are typically very susceptible to root-knot nematodes (Timper *et al*., 2006; Wang *et al*., 2004). A few winter legumes, such as 'Cahaba White' vetch (*V. sativa* L.) and some red clover (*Trifolium pratense* L.) germplasm, show a low to moderate level of resistance to some *Meloidogyne* spp. (Quesenberry *et al*., 1989; Timper *et al*., 2006). *Brassica* species may also have some potential as winter cover crops for nematode management (Monfort *et al*., 2007).

The objectives of this paper are neither to provide recommendations of specific rotation crops nor to compare rotation crops that could be used to manage root-knot nematodes, but rather to evaluate the usage and performance of successful rotation crops. In particular, several questions are addressed about the performance of rotation crops for managing root-knot nematodes. How effective are cover crops compared to standard nematicides? Can rotation crops and cover crops suppress nematode population levels below those achieved by fallow? How effective are rotation crops in reducing high nematode population levels? How long do the beneficial effects of rotations last before nematode numbers recover? How effective are rotation crops in maintaining low nematode population levels?

Approach

Publications of studies using crop rotation to manage root-knot nematodes in the southeastern United States were examined for data that could provide insights into specific questions. A number of studies provided similar treatments and similar types of data on nematode population numbers or crop yields, so that comparisons among studies could be made. Data from some studies could not be used because experiments were strongly affected or complicated by factors other than root-knot nematodes. Weeds are a common problem that can render crop rotations ineffective (Crow *et al*., 2001; McSorley *et al*., 2008; Overman *et al*., 1971). In some cases, effects from resistant cultivars of main crops were stronger than effects from rotation crops (Kinloch, 1983; Minton, 1992). In a few instances, much impact on the host crop was caused by diseases (Johnson *et al*., 1999) or by nematodes other than *Meloidogyne* spp. (Crow *et al*., 2001; Weaver *et al*., 1993).

Most studies examined involved the use of a rotation crop with the intention of reducing nematode population levels prior to planting a subsequent cash crop that is susceptible to root-knot nematodes. In general, the term "rotation crop" will be used to include rotated cash crops, summer cover crops, or winter cover crops, depending on the context of the individual study. The term "target crop" is used to indicate a susceptible host crop that follows the rotation crop, which is the target of some benefit (e.g., lower nematode population levels, improved yield), received from the rotation crop.

When appropriate, statistical analyses by the original authors are used to indicate differences among treatments. Numbers of J2 in soil are converted to numbers/100 cm^3 soil for standardization and easy comparison. When used, galling scales are discussed in text or reported in table footnotes. Soil population levels were reported more universally than root galling and were easier to standardize for comparisons across studies. Yield data from individual experiments are expressed as percentages, where 100% is the yield level of a susceptible target crop achieved with a standard nematicide, and yields of the target crop following rotation or control treatments are expressed as a percent of the nematicide treatment.

Comparison of crop rotation with standard nematicides

Yields of target crops. A number of studies have examined the performance of crop rotation relative to nematicide use for managing root-knot nematode population levels and improving yield of a susceptible nematode host crop (Table 1). Treatments involved in such studies often include a rotation crop grown in the year prior to the susceptible host crop, a control treatment in which the host crop is grown in both years, and a treatment in which a host crop is grown in both years but treated with a nematicide in each year. Data were examined from years when the susceptible host crop was grown in all treatments, and its yield in the rotation treatment was expressed as a percent of its yield in the nematicide-treated crop (Table 1). For example, in the study by Rodriguez-Kabana *et al.* (1987) where cotton was used as a rotation crop for managing *M. arenaria* in peanut, data from the 1986 season were used, since peanut was grown in all rotations in that year. Yield of peanut in the cotton rotation (not treated with nematicide) was 3499 kg/ha, or 109% of the 3200 kg/ha obtained in the continuous peanut treated with nematicide.

Some interesting trends were apparent when related data were examined from several studies (Table 1). As expected, the yield of a non-treated continuous rotation of a susceptible host was often inferior to one or more of the other treatments. However, this was not always the case, and in some instances these control treatments yielded relatively well (e.g. Weaver *et al.*, 1989; some scenarios from Johnson *et al.*, 1996). The most interesting point is that in all of these studies, the yield of the host crop in the rotation treatment was never significantly ($P < 0.05$) worse than its yield in the nematicide-treated sequence. In one study, soybean crops rotated with bahiagrass (*Paspalum notatum* Flugge) or velvetbean outyielded those from nematicide-treated plots, although this benefit probably did not result entirely from management of *Meloidogyne* spp., since *Heterodera glycines* Ichinohe was present and managed by these rotation crops as well (Weaver *et al.*, 1998). Rotation crops also tended to reduce crop-specific diseases such as southern blight of peanut that were more prevalent in continuous peanut systems and likely affected yield in those systems (Rodriguez-Kabana *et al.*, 1987). When multiple species of *Meloidogyne* are involved, cropping sequences may cause population shifts toward species that are more adapted and aggressive on key host crops, causing changes in results observed over time (Johnson *et al.*, 1996).

