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Cereal Cyst Nematode and Its

Australia has a long history of wheat-growing. The first crop was sown near Sydney in New South Wales after the arrival of the "First Fleet" from England in 1788. Wheat is grown in all states except the Northern Territory, and 80% of the crop is exported.

There are several distinct wheat belts in Australia, each having its own climatic peculiarities. The most important is the southern wheat belt extending through South Australia and Victoria (Fig. 1). It was first settled in the mid-1800s, although parts were not used for growing wheat until the rail system was extended 70 years ago. The native vegetation (predominantly gum trees, ie, *Eucalyptus* spp.) was cleared, and the land was used initially to graze sheep for the production of wool and meat and later for growing cereals. The soils of the southern wheat belt are deficient in phosphorus and nitrogen. The annual rainfall of the region is low, ranging from 240 mm in the north to 600 mm in the south, with the heaviest rains occurring during the winter months (May–September). Spring wheats are sown from May until July (autumn–winter), grow through the winter, and are harvested in December (early summer) (Fig. 2).

Cereal Cyst Nematode and Its Importance

The cereal cyst nematode (CCN) (*Heterodera avenae* Woll.) is now regarded as the most important pathogen of wheat and other cereals in the southern wheat belt. More than 2 million hectares in Victoria and South Australia are infested (Fig. 3), and annual losses in grain yield in wheat alone are conservatively estimated at $70 million (U.S. dollars).

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Fig. 1. Southern wheat belt of Australia.

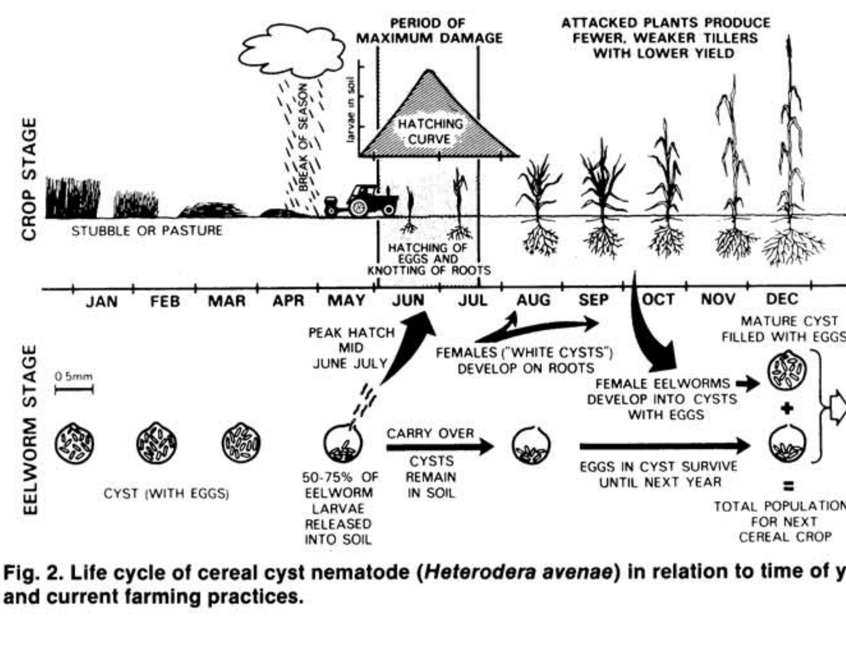

Fig. 2. Life cycle of cereal cyst nematode (*Heterodera avenae*) in relation to time of year and current farming practices.

Chemical Control in Australia

A native of northern Europe, CCN was first recognized as a pathogen of cereals in 1874 in Germany. CCN was first reported in Australia in 1930, but herbarium specimens dated 1904 in the plant disease collection at the Plant Research Institute in Burnley, Victoria, show that it was present in South Australia many years earlier.

CCN has become widely distributed throughout the southern wheat belt, largely as the result of movement of cysts by wind during the turbulent dust storms that occur periodically in this region. Despite the ease of dissemination of CCN, not all wheat-growing areas became infested, as distribution of the nematode and symptom expression are both influenced by soil type. CCN can be detected on well-structured soils (sands and clay loams) but is not usually found on heavy, poorly structured soils in nearby wheat-growing areas climatically similar to infested areas on the lighter soils. There is also a consistent association of increased disease severity with lighter soil types. In recent years, disease patches in cereal crops usually have been caused by CCN combined with such soilborne fungi as *Rhizoctonia solani* Kühn. Glasshouse experiments have shown that the effects of these pathogens combined are greater than those of either pathogen alone, but the nematode is more damaging than the fungus (8).

