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Integrated Control of Clubroot

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Abstract Clubroot caused by *Plasmodiophora brassicae* affects the Brassicaceae family of plants, including many important vegetable and broadacre crops. In the last 20 years increasing intensity of vegetable production and the rapid growth in popularity of oilseed rape as a broadacre or arable break crop have increased the severity of clubroot and the area of land affected in both the vegetable and broadacre industries. Resting spores of *P. brassicae* are long-lived in soil, but the number of spores can be reduced through crop rotation, fallowing, chemical application, and management of brassica weeds. The host-pathogen system is responsive to a range of control measures, including calcium and boron amendments, manipulation of soil pH, and fungicide application. Molecular tests have been developed to predict disease and resistant cultivars are available for some crops. Increasingly, a multifaceted or integrated approach is being used to manage clubroot. This approach has been particularly successful in vegetable production systems.

Keywords *Plasmodiophora brassicae* · Clubroot · Lime · Calcium · Boron · Fungicides

Introduction

For generations *Plasmodiophora brassicae* Woronin, the cause of clubroot, has been the most important soilborne pathogen of vegetable brassica crops, including broccoli, cauliflower, cabbage, Brussels sprouts (*Brassica oleracea* L.), Chinese cabbage, turnip (*Brassica* rapa L.), and a number of Asian greens (*Brassica* spp.). Resting spores of *P. brassicae* are readily transmitted on or in anything that carries contaminated soil. This includes farm machinery, boots, hooves of grazing animals, infected transplants, and surface floodwater. The number of resting spores in the soil can increase rapidly under continuous cropping systems (Murakami and others 2004). These spores can remain viable for in excess of 15 years, even in the absence of a suitable host (Wallenhammar 1996). Visible symptoms of clubroot, such as root galling and wilting, become obvious only when soil concentrations of *P. brassicae* exceed the threshold required for disease development. This threshold depends upon soil type and is also influenced by the plant species or cultivar, but values lower than 10 resting spores/g soil have been reported (Murakami and others 2002a). Generally, however, when soil inoculum loads are less than 10^2 resting spores/g soil, clubroot infection is low (disease indices <30; Murakami and others 2002a) and there is little impact on crop yield or aboveground symptoms. As it is not yet possible to predict and avoid infested land until symptoms of disease become obvious, spores can be spread inadvertently in soil and water from one property to another even though the farmer may consider the field to be clean. For these reasons, adequate control has been difficult to achieve.

Traditionally, clubroot has been managed in vegetable brassicas by rotation with non-brassica crops and application of agricultural lime (calcium carbonate) to change pH (Colhoun 1958). Recently, the increased use of cell-grown transplants, continuous cropping, and the trend toward shorter rotations has increased both the area of land affected and the inoculum load in the soil resulting in an increase in crop losses due to clubroot.

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In vegetable production systems there has been no "silver bullet" solution to clubroot. Resistant cultivars of Chinese cabbage (*Brassica rapa*) have been commercially available for many years, but resistance in these crops has not been durable and there are numerous reports of control failures using some of the older resistant types (see Piao and others, this issue; Diederichsen and others, this issue). Clubroot resistance in *Brassica oleracea* has only recently become commercially available, and clubroot-resistant cauliflower and cabbage are now on sale. Very few pesticides have proven to be effective against clubroot. Those that are, often are not widely available due to registration issues or are too expensive to use except where disease pressure is high. Fumigants have provided more consistent control, but cost of treatment and environmental and health concerns and the unreliability of disease occurrence have restricted their use. These factors, together with an increased awareness of the need for better soil health management and sustainable production practices, have been conducive to the development of an integrated approach to the management of clubroot in vegetable brassica crops. Such an approach, including detection of *P. brassicae* and prediction of yield loss due to clubroot, identification of hygiene risks in nurseries, and the development of methods to minimize these risks together with in-field cultural methods, manipulation of soil pH, calcium and boron amendment, strategic use of pesticides, and the integration of these methods, has been extremely effective in vegetable production systems.

