CSIRO PUBLISHING

Australian Journal of Experimental Agriculture, 2007, **47**, 620–634 www.publish.csiro.au/journals/ajea

The role of plant-parasitic nematodes in reducing yield of sugarcane in fine-textured soils in Queensland, Australia

B. L. Blair[A,B,C] *and G. R. Stirling*[A,D,E]

[A]Sugar Yield Decline Joint Venture.
[B]Queensland Department of Primary Industries, South Johnstone Research Station, PO Box 20, South Johnstone, Qld 4859, Australia.
[C]School of Biomedical Sciences, James Cook University, Townsville, Qld 4811, Australia.
[D]Biological Crop Protection, 3601 Moggill Rd, Moggill, Qld 4070, Australia.
[E]Corresponding author. Email: graham.stirling@biolcrop.com.au

Abstract. Damage to sugarcane caused by root-knot nematode (*Meloidogyne* spp.) is well documented in infertile coarse-textured soils, but crop losses have never been assessed in the fine-textured soils on which more than 95% of Australia's sugarcane is grown. The impact of nematodes in these more fertile soils was assessed by repeatedly applying nematicides (aldicarb and fenamiphos) to plant and ratoon crops in 16 fields, and measuring their effects on nematode populations, sugarcane growth and yield. In untreated plant crops, mid-season population densities of lesion nematode (*Pratylenchus zeae*), root-knot nematode (*M. javanica*), stunt nematode (*Tylenchorhynchus annulatus*), spiral nematode (*Helicotylenchus dihystera*) and stubby-root nematode (*Paratrichodorus minor*) averaged 1065, 214, 535, 217 and 103 nematodes/200 mL soil, respectively. Lower mean nematode population densities were recorded in the first ratoon, particularly for root-knot nematode. Nematicides reduced populations of lesion nematode by 66–99% in both plant and ratoon crops, but control of root-knot nematode was inconsistent, particularly in ratoons. Nematicide treatment had a greater impact on shoot and stalk length than on shoot and stalk number. The entire community of pest nematodes appeared to be contributing to lost productivity, but stalk length and final yield responses correlated most consistently with the number of lesion nematodes controlled. Fine roots in nematicide-treated plots were healthier and more numerous than in untreated plots, and this was indicative of the reduced impact of lesion nematode. Yield responses averaged 15.3% in plant crops and 11.6% in ratoons, indicating that nematodes are subtle but significant pests of sugarcane in fine-textured soils. On the basis of these results, plant-parasitic nematodes are conservatively estimated to cost the Australian sugar industry about AU$82 million/annum.

Introduction

Sugarcane is a perennial crop that is typically grown commercially as a planted crop and two to four ratoons. The old stool is then ploughed out because of a decline in vigour and the crop is replanted. During the first 60–80 years of the sugar industry in Queensland, a legume crop was usually planted between crop cycles, but the practice of plough-out and replant (no fallow) has increased in the last 30 years. Tillage has also become more intensive because soil compaction caused by mechanical harvesting must be alleviated before the crop is replanted. This farming system has reduced the capacity of the soil to grow sugarcane and has resulted in a problem that has been termed 'yield decline' (Garside *et al*. 1997). A wide range of physical, chemical and biological factors have been implicated in yield decline, but since yields are better in new than old land (Garside and Nable 1996) and soil fumigation improves root health and increases yield by ~30% (Magarey and Croft 1995), root pathogens are considered to be one of the causal factors. The sugarcane monoculture maintains population densities of sugarcane-specific pests and pathogens at relatively high levels, while intensive tillage between crop cycles depletes organic matter, lowers microbial diversity and destroys mechanisms that naturally suppress pathogens such as nematodes (Stirling *et al*. 2003).

In the current sugarcane farming system, plant-parasitic nematodes dominate the nematode community (Stirling *et al*. 2001) and surveys have shown that every sugarcane field in Queensland is infested with several pest species (Blair *et al*. 1999*a*, 1999*b*). Lesion nematode (*Pratylenchus zeae*), root-knot nematode (mainly *Meloidogyne javanica*), stubby root nematode (*Paratrichodorus minor*), stunt nematode (*Tylenchorhynchus annulatus*) and spiral nematode (*Helicotylenchus dihystera*) are widely distributed, and all are known pathogens of sugarcane (Spaull and Cadet 1990). However, the extent of yield losses from plant-parasitic nematodes in Australia and the role of nematodes in yield decline are largely unknown.

In previous Australian work, sugarcane yields have been improved using non-volatile nematicides. However, experiments in south Queensland (Bull 1979, 1981) targeted sandy, root-knot nematode infested soils where poor soil fertility may have exacerbated the impact of nematodes. In north Queensland, nematicide trials on sandy loam and loam soils produced inconsistent or poor responses (Chandler 1978, 1980), but

10.1071/EA05287 0816-1089/07/050620

economic restrictions on the amount of nematicide used and inadequate soil moisture often limited the level of nematode control obtained. Nevertheless, these results fostered the perception that nematode problems in the Australian sugar industry were largely confined to sandy soils in south Queensland.

Worldwide, the effects of nematodes on establishment and yield of sugarcane in sandy soils have been well documented (Spaull and Cadet 1990; Spaull 1995), and this has led to speculation that annual global yield losses due to nematodes are as high as 15% (Sasser and Freckman 1987). However, crop loss estimates of this magnitude probably cannot be substantiated because nematodes are relatively insidious pests in soils with high clay contents (Spaull and Cadet 1990), and few nematicide experiments have been done in soils with more than 6% clay. This is particularly the case in Australia, where sugarcane is mainly grown on fine-textured sandy loam, clay loam and clay soils.

This work aimed to quantify losses from nematodes on sugarcane in soils that are relatively common in the Australian sugar industry. To this end, non-volatile nematicides were applied 3–4 times per year, so that low nematode population densities would be maintained throughout the growing season. Differences in yields between untreated and treated plots were used to indicate the extent of losses due to nematodes. This approach differs from previous studies with nematicides on sugarcane (Bull 1979, 1981; Spaull and Cadet 1990), where roots were protected from nematode attack for only a few weeks after planting and again at the early tillering stage in the ratoon.

Materials and methods

Field sites

Experiments were located in sugarcane fields along the Queensland coast between Beenleigh (27.43S; 153.10E) and Mackay (21.08S; 149.11E), a distance of ~1200 km. This region contains the southern and central part of the Queensland sugar industry and grows about half of Australia's sugarcane. Experimental sites (Table 1) represented the major soil types cropped to sugarcane in Queensland and most sites had grown sugarcane for at least 50 years. Since growers were not employing any management strategies specifically for nematode control, nematodes were considered insignificant pests at all sites. None of the experiments were located in coarse sandy soils where root-knot nematode problems are severe and nematicides are routinely used by growers. Queensland varieties were grown in most experiments (Q124 at 14 sites and Q138 at site 2), but CP51-21 (from Canal Point, Florida) was planted at site 5.

Experimental design

Experiments were a paired comparison of treatments with and without nematicide, with six replicates of each treatment usually allocated in a randomised complete block design. Individual plots were six rows wide and 12 m in length and were situated in one area of the field. However, at site 8, plots were scattered over a 6-ha field in a paired plot design. At site 7, three pairs of untreated and nematicide-treated plots were located on opposite sides of a 5 ha field. At this site, nematode populations, irrigation frequency, and subsequent sugarcane growth varied markedly on each side of the field, so each group of plots was analysed as a separate experiment of three replicates (sites 7a, 7b). The Farleigh site also constituted two experiments of six replicates on different soil types at opposite ends of the same 4 ha field (sites 14a, 14b).

Nematicide program

The nematicides used were aldicarb (Temik 15G, Rhone-Poulenc Rural Australia Pty Ltd) and fenamiphos (Nemacur

Table 1. Location of nematicide experiments, site details and the number of nematicide applications at each site
P, plant crop; 1R, first ratoon; 2R, second ratoon

Site no.	Location[A]	Year[B]	Soil texture	Particle size analysis[C]	Duration of experiment	Irrigation status	No. of nematicide applications		
							P	1R	2R
1	Rocky Point	1995	Clay loam	16:32:18:34	P, 1R	Dryland	6	4	–
2	Coolum	1995	Clay	10:15:25:50	P, 1R	Dryland	4	3	–
3	Maroochydore	1995	Clay	12:16:22:50	P, 1R	Dryland	5	3	–
4	Yandina	1995	Clay	5:13:16:66	P, 1R	Dryland	5	3	–
5	Maryborough	1996	Silty sand loam	15:46:23:16	P, 1R, 2R	Irrigated	3	2	3
6	Childers	1996	Fine sandy loam	27:56:6:11	P, 1R, 2R	Irrigated	4	2	3
7a	Elliot Heads	1995	Loamy sand	44:40:8:8	P, 1R	Irrigated	5	3	–
7b	Elliot Heads	1995	Loamy sand	44:40:8:8	P, 1R	Irrigated	5	3	–
8	Fairymead	1995	Fine sandy loam	40:36:9:15	P, 1R	Irrigated	5	2	–
9	Fairymead	1995	Fine sandy loam	17:51:18:13	P, 1R	Irrigated	4	2	–
10	Bingera	1996	Fine sandy loam	28:49:7:16	P, 1R, 2R	Irrigated	4	2	2
11	Plane Creek	1997	Silty sand loam	19:43:25:13	1R	Irrigated	3	3	–
12	Racecourse	1997	Sandy loam	42:32:13:13	1R	Irrigated	4	2	–
13	Mirani	1998	Sandy clay loam	44:29:9:18	P	Dryland	4	–	–
14a	Farleigh	1998	Coarse sand loam	51:32:2:15	P	Dryland	3	–	–
14b	Farleigh	1998	Sandy loam	36:40:13:11	P	Dryland	3	–	–

[A] Sites 1–4 were within 100 km of Brisbane, sites 5–10 were in the Maryborough–Bundaberg region and sites 11–14 were near Mackay in central Queensland.
[B] Year each experiment commenced.
[C] The ratio of coarse sand : fine sand : silt : clay, expressed as percentages.

