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ORIGINAL ARTICLE

Host status of rotation crops in Asian rice-based cropping systems to the rice root-knot nematode *Meloidogyne graminicola*

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Abstract Rotation with nonhost crops is an important practice used for root-knot nematode (RKN) management. Screenhouse experiments were conducted to evaluate the response infection of 27 cultivars belonging to 14 crops (blackgram, cabbage, cauliflower, chickpea, cowpea, garlic, ginger, greengram, groundnut, maize, potato, sesame, soybean, sunflower), which are grown in rotation with rice in lowland and upland rice-based ecosystems, to the RKN *Meloidogyne graminicola*. Root galling indices observed on all crop rotation cultivars were significantly lower compared with the rice cv. Thihtatyin, used as positive control. Differences in host response to *M. graminicola* infection were observed between cultivars. All 27 cultivars were poor or non-hosts of *M. graminicola*, except cv. Yezin 4 of chickpea considered as good host. No significant differences in plant growth were observed between non-inoculated and inoculated plants of all plant/species cultivars, with the exception of a reduction in root length in the chickpea cv. Yezin 4 (good host) and the garlic cv. Shan (poor host). Rotation crops identified as poor or non-hosts of *M. graminicola* could be useful in the management of RKN in rice-based cropping systems.

Keywords Host response · Nematode management · *Oryza sativa* · Reproduction factor · Rotation crops · Root gall index

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Introduction

Populations of soilborne plant-parasitic nematodes (PPN) usually build up in the soil when the same susceptible crop is grown in the same field year after year (Bridge 1996; Greco and Di Vito 2009). This population build-up can be avoided by the use of crop rotation. The aim of crop rotation is to grow non-host, resistant or poor host plants in sequence with the susceptible crop to keep the nematode population densities below a threshold level that will allow maximum growth and yield of the next nematode-susceptible crop (Trivedi and Barker 1986). The efficacy of crop rotation depends upon several factors of which the level of resistance of the rotation crop is the most important: the higher the level of resistance the slower the nematode population build-up will be and the higher the chances of maximum yield being realized. To apply an effective crop rotation sequence for the management of a PPN species, evaluation of the host suitability of potential rotation crops is necessary. One should be careful to generalize the host status of a rotation crop because cultivars of the same

crop species can differ in their response to infection by the same nematode species (Davis and May 2003; Oka et al. 2004; Cabasan et al. 2016). Also, different populations from the same nematode species may differ in their reproductive and damage potential on the same crop species or cultivars (Sikora et al. 2005; Pokharel et al. 2007). Therefore, it is necessary to determine the host status of potential rotation crop cultivars to infection by local nematode-pest populations before a crop rotation sequence can be recommended to the farmers.

Previous studies reported that some crops such as castor (*Ricinus communis* L.), common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* L.), jute (*Corchorus capsularis* L.), okra (*Abelmoschus esculentus* L.), onion (*Allium cepa* L.), sesame (*Sesamum indicum* L.), soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.), sweet potato (*Ipomoea batatas* L.) and turnip (*Brassica rapa* L.) are either resistant or poor hosts of the rice root-knot nematode (RKN) *Meloidogyne graminicola* Golden and Birchfield, 1965 (Rao 1985; Rao et al. 1986; Gergon 2002). In contrast, many cultivars of crops that are also commonly grown in rotation with rice (*Oryza sativa* L.), such cabbage (*Brassica oleracea* var. *capitata* L.) and tomato (*Solanum lycopersicum* L.), are good hosts of *M. graminicola* (Jain et al. 2012).

During the past decade, *M. graminicola* has emerged as one of the most important soil-borne pathogens of rice. It was found in almost every Asian rice-based agro-ecosystem in South and Southeast Asia including irrigated and rainfed rice, lowland and upland rice, and deepwater rice (Prot and Rahman 1994; Bridge 1996; Padgham et al. 2004; Bridge et al. 2005; De Waele and Elsen 2007; Win et al. 2011; Jain et al. 2012). It is now also considered a major cause of yield losses in tropical aerobic rice (Kreye et al. 2009; De Waele et al. 2013). Because of its short life cycle, this nematode species can have up to six generations during a single rice crop cycle (Fernandez et al. 2013), build up high population densities and result in substantial yield losses (Arayarungsarit 1987; Netscher and Erlan 1993; Padgham et al. 2004). The use of nematicides to manage *M. graminicola* is not an option to most small-scale farmers due to their high cost and resistant or tolerant rice cultivars are not yet available. The objective of our study was to evaluate the host suitability of selected cultivated plants, which are commonly grown or could be grown in rotation with Asian rice (*Oryza sativa* L.) in both lowland and upland rice-based agro-ecosystems in Myanmar where *M. graminicola* is omnipresent (Win et al. 2011). Our study was also prompted by the observations that although upland Asian rice cultivars are susceptible to *M. graminicola* infection as lowland Asian rice cultivars, the occurrence of *M. graminicola* was low in the upland rice-based agro-ecosystems in Myanmar where rice is being grown in rotation with a variety of crops such as blackgram (*Vigna mungo* L.) and chickpea (*Cicer arietinum* L.) (Win et al. 2011, 2013, 2015).

