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Beyond chemical dependency for managing plant-parasitic nematodes: examples from the banana, pineapple and vegetable industries of tropical and subtropical Australia

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Abstract. Plant-parasitic nematodes are important pests of horticultural crops grown in tropical and subtropical regions of Australia. Burrowing nematode (*Radopholus similis*) is a major impediment to banana production and root-knot nematodes (predominantly *Meloidogyne javanica* and *M. incognita*) cause problems on pineapple and a range of annual vegetables, including tomato, capsicum, zucchini, watermelon, rockmelon, potato and sweet potato. In the early 1990s, nematode control in these industries was largely achieved with chemicals, with methyl bromide widely used on some subtropical vegetable crops, ethylene dibromide applied routinely to pineapples and non-volatile nematicides such as fenamiphos applied up to four times a year in banana plantations. This paper discusses the research and extension work done over the last 15 years to introduce an integrated pest management approach to nematode control in tropical and subtropical horticulture. It then discusses various components of current integrated pest management programs, including crop rotation, nematode monitoring, clean planting material, organic amendments, farming systems to enhance biological suppression of nematodes and judicious use of nematicides. Finally, options for improving current management practices are considered.

Introduction

In Australia, produce from the tropical and subtropical fruit and vegetable crops grown between latitudes 12°S and 30°S is worth about A$1200 million/annum. This represents ~12% of the total value of Australian horticultural production (Collins *et al*. 2004). Although some of this produce comes from the Northern Territory and Western Australia, the main production areas are in Queensland and northern New South Wales (Fig. 1).

Plant-parasitic nematodes are important pests of most tropical and subtropical horticultural crops, causing estimated losses in production of 6–10% (Stirling *et al*. 1992). The crops most affected by nematodes are banana, pineapple and a range of annual vegetables, including tomato, capsicum, zucchini, watermelon, rockmelon, potato and sweet potato. Collectively, these crops comprise more than 80% of the horticulture in northern Australia. The most important nematode pests are burrowing nematode (*Radopholus similis*), which is a major problem wherever bananas are grown, and root-knot nematodes (predominantly *Meloidogyne javanica* and *M. incognita*), which are a major impediment to pineapple and vegetable production when these crops are grown in sandy loam or well structured, clay loam soils.

During the last 15 years, Australia's tropical and subtropical horticultural industries have had to make major changes to the way in which nematodes are managed. In the early 1990s, soil fumigation with ethylene dibromide (EDB) was standard practice in the pineapple industry, methyl bromide was widely used in some parts of the subtropical vegetable industry, and two-thirds of banana plantations were routinely treated with non-volatile nematicides. The decision by Australia's chemical registration authority to withdraw EDB and methyl bromide from the market for environmental reasons, therefore, had a major impact on the industries that were dependent on soil fumigants. Concerns about off-site movement and the potential for groundwater contamination from organophosphate and carbamate nematicides also meant that the banana industry in particular had to rethink its nematode control strategies. This paper focuses on Australian research done in the last 15 years to reduce the need for chemically-based nematode control in tropical and subtropical horticulture.

Banana

The Australian banana industry produces ~350 000 tonnes of fruit annually, with all of this fruit being sold on the domestic market. The industry comprises two components: a subtropical industry based in northern New South Wales, south-east Queensland and around Carnarvon in Western Australia, and a tropical component located around Kununurra in Western Australia, Darwin in the Northern Territory and the increasingly important wet tropics region of north Queensland, where 88% of the country's bananas are produced (Collins *et al*. 2004). All banana farms are family-owned and in north Queensland they usually range from 15 to 20 ha in size, although some farms are as large as 500 ha. Yields are relatively high, ranging from 30 to 40 tonnes of fruit/ha. In subtropical areas, farms are much smaller (averaging 4 ha) and yields are only 20–26 tonnes/ha. Because labour costs are higher than many other banana producing countries, field operations are highly mechanised.

Although the distribution of plant-parasitic nematodes on banana in Australia varies to some extent between production

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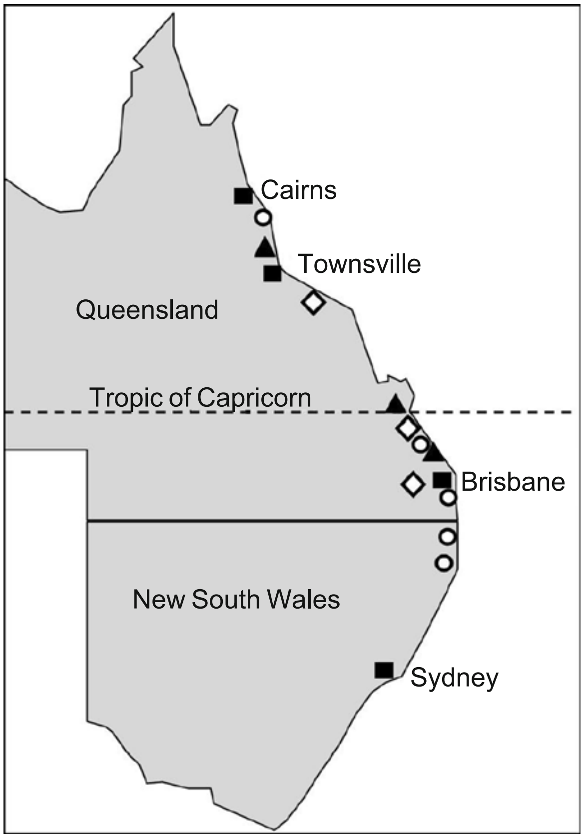

Fig. 1. Major production areas of bananas (○), pineapple (▲) and vegetables (◇) in tropical and subtropical Australia and their relationship to major cities (■) and the Tropic of Capricorn.

regions, the most common nematodes are burrowing nematode (*R. similis*), root-knot nematode (*Meloidogyne* spp.), spiral nematode (*Helicotylenchus dihystera* and *H. multicinctus*), lesion nematode (*Pratylenchus goodeyi*) and reniform nematode (*Rotylenchulus reniformis*). *R. similis* is by far the most important of these species, as plants infested with this nematode produce small bunches, have slow cropping cycles and are readily uprooted under the weight of the bunch or in wet, windy weather (Blake 1963). Although the genus *Radopholus* is indigenous to Australia, New Zealand and neighbouring countries, *R. similis* does not occur in natural habitats in Australia and was probably introduced from Fiji on the corms used as banana planting material.

Nematode management in the early 1990s

Although research on nematode control in bananas commenced in the 1960s, Australian banana growers were still experiencing losses from *R. similis* 30 years later. Symptoms such as plant toppling were commonly observed in the early 1990s and at that time it was estimated that nematodes were costing the industry around A$10–15 million annually (Pattison 1994). These losses were occurring, despite the fact that growers were spending nearly 30% of their plant protection budget on nematode control.

The reason nematode control costs were so high is that nematicides were the primary control tactic. Research in north Queensland had previously shown that non-volatile nematicides increased banana production over a 4-year production cycle (Broadley 1979*a*). The yield responses were quite spectacular, with fensulfothion, fenamiphos, ethoprofos and oxamyl increasing yield by 44, 29, 29 and 21%, respectively. Broadley (1974) commented that 'judicious use of ethoprofos and fenamiphos is likely to be of substantial value to the banana industry' and went on to show that the application of 2.0 g a.i. of fenamiphos/plant six times per year increased banana production by 60% over a 4-year period (Broadley 1979*a*). Non-volatile nematicides were applied commercially via micro-irrigation systems, a practice that reduced the severity of root rot and increased bunch weights, and was deemed simpler, safer and more cost effective than other application methods (Schipke and Ramsey 1994). However, despite increases in production with nematicides, their performance was erratic and numbers of nematodes found in treated areas rarely differed from untreated areas (Broadley 1979*a*).