10G, Bayer Australia Ltd), and they were usually alternated to minimise the development of enhanced biodegradation problems (Smelt and Leistra 1992; Stirling *et al.* 1992). However, at three central Queensland sites (13, 14a, 14b), fenamiphos was applied three times in succession to the plant crop. Because most of the nematicidal activity of aldicarb and fenamiphos dissipates in 30–60 days (Hough *et al.* 1975; Stirling and Dullahide 1987), applications were repeated to maintain control of nematodes for the entire crop cycle.

Stem cuttings (billets) with 2–3 nodal buds were planted end-to-end into the bottom of a planting furrow 20 cm deep, in rows 1.5 m apart. After primary shoots emerged, the sugarcane row was progressively profiled into a raised bed by transferring soil from the inter-row, according to established industry practice. Nematicides were usually applied before hilling, tillage or weed scarifying operations, but in situations where this was not possible, a hand rake was used to incorporate the nematicide granules into the soil. At sites where soil was covered with sugarcane residue after plant or ratoon crop harvest, the nematicide was either placed under the residue or sprinkled on the residue if rain was forecast or irrigation was scheduled.

Nematicides were applied (i) at, or soon after planting in August–September, (ii) at the 3–5 leaf stage in November, and/or (iii) in December when plants measured ~1 m to the top of the canopy. A 0.3-m wide band over the row was treated with 10 kg a.i./treated ha, which meant that Temik and Nemacur were applied at 2 g and 3 g of product/m of row, respectively. After the row mound had been established in December, nematicide applications were extended to cover a 1 m wide band centred on the row. Thus, Temik and Nemacur applications were 6.67 g and 10 g of product/m of row, respectively. Nematicide was usually applied to wide bands in January (~120 days after planting) and March (~190 days after planting). Similarly, ratoon crops were treated with 1 m wide bands of nematicide, with the first application soon after harvest of the plant crop, and the second and third applications during the growing season. Where nematode control was deemed to be satisfactory according to nematode counts, some applications were omitted. The number of nematicide treatments applied to plant and ratoon crops is listed in Table 1, while complete details of the nematicide program at all 16 sites are given by Blair (2005).

Nematode and crop sampling

Samples for nematodes were collected regularly from each site in both plant and ratoon crops. To avoid damaging roots in the middle two rows from which yields were collected, all samples were taken from the outer rows in each plot. Holes ~20 × 20 × 20 cm were dug near the stool and a handful of roots and soil was placed in a bucket. Material from 10 holes in each plot was then mixed and subsamples of soil (200 mL) and roots (50–100 g) were retained for analysis. Samples were kept cool in an insulated container, transported to the laboratory and processed within 1–2 days of collection. Nematodes were extracted by placing soil on a Baermann tray for 96 h (Whitehead and Hemming 1965) and by misting roots for 96 h (Hooper 1990). After processing, roots were dried and weighed. Nematode suspensions were concentrated by sieving twice through a 38-μm sieve, and nematodes were counted under a microscope at a magnification of 40×. The term 'mid-season' nematode population density in the text is used for results obtained from samples taken 150–200 days after planting (DAP) and 80–180 days after ratooning (DAR).

At some sites, 10 individual root pieces (10–15 cm long) were randomly selected from root samples collected in March or April, and root health was rated using a 1–5 scale, where 1 and 5 represented poor and good root health, respectively. Structural roots and fine roots were rated separately and the 20 ratings from each sample (plot) were then averaged to obtain a mean health rating. For structural roots, a rating of 5 indicated that primary roots were white and healthy and had many long secondary roots attached, whereas a rating of 1 indicated that primary roots were dark, necrotic or covered with lesions and secondary roots were sparse and stunted. For fine roots, root pieces were given a rating of 5 if they had a uniform mass of healthy fine roots that constituted a major proportion of total root length, whereas root pieces with few or no fine roots were rated 2 and 1, respectively. More complete details of the rating scheme are given in Blair (2005).

At most sites, the number of shoots (primary shoots and associated tillers) and the number of established stalks per 20 m of row was counted at ~120 and 200 DAP respectively. Twenty shoots/stalks were randomly tagged in each plot and their length was measured from ground level to the topmost visible dewlap. In ratoon crops, the number and length of stalks was measured at ~210 DAR. At harvest, yield (t/ha) was estimated by weighing stalks from two rows (5 or 10 m long) in the middle of each plot. At most sites, the amount of sugar recoverable from the stalk juice (i.e. commercial cane sugar or CCS) was estimated from a sample of six stalks.

Statistical analysis

All analyses were done using GENSTAT Version 6.0. The dynamics of nematode populations in nematicide-treated and untreated plots were examined using a treatment × sequential sampling analysis. Depending on the experimental design, analysis of variance (ANOVA) or a paired *t*-test was used to compare sugarcane yield and yield components in treated and untreated plots at individual sites. Where these tests revealed significant differences ($P < 0.05$), means were compared using least significant difference (l.s.d.) at $P = 0.05$.

Relationships between nematode numbers and crop production were examined by linear correlation using mean site data, but large site-to-site variation in the yield of untreated crops masked any general trends that may have been present. A plant response to the nematicide was therefore calculated for each site (biomass in nematicide-treated plots – biomass in untreated plots) and used in all further correlations.

Since the level of nematode control varied from site to site, the nematicide responses were correlated with the number of nematodes controlled by the nematicide (nematode density in untreated plots – nematode density in treated plots). An exception was during the first 90 DAP, when nematicide-treated soil was periodically contaminated by untreated soil during row filling operations. For data collected during this period, nematode densities in untreated soil at planting (P_i) were correlated with nematicide responses, on the assumption that nematodes in the underlying root zone were controlled by the nematicide.

Multiple linear regressions were used to correlate trends between nematode population density and yield response. When stalk length/m^2 of plot was used in these correlations, it was calculated from stalk number/m^2 × stalk length.

Results

Nematodes on plant crops

Lesion nematode occurred at all sites, usually at higher population densities than any other nematode species. Initial population densities (P_i) ranged from 16–390 nematodes/200 mL at planting, but by mid-season, numbers in untreated soil had increased markedly at all sites (Table 2). Root-knot nematode juveniles were detected at 75% of sites, but population densities were usually lower than for lesion nematode (Table 3). For both root-knot and lesion nematodes, initial populations at planting did not correlate with mid-season population densities.

Several ectoparasitic nematodes were present, including spiral nematode (*Helicotylenchus dihystera*), stunt nematode (*Tylenchorhynchus annulatus*), stubby root nematode (*Paratrichodorus minor*), ring nematode (various Criconematidae) and dagger nematode (*Xiphinema elongatum*), with high population densities being recorded at some sites (Table 4). Examples of the dynamics of nematode populations at selected sites (Figs 1–4) indicate that numbers of lesion and root-knot nematodes in soil or roots tended to reach a maximum at mid-season and then decline towards harvest.

Soil samples collected between 0–100 DAP indicated that population densities of all nematode species were reduced by ~50% in nematicide-treated plots compared with untreated plots

Table 2. Population densities of lesion nematode (*Pratylenchus zeae*) in untreated soil and roots, and the level of control in nematicide-treated plots at various sites

Site no.	Location	Nematode population density (nematodes/200 mL soil)^A	(nematodes/200 mL soil)^B	(nematodes/g root)^B	Nematode control (%)^C (in soil)	(in roots)
			Plant crop			
1	Rocky Point	205	2747	2571	80	84
2	Coolum	56	408	175	66	82
3	Maroochydore	89	947	467	81	91
4	Yandina	16	1621	2870	96	88
5	Maryborough	63	1035	4811	94	38
6	Childers	178	1368	10916	96	98
7a	Elliot Heads	390	2313	10734	98	96
7b	Elliot Heads	359	1133	14851	97	97
8	Fairymead	77	672	3180	94	97
9	Fairymead	169	647	1811	95	86
10	Bingera	50	1010	3301	94	96
11	Plane Creek	135	245	175	94	91
12	Racecourse	174	492	833	94	86
13	Mirani	113	617	1254	91	92
14a	Farleigh	130	1103	2816	46	71
14b	Farleigh	224	680	2662	97	98
			First ratoon crop			
1	Rocky Point	859	1216	2240	32	84
2	Coolum	178	278	181	68	81
3	Maroochydore	183	301	46	68	28
4	Yandina	254	1105	380	96	84
5	Maryborough	263	208	621	60	83
6	Childers	432	700	3353	29	29
7a	Elliot Heads	657	507	3178	95	99
7b	Elliot Heads	323	993	2863	99	97
8	Fairymead	355	337	1353	75	91
9	Fairymead	664	1776	1986	91	84
10	Bingera	970	303	1334	75	73
11	Plane Creek	825	527	154	99	99
12	Racecourse	507	453	110	98	97
			Second ratoon crop			
5	Maryborough	–	633	160	81	79
6	Childers	–	247	325	100	99
10	Bingera	430	317	290	97	93

[A] Initial nematode population density (P_i) at planting and at ratoon tillering.