Materials and methods

The response of 27 cultivars belonging to 14 commercial agricultural crops, which are grown in rotation with rice in both lowland and upland rice-based agro-ecosystems in Myanmar, to *M. graminicola* was evaluated from June 2010 to April 2012, totaling seven experiments. Plants were grown in screenhouse made chiefly of knitted polyethylene fabric which provided environmental protection from severe weather conditions as well as exclusion of pests. The lowland Asian rice cv. Thihtatyin was included in all experiments as the susceptible reference cultivar. The host status of the blackgram, cowpea, soybean and sunflower cultivars were re-examined to confirm the results in different seasons.

Plant material

Seeds of blackgram, chickpea, cowpea, greengram (*Vigna radiata* L.), groundnut (*Arachis hypogaea* L.), maize (*Zea mays* L.) sesame, soybean, and sunflower cultivars were provided by the Department of Agricultural Research (DAR), Yezin, Nay Pyi Taw. Seeds of the cultivars of cabbage, cauliflower (*B. oleracea* var. *botrytis*), garlic cloves (*Allium sativum* L.), ginger (*Zingiber officinale* Rosc.) and potato (*Solanum tuberosum*) tubers were obtained from private sources. The list of plant species/cultivars included in the study is presented in Table 1. The rice seeds were first soaked in tap water overnight and pre-germinated on wet paper in Petri dishes at room temperature (28 °C). All cultivars were grown from seeds in trays containing a sterilised clay loam soil (32.1 % clay) at different planting dates depending on the period of dormancy so that uniform seedlings were transplanted into the pots.

Nematode inoculation

Adult female nematodes were handpicked from the root systems with swollen and hooked galls (i.e., the characteristic symptoms of *M. graminicola*) using a stereoscope. Identification of the *M. graminicola* was based on the perineal pattern of mature females, and the morphology and morphometrics of the J2 (Mulk 1976, *data not shown*). The nematode inoculum consisted of the offspring of a single *M. graminicola* female isolated from an irrigated Asian rice plant (cultivar unknown) in Pathein region, Ayeyarwady Delta (Lower Myanmar) and multiplied on cv. Thihtatyin under an upland water regime (soil moisture: 50 % water holding capacity) in a screenhouse at an air temperature ranging from 25 to 38 °C. Galled roots infected with *M. graminicola* were chopped into approximately 1-cm-pieces and macerated in a kitchen blender two times during 10 s. The infective second-stage juveniles (J2) were extracted by using the Whitehead's tray method (Whitehead and Hemming 1965) at room temperature and only 24 h *M. graminicola* J2 were used as inoculum.

Table 1 Commercial plant species included in the study that are commonly grown in rotation with Asian rice in lowland/upland rice-based agroecosystems

Plant species	Common name	Cultivar	Code	Lowland/Upland
Allium sativum	Garlic	Shan	Shan	Upland
Arachis hypogaea	Groundnut	Sin Padaethar 7	SPDT 7	Lowland & Upland
		Sin Padaethar 11	SPDT 11	Lowland & Upland
Brassica oleracea var. *capitata*	Cabbage	Jagucar	JC	Upland
		Pride 004	P 004	Upland
B. oleracea var. *botrytis*	Cauliflower	ATRIA 153	A 153	Upland
		WIN 172	W 172	Upland
Cicer arietinum	Chickpea	Yezin 4	YZ 4	Lowland
		Yezin 6c	YZ 6c	Lowland
Glycine max	Soybean	Yezin 6 s	YZ 6 s	Lowland & Upland
		Yezin 8	YZ 8	Lowland & Upland
Helianthus annuus	Sunflower	Sin Shwekyar 2	SSK 2	Lowland
		Sin Shwekyar 3	SSK 3	Lowland
Oryza sativa	Rice	Thihtatyin	THY	Lowland
Sesamum indicum	Sesame	Sin Yadanar 3	SYDN 3	Lowland & Upland
		Sin Yadanar 4	SYDN 4	Lowland & Upland
Solanum tuberosum	Potato	Kufrijyoti	KFJ	Upland
		Up-To-Date	UTD	Upland
Vigna mungo	Blackgram	LBG 17	LBG 17	Lowland
		Yezin 2	YZ 2	Lowland
V. radiata	Greengram	Agriculture 1	AG 1	Lowland
		Paeti Shwewar	PTSW	Lowland
V. unguiculata	Cowpea	Bocake	BC	Lowland
		Sin Paelon Phyu 2	SPLP 2	Lowland
Zea mays	Maize	Yezin 5	YZ 5	Upland
		Yezin 6 m	YZ 6 m	Upland
Zingiber officinale	Ginger	Gingyi	GG	Upland
		Ginlay	GL	Upland