The favorable results of rotation crops relative to a nematicide were also observed in a similar type of study in South Carolina involving multiple species of *Meloidogyne* spp. on tobacco (*Nicotiana tabacum* L.) (Fortnum *et al.*, 2001). Yields of untreated tobacco following rotation crops of corn, cotton, sorghum, or rye-fallow in the previous year were 105 - 116% of the yield obtained from continuous tobacco fumigated with 1,3-D in the 1989 season, and 127% - 142% of the yield of continuous tobacco in the 1991 season.

When the rotation crops were cover crops grown in the same year as a target vegetable crop, favorable performances were also obtained from some rotation treatments. Yield of eggplant (*Solanum melongena* L.) following a summer cover crop of velvetbean was 144% of the yield of eggplant following soybean treated with aldicarb (Rodriguez-Kabana *et al.*, 1992). Yields of bell pepper (*Capsicum annuum* L.) following a summer cover crop of 'Iron Clay' cowpea did not differ ($P < 0.10$) from yields of pepper fumigated with methyl bromide (Saha *et al.*, 2007). However, yields of okra (*Abelmoschus esculentus* (L.) Moench) following sunn hemp in a pot test were only 66 – 87% of yields when okra followed fumigation with methyl bromide (Wang *et al.*, 2007).

Economics. Although models have been developed to estimate economic returns from crop rotation alternatives (Burt and Ferris, 1996; Noe *et al.*, 1991; Van den Berg and Rossing, 2005), few of the studies examined reported current economic data. In demonstration plots comparing tomato production under conventional (fumigation with methyl bromide was included) and alternative (no nematicide, rotation with bahiagrass) production systems, the conventional system outyielded the alternative system, but the alternative system provided an additional \$568/ha of net return mainly due to lower production costs (Chellemi *et al.*, 1999). Although favorable returns were obtained with the alternative system for one tomato season, the

Table 1. Effect of rotation crop treatments (year 1) on yield and nematode numbers on susceptible target crop in the next year.

Scenario[v]	Crops: Year 1	Crops: Year 2	Nematodes/ 100 cm^3 soil[w]	Yield of target crop	Reference
Ma, AL	Peanut	Peanut	72 a[x]	92% b	Rodriguez-Kabana *et al*., 1987
	Peanut*[y]	Peanut*	15 c	100% ab	
	Cotton	Peanut	41 b	109% a	
Ma, AL	Peanut	Peanut	192 b	99% b	Rodriguez-Kabana and Touchton, 1984
	Peanut*	Peanut*	310 a	100% b	
	Sorghum	Peanut	197 b	115% a	
Ma, AL	Peanut	Peanut	229 a	89% a	Rodriguez-Kabana and Touchton, 1984
	Peanut*	Peanut*	136 b	100% a	
	Corn	Peanut	142 b	99% a	
Ma, AL	Peanut	Peanut	227 a	69% b	Rodriguez-Kabana *et al*., 1988b
	Peanut*	Peanut*	283 a	100% a	
	Bahiagrass	Peanut	163 b	87% a	
Ma, AL	Peanut	Peanut	243 ab	64% b	Rodriguez-Kabana *et al*., 1989
	Peanut*	Peanut*	154 bc	100% a	
	Castor	Peanut	63 c	108% a	
	Jointvetch	Peanut	263 a	97% a	
	Partridge Pea	Peanut	123 c	97% a	
	Sesame	Peanut	124 c	102% a	
	Cotton	Peanut	267 a	96% a	
Ma, AL	Soybean	Soybean	54 a	92% a	Weaver *et al*., 1989
	Soybean*	Soybean	54 a	100% a	
	Corn	Soybean	71 a	107% a	
Ma+Mi, AL	Soybean	Soybean	104 ab	77% c	Weaver *et al*., 1998
	Soybean*	Soybean*	93 b	100% b	
	Bahiagrass	Soybean	125 a	158% a	
	Velvetbean	Soybean	59 c	170% a	
Ma+Mh+Mi,	Pot+SP[z]	Potato	107 a	97% a	Johnson *et al*., 1996
Ga, site 1	Pot+SP*	Potato*	60 ab	100% a	
	Pnut+Sor	Potato	23 b	99% a	
2nd crop	Pot+SP	SP	322 a	83% a	
	Pot+SP*	SP*	463 a	100% a	
	Pnut+Sor	SP	517 a	67% a	
Ma+Mh+Mi,	Pot+SP	Potato	25 a	98% a	
Ga, site 2	Pot+SP*	Potato*	0 a	100% a	
	Pnut+Sor	Potato	0 a	77% a	
2nd crop	Pot+SP	SP	1282 a	78% b	
	Pot+SP*	SP*	367 b	100% b	
	Pnut+Sor	SP	244 b	130% a	