[B] Nematode population density in untreated plots (mid-season).

[C] Percent reduction in nematode populations due to the nematicide (mid-season).

(data not presented). However, by mid-season, populations of lesion nematode in soil and roots were usually reduced by >90% at irrigated sites and by >66% at rain-fed sites (Table 2). Control of root-knot nematode was more variable, but numbers in soil and roots were usually reduced by >75% (Table 3). The control of ectoparasitic nematodes was highly variable (data not presented).

Nematodes on ratoon crops

During ratoon tillering (0–100 DAR), population densities of all species were often higher than P_i, but mid-season numbers usually did not reach the levels found on plant crops (Tables 2 and 3; Figs 1–4). This was particularly the case for root-knot nematode, which rarely exceeded mid-season population densities of 150 nematodes/200 mL of soil in ratoons. At ratoon tillering, root-knot nematode juveniles were detected at 72% of sites, compared with only 62% of sites by mid-season (Table 3).

In ratoons, the level of control of lesion nematode due to nematicide was not as great as in plant crops, but was usually >66% (Table 2). The control of root-knot nematode was variable, with more nematodes found in nematicide-treated plots than untreated plots by mid-season at some sites (Table 3). Nematicides usually reduced populations of ectoparasitic nematodes by ~50% in ratoons.

Plant crop growth and yield

Between 6 and 12 shoots/m^2 had emerged in untreated plots by 120 DAP (Fig. 5). Shoot numbers were then maintained at this level (Fig. 5*a*, *d*, *e*, *f*) or declined significantly (Fig. 5*b*, *c*), so that 6–10 stalks/m^2 were eventually established. Although 22%

Table 3. Population densities of root-knot nematode (*Meloidogyne* spp.) in untreated soil and roots, and the level of control in nematicide-treated plots at various sites

Site no.	Location	Nematode population density			Nematode control (%)[C]	
		(nematodes/ 200 mL soil)[A]	(nematodes/ 200 mL soil)[B]	(nematodes/ g root)[B]	(in soil)	(in roots)
			Plant crop			
1	Rocky Point	2	124	59	76	92
2	Coolum	3	167	9	66	78
3	Maroochydore	4	217	97	74	70
4	Yandina	4	319	1529	85	44
5	Maryborough	0	0	0		
6	Childers	3	270	4747	49	92
7a	Elliot Heads	0	730	6133	80	52
7b	Elliot Heads	0	113	475	98	69
8	Fairymead	23	12	321	50	83
9	Fairymead	9	0	7		–100
10	Bingera	13	838	5387	89	93
11	Plane Creek	0	0	0		
12	Racecourse	0	430	661	97	97
13	Mirani	5	47	0		
14a	Farleigh	34	150	1682	100	75
14b	Farleigh	12	0	0		
			First ratoon crop			
1	Rocky Point	0	0	0		
2	Coolum	4	6	0	50	
3	Maroochydore	5	58	4	31	0
4	Yandina	21	403	371	91	92
5	Maryborough	0	0	0		
6	Childers	302	1032	1786	–50	–95
7a	Elliot Heads	13	23	109	26	83
7b	Elliot Heads	23	0	15		80
8	Fairymead	0	0	0		
9	Fairymead	8	0	0		
10	Bingera	142	143	980	–78	–15
11	Plane Creek	0	0	0		
12	Racecourse	67	8	12	13	100
			Second ratoon crop			
5	Maryborough	–	0	0		
6	Childers	–	80	1830	89	86
10	Bingera	100	143	773	85	89

[A] Initial nematode population density (P_i) at planting and at ratoon tillering.

[B] Nematode population density in untreated plots (mid-season).

[C] Percent reduction in nematode populations due to the nematicide (mid-season).

more shoots were recorded in nematicide-treated plots at one site, and smaller increases occurred at other sites (Table 5), responses were never significant. Significant increases in stalk number, due to nematicide treatment, were only observed in one field (sites 7a, 7b). These responses developed between 120 and 210 DAP (Table 5; Fig. 5*e*). At other sites where nematicides appeared to increase shoot numbers before 120 DAP, the responses disappeared as the shoots developed into established stalks (Fig. 5*a*, *f*).

Visual responses to nematicides (due to an increase in shoot length) were often apparent, and significant increases in shoot length were observed at four of the seven sites where these measurements were taken at ~120 DAP (Table 5). By mid-season, nematicides had significantly increased stalk length at 10 of the 14 sites where these measurements were taken.

Untreated plant crops yielded 71–155 t/ha, and yields at most sites were above average for plant crops in the same district. Yields in nematicide-treated plots were usually 10–20% higher than untreated plots and the increase was significant at six sites (Table 6). The highest yielding site (site 5) was an exception, as nematicides had no effect on yield.

Ratoon crop growth and yield

By mid-season, there were 7–11 stalks/m^2 in untreated plots, and nematode control had resulted in significant increases at 3 of 12 sites where these measurements were taken (Table 5). Stalks were significantly longer in nematicide-treated plots at 7 of 12 sites (Table 5).

Yields of untreated ratoon crops ranged from 84 to 164 t/ha, and were usually greater than district averages for crops of the same age. In nematicide-treated plots, ratoon yields were usually larger than in untreated plots, with responses >10% observed at about half the sites (Table 6). Responses in first ratoon crops were more variable than those of the preceding plant crop. Where experiments were continued into the second ratoon, the nematicides significantly increased yield at two of three sites (Table 6).

Root health

At sites where root-knot nematode was present, obvious swellings or gross abnormalities were never seen on roots, presumably because populations were not high enough to cause severe damage. When galls were observed, they were relatively

Table 4. Mid-season population densities (no. of nematodes/200 mL soil) of ectoparasitic nematodes at various field sites

Site no.	Location	*Tylenchorhynchus*	*Helicotylenchus*	*Paratrichodorus*	Criconematidae	*Xiphinema*
			Plant crop			
1	Rocky Point	46	362	311	23	0
2	Coolum	226	538	41	2	0
3	Maroochydore	121	671	92	12	8
4	Yandina	0	239	0	32	0
5	Maryborough	2140	792	22	0	0
6	Childers	1043	8	382	0	5
7a	Elliot Heads	203	100	137	0	70
7b	Elliot Heads	620	105	155	0	0
8	Fairymead	1012	137	107	13	3
9	Fairymead	1956	90	80	0	6
10	Bingera	0	83	136	0	0
11	Plane Creek	730	131	3	2	2
12	Racecourse	382	167	82	0	0
13	Mirani	47	0	15	2	5
14a	Farleigh	22	14	25	30	0
14b	Farleigh	18	36	57	10	0
			First ratoon			
1	Rocky Point	24	146	91	45	0
2	Coolum	111	486	65	1	0
3	Maroochydore	24	327	51	4	24
4	Yandina	5	405	2	35	0
5	Maryborough	901	293	50	0	0
6	Childers	14	0	46	0	0
7a	Elliot Heads	417	40	258	0	117
7b	Elliot Heads	640	148	250	0	0
8	Fairymead	590	200	95	12	40
9	Fairymead	226	102	93	0	0
10	Bingera	0	23	25	0	7
11	Plane Creek	75	170	60	0	0
12	Racecourse	8	42	22	0	0
			Second ratoon			
5	Maryborough	649	257	26	0	0
6	Childers	126	13	321	1	1
10	Bingera	0	50	93	0	0

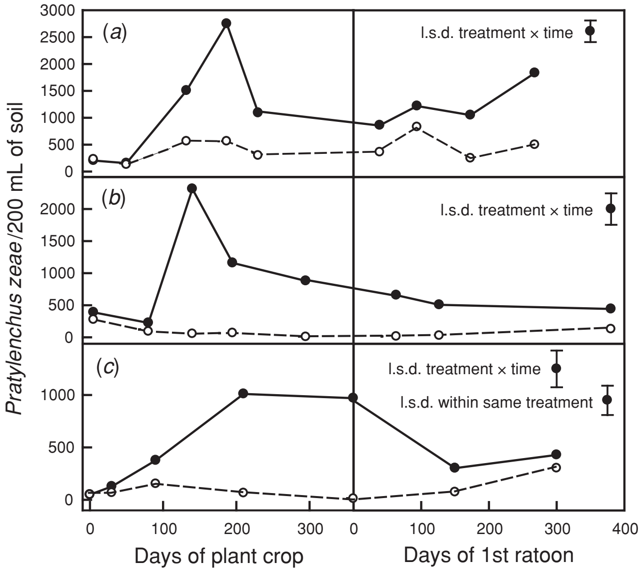

Fig. 1. Population dynamics of *Pratylenchus zeae* in untreated soil (●) and nematicide-treated soil (○) at (*a*) site 1, (*b*) site 7a and (*c*) site 10.

inconspicuous and were restricted to fine roots. Nevertheless, root health in untreated plots was generally poor, with the root system largely consisting of black primary roots with few secondary or tertiary (fine) roots. Where fine roots were present, they were generally dark in colour. Nematicide-treated root systems had more fine roots and these roots tended to be golden brown in colour rather than black. At the 12 sites where root health was assessed, root health ratings generally increased following nematicide treatment, with the increases being significant at about half the sites (Table 7).