A rapid growth in production of oilseed rape (*Brassica napus*) worldwide has been followed in many countries by yield decline due to clubroot. Uptake of methods developed to manage clubroot in vegetable production systems into oilseed rape production is restricted by the relatively low value of oilseed rape. The disease cycle is identical in both production systems; therefore the principles of control of clubroot are similar.

This article presents a review of the methods available to manage clubroot and efforts to integrate individual control measures into a management strategy. This work is based mainly upon studies in the vegetable industries worldwide.

Predicting Clubroot

The ability to predict disease and expected yield loss is the foundation upon which an integrated clubroot control strategy can be implemented. In its simplest form this involves a sound knowledge of site history, including the severity of disease in the most recent brassica crop, the rotational history, site preparation, and treatments applied in previous crops. This information is readily available to most growers, but often not recorded. A range of more sophisticated serologic (Wakeham and White 1996) and molecular methods have been developed in the last 15 years to detect *P. brassicae* (Faggian and others 1999a; Ito and others 1999; Wallenhammar and Arwidsson 2001; Cao and others 2007). These techniques offer rapid and reliable means for detecting and/or quantifying *P. brassicae.* They are reviewed elsewhere in this issue by Faggian and Strelkov. When combined with sound local knowledge of factors such as soil type and climatic conditions and basic site history, these techniques can be powerful decision support tools for farmers.

Farm and Nursery Hygiene

Plasmodiophora brassicae has been detected in irrigation pond sediment (Datnoff and others 1984), dams, bores, and brassica seedling nurseries (Faggian and others 1999b). In these cases, the source of contamination of water sources is likely to have been runoff from fields infested with the pathogen. Limited studies have been conducted to try and reduce the viability of *P. brassicae* and its movement in irrigation water and this is a major challenge for future research. Datnoff and others (1987) report that 2 mg chlorine/L water reduced clubroot in cabbage. Treatment of irrigation water with 200 mg chlorine/L also reduced the incidence of clubroot in the field but reduced plant growth and yield. In addition to the effects on plant growth, treatment of large volumes of water for irrigation purposes appears presently impractical. In a recent controlled study, resting spores of *P. brassicae* remained viable in water for 34 months and repeated irrigation with water containing as few as 10 spores/ml resulted in root galling (Donald 2005). In the same study, resting spores settled in undisturbed columns of water at a rate of 25 cm/day. It was concluded that in a farm dam most of the resting spore population could be expected to be concentrated in the sediment at the bottom of the dam and that the risk of spreading disease through irrigation with contaminated farm dam water could be reduced by locating the irrigation intake pipe in the stillest part of the dam, mounted on a float to source water from near the surface.

Plastic seedling trays being returned for reuse have been identified as a high risk of *P. brassicae* contamination in nurseries (Faggian and others 1999b). Often these trays have been placed on the ground and are contaminated with farm soil on their return. There are no commercial disinfectants designed specifically for control of *P. brassicae.* Evaluation of a range of commercial disinfectant products available in Australia found that with the exception of hypochlorite (1000 ppm), all were ineffective against *P. brassicae* at the rates used (Donald and others 2002).

Hypochlorite is cheap and readily available; however, its efficacy decreases rapidly in the presence of high organic matter loads. For this reason a high-pressure prewash is recommended to remove soil and organic matter before any disinfection treatment.

In Australia guidelines developed for growers, nurserymen, and contractors detail strategies for the prevention and quarantine of new infections, disinfection, and the production and distribution of brassica transplants (Porter and Cross 1995). Anecdotally, these guidelines have slowed the spread of clubroot within isolated growing regions.

Cultural Control

It has long been recognized that a number of cultural practices influence the severity of clubroot and the longevity of resting spores in the soil. Early studies reviewed by Karling (1942) and Colhoun (1958) led to recommendations for the removal of diseased plants, improved drainage, deep ploughing, ridging (or beforming), and crop rotation. Many of these are still widely practiced today.