Treatments to reduce nematode populations in vegetative planting material were also being used on most banana farms in the early 1990s. Hot water dips were first recommended by Blake (1961) and Colbran (1964*b*) when they showed that paring of corm material to remove surface nematode infestations, together with immersion in hot water at 53–55°C for 20 min, eliminated *R. similis* without markedly affecting germination. Later, Broadley (1979*b*) found that heavy paring of planting material followed by immersion in 250 ppm fenamiphos for 10 min was also able to reduce *R. similis* within planting material. Fenamiphos dips (after all symptomatic tissue was removed), became the preferred treatment, but later work (Pattison and Cobon 2003) showed that this did not completely eliminate nematodes from corm tissue.

Fallowing and rotation with a non-host crop were other management practices that had been investigated. Green panic (*Panicum maximum*) reduced populations of *R. similis* after 32 weeks (Colbran 1964*a*) but was never used as a rotation crop because it had the potential to become a weed problem, while the resistance of Jarra grass (*Digitaria milanjiana*) to *R. similis* (Hall *et al*. 1993) was not utilised because the grass was difficult to establish from runners or seed. In the early 1990s, most growers fallowed for 6–24 months between banana crops but the fallow usually consisted of weeds and volunteer bananas rather than a crop that was a poor host of *R. similis*.

A research program to reduce nematicide use in banana

In 1994, 61% of Queensland banana growers were regularly applying one of four nematicides (fenamiphos, ethoprofos, cadusafos, and oxamyl) registered for use on bananas. However, it was becoming apparent that these nematicides were potentially hazardous within the local environment, as they were readily moved in soil water and could be transported in colloidal suspensions of soil particles (Cáceres *et al*. 2002). Since the banana industry is located in a region receiving ~3800 mm of rain each year, much of it in torrential tropical downpours, there is always a risk that nematicides will move offsite. There had been reports of fish kills in north Queensland that may have been caused by movement of nematicides into waterways after heavy rainfall, but the involvement of nematicides was never confirmed. Another concern was that field staff working in recently treated fields would be exposed to nematicides.

Commencing in 1994, the Australian banana industry commissioned a research and extension program to develop and implement sustainable management practices for *R. similis* and other nematodes on banana. To ensure that any new nematode management practices were compatible with the production systems used within the industry, growers were involved in the work from the outset, commenting on research priorities and providing land for field experiments. This participative approach proved successful, as the research program is still continuing and several research outcomes have been adopted widely by industry.

Clean planting material

In the early 1990s, most banana planting material was sourced from fields that were being taken out of production because of low productivity. This vegetative material was then treated with either hot water or a nematicide. Clearly, this was a high risk approach because the planting material was usually heavily infested with nematodes and there was every chance that commercial treatments would not be entirely effective. The importance of selecting appropriate planting material and adhering strictly to recommended treatment guidelines was, therefore, emphasised in extension work in the banana industry. This approach proved successful, as 87% of growers questioned in 2003 indicated that they used clean planting material to manage the spread of nematodes (Pattison and Cobon 2003).

Tissue-cultured banana plantlets are free of soilborne pathogens and perform well when planted in the field (Drew and Smith 1990), and their availability has increased the certainty that planting material is not infested with nematodes. The quality of tissue-cultured material is now monitored under an industry-managed quality assurance scheme (Hamill and Smith 2004). About one-quarter of north Queensland growers regularly use it to establish their plantations. Others use tissue-cultured plantlets to establish nurseries dedicated to producing vegetative planting material that is free of nematodes.

Prevention of spread

Since the area planted to bananas in north Queensland increased from 5400 ha in 1994 to 10 100 ha in 2001 and much of this expansion was onto land that had not previously grown bananas, considerable effort was put into preventing the spread of nematodes into new production areas. Initially, regulations regarding the movement and use of banana planting material (Plant Protection Act 1989, Queensland) were used to discourage growers distributing planting material from plantations infested with *R. similis*. However, educational programs played an even greater role in prevention of spread by increasing awareness of the potential for nematode carryover on planting material. Specialised nursery operations were soon established and some owners of new plantations introduced their own quarantine procedures to prevent the introduction of *R. similis* on machinery and footwear.

Nematode monitoring

Monitoring is an important part of any integrated nematode management program (Stanton *et al*. 2001), and in bananas it can be done by counting nematodes extracted from roots and soil or by examining damage caused by *R. similis* on roots. Broadley (1979*c*) developed a disease index based on the severity of lesions in the root cortex and Stanton *et al*. (2001) found that it was more useful than nematode counts for assessing the nematode status of a field. Therefore, a monitoring system was developed that involved collecting a 25 × 25 × 25 cm block of soil from the front of the following sucker of a banana plant soon after flowering. Twenty different plants were randomly sampled in a field and five roots were then taken from each block of soil. Roots were split longitudinally, the amount of necrotic tissue in the root cortex was assessed and damage ratings were assigned according to the extent of necrotic lesion development: 0, no lesions; 1, 1–25% of root cortex occupied by lesions; 3, 26–50% of root cortex occupied by lesions; 5, 51–75% of root cortex occupied by lesions; and 7, 76–100% of the root cortex occupied by lesions (Stanton *et al*. 2001). The ratings were then used to calculate a disease index using the following equation:

$$\text{Disease index} = \frac{\sum \text{individual root ratings} \times 100}{\text{Total number of roots} \times 7} \qquad (1)$$

An economic threshold was developed by correlating the disease index with banana bunch weight. Since the value of subtropical banana crops was nearly half that in the tropics (because of lower yields in a cooler environment), economic losses were assumed to have occurred when bunch weight had been reduced by 11–19% in the subtropics and 6–9% in tropical areas. The economic threshold for nematode damage from disease index calculations was estimated to be 20.5–35.5% in the subtropics and 9.2–15.6% in the tropics (Stanton *et al*. 2001; Pattison *et al*. 2002).

The disease index method, as well as giving an indication of the level of nematode damage, was simple and quick to use. In a survey of banana grower practices in 2003, two-thirds of banana growers were aware of the root disease index method for monitoring nematode damage and nearly half were either using it regularly or having it done by a commercial monitoring service (Pattison and Cobon 2003).

Enhanced biodegradation of nematicides

In the early 1990s, nematicides were applied two to three times per year according to a calendar schedule, with heavy reliance on fenamiphos and ethoprofos. However, poor results in the field led to the suspicion that the efficacy of these products was being affected by enhanced biodegradation. Therefore, a simple bioassay was developed to indicate whether nematicides were being rapidly degraded by soil microorganisms. Maize seedlings growing in sterilised or field soil that had either been treated with a nematicide or left untreated were inoculated with *R. similis* 0, 2, 4 and 6 weeks after treatment. The number of nematodes that were able to penetrate into the roots of maize plants was assessed by extracting nematodes 1 week after inoculation. Soils in which a nematicide was effective in sterilised soil but was relatively ineffective in untreated soil (compared with untreated soil without nematicide) were considered to have unacceptably high rates of biological degradation (Pattison *et al*. 2000*a*). Results with the bioassay indicated that about half the banana farms in Queensland (mostly in north Queensland) had enhanced biodegradation problems with fenamiphos.