Control by Nonchemical Means

Since the late 1930s, control of CCN has been based on crop rotations that include varying periods of fallow or of a nonhost crop (native grasses, pasture legumes, lupines, field peas, etc.) between cereal crops (11). Losses in grain yield are greatest where heavy cropping, usually a fallow/wheat rotation, has resulted in a high level of infestation accompanied by depletion of soil nitrogen reserves (8). Inclusion of a legume in a 3-year rotation counteracts both these effects. Most farmers in the southern wheat belt derive

Fig. 3. Cereal cyst nematode damage in wheat.

their income from both sheep and wheat. The rotations they practice must be compatible with both enterprises, as one commodity or the other is emphasized, depending on relative net returns. Even though effective, crop rotation has limited value on small farms, ie, less than 260 ha. In addition, rotations that include a pasture phase are unpopular with growers who want to intensify their cereal cropping.

Some control of CCN can also be obtained by manipulating sowing dates. Sowing crops during May–June maximizes wheat yields. Eggs of CCN start to hatch during March and April, and the number of larvae in the soil is highest in mid-July (Fig. 2). In a season with average rainfall, the number in mid-July may be as high as 800 per 500 g of soil; in an excessively wet year, the number may exceed 1,500. In a wet year, sowing should be done earlier than May–June if possible; a month's delay, eg, from June until July, can result in a yield loss of 1 t/ha (4). Early sowing enables establishment of vigorous seedlings, since fewer larvae are present at sowing, but is possible only if rainfall is adequate during March and April. Otherwise the soil is too dry for the cultivation needed to control weeds and prepare seedbeds. Such practices as resowing of diseased crops, applying additional fertilizer to boost crop growth, and applying an herbicide to reduce competition from weeds have little practical value.

Fig. 4. Three-week-old wheat seedlings: (Left and right) Healthy, (center) nematode-infested.

The possibility of using resistant cultivars was considered in Australia 50 years ago. At that time, resistance in wheat was needed but sources of resistance were reported only in oats. In the late 1960s, further attempts were made to find sources of resistance in wheat and other cereals. Tests showed that the pathotype present throughout the southern wheat belt differed from those recognized internationally. Ten years ago the first source of resistance in wheat to the Australian pathotype of CCN was reported, and since then four other sources of resistance have been confirmed. Three of the five are durum wheats suitable only for making pasta and therefore of little value in our wheat-breeding programs. One of the two other sources (an unnamed spring wheat from Afghanistan) has been used to produce the cultivar Katyil, the world's first wheat bred specifically with resistance to CCN. Unfortunately, Katyil, as well as other lines nearing commercial release, has a low yield potential. Unless future resistant cultivars have the potential to outyield current cultivars, growers will have little incentive to sow them.

Chemical Control

The pioneering years (1967–1973). Our venture into the world of nematicides and their use on cereals began almost by accident in 1967. Little information was available on the levels of yield losses caused by CCN, and application of a nematicide to an infested field site provided a method of quantifying these losses. Earlier assessments had been made on rotation experiments where improvements in grain yield were due not only to nematode control but also to improvement in soil nitrogen levels resulting from growing legume pasture species. Despite their widespread use on other crops in Australia, nematicides had never been used on cereals.

The first nematicide trial was conducted in northern Victoria on a light sandy soil typical of much of the southern wheat belt. Four nematicides were applied as preplant treatments (Table 1). The fumigants ethylene dibromide (EDB) and dibromochloropropane (DBCP) were injected by handgun 4 weeks before sowing, and the nonvolatile nematicides aldicarb (Temik) and methomyl (Lannate) were broadcast onto the surface of the plots just before sowing. The plots were sown in May, and within 3 weeks large differences were evident in the growth and vigor of plants in the treated plots and those in the untreated plots (Figs. 4 and 5). All nematicide treatments increased grain yields and also lowered the number of white cysts (immature females) on plant roots. Yield was doubled by EDB treatment and tripled by Temik treatment (3).