[v]Nematode (Ma = *Meloidogyne arenaria*; Mh = *M. hapla*; Mi = *M. incognita*) and state where test was conducted.
[w]Pf = final nematode population level on target crop.
[x]For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to statistical tests performed in the corresponding reference.
[y]Asterisk (*) indicates crops treated with nematicide (usually aldicarb, except fenamiphos for Johnson *et al*., 1996 and EDB for Rodriguez-Kabana and Touchton, 1984). Crop yields standardized with yield of nematicide-treated = 100%.
[z]These experiments involved double crops each year. Crops grown in Year 1 were potato (Pot) + sweetpotato (SP) or peanut (Pnut) + sorghum (Sor). Target crops in Year 2 were potato (1st crop) and sweetpotato (2nd crop).

true cost of a 3-year rotation with bahiagrass would need to be considered over time, because the years in rotation crops that provide minimal income are missed opportunities to plant profitable fumigated tomato crops.

For short-term rotations with a single cover crop as the rotation crop, a major consideration is the cost of a typical nematicide treatment compared to the cost of maintaining a cover crop. Recent estimates of establishment costs for cover crops ranged from $148 to $370/ha, depending on the crop and seed costs (Newman *et al.*, 2010). Of course, planting a cover crop in the off-season may be a useful and desirable practice anyway, regardless of nematodes present. Not planting a cover crop in some seasons and locations in the southeastern United States may invite weed colonization or expose land to erosion.

Nematode numbers in target crops. Although root-knot nematodes may be evaluated from root galling or soil samples collected at various times during the season, several studies reported data on the final population levels (Pf) of root-knot nematodes at the end of the susceptible target crop, and so these are included for comparison (Table 1). These data provide a comparative indicator of nematode recovery once a susceptible target crop is grown. It is probably not surprising that in many cases, Pf on the host crop following a rotation crop was less ($P < 0.05$) than numbers in a continuous sequence of non-treated host crop. The trend was not as clear when the rotation crop treatment was compared to nematicide treatment. Numbers were similar in a few studies, but numbers in peanut following a cotton rotation were greater than numbers in nematicide-treated continuous peanut (Rodriguez-Kabana *et al.*, 1987), while numbers in soybean following velvetbean were lower than in the nematicide treatment (Weaver *et al.*, 1998). Variation among different rotation crops within the same study (e.g., Rodriguez-Kabana *et al.*, 1989) probably just indicates that some crops were more effective than others in maintaining low populations of the root-knot nematode isolate examined. Regardless of the rotation crop grown, the many examples with Pf > 50 nematodes/100 cm^3 soil illustrate and reinforce the idea that root-knot nematodes will recover once a favorable host crop is grown. Increase of root-knot nematodes to damaging levels was particularly severe when two host crops were grown in succession in the same year, as illustrated by Pf when sweetpotato (*Ipomoea batatas* L.) was the second crop in the sequence (Johnson *et al.*, 1996).

The examples in Table 1 used nonfumigant nematicides or EDB as standards of comparison with rotation crops. When methyl bromide was the nematicide of choice, reductions in nematode numbers throughout the target host crop were more consistent. In several examples (Table 2), nematode numbers recovered in the final sampling of a target vegetable crop that followed an effective summer rotation crop, however Pf remained very low when the target crop was planted after fumigation with methyl bromide. These low Pf following the first susceptible crop may make it possible to double-crop after methyl bromide fumigation, a practice that would be questionable following a rotation crop treatment due to the nematode resurgence.

Two-year rotations. In several cases, 2-year rotations of a non-host crop were effective in lowering Pf of *M. arenaria* relative to continuous peanut treated with nematicide (Table 3). Yields of peanut following 2 years of rotation crops were always equal to or better than yields of aldicarb-treated peanut. When yields of rotated peanut were superior to continuous peanut treated with nematicide, some of the additional benefit likely resulted from favorable effects of the rotations against *Sclerotium rolfsii* Sacc. (Rodriguez-Kabana *et al.*, 1991b; 1994). In general, results obtained from 2-year rotations were somewhat similar to results obtained from 1-year rotations of non-host crops. When comparing 2-year rotations of non-host crops (e.g. peanut-peanut-cotton) to one-year rotations (e.g., cotton-peanut-cotton) for management of *M. incognita* race 3 in cotton, no significant ($P < 0.10$) yield benefits were obtained (Kirkpatrick and Sasser, 1984). However, two years of peanut resulted in a lower ($P < 0.05$) level of root galling in the 3rd-year cotton crop than one year of peanut in rotation (0.2 vs 1.7 gall rating on a scale of 0 – 5), as did two years of soybean compared to one year of soybean (1.8 vs. 3.1 gall rating). Rodriguez-Kabana and Touchton (1984) found that 2-year rotations of corn or sorghum were no better than one-year rotations for managing *M. arenaria* on peanut, both in terms of nematode numbers and peanut yields.