Ploughing in roots of plants with a relatively low level of clubroot galls (disease index 20) has been shown to add 1×10^5 spores per gram of soil (Murakami and others 2004). Given that this concentration of resting spores in soil can cause severe clubroot under favorable conditions (Murakami and others 2002a), the importance of rouging (the practice of removing diseased plants) should not be underestimated, particularly as a tool to manage new outbreaks.

Crop rotation with non-host species is commonly practiced to avoid clubroot, but very few long-term studies on the effect of crop rotation on the survival of resting spores of *P. brassicae* have been conducted. Wallenhammar (1996) demonstrated a half-life for *P. brassicae* spore inoculum of 3.6 years. Therefore, at high soil inoculum concentrations, extremely long rotations are needed to reduce soil inoculum to levels below a disease-causing threshold. Wallenhammar (1996) found that 17.3 years were required to reduce the level of infestation in soil from 100% infection to below that which could be detected using a plant bioassay. In another study conducted over a 5-year period, continuous fallow, or cultivation with a clubroot-resistant Japanese radish caused the greatest decrease in resting-spore viability. Spinach, potato, strawberry, and welsh onion were the least effective at reducing *P brassicae* populations of the 11 crops used (Ikegami 1985). Reduction of *P. brassicae* spores using crop rotation depends upon the removal of cruciferous weeds (Colhoun 1958), including shepherd's purse and wild radishes and mustards, which are also hosts of *P. brassicae.* A number of non-cruciferous hosts are known in which at least the primary stages of the pathogen's life cycle can be completed (Colhoun 1958). The influence of these hosts on resting-spore populations is still largely unknown.

Root exudates from several non-host plant species such as leek (*Allium porrum* L.), winter rye (*Secale cereale* L.), and perennial ryegrass (*Lolium perenne* L.) stimulate germination of resting spores of *P. brassicae* (Friberg and others 2005) in nutrient solution. Exudates from *L. perenne* stimulated spore germination more than those from the susceptible host species *B. rapa* var. *pekinesis.* The potential of these plants to be used to manage *P. brassicae* was studied in subsequent glasshouse and field trials, but there was no evidence that any of them would be useful in the sanitation of *P. brassicae*-infested soils within short periods (Friberg and others 2006).

Biofumigant crops such as high-glucosinolate-containing cultivars of *B. rapa* and *B. napus* have been shown to reduce soil inoculum of *P. brassicae* (Cheah and others 2001, 2006). Because, however, these crops are hosts for *P. brassicae*, their use in rotation with vegetable brassicas carries significant associated risk. Cheah and others (2001) also found that addition of leaf and stem pieces from biofumigant crops could reduce inoculum of *P. brassicae*, and it is possible that development of biofumigant crop mulches or meals might provide the required glucosinolate-mediated effect without the risk of growing a susceptible crop in rotation.

Liming

Managing clubroot by raising soil alkalinity is one of the oldest and most widely practiced methods of control (Karling 1942). Incidence and severity of disease is generally reduced at soil pH 7.2 (Colhoun 1958; Karling 1942), but a number of control failures have been reported at or above pH 7.2 (Wellman 1930; Myers and others 1981).

The contradictory results may be explained in terms of the number of variables that exist when lime is applied in the field. Particle distribution, for example, depends upon soil preparation, moisture and texture, particle size and quantity of lime, and the incubation interval between application and planting.

The form of lime affects the amount of calcium supplied per unit weight of lime, the neutralizing value of the lime, and the rate of release of calcium (Campbell and Grethead 1989). The neutralizing value (NV) of a lime is a measure of how effective that lime is at reducing soil acidity. Pure calcium carbonate has a neutralizing value of 100%. All other limes have neutralizing values expressed relative to that of pure calcium carbonate. A higher neutralizing value reflects a greater ability of that lime (relative to calcium

carbonate) to neutralize soil acidity. Burnt lime (calcium oxide), with a higher neutralizing value and pH (NV = 160%, pH 12–12.5) than calcium carbonate-based limes (NV = 80–100%, pH 7.5), has effectively controlled clubroot in a large number of regions throughout Australia, especially when integrated with other methods (Porter and others 2004).