Since the frequency of fenamiphos usage appeared to be a major factor contributing to the development of the problem, a field experiment was established in 2000 to compare the efficacy of four registered nematicides when they were applied consecutively or in rotation. Nematicides were only applied at the economic threshold, as indicated by a disease index of 10 or greater. Root lesion development and populations of *R. similis* were assessed before each nematicide application. This allowed the calculation of disease and nematode progress over the 2-year experimental period by calculating the area under the nematode number and disease index curves by integration, for each treatment (Pattison and Cobon 2003). The above bioassay (with mungbean rather than maize seedlings) was also used to assess whether enhanced biodegradation was occurring at various times during the course of the experiment.

The results indicated that the area under the disease index and *R. similis* progress curves was greatest in untreated bananas and was not reduced significantly by continual application of fenamiphos or cadusafos (Table 1). The continual oxamyl treatment and a rotation of chemicals were the only reasonably effective treatments (Table 1). Bioassays for enhanced biodegradation suggested that at the time the experiment commenced, the soil already had some capacity to degrade fenamiphos, cadusafos and terbufos, and that this capacity was maintained or enhanced when nematicides were applied continuously (Table 2). Initially, the soil did not rapidly degrade oxamyl, but this trait appeared after seven applications in 2 years. Rotation of nematicides was able to slow the rate of development of enhanced biodegradation, but only to a limited extent.

Integrated nematode management

Since more than half the Australian banana crop is grown on land that is already infested with *R. similis*, a major emphasis of research has been on managing nematodes in established plantations. The work discussed previously highlighted the deficiencies in relying solely on chemicals for nematode control, and led to greater acceptance by growers of other nematode management strategies. Thus, integrated management is now more widely used and most growers only apply nematicides as a last resort.

Fallowing and crop destruction

R. similis is able to survive in decomposing root and corm material for up to 6 months (Blake 1969). Furthermore, the survival of *R. similis* on volunteer bananas that grow during the fallow period between cropping cycles is a major cause of carry over of nematodes to the next crop. Experimentally, the herbicide glyphosate was, therefore, applied to foliage and pseudostems in an attempt to eliminate regrowth from the previous crop. An injection treatment was found to be effective in significantly

Table 1. Area under disease index and *Radopholus similis* progress curves when consecutive nematicide applications were compared with a nematicide rotation on a banana farm over a 2-year period

From Pattison and Cobon (2003). Means in columns followed by the same subscript are not significantly different ($P < 0.05$)

Treatment	Nematicide applications	Area under disease progress curve (nine assessments, May 2000–May 2002)	
		Disease index	*R. similis* (100 g/root)
Untreated	0	597d	166d
Terbufos	8	447bc	143bc
Fenamiphos	8	539cd	164d
Cadusafos	8	497cd	156cd
Oxamyl	7	352ab	128ab
Rotation	7 (2 terbufos, 2 fenamiphos, 2 oxamyl, 1 cadusafos)	335a	119a

Table 2. Relative recovery of *Radopholus similis* from roots of bioassay plants inoculated 0, 2, 4 and 6 weeks after nematicide treatment and grown in banana soil with repeated applications of the same nematicide or a rotation of nematicides over a 2-year period

Modified from Pattison and Cobon (2003). n.s., nematode recovery from nematicide-treated bioassay plants did not differ significantly ($P < 0.05$) from untreated soil

Nematicide	Application method	Recovery of *R. similis* from nematicide-treated bioassay plants relative to plants in untreated soil (%)[A]		
		Pretreatment	Year 1	Year 2
Fenamiphos	Continuous	80	96n.s.	107n.s.
	Rotation	72	70	93n.s.
Terbufos	Continuous	45	72	98n.s.
	Rotation	53	69	83n.s.
Cadusafos	Continuous	92n.s.	90n.s.	99n.s.
	Rotation	99n.s.	62	96n.s.
Oxamyl	Continuous	4	3	45
	Rotation	6	7	36

[A]Calculated using integration of the area under the progress curve of nematode populations recovered 0, 2, 4 and 6 weeks after nematicide application.

Table 3. Survival of volunteer banana plants in a fallow following crop destruction using cultivation only, foliar application of glyphosate or injection of glyphosate into the banana pseudostem

Means in columns followed by the same subscript are not significantly different ($P < 0.05$)

Treatment	Number of volunteer bananas after treatment/10 m of row	
	3 months	7 months
Cultivation	63a	22a
Glyphosate foliar	74a	3b
Glyphosate injection	6b	3b

reducing but not eliminating regrowth (Table 3), and volunteer control with glyphosate is now a component of an integrated nematode management program in banana.

Crop rotation

Glasshouse work on the multiplication of *R. similis* on a wide range of crops showed that several grasses [including some sugarcane varieties, Rhodes grass (*Chloris gayana*) and Bahia grass (*Paspalum notatum*)] and various brassicas were relatively poor hosts of the nematode and were potentially useful rotation crops (Pattison *et al*. 2000*b*; Pattison 2006). However, the crops that have proved most acceptable to growers are Rhodes grass for fallows greater than 12 months, and *Brassica* spp. for a short winter fallow. These crops are now used by ~25% of banana growers in north Queensland, with another 8% using sugarcane as a long-term rotation crop (Pattison and Cobon 2003). Experience has shown that a well managed rotation (i.e. eliminating banana regrowth and weeds, and growing a nematode-resistant crop for at least 12 months) is able to reduce populations of *R. similis* to levels where at least six nematicides applications can be saved in each crop cycle.

Companion planting

In a recent study, shade tolerant ground covers such as carpet grass (*Axonopus affinis*) and forage peanut (*Arachis pintoi*) were grown around banana plants and in inter-rows and managed in a way that did not allow them to compete with the crop for water and nutrients. This practice was not detrimental to banana root growth but improved the physical and biological status of the soil (Pattison 2006). Although the ground covers did not reduce the number of plant-parasitic nematodes recovered from banana roots, companion planting is being further explored because of its likely long-term impact on soil health.

Crop residue management

The crop residues that accumulate on the soil surface as a result of de-leafing, de-suckering and harvesting operations in a ratoon banana crop usually amount to ~10–25 t dry matter/ha. Traditionally, this material was raked into the inter-row, leaving the soil bare around the plant to facilitate nematicide application. However, crop residues are now more commonly left to accumulate around the base of the banana plant, thereby increasing soil carbon (C) levels (Pattison *et al*. 2006). In the long term, this practice may increase suppressiveness to *R. similis*, but this is yet to be confirmed.

Table 4. Nematicide usage and the level of nematode monitoring in the Australian banana industry from 1994 to 2007[A]

	1994	1997	2003	2007
Nematicide use (% of growers)	61	42	39	36
Products used				
Fenamiphos	65	11	28	33
Cadusafos	19	33	11	0
Terbufos	NR[B]	1	16	0
Ethoprofos	8	20	2	NR
Oxamyl	8	34	33	66
Other	–	1	10	0
Banana production area monitored for nematode damage (%)	31	10	69	88

[A]Survey of tropical banana growers in 1994, 2003 and 2007, and subtropical growers in 1997.
[B]NR = not registered for use.