Table 1. Effects of nematicide treatments on cereal cyst nematode populations and wheat yield, Victoria 1968

Treatment (a.i./ha)	White cysts (no./plant)	Grain yield (t/ha)
Ethylene dibromide 50 L	4.7	1.4
Dibromochloropropane 4.5 L	14.6	1.3
Dibromochloropropane 23 L	1.8	1.0
Lannate 12 kg	8.4	2.0
Temik 1.1 kg	0.0	2.3
Untreated	52.5	0.7

Fig. 5. Australia's first nematicide trial in cereals, Victoria 1968.

The results were spectacular, and we were forced to consider more seriously the possibility of using nematicides to control CCN. Predictions that such treatments were feasible were greeted with skepticism. Nonvolatile nematicides appeared to offer the best prospects, so we decided to concentrate on them. Over the next 6 years we undertook a comprehensive program to evaluate the effectiveness of every available nematicide. Methods, rates, and times of application of the nematicides were examined with a view to their possible commercial use (1,2).

When applied as broadcast treatments, all the nematicides controlled CCN, with the level positively correlated with the rate of application. Temik consistently provided the best control and the biggest yield increases; 9 kg a.i./ha kept plants cyst-free and advanced crop maturity by at least 2 weeks.

Fig. 6. Jectarow EDB applicator: (A) Small-scale version. (B) Commercial version, showing extractor and gauges.

Fig. 7. Nematicide trial, Victoria 1981.

Drill-row treatments in which the nematicide was mixed with the fertilizer and applied at sowing were then compared with broadcast treatments. Results showed that nematode control and yield improvement were similar with 0.3 kg of nematicide in the drill row and 1 kg of nematicide broadcast, ie, 70% less nematicide was needed for drill-row application (2).

Application by means of seed treatment or by foliar spray was also attempted. In the absence of seed treatment formulations, the wettable powder formulation of Lannate was tried. This failed because not enough nematicide would adhere to the seed without a "sticker," and the use of a sticker was considered impractical. Foliar application of oxamyl (Vydate) 6 weeks after sowing also failed despite translocation of the chemical from the leaves to the roots (1). Studies on the phenology of wheat show that a large proportion of potential yield (perhaps as much as 70%) is determined physiologically during the first 6 weeks of growth, so it is not surprising this treatment did not succeed. Clearly, if grain yields are to be maximized, the seedling must be protected early, ie, the nematicide must be applied at sowing.

By 1973 we were convinced that chemical control of CCN was not only possible but was economically feasible over large areas. Several nematicides could have been used, but the most promising was Temik at the rate of 0.5 or 0.6 kg a.i./ha applied in the drill row at sowing. Despite our optimism, the chemical companies were not prepared to register their nematicides for use on cereals. Here was an exciting new and large market, yet there appeared to be little interest in its development and exploitation. It became obvious that, in the short term at least, nonvolatile nematicides were unlikely to be used on cereals in Australia.

Light at the end of the tunnel (1974–1977). We redirected our efforts to fumigant nematicides, particularly DBCP. Several fumigants were being used on other crops, but could they be applied at low volumes as drill-row treatments at sowing? Would they be phytotoxic? Several years of work with DBCP followed, and equipment was developed to apply the chemical through tubes attached to the back of the tines on the seeder. The applicator was made from polyvinyl chloride (PVC) plumbing fittings, was inexpensive, and allowed application of DBCP mixed with water at rates of 1.5–12 L/ha. These treatments controlled CCN and boosted grain yields, but in very wet years (when soils were also colder), the highest rate of application was phytotoxic (5).

The most economical rate of application was 3 L/ha. In 1977, we were ready to recommend this treatment to growers, but DBCP was withdrawn for health reasons from the world market.