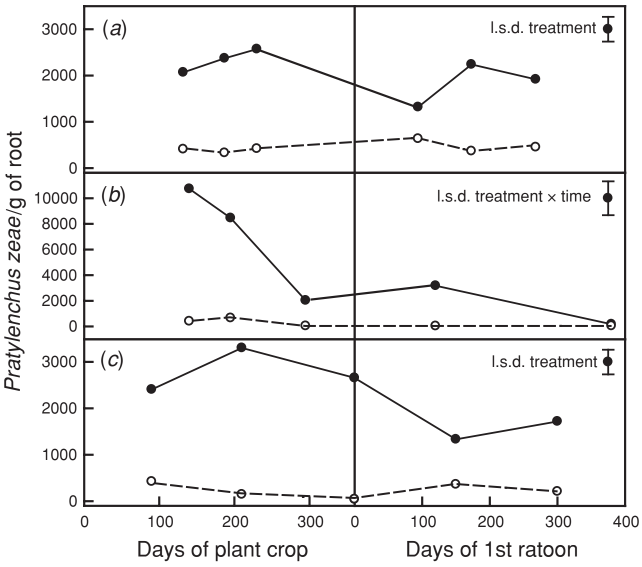

Fig. 2. Population dynamics of *Pratylenchus zeae* in untreated roots (●) and nematicide-treated roots (○) at (*a*) site 1, (*b*) site 7a and (*c*) site 10.

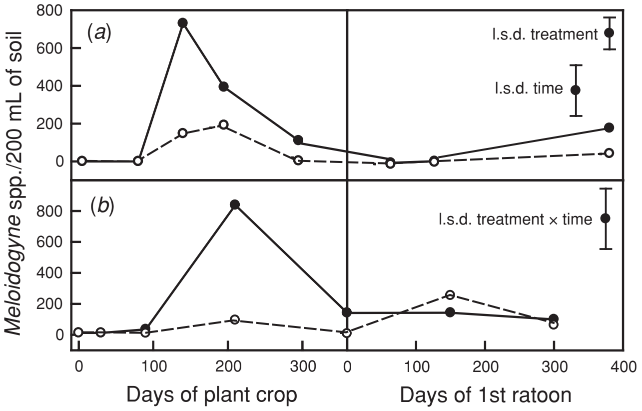

Fig. 3. Population dynamics of *Meloidogyne* spp. in untreated soil (●) and nematicide-treated soil (○) at (*a*) site 7a and (*b*) site 10.

Sucrose levels

CCS was measured in 10 plant crops and eight ratoon crops, and differences between untreated and nematicide-treated canes were always less than 5% (data not shown). At site 3 there was a significant increase in CCS of 2%, due to nematicide treatment, whereas at site 7a (where nematicide application produced a 51% increase in plant crop yield), there was a significant reduction in CCS of 4%.

Relationships between nematode density and plant crop responses

The total population of all plant-parasitic nematodes in the soil at planting (TP$_i$) was not correlated with shoot number or shoot length increases at 100 DAP due to nematicide (data not shown). However, TP$_i$ was related to increases in stalk length and stalk length/m^2 that had developed by mid-season (R^2 = 0.42 and 0.70), respectively (Fig. 6*a*, *b*). The response curve suggested that a TP$_i$ of ~500 nematodes/200 mL of soil was associated with an increase in total stalk length of ~4 m of stalk/m^2. However, TP$_i$ was not correlated with final yield.

Nematicide treatment significantly increased stalk numbers at two sites (Table 5), but the correlation between responses in

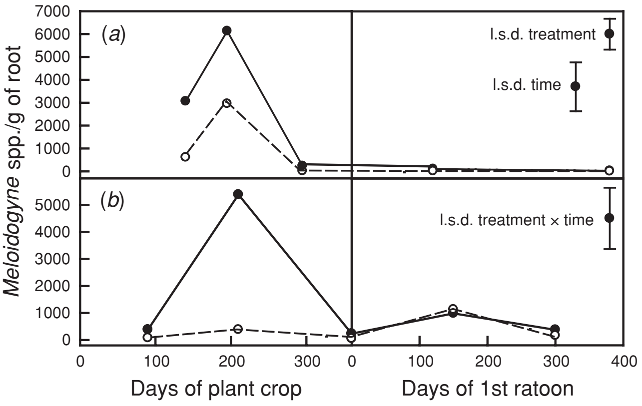

Fig. 4. Population dynamics of *Meloidogyne* spp. in untreated roots (●) and nematicide-treated roots (○) at (*a*) site 7a and (*b*) site 10.

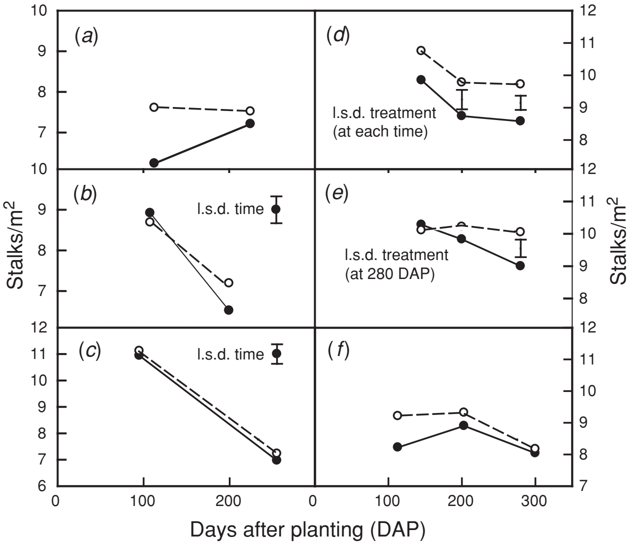

Fig. 5. Numbers of shoots emerged and developing into mature stalks in untreated (●) and nematicide-treated plots (○) at (*a*) site 1, (*b*) site 2, (*c*) site 3, (*d*) site 7a, (*e*) site 7b and (*f*) site 8.

stalk numbers and mid-season population densities of *P. zeae* + *Meloidogyne* spp. in roots was not significant (Fig. 7*a*). However, when three relatively high-yielding sites (denoted by squares in Fig. 7*a*) were removed from the dataset, there was a significant relationship between the two parameters, suggesting that nematodes may have a greater effect on stalk number in environments which limit yield. There was also a correlation between increases in stalk length and the number of *P. zeae* controlled in roots (R^2 = 0.62), with the control of ~8000 nematodes/g of root being associated with an increase in stalk length of ~30 cm (Fig. 7*b*).

Yield responses to nematicides were significantly correlated with mid-season numbers of plant-parasitic nematodes controlled inside roots, with a reduction of ~8000 *P. zeae*/g of root being associated with a yield increase of ~20 t/ha. The strength of the relationship between yield increases and the number of nematodes controlled by nematicides was relatively poor, but was similar for *P. zeae* + *Meloidogyne* spp. (R^2 = 0.32; Fig. 7*c*), and for *P. zeae* alone (R^2 = 0.28; Fig. 7*d*). In contrast, yield increases or any other plant response was not significantly correlated with the control of root-knot nematode or the total number of ectoparasitic nematodes in soil (data not shown).

Relationship between nematode density and ratoon crop responses

At ratoon tillering (0–80 DAP), the number of nematodes controlled by nematicide was not correlated with increases in stalk number or stalk length, or yield responses (data not shown). However by mid-season, increases in stalk length due to nematicide were significantly related to the number of endoparasites (*P. zeae* + *Meloidogyne* spp.) controlled in soil (R^2 = 0.79; Fig. 8*a*). This control was not related to stalk number responses. However, when stalk length and stalk numbers were considered together (i.e. stalk length/m^2), the increase was related to the total number of nematodes (endoparasites + ectoparasites) controlled in the soil (R^2 = 0.71; Fig. 8*b*). The control of lesion nematode provided the best singular correlation with stalk length responses, while the control of root-knot nematode provided the best singular correlation with stalk length/m^2 of plot.