Nutrient management

While it is difficult to show any direct affects of nutrient management on losses caused by plant-parasitic nematodes, the implementation of an integrated management strategy for nematodes has coincided with improvements in the way nutrients are managed. Since 1994 there has been a 40% reduction in the amount of nitrogen (N) fertiliser applied to banana crops. The consequent reduction in soil nitrate levels and higher levels of soil C have resulted in soils with greater biological diversity. Interestingly, soils with high labile C, low NO_3-N and high biodiversity were associated with lower populations of plant-parasitic nematodes (Pattison *et al*. 2006).

Nematicides

The gradual implementation of an integrated nematode management program has resulted in a steady decrease in the amount of nematicide used in the Australian banana industry (Table 4). Currently, one-third of banana growers use nematicides, generally with one or two (average 1.75) applications per year. This reduction in nematicide usage has not resulted in increased nematodes problems, as 88% of the banana production area is currently monitored for nematode damage (Table 4) and growers would, therefore, know whether nematode populations had risen to damaging levels.

Future directions in nematode management

In many banana production systems, problems due to plant-parasitic nematode are symptomatic of unsustainable production practices that rely heavily on synthetic pesticides and fertilisers. The Australian banana industry has reduced its reliance on such inputs by developing a more sustainable farming system. However, the proximity of the north Queensland banana industry to the Great Barrier Reef Marine Park means that further improvements may be required. The impact of farm management practices on the environment is increasingly being scrutinised (Anon. 2003) and this will have a major impact on the nematode management practices that are deemed acceptable in future.

Future improvements in nematode management are likely to come from harnessing the natural suppressive influences that are expected to begin operating once soils are managed in a more sustainable way. Crop rotation, companion planting, retention of crop residues, organic amendments, fertiliser inputs and tillage practices all have an impact on soil health and biological suppressiveness, and their effects must be examined in an holistic way to ensure that the banana industry has a farming system that is not only relatively free of nematode problems but is also productive and profitable.

One useful addition to integrated nematode management programs for banana would be the availability of varieties suitable for the Cavendish banana market that have some resistance to *R. similis*. Widely confirmed sources of resistance to *R. similis* are available in *Musa* spp. (Sarah 2000; De Waele and Elsen 2002) but because of the difficulties associated with conventional banana breeding, an acceptable nematode resistant replacement for Cavendish has not yet been produced. Genetic transformation provides a way of introducing desirable genes into banana cultivars (Smith *et al*. 2005) and may offer the opportunity to improve levels of nematode resistance while maintaining desirable bunch qualities. Regardless of the improvement method that is eventually used, any new variety would have to be able to cope with differences in pathogenicity that exist among populations of *R. similis*, and also be resistant to other fungal and bacterial pathogens such as *Fusarium oxysporum* f. sp. *cubense*. One concern about relying on resistance to reduce the impact of *R. similis* is that several other plant-parasitic nematodes are hosted by bananas, and they may increase in importance if this was the only management strategy available.

Pineapple

The Australian pineapple industry

The Australian pineapple industry is relatively small by world standards, producing ~125 000 tonnes of fruit each year. It also does not employ the large, plantation-style production methods used in other parts of the world, with all fruit being produced on ~170 family farms ranging in size from 40 to 160 ha. The industry is mainly located in south-east Queensland (Fig. 1) because historically, most of the crop was processed at a Brisbane-based fruit processing facility. However, that situation is changing as growers move to north Queensland to take advantage of the tropical climate, which is more suitable for producing pineapples for the fresh fruit market.

The subtropical climate in the main pineapple production areas of south-east Queensland provides excellent growing conditions during the 8 months from October to May. Mean maximum temperatures are ~27°C and since at least 90 mm of rain falls per month during this period, the crop can be grown successfully without irrigation. However, this region is further from the equator (latitude 25–27°S) than any other commercial pineapple growing area in the world, which means that its relatively cool winter climate limits growth and sugar accumulation during winter months. It is also the main reason that root-knot nematode (*M. javanica*) rather than reniform nematode (*R. reniformis*) is the dominant nematode pest. *R. reniformis* is widely distributed in the tropics and is the major nematode pest of pineapple in Hawaii and the Philippines, but *M. javanica* is better adapted to the cooler climate of subtropical Queensland.

Nematode management in the early 1990s

Although reniform nematode is present in north Queensland and lesion nematode (*Pratylenchus brachyurus*) is found on some farms throughout the state, root-knot nematode has always been the key nematode pest of pineapple in Queensland (Colbran 1960*a*). The nematode invades at the root tip, producing pronounced club-shaped terminal galls and preventing primary roots from elongating. This damage has a major impact on non-irrigated pineapple crops because root development is restricted and this stresses plants for moisture between rainfall events. Root-knot nematode can reduce the yield of plant crops, but is mainly a problem in ratoons because fruit size may be reduced to levels unsuitable for canning.

As with other pineapple-growing regions of the world, soil fumigation has played an important role in nematode management in Queensland. Soil fumigants were first tested on pineapple in 1955 (Colbran 1960*a*) and within a few years, EDB and mixtures of 1,3-dichloropropene (1,3 D) and 1,2-dichloropropane were being recommended for nematode control (Colbran 1960*b*). Over the next 30 years, soil fumigation became standard practice in the pineapple industry, with EDB applied routinely to all fields before pineapples were planted. The practice was so effective that root-knot nematode was largely eliminated as a problem in the plant crop, although it sometimes caused damage in ratoons.

Following the discovery of EDB contamination in groundwater in Hawaii (Oki and Giambelluca 1987, 1989) the Australian government indicated that EDB would be removed from the marketplace, but the pineapple industry was given several years to find alternative nematode control measures. The industry responded with a research program that examined the potential of a range of chemical and non-chemical management practices for nematode pests. The first step involved re-evaluating the industry's chemical control practices to see whether growers were justified in routinely fumigating every pineapple field.

Research on alternatives to soil fumigation

Initial studies by Stirling and Nikulin (1993) compared EDB, various fenamiphos treatments and an untreated control in fields that were representative of the soil types and microclimates of the south-east Queensland pineapple industry. Plant growth and yield responses were measured and nematode populations were monitored regularly in both plant and first ratoon crops. Monitoring during the 3–6-month fallow between pineapple crops showed that regardless of the number of nematodes on the previous crop, root-knot nematodes were almost undetectable at the end of the fallow period. Thus, under the warm moist conditions that usually occur for most of the year in south-east Queensland, second-stage juveniles remain active after hatching from eggs and, therefore, die of starvation in the absence of a host crop. This rapid decline in nematode populations during the fallow was an important observation, because it showed that growers were fumigating at a time when root-knot nematode populations were very low, thus raising questions about whether a pre-planting nematicide was really needed.

Once pineapples were replanted, observations in untreated plots showed marked differences between sites in the manner in which root-knot nematode populations increased on the newly planted crop. At half the sites, the nematode was detected in soil 12 and 15 months after planting and galls were observed on roots. However, at the other sites, the nematode remained undetectable or at low population densities in untreated plots for at least 30 months.