Comparison of crop rotation with fallow

Some of the most effective rotation crops against plant-parasitic nematodes are known to contain compounds that are toxic to nematodes (Ferraz and de Freitas, 2004; Hooks *et al.*, 2010; Wang *et al.*, 2002). However, many of these crops are also non-hosts to nematodes and may restrict nematode populations by starvation or other mechanisms besides allelopathic chemicals (Hackney and Dickerson, 1975; Hooks *et al.*, 2010; Wang *et al.*, 2001; 2002). If both a non-host effect and an antagonistic chemical effect are operating simultaneously, we may expect nematode population levels to be suppressed more by a plant with toxic compounds than by one that is simply a non-host. It may be difficult to design experiments that would clearly separate starvation and allelopathic effects on nematode populations in the field; however, it may be possible to compare a treatment that has only a starvation effect with a rotation crop that could possess both effects. Many experiments with rotation crops have used fallow as one of the treatments. Although not recommended due to adverse effects on erosion and other soil properties (Powers and McSorley, 2000),

Table 2. Effect of crop rotation treatments and fumigation with methyl bromide on nematode numbers at final harvest (Pf) of a subsequent susceptible target crop.

Scenario[x]	Treatment	Target crop	Nematodes/100 cm^3 soil[y]	Reference
Mi, FL 2003	Cowpea cover crop	Pepper	76 a[z]	Saha *et al*., 2007
	Methyl bromide	Pepper	1 b	
Mi, FL, 2004	Cowpea cover crop	Pepper	19 a	
	Methyl bromide	Pepper	0 b	
Mi, FL, SS	Sorghum-sudan crop	Okra	77 a	Wang *et al*., 2007
	Methyl bromide	Okra	1 b	
Mi, FL, SH	Sunn hemp cover crop	Okra	169 a	
	Methyl bromide	Okra	3 b	
M, FL	Sunn hemp cover crop	Pepper	138 a	Chellemi, 2006
	Cowpea cover crop	Pepper	82 b	
	Methyl bromide	Pepper	< 1 c	

[x]Nematode (Mi = *Meloidogyne incognita*; M = *Meloidogyne* spp.), state, and season or rotation crop main plot. Wang *et al*. (2007) was a split plot, with data from sorghum-sudangrass (SS) and sunn hemp (SH) main plots analyzed separately.
[y]Pf = final nematode population level on target crop.
[z]For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to statistical tests performed in the corresponding reference.

Table 3. Effect of two years of rotation crop treatments on yield and nematode numbers on susceptible target crop in the third year.

Scenario[v]	Crop			Nematodes/100 cm^3 soil[w]	Yield of target crop	Reference
	Year 1	Year 2	Year 3			
Ma, AL	Peanut	Peanut	Peanut	300 a[x]	75% b	Rodriguez-Kabana *et al*., 1991a
	Peanut*[y]	Peanut*	Peanut*	54 c	100% a	
	Castor	Castor	Peanut	52 c	109% a	
	Bahia[z]	Bahia	Peanut	148 b	103% a	
Ma, AL	Peanut	Peanut	Peanut	611 b	92% c	Rodriguez-Kabana *et al*., 1994
	Peanut*	Peanut*	Peanut*	401 c	100% c	
	Bermuda	Bermuda	Peanut	868 a	103% bc	
	Bahia	Bahia	Peanut	193 d	126% a	
	Cotton	Cotton	Peanut	147 d	118% ab	
Ma, AL, 1987	Peanut	Peanut	Peanut	144 b	76% b	Rodriguez-Kabana *et al*., 1991b
	Peanut*	Peanut*	Peanut*	281 a	100% a	
	Cotton	Cotton	Peanut	24 c	115% a	
Ma, AL, 1990	Peanut	Peanut	Peanut	283 a	74% c	
	Peanut*	Peanut*	Peanut*	226 a	100% b	
	Cotton	Cotton	Peanut	88 b	135% a	

[v]Nematode (Ma = *Meloidogyne arenaria*), state, and peanut season (data from multiple peanut target seasons included in Rodriguez-Kabana *et al*., 1991b).
[w]Pf = final nematode population level on target crop.
[x]For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to statistical tests performed in the corresponding reference.
[y]Asterisk (*) indicates crops treated with nematicide (aldicarb). Crop yields standardized with yield of nematicide-treated = 100%.
[z]Bahia = bahiagrass; Bermuda = bermudagrass.

clean fallow can provide a convenient standard of comparison, assuming that fallow provides a starvation effect but a negligible chemical effect.