The seedlings, uniform in size, were singly transplanted into 17 cm diameter pots containing 1.5 L of a sterilized clay loam soil (31.9 % sand, 34.5 % loam and 32.1 % clay, 2.5 % organic matter, 1.3 % C, 0.2 % nitrogen, 24.3 ppm P, 9.2 mg/100 g K_2O, pH = 5.8) and the soil saturated (i.e., 100 % of soil pore volume filled with water) at planting.

One week after planting, eight plants of each cultivar and of cv. Thihtatyin were inoculated with 3,000 J2/plant (initial population density, Pi). Eight non-inoculated plants species/cultivars and of cv. Thihtatyin were included as negative controls. At the time of inoculation, the soil in the pots was still saturated. The pots were arranged in a randomized complete block design in a screenhouse. Mean monthly rainfall and air temperature were recorded in each experiment.

Host status evaluation

At 8 weeks after inoculation (WAI), the plants were uprooted and the roots carefully washed under running water. The following plant growth variables were recorded: number of pods/plant of blackgram, chickpea, cowpea, greengram, groundnut and soybean, and of tillers for cv. Thihtatyin, root length, fresh root and shoot weight, and plant height. The severity of root galling was visually scored based on the percentage of roots with root tip galls according to the rice root-knot rating chart (root gall index, RGI) whereby, 0 = no swelling or galls, 1 = 10 %, 2 = 20 %, 3 = 30 %, 4 = 40 %, 5 = 50 %, 6 = 60 %, 7 = 70 %, 8 = 80 %, 9 = 90 % of the root system galled and 10 = all roots of the root system galled (Bridge and Page 1980).

The J2 were extracted from a 100 mL soil sub-sample using Whitehead's tray method (Whitehead and Hemming 1965). The eggs and J2 were extracted from one sub-sample of 3 g of roots of each plant or from the entire root system (root weight < 3 g). Roots were macerated in a kitchen blender and the nematodes extracted as referred before. After 24 h, the J2 that had moved through the sieve into the water were collected, concentrated in a 50-mL suspension by decanting the water through a sieve and counted. The eggs were re-extracted from the roots left on the Whitehead's tray sieve

using a modified sodium hypochloride (NaOCl) extraction method and counted (Stetina et al. 1997). The final population densities (Pf) of *M. graminicola* were expressed as the total number of eggs and J2 recovered from soil and roots. The number of J2/1.5 L soil, eggs and J2/g roots and root system were also presented. The reproduction factor (Rf = Pf/Pi) was calculated.

Host suitability was assessed only on the basis of Rf. Plants with Rf > 1 were considered good hosts; with 0.1 ≤ Rf ≤ 1 poor hosts; and Rf < 0.1 as non-hosts (modified from Ferris et al. 1993).

Statistical analysis

Prior to analysis of variance, data for nematode population densities and root galling severity were log(x + 1) and arcsin(x/100) transformed, respectively, to meet the assumptions of ANOVA (i.e., normality and homogeneity of variances). The Shapiro-Wilk's test was used to examine whether the dependent variable was normally distributed within groups while the homogeneity of the variances of the groups was tested with the Levene's test. The outliers were determined by calculating the standardized residuals falling outside the range from -2 to +2. One-way ANOVA was performed for mean comparisons of root galling severity and nematode population densities with Tukey's HSD test ($P \leq 0.05$). Factorial analysis of ANOVA was used to examine the effect of nematode inoculation on plant growth (compared with the non-inoculated control plants). In the case of absence of interaction between the two factors for a specific plant growth variable, the factor level means (*M. graminicola* inoculated and non-inoculated plants) were compared by Tukey's HSD test for all cultivars together. In the case of interaction between the two factors, individual comparisons were made between inoculated and non-inoculated plants with the *t*-test for each cultivar. All analyses were performed in STATISTICA 10.0 software

Results

The host status of the 27 rotation cultivated plants and the lowland rice cv. Thihtatyin to *M. graminicola* is presented in Table 2. The *M. graminicola* population density on roots (eggs and J2/g roots and root system) and the RGI were significantly ($P \leq 0.05$) lower in all cultivars compared with cv. Thihtatyin. No root galling was observed on maize cv. Yezin 5.