The nematicide treatments included in the above experiments consisted of pre-planting applications of either EDB or granular fenamiphos with or without foliar fenamiphos sprays in the first 12 months after planting. The responses to these treatments provided clues as to how root-knot nematode might eventually be managed in the absence of EDB. Yield responses in both plant and ratoon crop were obtained with nematicides at some sites, clearly indicating that root-knot nematode was a major factor limiting pineapple production on those farms. However, perhaps the most important observation was that growth or yield responses were broadly related to nematode population densities, with responses in ratoon crops only being obtained at sites where root-knot nematode was detectable at 15 months (Table 5). This result suggested that nematicide application was unnecessary on some farms and that a nematode monitoring service should be established to identify farms where a response was likely to be obtained.

The relationship between population densities of *M. javanica* and pineapple yield was studied by Stirling and Kopittke (2000) in an attempt to identify these situations with some degree of certainty. The results demonstrated that economically significant crop losses from root-knot nematode occurred when the nematode population density at 12 months was very low (in the order of 1–5 nematodes/200 mL soil), and that reasonably accurate estimates of nematode population density could be obtained by collecting a 50-core sample from pineapple fields.

Nematode management following the withdrawal of EDB

During the EDB era, pineapple growers made little attempt to identify the causes of their soilborne pest and disease problems or assess their relative importance because soil fumigation was seen as the universal solution to all potential problems. Thus, in the 2 years before the withdrawal of EDB, growers were encouraged to leave untreated areas in some fields, check roots for symptoms of all soilborne pests and pathogens and monitor fields for nematodes. This process provided information on whether root-knot nematode, *Phytophthora cinnamomi*, white grubs or symphyla were the main causes of crop loss on a particular farm, and allowed growers to determine which of the following management options would be most appropriate for their circumstances when EDB was finally withdrawn in June 1999.

Table 5. Populations of *Meloidogyne javanica* and the root gall index 12–15 months after planting pineapple at 11 field sites, and the yield responses in the ratoon crop to ethylene dibromide (EDB) and fenamiphos
Modified from Stirling and Nikulin (1993)

No. root-knot nematodes/ 200 mL soil		Root gall index (0–5)	% increase in canning fruit yield	
12 months	15 months		EDB	Fenamiphos
619	366	3.3	155	262
20	185	2.0	24	0
23	77	1.3	114	70
31	26	1.6	41	0
5	30	1.1	73	71
8	5	0.5	40	46
1	0	0.2	40	0
0	0	0.1	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

Move to an alternative fumigant

In situations where growers had a chronic root-knot nematode problem, they had little option but to change to metham sodium, as it was the only alternative fumigant available at the time. About 20% of growers took this option, but because metham sodium had not been thoroughly tested on pineapple, its likely effectiveness was largely unknown. Initial results showed that provided soil moisture levels were adequate at the time of application, metham sodium produced relatively good results. It was generally not as effective as EDB in controlling root-knot nematode (G. R. Stirling, unpubl. data), but its broader spectrum of activity meant that it improved root health, presumably by controlling fungal pathogens during crop establishment.

Apply foliar sprays of fenamiphos

Pineapple is unusual amongst agricultural crops in that the nematicide fenamiphos can be applied as a foliar spray and it will reduce nematode damage by moving systemically from the foliage to the roots. Based on the results of work done by W. Apt in Hawaii (Zeck 1971*a*) and field experiments in Australia, fenamiphos was registered as a foliar treatment for both plant and ratoon crops. Since root-knot nematode does not cause economic losses in pineapple unless the nematode can be detected in soil 12 months after planting, growers wishing to use fenamiphos were able to check for root-knot nematodes at 9–12 months and then decide whether to apply the nematicide. Similarly, a decision to use fenamiphos in the ratoon crop was to be based on results from soil samples taken after plant crop harvest. About 30% of growers chose to rely on fenamiphos for nematode control after EDB was withdrawn, although some of them applied it routinely rather than making application decisions on the basis of monitoring results.

Cease using nematicides

The option of not using a nematicide was only available to growers who did not suffer obvious losses from root-knot nematode. These growers comprised ~50% of the industry and usually had farms on light textured soils. Although the reasons that these farms were relatively free of root-knot nematode problems are not known, root rotting due to *Phytophthora* during periods of heavy rainfall, together with the limited capacity of sandy soils to retain moisture between intermittent rainfall events, may have limited nematode multiplication (Stirling and Nikulin 1993). Regardless of the reasons, growers without major nematode problems ceased using nematicides and turned their attention to managing

Phytophthora, which was often the main cause of their root disease problems.

The current situation with regard to nematode management

In the 8 years since EDB was withdrawn, one further change has taken place: 1,3 D is now registered for use on pineapple in Australia. This fumigant had been applied to pineapple elsewhere in the world for more than 60 years and Australian growers requiring a fumigant had always seen it as the preferred replacement for EDB. Interestingly, however, less than 10% of the pineapple-growing area is now treated with 1,3 D. One reason for this is that 1,3 D is more volatile than EDB and growers without access to irrigation water find it difficult to seal the soil adequately after the fumigant is injected. However, the main reason for the low uptake of 1,3 D is its relatively high price (>A$2000/ha), which amounts to ~8% of total production costs.

Only about one-third of the pineapple growing area is now fumigated, with most of this area treated with metham sodium. This chemical is about half the price of 1,3 D and growers using it have found it gives satisfactory results, provided the soil is evenly moist (following rainfall) at the time it is applied. In some grower comparisons of metham sodium and 1,3 D, metham sodium has produced higher yields in the ratoon crop, presumably because it provides better control of root pests and pathogens other than nematodes. On the remaining pineapple farms, nematodes are currently managed by judicious use of fenamiphos, applied as a foliar spray. Given the relatively low application rates (6 L/ha) of fenamiphos that are required, this is the most economically feasible option, as a single spray costs less than A$200/ha.

Monitoring nematodes and root health

Since Australian pineapple growers had relied on EDB for 30 years before it was withdrawn, they did not understand the aetiology of the nematode pests they were dealing with and never had to think seriously about how nematodes might be managed without fumigants. Therefore, extension staff and scientists working in pineapple put considerable effort into informing growers about integrated pest management (IPM) and how it might be applied to nematodes. Monitoring was seen an important component of an IPM program, because it allowed growers to determine whether nematodes were really their key pest, and to start making informed decisions about how nematodes might be managed in future. Initially, monitoring was done as a component of industry-funded research projects, but commercial diagnostic services took over once EDB was withdrawn. The process involved growers sampling fields four times during the crop cycle (before planting, 12 months after planting and after both plant and ratoon crop harvests), and sending the soil samples to a laboratory for nematode analysis. Growers also dug up plants periodically and inspected roots for galling caused by root-knot nematode or signs of damage from *Phytophthora* or other root pests.

This nematode monitoring and root health program had the desired effect, as it made growers realise that each farm and field had a unique set of root disease problems, depending on its particular circumstances in terms of soil type and location. Perhaps the most important finding was that *Phytophthora* was responsible for many of the poor growth problems that were thought to be caused by nematodes. In these cases, growers were able to target this problem and redirect money used previously for nematicides and fumigants to chemicals suitable for *Phytophthora* control (e.g. metalaxyl and phosphorous acid).

As with many monitoring programs for crop pests, the number of samples collected declined over the years as growers began to understand nematode population dynamics on their farms and were able to identify the soil types or fields where nematodes did or did not cause problems. However, 8 years after EDB was removed from the market, some growers still use commercial nematode diagnostic services to provide nematode counts that help them make decisions about whether a nematicide should be applied.