In ratoon crops, the density of endoparasites (*P. zeae* + *Meloidogyne* spp.) controlled in soil was significantly correlated with increases in final yield (R^2 = 0.36), with reductions in nematode populations of ~1000 endoparasites/200 mL of soil associated with yield increases of ~22 t/ha (Fig. 8*c*). The control of ectoparasitic nematodes

Table 5. Percentage change in number and length of shoots or stalks following nematicide treatment

P, plant crop; 1R, first ratoon; 2R, second ratoon; shoots were measured ~120 days after planting, and stalk data were collected ~200 days after planting or ratooning; values in bold type indicate a significant change due to nematicide (P = 0.05)

Site no.	Location	No. of shoots or stalks				Length of shoot or stalk			
		P Shoots	P Stalks	1R Stalks	2R Stalks	P Shoots	P Stalks	1R Stalks	2R Stalks
1	Rocky Point	22	4	–	–	**33**	**9**	–	–
2	Coolum	–3	10	–4	–	3	**6**	**6**	–
3	Maroochydore	2	4	**9**	–	5	**5**	**6**	–
4	Yandina	2	2	–	–	9	9	–	–
5	Maryborough	–	1	1	–	–	**5**	0	–
6	Childers	–	6	–2	**14**	–	**15**	–2	4
7a	Elliot Heads	9	**13**	**17**	–	**31**	**22**	**22**	–
7b	Elliot Heads	–2	**12**	–10	–	**19**	**12**	**13**	–
8	Fairymead	11	2	2	–	**17**	**13**	**7**	–
9	Fairymead	–	3	5	–	–	3	**8**	–
10	Bingera	–	6	0	5	–	**10**	0	**8**
11	Plane Creek	–	–	6	–	–	–	6	–
12	Racecourse	–	–	–	–	–	–	–	–
13	Mirani	–	3	–	–	–	**6**	–	–
14a	Farleigh	–	0	–	–	–	1	–	–
14b	Farleigh	–	8	–	–	–	3	–	–

Table 6. Sugarcane yield in untreated plots and percent yield increase due to nematicide at 16 field sites
P, plant crop; 1R, first ratoon; 2R, second ratoon; values in bold type indicate a significant yield increase due to nematicide ($P = 0.05$)

Site no.	Location	Yield in untreated plots (t/ha)			Yield increase due to nematicide (%)		
		P	1R	2R	P	1R	2R
1	Rocky Point	85	121	–	**13**	2	–
2	Coolum	81	131	–	**19**	2	–
3	Maroochydore	86	117	–	14	11	–
4	Yandina	104	136	–	12	5	–
5	Maryborough	155	–	84	–1	–	8
6	Childers	113	123	107	**23**	3	**26**
7a	Elliot Heads	71	129	–	**51**	**37**	–
7b	Elliot Heads	103	164	–	**16**	0	–
8	Fairymead	117	130	–	**13**	**11**	–
9	Fairymead	93	108	–	8	**20**	–
10	Bingera	112	94	104	10	8	**14**
11	Plane Creek	–	113	–	–	**20**	–
12	Racecourse	–	110	–	–	7	–
13	Mirani	89	–	–	11	–	–
14a	Farleigh	88	–	–	16	–	–
14b	Farleigh	105	–	–	10	–	–

(i.e. *T. annulatus*, *H. dihystera* and *P. minor*) was also significantly but rather poorly correlated with increased final yield ($R^2 = 0.32$), and was independent of endoparasites in the soil. The control of 512 ectoparasitic nematodes/200 mL of soil was associated with a yield increase of ~20 t/ha (Fig. 8*d*).

Discussion

Previous Australian studies with nematicides have shown that plant-parasitic nematodes are important pests of sugarcane in sandy soils (Bull 1979, 1981). However, our experiments represent the first attempt to assess crop losses in the fine-textured sandy loam, clay loam and clay soils on which the bulk of Australia's sugarcane is grown. Since commercial applications of nematicides in the sugar industry are designed to maximise economic returns and do not provide long-term control of nematodes, we chose to apply aldicarb and fenamiphos several times each year. Our results vindicate that decision because, in most irrigated soils, populations of plant-parasitic nematodes were maintained at very low levels throughout both the plant and ratoon crop. The nematicides were less effective in non-irrigated clay loam and clay soils, and control was sometimes relatively poor in ratoon crops. Failure to achieve good control in ratoons was probably due to lack of incorporation of the nematicide (because of the presence of a blanket of sugarcane trash from the previous harvest) and limited downwards movement in soil after it was compacted by harvest machinery. Nevertheless, the level of control was still sufficient to demonstrate that nematodes were causing economic damage in most situations.

Table 7. Mid-season root health ratings for nematicide-treated and untreated sugarcane at various field sites
P, plant crop; 1R, first ratoon; 2R, second ratoon; n.s., not significant at $P = 0.05$

Site no.	Location	Crop stage	Untreated	Nematicide	l.s.d. ($P = 0.05$)
1	Rocky Point	P	2.08	2.78	0.55
1	Rocky Point	1R	2.16	2.55	n.s.
2	Coolum	P	1.96	1.95	n.s.
2	Coolum	1R	2.07	3.00	0.31
3	Maroochydore	P	1.65	2.47	0.27
3	Maroochydore	1R	1.63	2.37	0.45
4	Yandina	1R	2.88	3.35	n.s.
6	Childers	2R	2.24	2.72	0.14
7a	Elliot Heads	P	2.60	2.86	n.s.
7b	Elliot Heads	P	2.50	2.60	n.s.
8	Fairymead	P	2.57	3.08	0.23
10	Bingera	P	2.93	3.28	0.34
11	Plane Creek	1R	3.53	3.72	n.s.
13	Mirani	P	3.05	3.80	0.20
14a	Farleigh	P	2.63	3.22	0.41
14b	Farleigh	P	3.05	3.38	n.s.

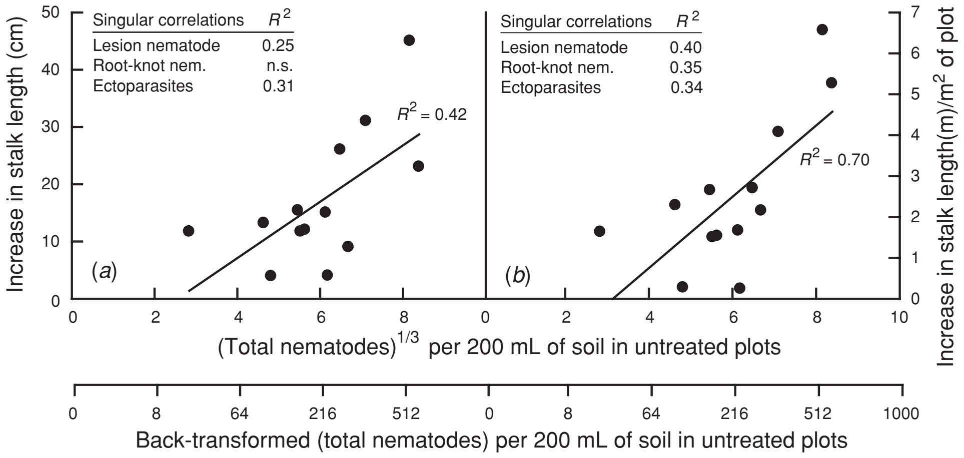

Fig. 6. Relationship between (*a*) stalk number and (*b*) stalk length responses in plant crops following nematicide treatment and the total number of nematodes (endoparasites + ectoparasites) at planting (P_i).

Effect of nematodes on shoot establishment

Poor shoot establishment due to nematodes is well documented in coarse-textured soils around the world (Spaull and Cadet 1990). In soils containing only 2–3% clay, attack by root-knot and lesion nematode on sett roots resulted in 26 and 34% fewer primary shoots and 82 and 43% fewer secondary tillers in West and South Africa, respectively (Cadet and Spaull 1985). Similarly, in sandy soils in Australia, nematicides applied at the 3–5 leaf stage increased shoot numbers and improved yield by 13–64%, with nematode damage being most severe in low yielding crops on infertile soils (Bull 1979, 1981). The timing of the nematicide application and the presence of root galls in untreated plots suggested that attack by root-knot nematode on newly emerging shoot roots was the main cause of the low shoot numbers in Bull's experiments, but nutrient deficiencies and lack of moisture are likely to have exacerbated the problem.

In our experiments on finer textured soils, increases in shoot number due to nematicide treatment were never significant, and

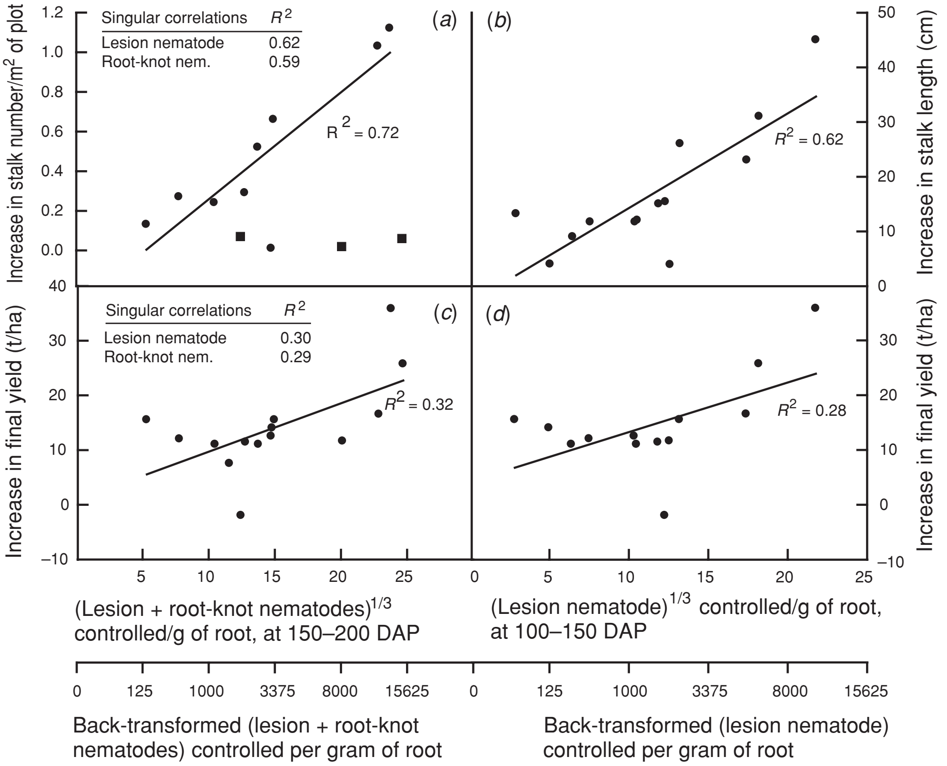

Fig. 7. Relationship between (*a*) stalk number, (*b*) stalk length and (*c*, *d*) final yield responses in plant crops following nematicide treatment and the number of endoparasitic nematodes controlled by the nematicide.

were poorly correlated with P_i. However, there were rarely more than 13 root-knot nematodes/200 mL soil in untreated plots at planting, and these relatively low population densities are the most likely reason for the relatively poor responses. Root-knot nematode infestations of this magnitude may cause yield losses in highly susceptible vegetable crops (Vawdrey and Stirling 1996), but poor tillering of sugarcane is associated with higher initial population densities (Bull 1981). The fact that nematicide responses before 150 DAP were unrelated to the number of root-knot nematodes controlled in roots further suggests that, in most cases, population densities of this nematode were too low to have a major impact in our experiments.