Success at last! (1978–1981). In 1978, a South Australian chemical company, Agchem Pty. Ltd., began trials with EDB applied at low rates in the drill row. Results were excellent, with no signs of phytotoxicity, at application rates of 1.25–10 L/ha. We obtained similar results in our own trials. In 1979, EDB, at the rate of 3.7 L/ha and sold under the trade name Nemadi, became the first nematicide registered for use on cereals in Australia. A special applicator (Jectarow) (Fig. 6) was developed and is now marketed commercially (6). Jectarow is made from PVC irrigation fittings, and EDB is applied through drip irrigation tubing mounted behind the seeder tines. Various models are available to suit a wide range of seeding equipment (conventional seeders, air seeders, etc.). The registration of EDB as Nemadi provided the stimulus needed, and over the next few years there was intense activity by many companies to obtain the data needed to support their applications for registration (Fig. 7). This activity culminated in the registration of four nonvolatile nematicides: Counter (15G), Vydate (L), Temik (15G), and Furadan (360F and 350ST).

Before Counter and Temik arrived on the Australian scene, cereal growers had never used pesticides in granular form. Granule applicators were not used on their farms, and consequently how to apply these nematicides effectively was a problem. Counter, because of its granule characteristics (bulk density), can be mixed with superphosphate and applied when the crop is sown, but this method is not suitable for Temik. Either nematicide can be applied through a "small seeds box" on the seed drill (normally used for undersowing a legume pasture species when the cereal crop is sown), obviating the need for a granule applicator. Gandy-type granule applicators are now commercially available, but not many growers are prepared to buy an applicator needed only a few days each year. Air seeders can also be used to apply granular nematicides.

Vydate is registered as a seed treatment, but this method of application is suitable only for growers with large properties and bulk-handling systems for wheat seed and fertilizer. At a rate of 1.5 L (360 g a.i.)/100 kg, Vydate is sprayed through nozzles mounted on the barrel of a grain auger onto the seed as it is transferred from the bulk seed bin to the seeder (Fig. 8). As the seed travels through the auger, it is coated with nematicide. Vydate is dyed green so that any treated grain accidentally spilled is not attractive to birds. Application of Vydate other than by seed treatment is not permitted, nor is storage of treated seed. This approach to CCN control has an added advantage: Nematicide costs can be reduced by lowering seeding rates, as all other nematicide treatments (except Furadan ST) are applied to the soil. Traditionally, most growers in Victoria sow their wheat crops at the rate of 67 kg/ha, but long-term experiments show that there are no significant differences in grain yield at seeding rates ranging from 49 to 99 kg/ha. Therefore, growers can lower their seeding rate without reducing grain yield.

Two formulations of Furadan are available to growers. Furadan ST is applied as a seed treatment in the same way as Vydate is applied. The flowable formulation is mixed with water in a spray tank and pumped through a modified Jectarow applicator (at a minimum total volume of 10L/ha) into the drill row when the seed is sown.

Fig. 8. Vydate being applied as seed treatment on wheat.

Fig. 9. Acrameter pump for applying EDB mounted on a seeder.

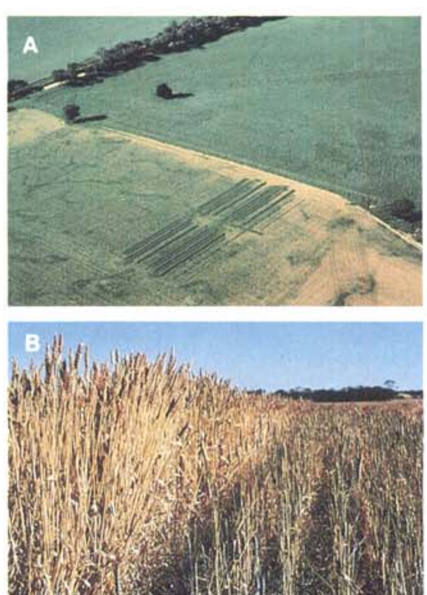

Fig. 10. Nematicide trial, Victoria 1973: (A) Aerial view 12 weeks after sowing. (B) At harvest, with healthy wheat at left and nematode-infested wheat at right.

Significant Developments in Application Technology

Major and innovative developments in application technology since 1981 have made using nematicides easier for growers. The greatest advances have been in the Jectarow system for applying EDB. The early models utilized a truck tire (800 × 20) inflated to 80 kPa as the pressure source for the system. This simple method of pressurization allowed growers to sow 75–80 ha of seed at the required pressure of 70 kPa. As the applicator became more sophisticated, compressed air, carbon dioxide, or nitrogen from a gas cylinder was substituted as the pressure source.