In many experiments, rotation crops were not more effective than fallow in reducing root-knot nematode population levels or galling (Table 4). An exception occurred when bermudagrass (*Cynodon dactylon* (L.) Pers.) rotations were maintained for several years (Johnson *et al.*, 1997). In other cases, weedy fallow rather than clean fallow was used (Bhan *et al.*, 2010; McSorley *et al.*, 1994c). However even in these studies, the weedy fallow treatments often resulted in nematode population levels similar to those achieved with rotation crops. Weedy fallow was initially as effective as several summer rotation crops in maintaining low levels of *Meloidogyne* spp., but numbers in the weedy treatment recovered more quickly by the end of the following target crop (McSorley *et al.*, 1994c). Results showing similar performance of rotation crops and fallow are not confined to the southeastern United States. Of many rotation crops tested in Hawaii, none were better than fallow for reduction of *M. javanica* (Treub) Chitwood population levels after the rotation crop season (Sipes and Arakaki, 1997). Even rotations with marigolds could not consistently lower nematode population levels below those achieved by fallow (Hooks *et al.*, 2010). These examples suggest that even the most effective rotation crops cannot suppress root-knot nematode numbers below those achieved by clean fallow. They do not rule out the possibility of some chemical effect, but any combined non-host + allelopathic effect from these plants appears to be no more effective in practice than the starvation that could be achieved through fallow. In an earlier study, Hackney and Dickerson (1975) did not find any nematicidal effects from living plants on nematodes in soil. Of course, additional chemical effects may result from decomposition of cover crop residues that remain as amendments on the site (Wang *et al.*, 2008).

Reduction of high nematode population levels

Rotation crops used in the summer months have been successful in reducing nematode numbers when initial population levels were very high (Table 5). Several of these studies examined a number of different rotation

Table 4. Comparisons of rotation crops or cover crops with fallow, based on nematode numbers (soil counts or root galling).

Scenario[w]	Performance relative to fallow	Reference
Ma, FL	Fallow = corn, cotton, hairy indigo, jointvetch, lespedeza, peanut, pearl millet, sorhum, SS[x]	Kinloch and Dunavin, 1993
Ma, FL	Fallow = castor, cotton, crotalaria[y], hairy indigo, horsebean, jointvetch, sesame, SS velvetbean	McSorley *et al.*, 1994b
Ma+Mi, FL	Weedy fallow = castor, jointvetch, sesame, SS, velvetbean after cover crop but not always in next vegetable crop	McSorley *et al.*, 1994c
Mi, FL	Fallow = pangolagrass; Fallow better than several other grasses	Winchester and Hayslip, 1960
Mi, FL	Fallow = hairy indigo; Fallow = or better than SS, sesbania, weeds	Rhoades, 1983
Mi, FL	Fallow = hairy indigo, jointvetch; Fallow better than sorghum+sesbania	Rhoades and Forbes, 1986
Mi, FL	Fallow = castor, cotton, cowpea, marigold, sesame, velvetbean; Fallow better than jointvetch, SS, weeds	McSorley and Dickson, 1995
Mi, FL	Fallow = ‘Iron Clay’ cowpea	Wang *et al.*, 2003
Mi, FL	Weedy fallow = or better than pearl millet, SS, sunn hemp, velvetbean; Sunn hemp better than weedy fallow in one instance	Bhan *et al.*, 2010
Mi, Ga	Fallow = or better than corn, crotalaria[y], millet[z]	Brodie and Murphy, 1975
Mi, GA	Fallow = oat, rye, wheat winter cover crops	Minton and Bondari, 1994
Mi, GA	Fallow = 1-yr bermudagrass; 2-yr rotation sometimes better than fallow; 3-yr rotation better than fallow	Johnson *et al.*, 1997
Mi+Mj, GA	Fallow = or better than crotalaria, pearl millet, pigeonpea, sorghum, soybean	Johnson and Campbell, 1980
Mi+Mj, GA	Fallow = rapeseed, hairy vetch	Johnson *et al.*, 1992

[w]Nematode (Ma = *Meloidogyne arenaria*; Mi = *M. incognita*; Mj = *M. javanica*), state.
[x]SS = sorghum-sudangrass.
[y]Crotalaria = usually *Crotalaria spectabilis*; *C. mucronata* in Brodie and Murphy (1975).
[z]Millet = *Panicum ramosum* in this study.

Table 5. Reductions of root-knot nematode populations levels by selected rotation crops in sites with high initial populations levels.

Scenario[x]	Rotation treatment	Pi[y] = J2/100 cm^3 soil	Pf [z] as % of Pi	Reference
Ma 1, FL	7 best treatments	924-1276	7-13%	McSorley *et al*., 1994b
	Cotton	944	7%	
	Crotalaria	1276	7%	
	Fallow	994	10%	
Ma 2, FL	8 best treatments	150-320	6-29%	Kinloch and Dunavin, 1993
	Cotton	300	13%	
	Peanut	320	6%	
	Fallow	250	8%	
Mi l, FL	8 best treatments	180-352	2-15%	McSorley and Dickson, 1995
	Cotton	201	5%	
	Cowpea	225	2%	
	Fallow	200	2%	
Mi 3, GA	Peanut	99	2%	Johnson *et al*., 1998
	Peanut	220	< 1%	

[x]Nematode (Ma1 = *Meloidogyne arenaria* race 1; Ma2 = *M. arenaria* race 2; Mi1 = *M. incognita* race 1; Mi3 = *M. incognita* race 3), state.
[y]Pi = initial numbers of second-stage juveniles (J2) before crop rotation treatment.
[z]Pf = final nematode numbers following crop rotation treatment, expressed as % of Pi.