The particle size of lime has a large influence on the reactivity of the lime. Finely ground limes have a greater surface area to contact with hydrogen ions than coarser limes (Leonard and Bolland 1996) and potentially can be better distributed throughout a soil profile. Dobson and others (1983) together with Tremblay and others (2005) report significantly reduced incidence of clubroot in soil limed with a fine limestone than with a coarser fraction. The work of Dobson and others (1983) suggests that the source of the lime is less important than the surface area of the lime particles. Dobson and others (1983) report variation in soil pH (measured in 0.01 M $CaCl_2$) of up to two pH units from soil microsites (5-g samples) in a moist silt loam rototilled with lime to achieve an average soil pH of 6.7. They concluded that in poorly mixed soils control failures could be explained in terms of the growing root passing through acidic microzones where the pathogen could remain active. This finding supports the earlier work of Haenseler (1937) who reported pH ranges of 5.73–8.45 in microsoil samples taken from a composite sample with a pH of 7.87 following 8 years of liming.

Timing the application of liming materials so that soil pH is highest at transplanting is also critical. For example, Webster (1986) found that the number and maturation of root hair infections is minimized by exposure to alkaline pH within 3 days of inoculation. Prolonged exposure beyond 3 days gave no further reduction in root hair infection number or maturation but did suppress the development of symptoms of disease. Most significant reductions in disease index required alkaline pH applied over a 3–7-day period after inoculation.

Different soil types are known to vary considerably in their response to application of liming materials. The pH of soils with a high buffering capacity, such as those found in Santa Cruz and Monterey counties, California (Welch and others 1976), is difficult to adjust. In other soils termed "lime nonresponsive" by Myers and others (1981), lime failed to control clubroot even where the pH of the soil was changed to 7.7.

In a subsequent study of soils in the Salinas Valley, California, Campbell and others (1985) correlated soil pH and extractable cations (calcium and magnesium) with control and proposed that cation concentration was a second important consequence of liming that affects disease control. They predicted that the actions of pH and cation concentration on the development of clubroot are not independent. This view was challenged by Dixon and Webster (1988). Their use of organic buffers enabled the effects of pH, calcium, and boron to be distinguished. They concluded that although the effects on *P. brassicae* are independent, when combined they act synergistically.

Nutritional Control

Reed (1911) analyzed healthy and clubbed roots and established that although ash constituents were more abundant in diseased than in healthy roots, the greatest increase of any single element in diseased roots was that of potassium. In an early study on the effect of host nutrition on clubroot development, Pryor (1940) reported a 60% reduction of disease development in susceptible cultivars grown in potassium-deficient media. Walker and Hooker (1945) report a similar effect of potassium, obtaining a consistently higher disease index at higher concentrations of potassium. These works indicate that potassium may be necessary for the growth of *P. brassicae* as well as its host and provide early evidence that disease development can be manipulated by plant nutrition.

Several studies suggest that calcium or magnesium in lime may affect disease development independent of pH (Myers and Campbell 1985; Murakami and others 2002b). This interrelationship between mineral nutrients in the soil system is complex. For example, Palm (1963) provided one of the earliest reports of an interrelationship between calcium and boron affecting the potential ability of lime to control clubroot. In a series of seven experiments, the response curve for calcium was found to vary according to the amount of available boron, leading the author to conclude that in limed soils, boron deficiency may limit the ability of the calcium ion to inhibit disease development. He also used a sand solution nutrient system to compare the effects of calcium, potassium, and pH on the development of clubroot. At pH 5.9, sharp peaks of infection occurred at 2 milliequiv. calcium per liter and 7 milliequiv. potassium per liter. The nature of the infection curve for calcium suggested that the primary action of calcium above 2 milliequiv./L was not action against *P. brassicae* but that excess calcium might have changed the rate of differentiation of epidermal cell walls, making them more resistant to infection. Calcium response curves showed that when boron was omitted from the solution, the effect of increasing concentrations of calcium was suppressed. Large concentrations of potassium (8–16 milliequiv./L) were required to inhibit infection. Initially, this result may seem at odds with those of Pryor (1940) and Walker and Hooker (1945). In further studies of subsequent gall development, Palm (1963) indicated that abundant supplies of potassium following infection encouraged an expansion