Pre-plant counts of lesion nematode were much higher than for root-knot nematode, with 10 of our experimental sites having infestations of more than 100 lesion nematodes/200 mL soil at planting. Initial population densities of this magnitude can result in high numbers of nematodes (>2000 lesion nematodes/g root) in sett roots soon after planting (Pankhurst *et al.* 2001), and control of this nematode with fallowing, crop rotation and soil fumigation is associated with increased shoot numbers in the following sugarcane crop (Garside *et al.* 1999, 2000, 2002*a*). However, our poor correlations between numbers of lesion nematode and shoot numbers suggest that lesion nematode does not have a major impact on crop establishment in fine textured soils. Pankhurst *et al.* (2001) suggested that biotic factors other than nematodes were primarily responsible for poor shoot establishment because, in a short-term experiment, soil fumigation had a much greater impact on secondary tillering than a nematicide. This observation was supported by a later study which showed that a fungicide had a greater impact than a nematicide on numbers of secondary tillers (Pankhurst *et al.* 2002).

Effect of nematodes on growth and yield of the plant crop

During the first 120 DAP, shoot length increased significantly at many sites following nematicide treatment, indicating that nematodes had a greater effect on shoot length than shoot number. These responses were maintained through to mid-season and were related to the total population of nematodes at planting (R^2 = 0.42) and the number of lesion nematodes controlled in roots (R^2 = 0.62). A correlation (R^2 = 0.7) between TP_i and stalk length/m^2 suggested the entire community of plant-parasitic nematodes partly influenced stalk length and stalk number responses that developed by 200 DAP.

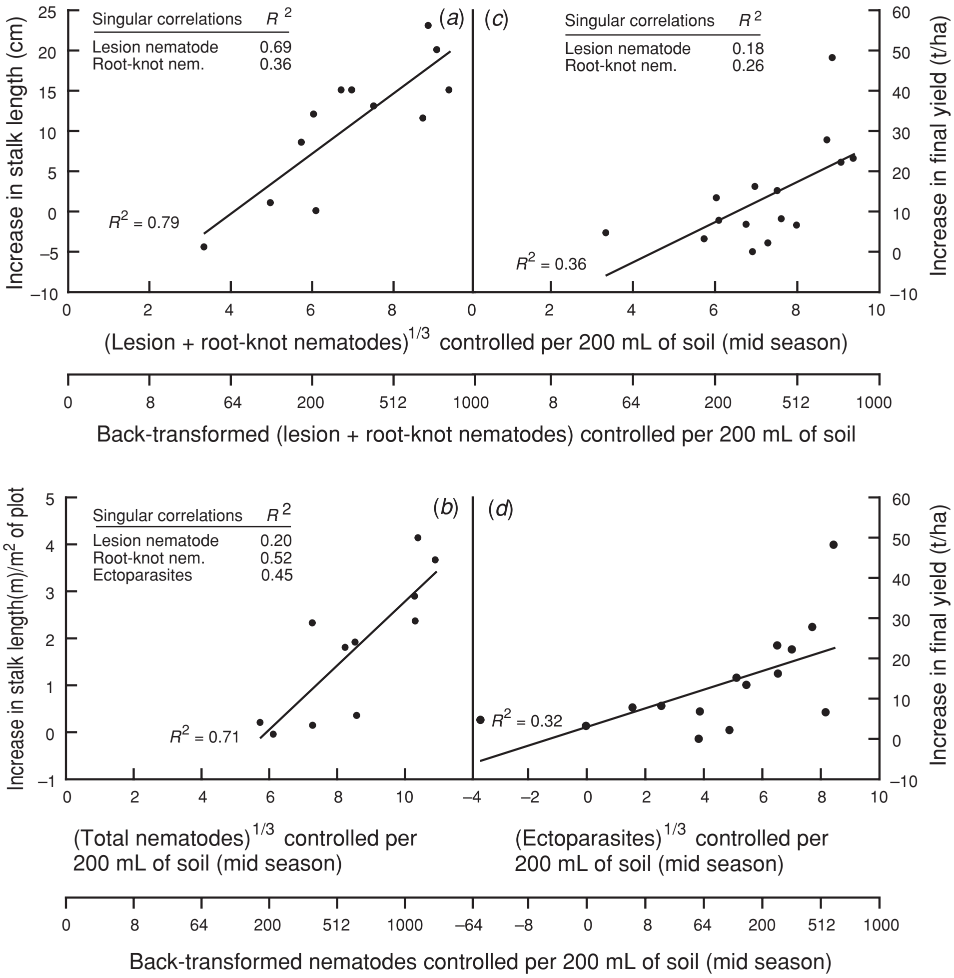

Fig. 8. Relationship between (*a*) stalk length by number, (*b*) stalk length and (*c*, *d*) final yield responses in ratoon crops following nematicide treatment and the number of nematodes controlled by the nematicide.

As the crop grew, some shoots failed to become harvestable stalks, as is common for sugarcane (Garside *et al*. 2000). This is attributed to competition for light, water and nutrients at canopy closure. Thus, when more than 30 shoots/m^2 are established following soil fumigation or high density planting, relatively few of them (10 shoots/m^2) become mature canes, with the number depending on environmental conditions (Garside *et al*. 2002*b*). Given the dynamics of stalk survival, it is therefore not surprising that early differences in shoot number between nematicide-treated and untreated plots were sometimes lost by harvest. The 6–10 stalks/m^2 established in untreated plots in our experiments is standard for the Australian sugar industry, and final responses to nematicide at most sites were less than 0.4 stalks/m^2.

In general, the responses to nematicides in fine-textured soils showed that nematodes may affect the number of harvestable stalks, but increased stalk length was a more significant component of the responses observed following nematicide treatment. The damaging effects of plant-parasitic nematodes therefore appear to be mainly manifested through effects on stalk elongation, rather than establishment. This may explain why soil fumigation, crop rotation and bare fallow sometimes increase yield without increasing the number of established stalks (Garside *et al*. 1999). Since stem biomass in spring-planted sugarcane crops is mainly accumulated after 125 DAP (Muchow *et al*. 1993), any mid- or late-season reduction in the efficiency of the root system due to nematode damage has the potential to impact on yield.

Effect of nematodes on ratoon crop growth and yield

Nematode densities at ratoon tillering were not related to early growth of ratoon crops. This was possibly because the axillary buds which produce new shoots are initially dependent on reserves from the stool and are therefore not vulnerable to root pathogens. Application of nematicides can be delayed for up to 60 DAR without compromising yield responses in nematode infested ratoons in South Africa (Rostron 1976; Spaull and Donaldson 1983). This suggests that shoot emergence from buds is insensitive to nematode attack, even in situations where nematode populations are high.

Nematicide treatment significantly increased stalk number in ratoons at 25% of sites, but the number of nematodes controlled mid-season (80–200 DAR) was not correlated with responses in stalk number. As for plant crops, nematicides had a greater impact on stalk length, as responses were observed at 58% of sites by mid-season. Responses were related to numbers of lesion and root-knot nematode controlled in soil ($R^2 = 0.79$) during the period 80–180 DAR, which further implicates lesion and root-knot nematode as important pests of sugarcane. In ratoons, the control of ectoparasites (*T. annulatus*, *H. dihystera* and *P. minor*) was partly related to increases in stalk length/m^2 of plot ($R^2 = 0.45$). This demonstrates that, as the crop ages, the whole community may need to be considered when assessing the impact of plant-parasitic nematodes.

Provided that account is made of row gaps due to stool damage from harvesters, a decline in vigour of ratoon crops is usually not attributable to low stalk numbers (Chapman *et al*. 1993). The inability of the root system to promote shoot elongation has therefore been implicated in ratoon decline, and has been attributed to soil compaction and a build-up of soil pathogens. The significant responses observed following nematicide treatment in our experiments, together with the strong correlations we obtained between stalk length and numbers of nematodes controlled in ratoon crops, suggest that plant-parasitic nematodes are one of the factors contributing to ratoon decline.