To date, nematode monitoring in pineapple has been done by extracting nematodes from soil using standard methods and manually counting them under a microscope. However, following the development of DNA tests for a range of fungal and nematode pathogens in cereals (Ophel-Keller *et al*. 1999) and their extension to root-knot nematode on vegetable crops (Stirling *et al*. 2004), this technology was tested in pineapple-growing soils. *Meloidogyne* counts obtained from the manual and DNA method were similar (Ophel-Keller *et al*. 2008) indicating that if manual processing was no longer possible due to high labour costs or loss of skills in nematode identification, samples could be processed satisfactorily using DNA methods.

Non-chemical controls

Since growers believed that the economic viability of the pineapple industry was threatened by the decision to withdraw EDB from the market, research programs on alternatives focussed primarily on chemicals that might replace EDB. However, the possibility that non-chemical controls might also be useful was also considered. Colbran (1969) had investigated the potential of various rotation crops and this work was extended by demonstrating that some cultivars of forage sorghum (particularly cv. Jumbo) were resistant to *M. javanica* and could be grown in the intercycle period between pineapple crops without compromising the decline in nematode populations that occurred in a bare fallow.

Because of industry interest in the concept of biofumigation (defined by Matthiessen and Kirkegaard (2006) as 'that part of the suppressive effects of *Brassica* species on soilborne organisms that arise quite specifically through liberation of isothiocyanates from the glucosinolates that characterise the Brassicaceae'), various *Brassica* species were also investigated as potential rotation crops for pineapple. This work showed that *M. javanica* reproduced on *B. juncea*, *B. napus* and a commercial seed mix containing three *Brassica* species. However, if brassicas were only grown during winter when low temperatures limit nematode development, nematode populations did not increase (Stirling and Stirling 2003). The same study failed to show a biofumigation effect when *Brassica* residues were incorporated into soil, possibly because the soil was too dry or the degree of tissue disruption was insufficient to maximise isothiocyanate release. Since excess water is required to maximise isothiocyanate release from *Brassica* tissue (Matthiessen and Kirkegaard 2006) and Australian pineapple growers do not have access to irrigation water and can only grow brassicas during winter (the driest time of the year), it was concluded that *Brassica* species were unlikely to be useful winter rotation crops in the pineapple industry (Stirling and Stirling 2003).

Since previous work in the sugar industry had shown that amendments of sugarcane trash reduce numbers of *Pratylenchus zeae* in sugarcane roots by 95%, possibly by enhancing fungal predation on nematodes (Stirling *et al*. 2005), and tillage had been found to impair the suppressive mechanisms that help keep nematodes under control (Stirling 2008), the impact of organic amendments and reduced tillage on nematode populations in pineapple was investigated. Minimum till treatments consisted of planting pineapple into residues of pangola grass (*Digitaria decumbens*) after the grass had been grown on beds for 6 months and then killed with herbicide. Amendment treatments consisted of sugarcane trash that was incorporated into beds as they were formed or applied as mulch after the pineapples were planted. Although results indicated that both treatments increased microbial activity (Stirling 2005), this activity was largely due to bacteria and the treatments did not generate the fungal-dominant microflora associated with nematode suppression in other studies (Stirling *et al*. 2005; Stirling 2008). Since high N inputs (650 kg N/ha.annum) were the most likely reason for a predominance of bacteria and the paucity of fungi in this experiment, it was concluded that attempts to enhance suppressiveness to nematodes in pineapple-growing soils are likely to be compromised by the fertilisation practices used in the pineapple industry.

Future directions in nematode management

At present, the Australian pineapple industry is undergoing substantial change and it is difficult to predict how nematodes will be managed in future. The number of pineapple growers has been declining for many years and a recent government decision to allow pineapples to be imported into Australia from neighbouring Asian countries is likely to exacerbate that trend. The demise of the small family farm, the trend towards larger farms and the possibility that some of the major international pineapple companies will establish operations in Australia is likely to see the industry shift towards corporate-style farming. If this occurs, the chemical-dominant nematode management programs used overseas are likely to become the norm in Australia. However, fenamiphos is unlikely to be a component of such programs because it was recently withdrawn from the United States market and its status is under review in Australia.

One other trend that will impact on nematode management is the gradual relocation of the industry to the tropical environment of north Queensland, where growing conditions are more suitable for fresh fruit production. However, this move northwards is likely to provide new challenges in terms of nematode management. *R. reniformis* is widely distributed in tropical regions of the world and high population densities already occur on long-established pineapple plantations in north Queensland, which suggests that it will become the dominant nematode pest in this region. The aetiology of reniform nematode on pineapple is well understood (Caswell *et al*. 1991) and it should, therefore, be possible to adapt the nematicide recommendations used overseas to Australian conditions. However, there is no guarantee that currently registered nematicides will be available when needed, and so future research should focus on developing farming systems for north Queensland that prevent reniform nematodes from becoming a chronic problem. Rotation crops, tillage practices, residue retention, inputs of organic matter and N fertilisation practices are the main areas that warrant attention.

Vegetable crops

The vegetable industry in the tropics and subtropics

The Australian vegetable industry is scattered across the country in several quite different climatic zones and is, therefore, able to supply fresh vegetables throughout the year. Two vegetable-growing areas in Queensland (Fig. 1) are a vital link in this year-round supply chain because their main production season is during winter, when it is too cold in southern states to grow warm-season vegetable crops. Thus, the tropical region (located around Bowen and in the irrigation area along the Burdekin River) and the subtropical region (located near Bundaberg and Childers) supply most of Australia's winter production of tomato, capsicum, zucchini, sweet corn, snow peas, potatoes and sweet potatoes, and most of the rockmelon and watermelon produced in spring and early summer.

From the perspective of nematode problems, these two regions are quite different. Most vegetable farms in the tropical region of north Queensland have relatively heavy clay soils, and except for a small area of light-textured soils in the Burdekin River delta, damage from root-knot nematode is rarely observed. In contrast, the vegetables in the southern or subtropical region are grown on either light textured, sandy loam soils or well structured volcanic soils, both of which are ideally suited to root-knot nematode (*M. javanica* and *M. incognita*). This review focuses on the latter region, which produces tomato, capsicum, rockmelon, zucchini and other vegetables worth ~A$200 million/annum.

Nematode management in 1995

The year 1995 has been chosen as the starting point for this review because it was the year that Australia, as a signatory to the Montreal Protocol on Substances that Deplete the Ozone Layer, began developing strategies to phase out methyl bromide. At the time, ~20% of the 1000 tonnes of methyl bromide imported into Australia every year were used in the subtropical vegetable industry (Anon. 1998). The main crops fumigated were tomato, capsicum and cuburbits (particularly zucchini and rockmelon).

The main reason that fumigation with methyl bromide was being used routinely by subtropical vegetable growers is that most farms had a 30–60-year history of vegetable production and soilborne pests and diseases had become a chronic problem. Root-knot nematode had the potential to cause problems on all crops, *Fusarium oxysporum* f. sp. *lycopersici* (the cause of fusarium wilt) was widespread in the tomato industry, *Pythium myriotylum* and *P. aphanidermatum* caused root rotting in capsicum and were also thought to be involved in a disease known as sudden wilt, while persistent weeds such as nutsedge (*Cyperus rotundus*) were difficult to control by means other than soil fumigation.