of gall tissue. This study, the earliest extensive report on the effects of mineral nutrition on clubroot, provided a simple, although somewhat incomplete, explanation for the observed control failures using lime. Infection and establishment of the pathogen and subsequent gall development were affected by changes in available calcium, the ratio of calcium to potassium, pH, and the ratio of calcium to boron. In the complex soil environment, therefore, these or any number of other mineral interactions may override the effect of pH. Further investigation of these interactions required the development of a nonphosphate nutrient solution that would permit concentrations of mineral nutrients to be altered in solution independent of pH.

A nonphosphate buffer system was developed by Myers and Campbell (1985). The results obtained using this sand solution system indicated that although pH is probably the most important factor influencing the development of disease prior to liming, high concentrations of calcium and magnesium may give control at pH below 7.2. Similarly, low concentrations may explain control failures using lime at pH above 7.2. Both calcium and magnesium exhibited pH-dependent inhibition of disease. These results support field evidence (Fletcher and others 1982) using calcium and sodium salts, which suggests that the calcium ion (as gypsum, calcium sulfate) decreases the incidence and severity of clubroot, although not to the extent of changing pH by application of carbonates of calcium or sodium.

Calcium

A direct effect of calcium on the viability of resting spores of *P. brassicae* has been established for high (1 M) calcium concentrations (Myers and Campbell 1985). A similar direct effect of pH on the viability of resting spores has been reported (Lee and Hsieh 1992). Because pH levels in excess of 10 were required to observe significantly decreased viability and the effect of calcium was significant only at very low inoculum concentrations (10^2 spores/g), it can be assumed that both pH and calcium must act in some other way in most agricultural soils. Tissue analyses conducted during the controlled experiments of Myers and Campbell (1985) suggest pH-dependent uptake of calcium by the host. Whether, as suggested by Palm (1963), calcium acts simply to strengthen epidermal cell walls of the host, rendering them less susceptible to infection, or it occurs by some more complex host-parasite interaction was the subject of a detailed study conducted by Webster and Dixon (1991a). Their work provides evidence that the effect of calcium is more than merely structural. In a series of studies, calcium reduced root hair infection but also inhibited the production of differentiated and dehisced sporangia of *P. brassicae* within infected root hairs. The developmental stages of *P. brassicae* that occurred within root hairs 4–7 days after inoculation were most vulnerable to high calcium. In solution culture, exposure to high calcium (30 or 55 milliequiv.per liter)) was most effective at reducing root hair infection over days 0–3, and exposure over days 0–7 provided the most effective reduction in disease index (Webster 1986).

Root hair stages were also the most vulnerable to high pH. Both calcium and pH were shown to reduce the number of primary infections, and high calcium in combination with high pH provided more effective disease control than either acting alone (Webster 1986). Dixon and Webster (1988) proposed an intracellular effect of calcium and pH on the development of *P. brassicae* in host tissue and suggested that such intracellular processes might be more significant than any effect on the pathogen in the soil or during host invasion.