treatments (including fallow), and the performances of the 7-8 best treatments were statistically similar. Data on three rotation treatments are shown from each of those studies, including cotton and fallow, which were common to all three studies. Rotation crops were effective in lowering the high numbers to levels that were < 1% to 29% of the original Pi. Although these reductions are impressive, nematode numbers may recover quickly once a susceptible crop is planted. When rotation treatments were followed by a soybean crop in the study by Kinloch and Dunavin (1993), Pf on soybean in the 8 best rotation treatments ranged from 1740 to 2850 J2/100 cm^3 soil. In another example, reductions of exceptionally high Pi to only 7% - 13% of their original levels still resulted in Pf following the best rotation crops ranging from 67 to 150 J2/100 cm^3 soil (McSorley *et al*., 1994b). These population levels were still quite high and resulted in moderate to high levels of galling on a subsequent crop of yellow squash (*Cucurbita pepo* L.).

Recovery of nematodes after rotation crops

Although rotation crops may be quite effective in lowering nematode numbers, they can recover quickly when a susceptible crop is grown (Table 6). Recovery occurred whether the rotation crop was a winter cover crop, summer cover crop, annual rotation crop, or multi-year pasture rotation. In these examples, low nematode levels in soil following the rotation crop often increased to fairly high levels on subsequent target crops that were excellent nematode hosts. Rapid buildup was noted even in target vegetable crops that were only 2-2.5 mo in duration. Nematode levels following some effective rotation crops recovered to levels similar to those rotated with a susceptible soybean control, as illustrated by data from two studies (Kinloch and Dunavin, 1993; McSorley and Dickson, 1995).

An overview of these examples reveals some interesting trends. Every entry (Table 6) with Pi ≥ 2 J2/100 cm^3 soil resulted in Pf > 50/100 cm^3, and most (3 exceptions) resulted in Pf > 100/100 cm^3. The 10 entries with Pi ≤ 1/100 cm^3 are of particular interest because some of these also resulted in the lowest Pf values (Table 6). The study by Dickson and Hewlett (1989) is included among these because J2 were not detected initially in soil; a bioassay test was used to confirm nematode presence. Of these 10 entries with lowest Pi, half of them resulted in Pf ≥ 50/100 cm^3, and 3 of them resulted in Pf > 100/100 cm^3. These results suggest that resurgence to levels > 50/100 cm^3 is likely on a susceptible target crop even if a rotation crop provided a Pi as low as 2/100 cm^3. With Pi ≤ 1/100 cm^3, there is a possibility (50% of these examples) that Pf will remain below 50/100 cm^3, although high resurgence is possible even when no nematodes are detected (Pi = 0). Roberts *et al.* (2005) also observed differences in root-knot nematode recovery under low Pi and high Pi scenarios, with higher levels of galling on tomato (*Solanum lycopersicum* L.) following cowpea in the high Pi scenarios. However, their distinction between high and low Pi involved much greater ranges than those observed here (Table 6), where even Pi as low as 2/100cm^3 showed strong resurgence.

Maintenance of low nematode population levels

While rotation crops may be effective in lowering very high initial nematode population levels, they may also be helpful in maintaining low initial numbers for a period of time. Selected rotation crop treatments (including fallow) were examined in several studies with moderate to low initial levels of root-knot nematodes (Table 7). Three of these studies involved winter cover crops followed by a nematode-susceptible target crop, while the work by Bhan *et al.* (2010) used summer cover crops. Nematode levels were low after the first planting of the rotation crops, and for the best rotation crop treatments they remained relatively low (at least < 50/100 cm^3) up until the end of the first planting of the susceptible target crops. But even at this time, significantly ($P < 0.05$) higher numbers were already noted following more susceptible cover crops like hairy vetch or crimson clover (Wang *et al.*, 2004), or after the susceptible sorghum-sudangrass cultivar Brown Midrib (Bhan *et al.*, 2010). By the end of the second year of a similar cropping system, nematode numbers recovered on the susceptible target crops and reached relatively high levels in most cases. Only the sunn hemp rotation in the experiment by Bhan *et al.* (2010) resulted in a lower ($P < 0.05$) population level than some other treatments. Thus there is some evidence that in sites with low to moderate Pi, nematode numbers may remain somewhat low throughout the next crop, but numbers usually recovered if the cropping system was repeated in the next year.

The study by Bhan *et al.* (2010) is interesting because it was conducted in a site that was in the process of being colonized by root-knot nematodes, which were not detected in the site initially. A cowpea crop was planted over the entire site in spring 2006 and inoculated with *M. incognita* from greenhouse cultures, but the inoculum was diluted over the large geographic area, so that J2 were still not detected by soil sampling at the beginning of the rotation crop experiment in late July. Root-knot nematodes were first detected and built up in the cropping system with the susceptible sorghum-sudangrass cultivar, but remained relatively low in several of the other cropping systems, although the target crop was actually a double crop of squash followed by pepper. Buildup of nematode population levels on this double crop (squash-pepper) was remarkably slow, probably a result of the very low initial population. But as these cropping systems continued into their second year, nematode numbers began to build to high levels in some crops (Table 7).