Any pressurized system carries the risk of an explosion or, if a pressure relief valve fails, of drums bursting. For many years, Agchem Pty. Ltd. sought a suitable pump (mechanical or electrical) to obviate the need for a pressurized system, but EDB corroded the components of all the pumps tested. Then, in 1983 the Acrameter pump was developed (Fig. 9). The pump, which can be calibrated easily for any delivery rate, is made from stainless steel and brass with Viton seals, is double-acting, and is driven by a ground wheel on the seed drill. The delivery rate is determined by the ground speed of the tractor, and the pump is easily stopped by lifting the drive wheel off the ground wheel. This development, produced commercially from the design of a cereal grower, improves operator safety by allowing EDB to be applied through a "nonpressurized" system.

Originally, Vydate was transferred from the 20-L plastic drum in which it is sold to the spray nozzles on the grain auger by means of a hose connected to an electric general-purpose farm pump (240 V AC, minimum capacity 9 L/min at a pressure ranging from 150 to 350 kPa). This system could not be used away from a domestic power source. In 1982, a new pump (12 V DC) with a built-in extracting probe and associated spray nozzles and mounts was developed commercially. The pump attaches directly to the drum of Vydate, with the probe inserted through the outlet, and can be operated conveniently from the battery on a tractor or motor vehicle. This arrangement minimizes the handling of hoses and open drums of Vydate and lessens the likelihood of accidental spillage if a drum is knocked over or of the operator being poisoned.

Counter is sold in a 40-kg pack (metal drum) that is difficult to empty manually into the fertilizer or small seeds box on the seed drill. In 1982, Ciba-Geigy in conjunction with American Cyanamid developed a Counter granule applicator.

Table 2. Effects of nematicide treatments on cereal cyst nematode populations and wheat growth and yield, Victoria 1973

Treatment (kg a.i./ha)	White cysts (no./plant)	Leaf area (cm^2/plant)	Tillers (no./m of row)	Grain yield	
				t/ha	% increase
Methyl bromide/chloropicrin 45[a]	40	178	45.4	1.3	36
Methyl bromide/chloropicrin 450	0	332	117.6	3.6	278
Temik 9	2	133	56.9	1.5	56
Untreated	53	111	37.8	0.9	...
Methyl bromide/chloropicrin 45 + nitrogen[b]	48	141	71.8	2.2	130
Methyl bromide/chloropicrin 450 + nitrogen	0	386	140.2	4.0	323
Temik 9 + nitrogen	5	199	95.4	2.6	170
Untreated + nitrogen	65	179	58.0	1.7	80

[a]Applied 1:1 3 weeks before sowing.
[b]Nitrogen applied as ammonium sulfate, 250 kg/ha.

Table 3. Effects of nematicide treatments and time of sowing on cereal cyst nematode populations and wheat growth and yield, Victoria 1981

Treatment (a.i./ha)	Time of sowing[a]	White cysts (no./plant)	Tillers (no./m of row)	Grain yield (t/ha)
Nemadi 3.7 L	Early	6.3	106.8	3.4
	Late	5.1	81.4	2.0
Temik 4 kg	Early	7.6	93.8	3.2
	Late	5.6	74.3	2.0
Counter 0.6 kg	Early	22.8	45.5	1.3
	Late	25.5	41.6	0.7
Vydate 0.2 kg[b]	Early	43.0	44.8	1.1
	Late	20.5	45.9	0.7
Untreated	Early	75.3	41.9	0.6
	Late	46.0	37.6	0.3

[a]Early = May; late = June.
[b]Applied as seed treatment.

The applicator consists of a cylinder attached to a funnel with an adjustable butterfly valve, calibration scale, and outlet hose that allows delivery of the granules at a metered rate. The cylinder fits over the opened drum of Counter, which is then inverted by means of a mounting bracket, hand winch, and pulleys and used as a hopper. Heavy drums can be handled easily and Counter granules can be emptied into the appropriate boxes on the seeder or can be metered into superphosphate. An attachment allows the granules to be added to superphosphate through a hole in the barrel of an auger when bulk handling systems are used.

Are Nematicides Necessary?