Calcium is commonly the major cation of the middle lamella of cell walls, where it is bound to polygalacturonic acids (pectins) as calcium pectate and is essential for the structural strength of cell walls. It has been proposed that calcium pectate increases tolerance to the action of cell wall-degrading enzymes (Punja and others 1986). Deficient cells cease growing, become disorganized and discolored, and under severe deficiency die (Epstein 1972). Calcium provides this structural strength by crosslinking the pectic chains of the middle lamella (Marschner 1995). Calcium is also essential for the normal membrane structure (by crosslinking of phospholipids and proteins), transport, and retention of ions. When calcium is limiting, low-molecular-weight compounds move from the cytoplasm into the apoplasm. These effects on cell wall and membrane stability are likely to inhibit the invasion of *P. brassicae.*

Zoospore motility and chemotaxis play a critical role in the early stages of infection by *P. brassicae*. Potentially, a role exists for calcium regulation of both these processes. Although there is no direct evidence in *P. brassicae*, studies using *Phytophthora* indicate that zoospore motility is reduced in calcium-deficient media (Cho and Fuller 1989). Immunolabeling studies have shown high concentrations of the calcium-binding proteins, calmodulin (Gubler and others 1990), and centrin (Hardham 1992) associated with *Phytophthora* flagella. Calmodulin is distributed differently in the two flagella; this may elicit a differential response to changes in external calcium, thereby governing directional movement (Gubler and others 1990). High levels of calcium could impair flagellar motion and the movement of zoospores toward the host root.

In the field, calcium nitrate has been widely used to manage clubroot (Page 2001; Donald and others 2006). Calcium nitrate directly affects the viability of *P. brassicae* resting spores and can reduce the extent of root galling even when applied after infection (Page 2001). Dixon and Page (1998) detail a more complex relationship between

calcium, nitrogen, and boron in the primary stages of the life cycle of *P. brassicae* from the germination of resting spores through to the development of primary sporangia in the root hairs. In this work, the growth of primary plasmodia into sporangia in root hairs was delayed by nitrate–nitrogen, calcium, and boron.

Calcium Cyanamide

In addition to the many forms of lime that have been used to amend clubroot-contaminated land, calcium in the form of calcium cyanamide has also been widely used (Karling 1942). As with lime, the mode of action of calcium cyanamide is not fully understood, although considerable research has been devoted to addressing this question. Upon reaction with soil moisture, calcium cyanamide breaks down initially to hydrated lime and hydrogen cyanamide, which then forms urea, ammonia, and nitrate in sequence. The release of hydrated lime increases soil alkalinity and releases Ca^{2+} upon hydrolysis (liming effect). By comparing calcium cyanamide with corresponding amounts of its hydrolysis products, Walker (1935) found the fungicidal value of calcium cyanamide to be greater, indicating that its fungitoxicity is a result not only of its breakdown products but also of reactive intermediates. Conforth (1971) found that the intermediate anion CN^{2-} is probably fungitoxic. Phytotoxicity reported by a number of authors (Naiki and Dixon 1987; Williamson and Dyce 1989) is also reportedly due to the action of this intermediate anion during glasshouse tests using seedlings. Care must therefore be taken to use the appropriate recommended period between product application and transplantation to ensure complete decomposition of calcium cyanamide. This rate of decomposition depends upon soil type, temperature, application rate, humidity, crop type, and cultivation technique (Klasse 1996). Product efficacy also depends upon the particle size of the product, with the fine-particle components being more effective than larger granules (Donald and others 2004). Studies conducted mainly in Scotland and reviewed by Humpherson-Jones and others (1992) indicate that in the period of 1979–1983, application of calcium cyanamide at 1500–1600 kg product/ha consistently provided good disease control and was at least as effective as the then standard Calomel™ treatments, which are no longer available because of the risks they posed to environmental health. Product efficacy was increased when the period between treatment application and planting was increased to between 14 and 21 days.

Depending on soil conditions, calcium cyanamide is broken down into urea and dicyandiamide within 5–20 days (Klasse 1996). Dicyandiamide slows the breakdown of ammonia into nitrate. This type of slow-release nitrogenous fertilizer is less polluting than other types of nitrogenous fertilizer because ground water contamination through leaching of excess nitrate is reduced.

Williamson and Dyce (1989) and Naiki and Dixon (1987) proved a direct effect of calcium cyanamide on the viability of resting spores. Incubation of resting spores in solutions containing 200 mg calcium cyanamide/L for 1 day reduced the number of zoosporangial clusters from 228 in the untreated control to 18, and this was greater than that of four other chemicals tested (Naiki and Dixon 1987). Subsequent studies (Dixon, unpublished) suggest that application of calcium cyanamide enhances elements of biocontrol of *P. brassicae*.