The vegetable production system in the Bundaberg–Childers region involves growing crops in beds mulched with polyethylene (plastic) film and delivering water, nutrients and pesticides to the soil via trickle irrigation tubing, a farming system that is sometimes referred to as 'plasticulture'. Because of the specialised nature of vegetable production and the costs involved in purchasing and laying plastic, land is usually planted to vegetables every year and double or multiple cropping is a common practice (i.e. one or two follow-on crops are grown after the main crop) before the plastic mulch is removed and the field is cultivated. Production systems of this nature cannot be maintained without soil fumigation.

Research on alternatives to methyl bromide

During the industry consultation process that was associated with the development of an action plan to phase out methyl bromide from the vegetable industry by 2005, many industry representatives argued that most of the limited research budget should be spent on confirming the efficacy of fumigant alternatives to methyl bromide. However, others were prepared to accept that there was ample evidence from previous research (Goring 1972; McKenry and Thomason 1974*a*, 1974*b*) and recent trials in other countries (e.g. Eger 2000) to show that alternative fumigants were as efficacious as methyl bromide. Thus, although some soil fumigation trials were eventually established, the primary focus of research was on developing integrated management strategies for the key soilborne pests and pathogens of subtropical vegetables (Porter *et al*. 1999; Stirling 1999).

Stirling (1999) discussed the reasons why IPM strategies for soilborne diseases had not been widely adopted in annual crops and argued that adoption rates would only improve if research was aimed at: (1) developing better pathogen detection and quantification techniques, (2) improving methods of predicting losses from pathogens, (3) developing expert systems for soilborne diseases, (4) integrating various control measures into practical farming systems, (5) understanding the relationship between soil health and disease suppression, and (6) increasing the number of sustainable control options available to growers. Therefore, research efforts in the subtropical vegetable industry have concentrated on these issues during the last 10 years.

Detection and prediction of pathogens

A survey of subtropical tomato farms showed that fusarium wilt, root-knot nematode, base rot caused by *Sclerotium rolfsii* and nutsedge were the soilborne pests and pathogens most likely to cause yield losses (Stirling and Ashley 2003). However, pest and disease incidence and severity was relatively low on most farms, even in fields that were not fumigated with methyl bromide. These observations suggested that IPM strategies involving crop rotation, disease resistance, cultural controls and pathogen-specific chemicals would provide acceptable control. Since such practices can only be used effectively when growers are able to reliably predict which pests or pathogens should be targeted in the next tomato crop, the next step was to improve prediction procedures.

In a follow-on study, Stirling *et al*. (2004) used a two-step process to assess the risk of losses from root-knot nematode and fusarium wilt in fields to be planted to tomatoes. The first step involved deciding well before planting whether the level of disease risk was high enough to justify collecting samples to determine pathogen inoculum density. This interim risk assessment was done using readily available information on the major factors likely to affect disease risk (e.g. cropping history, disease history, soil texture and expected temperature during the growing season), in order to calculate a hazard index (a score between 0 and 50). Although the usefulness of the hazard index was sometimes limited by a lack of reliable data on disease history, it had some predictive value. All sites with hazard indexes greater than 40 were later found to have moderate infestations of root-knot nematode, and most sites with hazard indexes greater than 35 were later found to have more than 3% of plants affected by fusarium wilt.

Since experiments in pots and the field confirmed that the incidence and severity of fusarium wilt and root-knot nematode was related to pre-planting inoculum density, the second step in the prediction process involved using DNA tests to estimate population densities of these pathogens. The DNA test for root-knot nematode was useful from a practical point of view, as it detected nematode populations capable of causing economically damaging levels of galling at harvest. However, the test for *F. oxysporum* f. sp. *lycopersici* was not sensitive enough to always detect the pathogen in soils where 4–10% of plants were diseased (Stirling *et al*. 2004).

There were two important conclusions from these studies. First, a wide range of soilborne pathogens may be present on a farm but usually only one or two of them actually cause economic losses in individual fields (Stirling and Ashley 2003). Second, risk assessment procedures based on knowledge of the hazard index and the inoculum density have the potential to predict the likely level of damage from these pathogens in the next tomato crop (Stirling *et al*. 2004).

From the perspective of nematode management, progress has already been made in implementing risk assessment and prediction processes in the subtropical vegetable industry. Since most growers employ pest management consultants and agronomists to monitor insect pests, collect soil and plant samples for nutrient analysis and provide agronomic advice, it was a relatively simple step for these consultants to also provide nematode monitoring services and advice on nematode management. Some consultants now offer such services, although the soil samples they collect are processed by nematology laboratories using traditional techniques. DNA technologies are likely to provide an alternative in the future (Ophel-Keller *et al*. 2008).

It is now 2 years since methyl bromide was withdrawn from Australia's subtropical vegetable industry and most growers have simply replaced methyl bromide with an alternative fumigant [i.e. either Telone C-35 (62% 1,3 D and 35% chloropicrin) or metham sodium]. Currently, one of the main stumbling blocks preventing vegetable growers adopting an IPM approach to managing nematodes and other soilborne diseases is that soil fumigation is viewed as good insurance. Vegetable growers have contracts with supermarket chains that must be fulfilled and they also have large investments in land and infrastructure. Growers are, therefore, not prepared to accept the risks associated with IPM, particularly during the introductory phase (Stirling 1999). Perhaps the solution to this problem is for the large vegetable retailing companies to support their contracted growers if yield and/or quality falls below expectations when IPM is introduced. Risk management support of this nature is only likely to be required for a few years (while the teething problems involved in implementing IPM are solved), but it would have a major impact on the rate of adoption of IPM.

Soil health and disease suppression

The results of a survey carried out in the Bundaberg area by Pung *et al*. (2003) and discussed in detail by Stirling (2008) clearly show that that the soils used for subtropical capsicum production are degraded from a chemical and biological perspective. Regardless of the way the soil's biological status was assessed, all measured parameters were substantially poorer in soils under capsicum than in similar soils in adjacent reference sites under undisturbed pasture. There are many reasons for the unhealthy state of capsicum-growing soils, but a lack of organic inputs is probably the most important. Fields are bare fallowed for several months each year and even when beds are formed, there may be a further month or two of fallow (perhaps with an additional solarisation effect from the plastic mulch) before a crop is planted. Since vegetable crops grow for no more than 3–4 months and have relatively small and shallow root systems, there are virtually no organic inputs unless a green manure crop is grown. When such inputs do occur, they are largely negated by the tillage practices used to prepare the land for the next vegetable crop. Finally, the application of a soil fumigant with a broad spectrum of activity further depletes the soil biota and reduces the soil's biological buffering capacity to the point where pathogens rapidly reestablish and the soil must be fumigated before every crop.