Impact of the environment on the response to nematicides

Yield responses from nematicides tended to be greatest in poorly managed crops and in crops that were grown in a harsh environment (i.e. situations where untreated yields were <90 t/ha). When environmental conditions and the level of crop management were favourable for producing high yields, nematodes had a minimal impact on yield. This is shown by the lack of responses in stalk number that were observed when nematodes were controlled at relatively high-yielding sites (Fig. 7*a*). It is also apparent from the data in Table 6, as there was no response to nematicide treatment in the high-yielding plant crop at site 5 and the high-yielding ratoon crop at site 7b, despite the fact that nematicides killed large numbers of *P. zeae* and other plant-parasitic nematodes.

Our conclusion that environmental factors influence the expression of nematode damage in sugarcane is supported by Blair (2005), who showed improved correlations ($R^2 = 0.69$) between populations of endoparasitic nematodes and yield responses to nematicide when our data were reanalysed using crop size as a cofactor. Observations that responses to nematicide were greatest when sugarcane was stressed for water (Donaldson 1985; Donaldson and Turner 1988), that sugarcane did not respond strongly to soil fumigation when it was grown in favourable environments (Muchow *et al*. 1994; Garside *et al*. 2000), and that similar environmental interactions occur in other crops (McSorley and Phillips 1993) provide further supportive evidence.

Effect of nematodes on sugar yield

High yielding crops of sugarcane sometimes have low CCS levels because sugar storage in the stem is delayed when plants are growing actively (Cadet *et al*. 2004). However, nematode control did not affect CCS at the majority of our experimental sites, suggesting that the increased crop tonnage resulting from nematode control will generally result in increased sugar yield.

Relationships between nematode density and yield

Our experimental sites were deliberately selected to encompass the variability in soils and climate that exist within the Queensland sugar industry and the differences in management expertise that occur between farms. Experiments were located in both tropical and subtropical environments, the clay contents of soils ranged from 8 to 66%, and some crops were irrigated while others relied entirely on rainfall. Since fertiliser inputs, irrigation frequency, cultivation practices and other management inputs also differed from site to site, it is not surprising that untreated yields varied from 71 to 164 t/ha. Given this diverse range of situations, close relationships between crop yield and any specific chemical, physical or biological parameter that could impact on yield were never likely to be obtained. The significant correlations that we obtained between various nematode parameters and nematicide responses in both plant and ratoon crop yields (Figs 6–8) therefore warrant consideration; they suggest that plant-parasitic nematodes are influencing yield across a diverse range of environments. Not unexpectedly, correlation coefficients were relatively low (R^2 ranging from 0.28 to 0.36), demonstrating that environmental, management and climatic factors have a major effect on the magnitude of the yield response obtained when nematodes are controlled with nematicides. In an industry as large and as diverse as the Queensland sugar industry, nematode counts are therefore likely to be a poor predictor of likely losses from plant-parasitic nematodes.

Reasons for growth and yield responses from nematicides

There are several reasons why the growth and yield increases observed in our experiments were probably due to nematode control:

(i) Symptoms on roots in untreated plots (i.e. darkened primary and secondary roots and pruned tertiary roots) were similar to those which occur when sugarcane was inoculated with *P. zeae* in microplots (Blair 2005), and root health improved when nematicides were applied.

(ii) The growth-promotion effects sometimes observed with aldicarb on other crops (Barker and Powell 1988) have never been observed on sugarcane with either aldicarb or fenamiphos (Spaull 1995; Blair 2005).

(iii) Stalk number, stalk length and final yield responses were correlated with reduced densities of nematodes in the both the soil and roots. In particular, numbers of lesion nematode + root-knot nematode were correlated with reduced final yields in plant crops, and lesion nematode was correlated with reduced stalk length throughout the crop cycle. Both nematodes are known pathogens of sugarcane (Spaull and Cadet 1990).

(iv) Control of other pests did not appear to contribute to the yield responses observed. Aldicarb is systemic and has the potential to impact on foliar sucking insects such as aphids, scale insects, mealybugs, planthoppers and froghoppers. However, these pests do not normally cause crop losses and were not usually observed in untreated plots in our experiments. Root-feeding pests such as symphylans, whitegrubs, wireworm and ground pearls were hardly ever detected when soil and roots were sampled, and insect damage to roots or shoot bases was not observed. Also, chlorpyrifos was applied at most experimental sites to provide protection against whitegrubs and wireworm.

(v) Nematicides do not usually affect soil-borne pathogens other than nematodes. Fenamiphos did not alter total numbers of bacteria, fungi or actinomycetes on sugarcane in the glasshouse (Magarey and Bull 1996), while aldicarb primarily affected nematodes rather than other soil organisms in wheat-growing soils in Queensland (Thompson *et al.* 1980).

Although non-volatile nematicides are usually considered specific enough to be used in crop loss studies with nematodes, it would be presumptuous to assume that the yield responses observed in our experiments were entirely due to nematode control. Organophosphate and carbamate nematicides are insecticidal. Given that, in most cases, they were applied 5–8 times over a 2-year period, fenamiphos and aldicarb are likely to have had some impact on soil invertebrates other than nematodes. Also, unexpected off-target effects from nematicides sometimes occur, such as the temporary effect of aldicarb on rhizosphere-inhabiting bacteria and mycorrhizal fungi that was observed by Pankhurst *et al.* (2001). Thus, we cannot rule out the possibility that factors other than plant-parasitic nematodes were partly responsible for the growth and yield increases observed in our experiments.

Estimated crop losses due to nematodes

Increases in plant and ratoon crop yields of up to 20 t/ha were observed at many of our experimental sites following nematicide treatment. However, because untreated crops appeared relatively healthy and often yielded more than 100 t/ha, these responses were not always apparent on visual inspection. This indicates that nematode damage in fine-textured soils is subtle and is not necessarily manifested as patches of visibly poor growth, as is the case with localised attacks due to insect pests or acute problems caused by root-knot nematode. It also explains why losses due to plant-parasitic nematodes (particularly lesion nematode) have been overlooked by the sugar industry for many years.

The 16 sites used in this study were typical of the Queensland sugar industry, as the nematode species present and their population densities were similar to those found in comprehensive surveys of sugarcane fields in south, central and north Queensland (Blair *et al.* 1999*a*, 1999*b*). Also, yields in untreated plots were comparable to average yields for the regions where experiments were located. Although all experiments were done in south and central Queensland, there is no reason to expect different results in other parts of the state because the farming system is similar throughout the industry, increases in yield from nematicides have been obtained in north Queensland (Chandler 1980) and responses to long fallow, rotation crops and soil fumigation have been observed throughout Queensland (Garside *et al.* 1999, 2000; Stirling *et al.* 2001).

Our results show that when nematicides were applied repeatedly to sugarcane crops, yield increases in plant and ratoon crops averaged 15.3% and 11.6%, respectively. Some of the response to nematicides may be due to factors other than nematodes, but it is not unreasonable to conclude that plant-parasitic nematodes cause a 10% loss in productivity in plant crops and 7% losses in ratoons. If it is assumed that Australian sugarcane production is 40 million tonnes/annum and that 20% of this tonnage is derived from plant crops and 80% from ratoons, this means that 3.29 million tonnes of sugarcane is lost from nematode damage each year. Assuming sugarcane is valued to $25/tonne (based on a sugar price of $300/tonne and an average CCS content of 13), this lost productivity currently costs the Australian sugar industry about AU$82 million/annum. However, in future this estimate may have to be revised downwards as improvements are made to the sugarcane farming system. Practices such as controlled traffic, reduced tillage and legume fallows reduce populations of plant-parasitic nematodes and improve soil physical, chemical and biological properties (Bell *et al.* 2003), and their introduction is expected to reduce the impact of nematodes.

Acknowledgements

This study was a component of the Sugar Yield Decline Joint Venture. Funding was provided by the Sugar Research and Development Corporation, Queensland Department of Primary Industries and Fisheries (QDPIF) and BSES Limited. James Cook University also provided support, as this study was part of Dr Blair's PhD studies. Alan Garside and Mike Bell provided helpful comments on agronomic aspects of the work, Bob Mayer (QDPIF) helped with statistical analyses, BSES extension staff located suitable field sites in south and central Queensland, and Peter Whittle, Julie Pattemore and Daniel Roberts provided assistance at various times. The cooperation of the sugarcane growers who provided sites for our experiments is also gratefully acknowledged.

References

Barker KR, Powell NT (1988) Influence of aldicarb on growth and yield of tobacco. *Journal of Nematology* **20**, 432–438.

Bell MJ, Halpin NV, Garside AL, Moody PW, Stirling GR, Robotham BJ (2003) Evaluating combinations of fallow management, controlled traffic and tillage options in prototype sugarcane farming systems at Bundaberg. In 'Proceedings of the Australian Society of Sugarcane Technologists 25'. (CD-ROM)

Blair BL (2005) The incidence of plant-parasitic nematode on sugarcane in Queensland, and studies on pathogenicity and associated crop losses, with particular emphasis on lesion nematode (*Pratylenchus zeae*). PhD Thesis, James Cook University, Townsville, Australia. Available at http://eprints.jcu.edu.au/142/02/02whole.pdf [Verified 7 March 2007]

Blair BL, Stirling GL, Whittle PJL (1999*a*) Distribution of pest nematodes on sugarcane in south Queensland and relationship to soil texture, cultivar, crop age and region. *Australian Journal of Experimental Agriculture* **39**, 43–49. doi:10.1071/ea98085

Blair BL, Stirling GL, Pattemore JA, Whittle PJL (1999*b*) Occurrence of pest nematodes in Burdekin and central Queensland sugarcane fields. *Proceedings of the Australian Society of Sugarcane Technologists* **21**, 227–233.