Effects of very long rotations

Very long rotations may not always be practical but sometimes sites are available which have been in non-host crops for a long period of time. Brodie and Murphy (1975) established rotations of summer rotation crops and tomato transplants on land that had been recently cleared of pine trees. *Meloidogyne incognita* was not detected in the first year of the experiment, but appeared in tomatoes rotated with okra, corn, or *Crotalaria mucronata* Desv. in the 2nd year. Tomato rotated with browntop millet (*Panicum ramosum* L.) or fallow was free of the nematode for the entire 3 years of the study. When corn was planted following a 14-year rotation of sorghum, *M. incognita* was not detected until the 2nd year in corn (McSorley and Gallaher, 1993). Nematode numbers remained low (Pf after corn ≤ 3 J2/100 cm^3 soil) through the 2nd and 3rd years of corn. Chellemi *et al.* (1999) noted that root-knot nematodes were detected in tomato that followed 2 year of bahiagrass but not in tomato that followed 5 year of bahiagrass. These examples suggest that nematode colonization may be delayed for several years in sites with long histories of non-host crops. However, Good (1968) found light galling from *M. incognita* on tomato in the first year following 6 year of bahiagrass, and any advantage from this long rotation was lost by the 2nd year of tomato. Such variable results may depend on the very long-term history of the site and to what extent the site was contaminated with small numbers of weed hosts. In the last example, it is possible that the long rotation of bahiagrass at an experiment station in Tifton, GA (Good, 1968) may have been established in a site where vegetable crops or other nematode hosts were grown previously, leaving small residual nematode populations in the site.

Once root-knot nematodes are firmly established, remediation of an infested site may be difficult even with long rotations of poor hosts. In a study from south GA (Murphy *et al.*, 1974), a tomato production site infested with *M. incognita* was abandoned and left in pasture grasses for 5 years. After that, multi-year rotations of several cover crops were examined. Root-knot nematodes were reduced below detectable levels after one year of fallow or *C. mucronata*, but it took 3 years of marigold (*T. erecta* L.) or 4 years of bahiagrass or bermudagrass to lower nematode numbers below detectable levels. Johnson (1982) observed that 2-year rotations with non-hosts were needed to manage root-knot nematodes on tobacco in infested fields in NC, but 3-year rotations were needed in the warmer climate of GA. When sites had only low population densities of *Meloidogyne* spp., a 3-year rotation of peanut-peanut-tobacco was successful in managing the nematodes on tobacco for a 27-year period (Johnson, 1982).

Overall, effective rotation crops performed well in comparison with standard nematicides, especially nonfumigants, both in terms of comparative yields and nematode numbers in a susceptible target crop. However, fumigation with methyl bromide maintained low nematode numbers up to Pf of the target crop, while numbers of nematodes recovered following rotation crops. Rotation crops resulted in nematode

Table 6. Recovery of root-knot nematode J2 numbers on a susceptible target crop following selected rotation treatments.

Scenario[w]	Rotation treatment	Target crop, duration	Nematodes/100 cm^3 soil[x] Pi	Pf	Reference
Winter cover crops:					
Mi, FL	Wheat	Corn, 3.5 mo	3	759	McSorley and Gallaher, 1992
	Rye		5	1076	
	Crimson clover		353	706	
	Hairy vetch		462	1262	
Mi, FL	Wheat	Corn, 4.5 mo	2 a[y]	145 ab	Wang *et al.*, 2004
	Rye		0 a	41 bc	
	Oat		0 a	41 c	
	Crimson clover		4 a	225 ab	
	Hairy vetch		3 a	215 a	
Summer cover crops:					
Mi, FL	Castor	Eggplant, 4 mo	1 b	314 a	McSorley and Dickson, 1995
	Velvetbean		6 b	139 abc	
	Cowpea		< 1 b	18 c	
	Jointvetch		1 b	40 bc	
	Cotton		2 b	145 abc	
	Sorghum-sudan		3 b	190 ab	
	Soybean		134 a	269 ab	
Mi, FL	Cowpea	Bean, 2 mo	2	658	Wang *et al.*, 2003
	Cowpea	Turnip, 2.5 mo	2	145	
Mi, FL	Sorghum-sudan	Okra, 4 mo	4	77	Wang *et al.*, 2007
	Sunn hemp	Okra, 4 mo	0	169	
Annual rotation crops:					
Ma, FL	Jointvetch	Soybean, 5 mo	30 b	1760 a	Kinloch and Dunavin, 1993
	Cotton		40 b	1980 a	
	Pearl millet		60 b	1860 a	
	Peanut		20 b	2390 a	
	Sorghum-sudan		50 b	2060 a	
	Soybean		230 a	2191 a	
Mi, GA, '89	Peanut	Cotton, 6 mo	0	50	Johnson *et al.*, 1998
1991	Peanut	Cotton, 6 mo	1	59	
1993	Peanut	Cotton, 6 mo	2	71	
Perennial rotation crops:					
Ma, FL	Bahiagrass 2 yr	Peanut, 5 mo	0.8[z]	892	Dickson and Hewlett, 1989
M, FL, #1	Bahiagrass 2 yr	Tomato, 3-4 mo	10	52	Chellemi *et al.*, 1999
#2	Bahiagrass 2 yr	Tomato, 3-4 mo	< 1	18	