In experiment 1, the number of J2 recovered from the rhizosphere and the RGI of both blackgram and greengram cultivars were significantly ($P \leq 0.05$) lower compared with sunflower cv. Sin Shwekyar 2 and cv. Thihtatyin of rice. The blackgram cv. LBG 17 and the greengram cv. Paeti Shwewar had the lowest number of eggs and J2 per root system compared with all other cultivars. Both cultivars had Rf < 0.1 and can be considered as non-hosts of *M. graminicola*. The blackgram cv. Yezin 2, greengram cv. Agriculture 1 and sunflower cv. Sin Shwekyar 2 had 0.1 < Rf < 1 and can be considered as poor hosts of *M. graminicola*.

In experiment 2, the number of J2 recovered from the rhizosphere of cv. Thihtatyin was significantly ($P \leq 0.05$) higher compared with both cowpea and soybean cultivars. The number of eggs and J2 per root system and the RGI of soybean cv. Yezin 8 was significantly ($P \leq 0.05$) higher compared with cv. Yezin 6 s and cowpea cultivars. These two soybean cultivars had 0.1 < Rf < 1 and can be considered as poor hosts of *M. graminicola* and cowpea cultivars as non-hosts (Rf < 0.1).

In experiment 3, the number of J2 recovered from the rhizosphere of cv. Thihtatyin was not significantly different of all other cultivars, except blackgram cv. LBG 17. The number of eggs per root system and the RGI of chickpea cv. Yezin 4 was significantly ($P \leq 0.05$) higher compared with all other cultivars, except sunflower cv. Sin Shwekyar 3 and cv. Thihtatyin of rice. Re-examination of both blackgram cultivars confirmed the results obtained in experiment 1. The chickpea cv. Yezin 6c and sunflower cv. Sin Shwekyar 3 had 0.1 < Rf < 1 and can be considered as poor hosts while the chickpea cv. Yezin 4 was a good host of *M. graminicola* (Rf = 3.7).

In experiment 4, the number of J2 recovered from the rhizosphere of cv. Thihtatyin was significantly ($P \leq 0.05$) higher compared with cowpea cv. Bocake and soybean cv. Yezin 6 s, confirming the results of experiment 2. No J2 were recovered from the rhizosphere of cowpea cv. Sin Paelon Phyu 2 and sesame cv. Sin Yadanar 3. The number of J2 recovered from the rhizosphere of sesame cv. Sin Yadanar 4 was not significantly different from cv. Thihtatyin, however very few J2 were recovered from the root systems. The number of eggs and J2 per root system and the RGI of soybean cv. Yezin 6 s was significantly ($P \leq 0.05$) higher compared with all other cultivars examined. The sesame cv. Sin Yadanar 3 had Rf < 0.1 and cv. Sin Yadanar 4 had 0.1 < Rf < 1 and can be considered as a non-host and a poor host of *M. graminicola*, respectively. Re-examination of both cowpea cultivars and soybean cv. Yezin 6 s confirmed their host status as non-hosts and poor host of *M. graminicola*, respectively.

In experiment 5, no J2 were recovered from the rhizosphere of groundnut cultivars. Both cultivars of groundnut had significantly ($P \leq 0.05$) lower number of eggs and J2 per root system compared with all other cultivars. The number of J2 recovered from the rhizosphere of sunflower cultivars were not significantly different compared with rice cv. Thihtatyin and confirmed the results obtained in experiments 1 and 3. Re-examination of sunflower cultivars and soybean cv. Yezin 8 confirmed the host status of these cultivars as poor hosts of *M. graminicola*. Both groundnut cultivars had Rf < 0.1 and can be considered as non-hosts.