Concurrently with our nematicide trials we conducted field and microplot experiments to study the population dynamics of CCN, to quantify yield losses (7,9), and to determine for the first time in Australia the yield potential of wheat in the absence of soilborne pathogens (10). The average wheat yield of the southern wheat belt is only 1.6 t/ha, but this low yield is influenced by such factors as various soilborne diseases, nutritionally poor soils, and lack of rainfall. Rainfall in 1973 was double the average annual amount, and soil fumigation experiments with mixtures of methyl bromide and chloropicrin in Victoria boosted grain yields by 2.7 t/ha—and by 3.1 t/ha when plots were top-dressed with ammonium sulfate (Fig. 10). The plants in fumigated plots were free from root diseases, and the results showed that the yield potential of existing wheat cultivars is at least three times greater than the average for the region (Table 2).

From microplot studies where CCN population levels were manipulated by growing resistant and susceptible cultivars for successive years, we know that the potential ceiling (the maximum level at which a population can be sustained) is 23 eggs/g of soil. Initial population levels as low as 2 eggs/g depress yields by 20%; with 4 eggs/g the loss is 35%. In the field, levels of 3–5 eggs/g are common, and some fields have levels greater than 10 eggs/g. In all these situations, significant losses in grain yield will occur if susceptible cultivars are sown without a nematicide treatment (Table 3).

The Sironem Bioassay

Failure to apply a nematicide on a heavily infested field may result in costly yield losses, but the unnecessary use of a nematicide may be just as expensive (some cereal growers have spent up to $20,000 on nematicide for CCN control). What criteria are used by growers in deciding whether or not to use a nematicide? How do they know when CCN population levels in their fields are

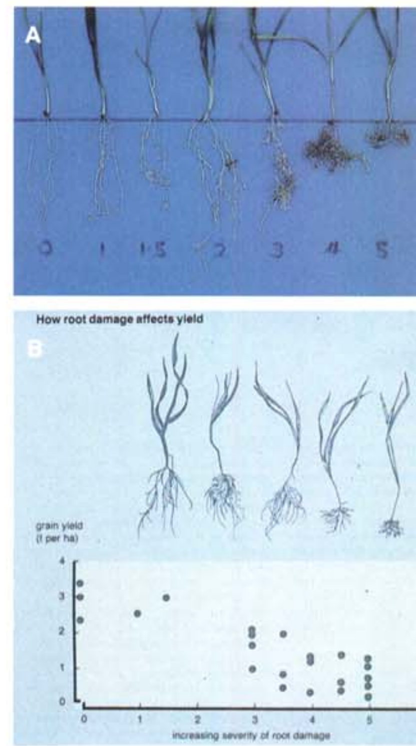

Fig. 11. Sironem bioassay ratings: (A) On wheat seedlings. (B) Relationship with wheat yield (after Rovira 1982).

above damage thresholds? Extensive areas are cropped each year, but with existing nematology resources in Victoria and South Australia, it is impossible to assess population levels of individual fields.

In an attempt to overcome this problem, the C.S.I.R.O. Division of Soils (a federal government research organization) developed a preseason soil test—the Sironem bioassay—in 1978 (12). The bioassay has been commercialized, and two companies offer their services to growers at a cost of about $25/40 ha. Both companies provide free "bioassay kits" that are available from chemical agents in rural areas. The kit provided by Agchem Pty. Ltd. consists of five 1-L waxed paper milk cartons with ties for the tops and labels; details on sampling procedure; a form to record previous cropping history of the field, planned

Table 4. Nematicides registered for control of cereal cyst nematode in Australia

Trade name	Common name	Type	Formulation	Concentration	Mode of action	Application rate	Method of application	Price	Cost/ha
Nemadi	Ethylene dibromide (EDB)	Fumigant	Liquid	2 kg/L	Fumigant	3.7 L/ha	Through Jectarow	$4.76/L	$17.60
Counter	Terbufos	Nonvolatile	Granule	150 g/kg	Contact and systemic	4 kg/ha	Mixed with superphosphate; small seeds box; granule applicator	$4.00/kg	$16.00
Vydate	Oxamyl	Nonvolatile	Liquid	240 g/L	Contact and systemic	1.5 L/100 kg of seed	Seed treatment	$23.00/L	$21.00[a]
Temik	Aldicarb	Nonvolatile	Granule	150 g/kg	Contact and systemic	2 kg/ha	Small seeds box; granule applicator	$13.00/kg	$26.00
Furadan	Carbofuran	Nonvolatile	Flowable	360 g/L	Contact and systemic	1.1 L/ha	Through modified Jectarow	$15.85/L	$17.45[a]
		Nonvolatile	Liquid	350 g/L	Contact and systemic	1.8 L/100 kg of seed	Seed treatment	$18.30/L	$19.75

[a]At seeding rate of 60 kg/ha.

crop species and cultivar (wheat, oats, resistant, susceptible, etc.), and proposed use of postemergence herbicide, fertilizer, etc.; and a preaddressed cardboard box for returning the samples to the company's laboratory.