The main pathogens targeted by soil fumigation in the subtropical capsicum industry are root-knot nematode (*M. incognita*) and two species of *Pythium* (*P. myriotylum* and *P. aphanidermatum*. Recent research (Stirling and Eden 2008) has, therefore, focussed on finding more sustainable control measures for these pathogens. The potential of organic amendments was investigated because they have long been used to enhance the suppressiveness of soils to nematodes (Muller and Gooch 1982; Stirling 1991; Akhtar and Malik 2000) and *Pythium* spp. (Hu *et al*. 1997; Hoitink and Boehm 1999), while organic mulch was used instead of plastic in an attempt to make the soil environment less conducive to Pythium root rot. Forage sorghum was the source of the organic mulch because it is relatively resistant to root-knot nematode and is often grown as a rotation crop in the subtropical vegetable industry. Sugarcane residue was used as an amendment because it is readily available in subtropical vegetable-growing areas and had given good control of *Meloidogyne* and *Pratylenchus* in previous experiments (Stirling *et al*. 2003, 2005).

The results of the study of Stirling and Eden (2008) showed that amending soil with sugarcane residue plus N, 4 months before planting capsicum enhanced microbial activity, increased numbers of free-living nematodes, decreased populations of root-knot nematode and reduced the severity of galling caused by the nematode (Table 6). The amendment also reduced the severity of Pythium root rot. Root rotting was also less severe in beds mulched with forage sorghum residue than in plastic-covered beds, probably because the organic mulch reduced soil temperatures to levels that were suboptimal for *Pythium* spp. that thrive at high temperatures.

Components of sustainable vegetable farming systems

Growers who routinely fumigate their soil before planting a vegetable crop are unlikely to adopt more sustainable management practices for soilborne diseases until an alternative farming system is in place that is relatively easy to implement, is as profitable and productive as the current system and is not prone to unexpected losses from soilborne diseases. A farming system with these characteristics has not yet been developed, but is likely to be based on the following elements.

Crop rotation

Forage sorghum is an excellent rotation crop for reducing populations of root-knot nematode in subtropical climates (Gallaher *et al*. 1991; McSorley and Gallaher 1991, 1993) and experience in Queensland has shown that when some cultivars are

Table 6. Effect of soil management treatments in a field trial at Bundaberg, Queensland on numbers of free-living nematodes, microbial activity, populations of root-knot nematode and the severity of galling caused by the nematode

Modified from Stirling and Eden (2008). SCN, sugarcane residue + nitrogen; C, compost; F, fenamiphos; FS, forage sorghum; P, plastic. For each parameter measured, means followed by the same letter are not significantly different (P = 0.05)

Treatment				No. free-living nematodes/200 mL soil[A]	Microbial activity (µg FDA/g/min)[A]	No. root-knot nematodes/ 200 mL soil[A]		Gall rating[B]	
Amendment	Tillage	Mulch	Other			Pre-planting	Harvest	38 days	Harvest
Nil	–	FS	–	1585bc	0.59c	247a	5130abc	6.8a	6.9ab
Nil	–	P	–	1860b	0.62c	149a	4470bc	6.0a	7.3a
Nil	+	P	–	1350bcd	0.60c	11bc	7585ab	3.8b	6.1b
SCN	–	FS	–	3235a	0.88b	29b	3470bc	2.8b	4.9d
SCN	–	P	–	3020a	1.00a	10bc	3390bc	3.3b	5.3bcd
SCN	+	P	–	1150cd	0.92ab	1c	10715a	4.0b	5.1cd
C	+	P	C	1020d	0.61c	5c	10715a	4.0b	5.7bc
Nil	+	P	F	1200cd	0.49d	3c	6025abc	1.5c	4.9d

[A]Data are means for samples taken before planting and 19 days after planting.
[B]Galling rated on the 0–10 scale of Zeck (1971*b*).

grown as a green manure crop, nematode populations usually decline to levels that do not damage vegetable crops. Additionally, forage sorghum grows fast enough to out-compete weeds that are often hosts of the nematode, and it has a positive impact on soil health by producing a large amount of biomass in a relatively short period. Crops with these characteristics should, therefore, be the mainstay of vegetable farming systems in the subtropics.

High inputs organic matter

In the long term, the subtropical vegetable industry cannot continue to ignore the positive effects of soil organic matter on important soil properties such as aggregate stability, cation exchange capacity, nutrient retention and release, water infiltration and water holding capacity (Weil and Magdoff 2004). Therefore, steps must be taken to increase C inputs through cover cropping, retention of crop residues and the addition of organic amendments. The amount of tillage must also be reduced because of its negative impact on levels of soil organic C (Franzluebbers 2004).

Pathogen-suppressive soils

Since organic-matter mediated disease suppression is a well documented phenomenon (Stone *et al*. 2004), it should be possible to develop vegetable farming systems that are resilient enough to cope with the effects of soilborne pathogens. The best way of achieving this is to use a systems approach in which the cultural practices and inputs required to generate disease suppressive soils are identified and these practices are then integrated into a practical farming system.

Data on pathogens and beneficial organisms

As already indicated, DNA tests for some important vegetable pathogens have been developed and the number of tests available is likely to increase rapidly in the next few years. Thus, the tools needed to monitor the main soilborne pathogens of vegetables will eventually become available. However, tests for key indicators of a soil's biological status must also be developed because the number and diversity of organisms within the food web has a major impact on disease severity.

Pathogen-resistant or tolerant cultivars

Resistant and/or tolerant cultivars are currently used in the subtropical tomato industry to limit losses from race 3 of *F. oxysporum* f. sp. *lycopersici*. It is essential that genetic solutions to soilborne disease problems remain an option in the future, but this will only occur if growers use resistance in a way that does not encourage the development of resistance-breaking biotypes of the pathogen.

Pathogen-specific chemicals

A new generation of pesticides with low mammalian toxicity and relatively specific modes of action is now being produced by the agrochemical industry. From the perspective of nematode and soilborne disease management, a key requirement is that chemicals are developed that can be used in IPM programs to target specific soilborne pathogens.

Future vegetable farming systems

The challenge of the future is integrate the above elements into farming systems that are productive and profitable, and relatively free of the risk of soilborne diseases. One option for the subtropical vegetable industry that warrants further research is the integrated sugarcane-vegetable farming system advocated by Stirling (2008). In such a system, sugarcane is grown on permanent, non-tilled beds that are never trafficked because global positioning system guidance is installed on machinery, and vegetables are used as the primary rotation crop. Vegetable crops would be planted by direct-drill techniques into trash covered beds in much the same way as current rotation crops such as soybean. In areas where it is not possible to grow sugarcane, other grasses (e.g. forage sorghum or Rhodes grass) could be used as mulch producers in a permanent bed, no-till vegetable production system. Such farming systems are likely to minimise the impact of nematodes and other soilborne pathogens by reducing inoculum densities and restoring soil health to the point where biological mechanisms of suppression begin to operate. Other control measures (e.g. resistant cultivars and pathogen-specific chemicals) would never be the primary control tactic but would be available as a backup if required.

Future directions in nematode management in tropical and subtropical horticulture

During the last 15 years, Queensland's tropical and subtropical horticultural industries have had to cope with the withdrawal of methyl bromide and EDB and become less reliant on organophosphate and carbamate nematicides. The banana, pineapple and vegetable industries have met those challenges and are now taking the first tentative steps towards a future where nematicides will be a secondary rather than a primary nematode control tactic. Growers are generally prepared to move in that direction but will not accept control measures that are unreliable or incompatible with modern horticultural farming systems. Thus, the primary focus of future research will be on integrating crop rotation, organic inputs, tillage practices and other soil and crop management practices into practical farming systems that sustain productivity, enhance soil health and consistently minimise losses from nematodes and soilborne pathogens.

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