In experiment 6, the number of J2 recovered from the rhizosphere of all crop rotation cultivars examined was

Table 2 Soil and root population densities of *Meloidogyne graminicola*, root galling index (RGI), nematode reproduction factor (Rf) and host status of 27 selected commercial plant species/cultivars, at 8 weeks after inoculation with 3,000 *M. graminicola* second-stage juveniles (J2) per plant

Plant common name (cultivar)[1]	Population density					RGI[2,3]	Pf[4]	Rf[5]	Host status[6]
	J2/1.5 L soil[2]	J2/g roots[2]	Eggs/g roots[2]	J2/root system[2]	Eggs/root system[2]				
Experiment 1									
Blackgram (LBG 17)	42 ± 33a	32 ± 22a	11 ± 8a	24 ± 25a	9 ± 10a	0.2 ± 0.2a	75	<0.1	NH
(YZ 2)	98 ± 34a	41 ± 26ab	55 ± 68ab	61 ± 26abc	81 ± 76ab	0.1 ± 0.2a	240	0.1	PH
Greengram (Agri 1)	72 ± 42a	129 ± 103bc	481 ± 479b	106 ± 87bc	408 ± 510b	0.6 ± 0.6a	586	0.2	PH
(PTSW)	55 ± 58a	53 ± 28ab	41 ± 78a	28 ± 25ab	15 ± 22a	0.8 ± 0.9a	98	<0.1	NH
Sunflower (SSK 2)	229 ± 391b	262 ± 136c	255 ± 174b	233 ± 124c	228 ± 239b	4.3 ± 1.6b	690	0.2	PH
Rice (THY)	150 ± 270b	22,821 ± 7,543d	18,898 ± 11,586c	26,147 ± 13,354d	22,626 ± 17,452c	8.7 ± 1.5c	48,923	16.3	GH
Experiment 2									
Cowpea (BC)	13 ± 36a	18 ± 7a	55 ± 97a	32 ± 23a	57 ± 80a	0.6 ± 0.3a	102	<0.1	NH
(SPLP 2)	19 ± 54a	34 ± 45a	129 ± 146ab	44 ± 59a	150 ± 199a	1.0 ± 0.7a	213	<0.1	NH
Soybean (YZ 6 s)	443 ± 673b	48 ± 26a	52 ± 39a	107 ± 77a	107 ± 35a	2.5 ± 0.6b	657	0.2	PH
(YZ 8)	254 ± 219b	548 ± 324b	508 ± 349b	904 ± 636b	746 ± 551b	4.2 ± 0.8c	1,904	0.6	PH
Rice (THY)	13,636 ± 15,599c	9,632 ± 7,871c	28,428 ± 17,555c	12,386 ± 8,441c	33,243 ± 21,522c	8.0 ± 0.8d	59,265	19.8	GH
Experiment 3									
Blackgram (LBG 17)	60 ± 36b	12 ± 12b	17 ± 13b	23 ± 6b	31 ± 14a	0.3 ± 0.4a	114	<0.1	NH
(YZ 2)	1,004 ± 213a	9 ± 6b	17 ± 29b	14 ± 11b	24 ± 15a	0.4 ± 0.4ab	1,042	0.3	PH
Chickpea (YZ 4)	6,877 ± 9,171a	1,017 ± 676a	5,231 ± 1,576a	537 ± 390a	3,760 ± 2,757c	2.8 ± 0.8c	11,174	3.7	GH
(YZ 6c)	1,082 ± 1,292a	691 ± 643a	3,668 ± 3,687a	240 ± 151a	727 ± 591b	0.7 ± 0.8ab	2,049	0.4	PH
Sunflower (SSK 3)	1,036 ± 1,570a	333 ± 245a	1,052 ± 840a	582 ± 727a	1,060 ± 2,854bc	1.8 ± 1.4bc	2,678	0.9	PH
Rice (THY)	5,865 ± 9,185a	743 ± 1,240c	49,809 ± 14,922c	53,644 ± 20,858c	735,363 ± 235,413d	7.4 ± 1.3d	794,872	265.0	GH
Experiment 4									
Cowpea (BC)	9 ± 25c	9 ± 4a	2 ± 2a	54 ± 47a	12 ± 14ab	0.4 ± 0.4a	75	<0.1	NH
(SPLP 2)	0	10 ± 6a	119 ± 192bc	24 ± 23ab	355 ± 374bc	0.2 ± 0.2a	379	<0.1	NH
Sesame (SYDN 3)	0	17 ± 7a	1 ± 3a	51 ± 42a	4 ± 9a	0.5 ± 0.4a	55	<0.1	NH
(SYDN 4)	691 ± 1,073ab	1 ± 1b	0	3 ± 3b	0	0.3 ± 0.3a	694	0.2	PH
Soybean (YZ 6 s)	163 ± 73a	67 ± 60c	310 ± 481c	212 ± 147c	921 ± 1,192c	2.2 ± 0.6b	1,296	0.4	PH
Rice (THY)	2,402 ± 1,423b	2,654 ± 1,493d	24,261 ± 6,508d	43,948 ± 13,019d	429,739 ± 9,1268d	7.8 ± 0.7c	476,089	158.7	GH
Experiment 5									
Groundnut (SPDT 7)	0	7 ± 3a	5 ± 3b	47 ± 23b	34 ± 32b	0.5 ± 0.3a	81	<0.1	NH
(SPDT 11)	0	10 ± 14a	3 ± 5b	71 ± 88b	22 ± 32b	0.6 ± 0.5a	93	<0.1	NH
Soybean (YZ 8)	161 ± 281b	82 ± 94a	79 ± 88a	452 ± 359a	434 ± 370a	1.8 ± 1.1ab	1,047	0.3	PH
Sunflower (SSK 2)	741 ± 1034a	195 ± 78a	179 ± 93a	503 ± 214a	420 ± 370a	3.8 ± 1.5c	1,664	0.6	PH
(SSK 3)	1,031 ± 888a	113 ± 106a	255 ± 132a	302 ± 36a	740 ± 185a	3.0 ± 1.3bc	2,073	0.7	PH
Rice (THY)	1,190 ± 1,438a	1,142 ± 569b	6,716 ± 2,820c	15,575 ± 3,117c	93,777 ± 35,107c	6.4 ± 0.9d	110,542	36.8	GH
Experiment 6									
Cauliflower (A 153)	287 ± 163a	37 ± 12a	10 ± 6a	835 ± 298c	215 ± 143ab	0.6 ± 0.2a	716	0.2	PH
(W 172)	266 ± 372a	55 ± 18a	25 ± 3a	498 ± 160bc	230 ± 70ab	0.6 ± 0.2a	1,337	0.4	PH
Garlic (Shan)	84 ± 53a	63 ± 49a	267 ± 53b	111 ± 90ab	521 ± 547b	3.1 ± 1.3b	994	0.3	PH
Potato (KFJ)	113 ± 64a	65 ± 87a	79 ± 155ab	96 ± 68a	108 ± 188a	1.6 ± 0.9a	317	0.1	PH
(UTD)	77 ± 31a	2 ± 3b	0	2 ± 3d	1 ± 3c	1.2 ± 0.3a	80	<0.1	NH
Rice (THY)	2,932 ± 1,940b	18,133 ± 5,161c	42,812 ± 15,379c	18,3540 ± 67,009e	431,172 ± 100,619d	9.4 ± 0.3c	617,644	205.9	GH
Experiment 7									
Cabbage (JC)	188 ± 156a	123 ± 18b	4 ± 2a	1,227 ± 250c	44 ± 24ab	0.6 ± 0.2a	1,459	0.5	PH
(P 004)	275 ± 84a	59 ± 50ab	5 ± 2a	635 ± 631bc	56 ± 30ab	0.5 ± 0.0a	966	0.3	PH
Ginger (GG)	29 ± 23b	33 ± 17a	22 ± 3a	319 ± 263abc	209 ± 99c	1.3 ± 0.7a	557	0.1	PH
(GL)	0	87 ± 73ab	26 ± 50a	199 ± 238ab	91 ± 75a	1.0 ± 1.2a	290	0.1	PH
Maize (YZ 5)	0	1 ± 1c	0	37 ± 32a	0	0.0	37	<0.1	NH
(YZ 6 m)	0	2 ± 1c	0	95 ± 78a	0	0.5 ± 0.0a	95	<0.1	NH
Rice (THY)	5,082 ± 5,456c	10,262 ± 1,126d	25,665 ± 5,514b	312,786 ± 83,972d	993,550 ± 33,756d	8.0 ± 0.6b	1,311,418	437.1	GH