Bull RM (1979) New chemicals for nematode control in the Bundaberg district. *Proceedings of the Australian Society of Sugarcane Technologists* **1**, 99–103.

Bull RM (1981) Studies and observations on nematode control in the Bundaberg district. *Proceedings of the Australian Society of Sugarcane Technologists* **3**, 267–273.

Cadet P, Spaull VW (1985) Studies on the relationship between nematodes and sugarcane in South and West Africa: plant cane. *Revue de Nematologie* **8**, 131–142.

Cadet P, Guichaoua L, Spaull VW (2004) Nematodes, bacterial activity, soil characteristics and plant growth associated with termitaria in a sugarcane field in South Africa. *Applied Soil Ecology* **25**, 193–206. doi:10.1016/j.apsoil.2003.10.001

Chandler KJ (1978) Non-volatile nematicides: an initial assessment in north Queensland sugarcane fields. *Proceedings of the Queensland Society of Sugarcane Technologists* **45**, 85–91.

Chandler KJ (1980) Continued experiments with non-volatile nematicides in north Queensland sugar cane fields. *Proceedings of the Australian Society of Sugarcane Technologists* **2**, 75–82.

Chapman LS, Ferraris R, Ludlow MM (1993) Ratooning ability of cane varieties: variation in yield and yield components. *Proceedings of the Australian Society of Sugarcane Technologists* **14**, 130–138.

Donaldson RA (1985) The effects of soil pH, clay content, rainfall and age at harvest on the yield response of sugarcane to Temik. In 'Proceedings of the South African Sugar Technologists' Association 59'. pp. 164–167.

Donaldson RA, Turner PET (1988) A preliminary report of the effect of soil moisture level on responses to Temik and Curaterr. In 'Proceedings of the South African Sugar Technologists' Association 62'. pp. 164–168.

Garside AL, Nable RO (1996) Sugarcane growth and yield comparisons for new and old land sites. In 'Sugarcane: research towards efficient and sustainable production'. (Eds JR Wilson, DM Hogarth, JA Campbell, AL Garside) pp. 248–250. (CSIRO Division of Tropical Crops and Pastures: Brisbane)

Garside AL, Smith MA, Chapman LS, Hurney AP, Magarey RC (1997) The yield plateau in the Australian sugar industry: 1970–1990. In 'Intensive sugarcane production, meeting the challenges beyond 2000'. (Eds BA Keating, JR Wilson) pp. 103–124. (CAB International: Wallingford, UK)

Garside AL, Bell MJ, Cunningham G, Berthelsen J, Halpin N (1999) Rotation and fumigation effects on the growth and yield of sugarcane. *Proceedings of the Australian Society of Sugarcane Technologists* **21**, 69–78.

Garside AL, Bell MJ, Berthelsen JE, Halpin NV (2000) Effects of breaks and nitrogen fertiliser on shoot development, maintenance, and cane yield in an irrigated plant crop of Q117. *Proceedings of the Australian Society of Sugarcane Technologists* **22**, 61–67.

Garside AL, Berthelsen JE, Pankhurst CE, Blair BL, Magarey RC, D'Amato CD, Bull JI (2002*a*) Effects of breaks from sugarcane monoculture and biocides on the growth and yield of a subsequent sugarcane crop. *Proceedings of the Australian Society of Sugarcane Technologists* **24**, 82–91.

Garside AL, Bell MJ, Berthelsen JE, Halpin NV (2002*b*) Effect of fumigation, density and row spacing on the growth and yield of sugarcane in two diverse environments. *Proceedings of the Australian Society of Sugarcane Technologists* **24**, 19.

Hooper DJ (1990) Extraction and processing of plant and soil nematodes. In 'Plant parasitic nematodes in subtropical and tropical agriculture'. (Eds M Luc, RA Sikora, J Bridge) pp. 45–68. (CAB International: Wallingford, UK)

Hough A, Thomason IJ, Farmer WJ (1975) Behaviour of aldicarb in soil relative to control of *Heterodera schachtii. Journal of Nematology* **7**, 214–221.

Magarey RC, Bull JI (1996) Effect of heat, fungicide and fumigation treatments on the microbiology of sugarcane soils affected by yield decline. In 'Sugarcane: research towards efficient and sustainable production'. (Eds JR Wilson, DM Hogarth, JA Campbell, AL Garside) pp. 230–231. (CSIRO: Brisbane)

Magarey RC, Croft BJ (1995) A review of root disease research in Australia. *Proceedings of the International Society of Sugarcane Technologists* **22**(2), 505–513.

McSorley R, Phillips MS (1993) Modelling population dynamics and yield losses and their use in nematode management. In 'Plant parasitic nematodes in temperate agriculture'. (Eds K Evans, DL Trudgill, JM Webster) pp. 61–85. (CAB International: Wallingford, UK)

Muchow RC, Wood AW, Spillman MF, Robertson MJ, Thomas MR (1993) Field techniques to quantify the yield-determining processes in sugarcane. 1. Methodology. *Proceedings of the Australian Society of Sugarcane Technologists* **15**, 336–343.

Muchow RC, Robertson MJ, Wood AW, Spillman MF (1994) Effect of soil fumigation on sugar cane productivity under high yielding conditions in north Queensland. *Proceedings of the Australian Society of Sugarcane Technologists* **16**, 187–192.

Pankhurst CE, Blair BL, D'Amato CD, Bull JI, Magarey RC (2001) Quantification of the effects of fumigation and nematicide treatments on the early shoot and root growth of sugarcane in a yield decline soil. *Proceedings of the Australian Society of Sugarcane Technologists* **23**, 260–267.

Pankhurst CE, Blair BL, Magarey RC, D'Amato CD, Bull JI, Garside AL (2002) Use of biocides to determine the impact of detrimental fungi and nematodes on establishment and early growth of sugarcane following rotation breaks. *Proceedings of the Australian Society of Sugarcane Technologists* **24**, 75–81.

Rostron H (1976) Rate, time and method of Temik application in ratoon sugarcane. In 'Proceedings of the South African Sugar Technologists' Association 50'. pp. 29–33.

Sasser JN, Freckman DW (1987) A world perspective on nematology: the role of the Society. In 'Vistas on nematology'. (Eds JA Veetch, DW Dickson) pp. 7–14. (Society of Nematologists: Hyattsville, MD)

Smelt JH, Leistra M (1992) Availability, movement and (accelerated) transformation of soil-applied nematicides. In 'Nematology from molecule to ecosystem'. (Eds FJ Gommers, P Th Maas) pp. 266–280. (Dekker and Huisman: Wildervank, The Netherlands)

Spaull VW (1995) A revised estimate of crop loss in sugarcane caused by nematodes. In 'Proceedings of the South African Sugar Technologists' Association 69'. pp. 28–34.

Spaull VW, Cadet P (1990) Nematode parasites of sugarcane. In 'Plant parasitic nematodes in subtropical and tropical agriculture'. (Eds M Luc, RA Sikora, J Bridge) pp. 461–491. (CAB International: Wallingford, UK)

Spaull VW, Donaldson RA (1983) Relationship between the time of nematicide application, numbers of nematodes and response to treatment in ratoon sugarcane. In 'Proceedings of the South African Sugar Technologists' Association 57'. pp. 123–127.

Stirling GR, Dullahide SR (1987) Vertical and lateral movement and nematicidal activity of fenamiphos applied to soil by trickle irrigation. *Plant Protection Quarterly* **2**, 151–155.

Stirling AM, Stirling GR, MacRae IC (1992) Microbial degradation of fenamiphos after repeated application to a tomato-growing soil. *Nematologica* **38**, 245–254.

Stirling GR, Blair BL, Pattemore JA, Garside AL, Bell MJ (2001) Changes in nematode populations on sugarcane following fallow, fumigation and crop rotation, and implications for the role of nematodes in yield decline. *Australasian Plant Pathology* **30**, 323–335. doi:10.1071/AP01044

Stirling GR, Wilson EJ, Stirling AM, Pankhurst CE, Moody PW, Bell MJ (2003) Organic amendments enhance biological suppression of plant-parasitic nematodes in sugarcane soils. *Proceedings of the Australian Society of Sugarcane Technologists* **25**, 11.

Thompson JP, Mackenzie J, Sheedy GH (1980) Long fallow disorder of wheat and 'wheat sickness'. Biennial Report 1978–80, Queensland Wheat Research Institute, Toowoomba, Qld.

Vawdrey LL, Stirling GR (1996) The use of tolerance and modification of planting time to reduce damage caused by root-knot nematodes (*Meloidogyne* spp.) in vegetable cropping systems at Bundaberg, Queensland. *Australasian Plant Pathology* **25**, 240–246. doi:10.1071/AP96044

Whitehead AG, Hemming JR (1965) A comparison of some quantitative methods of extracting some small vermiform nematodes from soil. *The Annals of Applied Biology* **55**, 25–38.

Manuscript received 1 November 2005, accepted 19 September 2006