Soil samples are collected by growers during the summer (late November to February) from fields being prepared for the next crop. Each 1-L sample is a composite of several subsamples and represents an area of 8 ha. When received by the laboratory, each sample is moistened and incubated at about 10 C for 4 weeks to allow any CCN eggs to hatch. A pregerminated seedling of a susceptible wheat cultivar is planted in the soil and grown under artificial light at about 15–20 C for 4 weeks. The seedling is then washed from the soil and, after the roots are examined for CCN damage, rated on a scale of 0 (not infected) to 5 (heavily infected) (Fig. 11).

The bioassay result indicates *the potential for damage to occur* should the season be favorable for the nematode and does not guarantee that damage will occur. The grower receives a report on the bioassay result and is advised on available control options—use of a resistant cultivar, nematicide, etc. In practice, a bioassay rating of 1.5 equates with a potential yield loss of 10% in a susceptible wheat cultivar. The use of a nematicide can be justified economically when the rating exceeds 1.5. Grower acceptance of the bioassay is increasing, from 4,000 individual soil samples bioassayed in 1981 to an estimated 10,000 in 1984.

The Current Situation

The results of 15 years of research in which more than 150 large-scale field trials have been conducted in Victoria alone show that nematicide application can provide excellent control of CCN and improve grain yields. The advantages nematicide-treated crops have over untreated crops include quicker establishment, more vigorous growth, better competition with weeds, and earlier maturity. It should be emphasized that nematicide treatments, especially at the very low application rates recommended for cereals, reduce CCN numbers but do not eliminate them. Therefore, a field may have to be re-treated when cropped again.

The five nematicides now registered for use on cereals permit a wide selection of application methods, and the grower has several options for meeting particular requirements (Table 4). Nematicide treatments cost between $16 and $26/ha, depending on the product chosen. Wheat is currently valued at $135/t, and a yield increase of 11–13% is all that is needed to cover the cost of treatment. Most growers using nematicides have improved yields by 30% or more.

Where Do We Go from Here?

There is little doubt that nematicides have provided Australian cereal growers with an effective new method of controlling CCN. The principles on which chemical control of the nematode are based have been clearly established, and all current nematicide treatments take account of them. Less than 10% of the area infested has been treated so far, and larger areas most certainly will be treated in the future. The methods by which nematicides can be applied in the field have been rigorously tested. All methods have received grower endorsement, although individual growers, for various reasons, may prefer one method over another. The extent of the CCN problem in the southern wheat belt has been adequately highlighted, as has the market potential for nematicides. Several new nematicides are being evaluated, and if eventually commercialized, they will have to compete with existing products. This competition can only benefit the growers, who will have a wide range of available nematicides and application options.

Despite the demise of EDB as a soil fumigant in the United States, its use against CCN has not been banned in Australia, principally because the application rate is low (3.7 L/ha) and because shallow water tables are absent in the southern wheat belt, with little likelihood of residues being leached down the soil profile.

Effective control of CCN can never be based solely on the use of nematicides. The future undoubtedly lies in integrated control programs relying on well-planned rotations, good weed control, manipulation of sowing dates, resistant cultivars when available, and judicious use of nematicides.

What we need now is to put all these into practice.

Acknowledgments

I acknowledge with thanks the support provided over the years by the Australian agricultural chemical industry. I particularly thank Agchem Pty. Ltd., Ciba-Geigy Australia Ltd., Cyanamid Australia Pty. Ltd., Du Pont (Australia) Ltd., FMC (Australia) Ltd., George Wills and Co. Ltd., ICI Australia Operations Pty. Ltd., and Union Carbide Australia Ltd. Without their active and continuing support none of this would have been achieved.

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