[1] For the full names of the cultivars see Table 1

[2] Data represent means ± SD ($n = 8$). Means in the same column followed by the same letter for every experiment are not significantly different according to Tukey's HSD test ($P \leq 0.05$)

[3] RGI (root gall index): % galled root tips on a scale from 0 (no galls) to 10 (all roots of a root system galls) (Bridge and Page 1980)

[4] Pf (final population density) = number of J2 in soil and eggs and J2 in roots

[5] Rf (reproduction factor) = Pf/initial population density (3,000 J2)

[6] Host status: good host (GH, Rf > 1), poor host (PH, 0.1 < Rf < 1) and non-host (NH, Rf < 0.1) [modified from Ferris et al. (1993)]

significantly ($P \leq 0.05$) lower compared with cv. Thihtatyin. The number of eggs and J2 recovered per root system was significantly ($P \leq 0.05$) lower in potato cv. Up-To-Date compared with all other cultivars. The RGI of garlic cv. Shan was significantly ($P \leq 0.05$) higher compared with all other cultivars. The potato cv. Kufrijyoti, the garlic cv. Shan, and both cauliflower cultivars had $0.1 < Rf < 1$ and can be considered as poor hosts of *M. graminicola*. The potato cv. Up-To-Date had $Rf < 0.1$ and can be considered as a non-host.