[w]Nematode (Mi = *Meloidogyne incognita*; Ma = *M. arenaria*; M = *Meloidogyne* spp.), state, and year of cotton crop (Johnson *et al.*, 1998) or experiment number (Chellemi *et al.*, 1999). *M. arenaria* was race 1 in Dickson and Hewlett (1989) and race 2 in Kinloch and Dunavin (1993).
[x]Pi = nematode population level before target crop; Pf = final nematode population level on target crop.
[y]For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to statistical tests performed in the corresponding reference. No letters indicate statistical analysis not conducted (separate sites or experiments in same study).
[z]Average of 0.8 galls per plant when soil from 0 to 15 cm depth examined by bioassay.

Table 7. Root-knot nematode population increase over 2 years in susceptible target crops (TC) that followed selected rotation crop (RC) treatments.

		Nematodes/100 cm³ soil[x]					
		Year 1			Year 2		
Scenario[v]	Treatment[w]	Pi	RC-Pf	TC-Pf	RC-Pf	TC-pf	Reference
Ma, AL	Cahaba vetch	10 a[y]	2 a	17 a	50 a	982 a	Guertal *et al*., 1998
	Hairy vetch	75 a	2 a	9 a	75 a	1604 a	
	Crimson clover	4 a	1 a	2 a	68 a	1142 a	
	Fallow	63 a	1 a	17 a	162 a	1201 a	
Mi, FL	Wheat	0 a	2 a	145 ab	15 ab	187 a	Wang *et al*., 2004
	Rye	1 a	0 a	41 bc	3 c	155 a	
	Oat	5 a	0 a	41 c	8 c	202 a	
	Hairy vetch	0 a	3 a	215 a	44 a	264 a	
	Crimson clover	0 a	4 a	225 ab	8 abc	162 a	
Mi, GA	Weed fallow	21 a	8 a	18 a	15 b	228 a	Timper *et al*., 2006
	Rye	27 a	2 a	3 a	14 b	199 a	
	Crimson clover	12 a	17 a	26 a	42 b	110 a	
	Hairy vetch	8 a	11 a	16 a	115 a	198 a	
	Cahaba vetch	8 a	3 a	17 a	7 b	212 a	
Mi, FL	Weed fallow	--[z]	0 a	7 ab	4 a	46 ab	Bhan *et al*., 2010
	Pearl millet	--	0 a	14 ab	0 a	57 ab	
	Sorghum-sudan	--	6 a	53 a	5 a	142 a	
	Sunn hemp	--	0 a	0 b	1 a	37 b	
	Velvetbean	--	0 a	0 b	8 a	110 a	

[v]Nematode (Ma = *Meloidogyne arenaria*; Mi = *M. incognita*), state.
[w]Cover crop treatment or fallow. Cahaba vetch = *Vicia sativa* cv Cahaba White; hairy vetch = *V. villosa*.
[x]Pi = nematode population level before first rotation crop; Pf = final nematode population level on rotation crop (RC) or following target crop (TC). Target crops used are okra (Guertal *et al*., 1998); corn (Wang *et al*., 2004); and cotton (Timper *et al*., 2006). Target crops used by Bhan *et al*. (2010) are a double crop (squash followed by pepper); TC-Pf = number following the pepper crop.
[y]For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to statistical tests performed in the corresponding reference. In study by Wang *et al*. (2004), mean separations were based on log-transformed data.
[z]Not detected, see text.

numbers similar to those from clean fallow in many studies. Although some cover crops are known to be nematicidal (Ferraz and de Freitas, 2004), there was little evidence from field experiments that these "antagonistic" crops could suppress nematode numbers below those obtained through clean fallow. Sometimes antagonistic rotation crops were no better than weedy fallow, provided the weeds did not include good nematode hosts. Large reductions in nematode populations can often be achieved following rotation crops, but nematode numbers will usually recover once a susceptible target crop follows the rotation crop. Better results were obtained in sites with relatively low initial populations, where use of effective rotation crops maintained relatively low nematode numbers through the following susceptible target crop, and full nematode recovery was not observed until the 2nd year of a susceptible crop. Best results were obtained with very long rotations, such as bahiagrass pastures (Chellemi *et al*., 1999), although results were not always consistent (Good, 1968). Rehabilitation of infested sites is difficult and could require several years of rotation crops, and after that, the benefit gained may last only through one susceptible target crop.

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