In experiment 7, no J2 were recovered from the rhizosphere of maize cultivars and ginger cv. Ginlay. The number of J2 recovered from the rhizosphere of ginger cv. Gingyi, and cabbage cultivars was significantly ($P \leq 0.05$) lower compared with cv. Thihtatyin. Only minor or no root galling was observed on all of these cultivars. The number of J2 recovered from the root system of maize cultivars was significantly ($P \leq 0.05$) lower compared with all other cultivars. Both maize cultivars had $Rf < 0.1$ and can be considered as non-hosts; ginger and cabbage cultivars had $0.1 < Rf < 1$ and can be considered as poor hosts of *M. graminicola*.

In all experiments, a significant ($P \leq 0.05$) interaction between rotation crop cultivars and nematode inoculation was observed for all plant growth variables measured (*data not shown*). Hence, the effect of nematode inoculation was analysed for each cultivar separately. For all rotation crop cultivars no significant differences between non-inoculated and inoculated plants were observed in root length, fresh root and shoot weight, plant height and number of pods; except a reduction of root length in chickpea cv. Yezin 4 (15.6 %) and garlic cv. Shan (35.1 %) in experiments 3 and 6, respectively. In this study, at 8 WAI, the average fresh root weight of non-inoculated rice plants cv. Thihtatyin in experiments 1 and 2 was 1.7 and 5.1 g, respectively, and of inoculated rice plants 0.6 and 3.9 g, respectively. However, in the other experiments, the average fresh root weight of non-inoculated rice plants ranged from 12.9 to 30.3 g and of inoculated rice plants from 9.2 to 28.9 g. For rice cv. Thihtatyin, a significant ($P \leq 0.05$) reduction in root length (28.1–40.2 %), fresh root and shoot weight (11.5–45.6 % and 23.9–55.6 %, respectively), number of tillers/plant (7.9–45.5 %) and plant height (12.3–27.2 %) was observed in inoculated plants compared with non-inoculated plants in all experiments, except root length (experiments 2, 4 and 7), fresh root weight (experiments 3, 4 and 5), number of tillers/plant (experiment 4) and plant height (experiments 2, 3 and 5).

Experiments 1 and 2 were conducted during the 2010 rainy season, the rainfall ranged from 268–446 mm/month and the average air temperature from 27 to 29.2 °C. Experiments 3, 4 and 5 were conducted during the 2010–2011 winter season, the rainfall ranged from 11 to 50 mm/month and the average air temperature from 25.1 to 28 °C. Experiments 6 and 7 were conducted during the 2012 dry summer season. No rainfall was recorded during this season and the average monthly air temperature ranged from 28 to 31.7 °C.

Discussion

Cultivars of cowpea (Bocake and Sin Paelon Phyu 2), groundnut (Sin Padaethar 7 and Sin Padaethar 11) and maize (Yezin 5 and Yezin 6 m) and cv. LBG 17 of blackgram, cv. Paeti Shwewar of greengram, cv. Up-To-Date of potato and cv. Sin Yadanar 3 of sesame were classified as non-hosts of *M. graminicola*. Cultivars of cabbage (Jagucar and Pride 004), cauliflower (ATRIA 153 and WIN 172), ginger (Gingyi and Ginlay), soybean (Yezin 6 s and Yezin 8) and sunflower (Sin Shwekyar 2 and Sin Shwekyar 3), and cv. Yezin 2 of blackgram, cv. Yezin 6c of chickpea, cv. Shan of garlic, cv. Agriculture 1 of greengram, cv. Kufrijyoti of potato and cv. Sin Yadanar 4 of sesame were classified as poor hosts. Only the chickpea cv. Yezin 4 was classified as a good host. Our results agree, in general, with many earlier reports in which groundnut and maize were reported as non-hosts of *M. graminicola* (Pokharel 2007; Khan 2008); cowpea, sesame, soybean and sunflower as poor hosts (Rao et al. 1986) or non-hosts (Khan 2008). Our results also agree with Pokharel et al. (2007) who reported that the population densities of *M. graminicola* did not increase on cabbage. There are, to our knowledge, no reports on the host status of ginger to *M. graminicola* infection.

Differences in host response to *M. graminicola* infection were observed between the cultivars of blackgram, chickpea, greengram, potato and sesame. This observation is in line with earlier reports that *M. graminicola* reproduction may differ in cultivars belonging to the same plant species, such as maize and cowpea (Gergon et al. 1998). Zamora et al. (1997) reported that greengram cv. Taiwan Green was found moderately resistant while cv. Mg-9 was found susceptible to *M. graminicola*. In our study, greengram cv. Agriculture 1 was classified as a poor host while cv. Paeti Shwewar as a non-host. Duxbury (2002) reported that chickpea was a good host of *M. graminicola*. Chickpea cv. Yezin 4 was classified as a good host; however cv. Yezin 6c was classified as a poor host. Khan et al. (2010) considered potato (cultivar not mentioned) as non-host of *M. graminicola*, which agrees with the result obtained for potato cv. Up-To-Date. Potato cv. Kufrijyoti, on the other hand, was classified as a poor host of *M. graminicola*. In contrast, some of the results of our study are not in line with some earlier studies in which blackgram, cabbage, cauliflower, cowpea, greengram, maize, potato and soybean were reported as hosts of *M. graminicola* (MacGowan and Langdon 1989; Webster and Gunnell 1992). These contradicting results may be due to several factors such as differences in virulence among the *M. graminicola* populations, differences in susceptibility among the plant cultivars tested, methodological differences among experiments such as the nematode extraction method and criteria used to evaluate the host response, and experimental conditions such as temperature and humidity.

Varying degrees of severity of root galling induced by *M. graminicola* were observed on the roots of all plant species/cultivars examined, except on maize cv. Yezin 5 (no root galls observed). However, RGI were always significantly lower when compared with cv. Thihtatyin of rice, used as control.

Meloidogyne graminicola reproduced well on the susceptible lowland rice cv. Thihtatyin, however, the Rf ranged from 16.3 and 437.1 among experiments and $6.4 \leq RGI \leq 9.4$. Pokharel (2007) reported that the Rf (based on eggs + J2 in the roots) of *M. graminicola* on the lowland Asian rice cv. Labelle ranged from 14.3 to 121 among the screenhouse experiments. This author assigned these differences to environmental factors, which may have affected the growth of rice plants and nematode migration towards the roots, penetration, development and reproduction. At 8 WAI, cv. Thihtatyin, used as control, was highly infected with $Rf > 20$ in five experiments (36.8 to 437.1) and $1 < Rf < 20$ in two experiments (16.3 to 19.8) where the roots weighed the lowest. It is possible that root growth of the rice plants was influenced by climatic conditions. The experiments were carried out at different years and seasons. Experiments 1 and 2 were carried out during the 2010 rainy season with many cloudy days. Thus, sunlight intensity, which is essential for the growth of rice plants (Warrier et al. 2011), was less favorable compared with the 2010–2011 winter season (experiments 3, 4 and 5) and the 2012 dry summer season (experiments 6 and 7). Although the monthly mean air temperature during 2012 dry summer season in experiments 6 and 7 was higher compared during the 2010–2011 winter season in experiments 3, 4 and 5, the differences in Rf between seasons were not distinct. Fernandez et al. (2013) had observed that development and reproduction of *M. graminicola* were not much affected by high temperatures.

Rotation with a non-host crop is a very effective practice for the management of PPN. However, a non-host grown for the management of one PPN species may be a good host for another, non-target PPN species (Sikora et al. 2005). In an ideal crop rotation sequence, the preceding crop prevents damage to the following crop by suppressing the target nematode population density without increasing the population densities of other nematode species that may be pathogenic for the next crop (Johnson 1985). In most cases, the occurrence of multiple PPN species can be found in the rhizosphere and roots of agricultural crops (De Waele and Elsen 2007), such as the rice (Bridge et al. 2005). In Myanmar, 15 % of the summer-irrigated lowland rice fields surveyed were infested with *M. graminicola* and the rice root nematode *Hirschmanniella oryzae* (Win et al. 2011). However, during the summer season *M. graminicola* was almost the only nematode species inside the rice roots while during the rainy season this was *H. oryzae* (Maung 2011). Management strategy for *M. graminicola* needs to be further investigated if it will either favor or not favor the reproduction of *H. oryzae* (or another nematode species). Several rotation crops such as blackgram, cowpea, greengram, groundnut, soybean and sesame which are classified as poor hosts or non-hosts of *M. graminicola* in our study have also been reported as non-hosts of *H. oryzae* (Edward et al. 1985; Prot 1992; Korayem 1993; Bridge et al. 2005; Maung 2011).

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