In spite of the liming, fertilizer, fungicidal, and environmental benefits of this product, broadcast application of calcium cyanamide can be a relatively expensive treatment option in countries such as Australia where the cost of transport from the production facility in Germany, together with unfavorable currency prices, can have a significant impact on the cost of this product. This high cost of application of calcium cyanamide can be reduced, however, by approximately two thirds by incorporation of the product into bands along the transplant row (Donald and others 2004; Tremblay and others 2005).

Boron

Like calcium, boron has long been recognized for its ability to inhibit clubroot and has been applied to clubroot-contaminated soil usually as borax (boric acid) (O'Brien and Dennis 1936). The mode of action of boron in the *P. brassicae* host-parasite system has been the subject of only a limited number of studies. In contrast to calcium and pH (Webster and Dixon 1991a), the effect of boron is not limited to primary infection within root hairs. Both primary and secondary stages of infection were inhibited by boron, but there was no effect of boron on the number of root hairs infected, indicating that the effect of boron is intracellular (Webster 1986; Webster and Dixon 1991b).

There are numerous reports of the roles of boron in plants, although most have been deduced indirectly, usually from studies with boron-deficient plants. Postulated roles for boron include sugar transport, cell wall synthesis, lignification, cell wall structure, carbohydrate metabolism, RNA metabolism, respiration, indole acetic acid metabolism, phenol metabolism, and membrane stability (Marschner 1995).

One of the most obvious early changes induced by boron deficiency is the inhibition of root and shoot elongation. There are a number of potential roles for boron in the root elongation process, including cell division and cell elongation. Cell elongation requires loosening of cell wall components by acidification of the apoplasm and

replacement of calcium from the crosslinks of the pectic chain, an auxin-induced process (Marschner 1995). Potentially, a role exists for boron in the regulation of endogenous auxin (Bohnsack and Albert 1977). Auxin also activates calcium channels in the plasma membrane, increasing cytosolic free Ca^{2+}, which stimulates the synthesis of cell wall precursors (Marschner 1995). Through regulation of auxin activity, boron may contribute to cell wall integrity thereby disrupting the movement of *P. brassicae* within the host plant. A more direct effect of boron-mediated regulation of auxin in the development of cortical symptoms may be through auxin-mediated hypertrophy of infected cells (Dixon and Webster 1988).

The earliest known effect of boron deficiency is an increased uptake of certain labeled precursors of RNA in root tips (Jackson and Chapman 1975). A similar response can be induced by application of auxin (Matthysse and Phillips 1969), adding further weight to the link between boron and auxin production. A decreased content of both RNA (Albert 1965) and DNA (Shkol'nik 1974) is well documented in boron-deficient plants, together with a decrease in the rate of DNA synthesis (Shkol'nik 1974).

Several roles have been proposed for boron in maintaining the structural integrity of cell walls and membranes. These proposed roles stem from the ability of boron to readily form *cis*-diol complexes with some sugars and phenols and may indirectly affect the transport of host sugars and other ions through the functioning of the plasma membrane-bound H^+-ATPase (Marschner 1995).

A synthesis of the nutritional and other elements in an integrated control strategy has been attempted by Dixon (2009).

Solarization

Thermal inactivation of *P. brassicae* caused by the heating of air beneath a polyethylene sheet, a technique known as soil solarization, has been shown to control diseases caused by a number of fungal pathogens, including *Verticillium* spp., *Pythium* spp., *Fusarium* spp., *Thielaviopsis basicola, Sclerotium rolfsii*, and *Rhizoctonia solani* (Katan 1980; Pullman and others 1981). The efficacy of the treatment has been shown to depend upon achieving lethal time-temperature combinations for a given pathogen (Pullman and others 1981; Horiuchi and others 1982). Soil solarization, therefore, is best suited to warm climates and has been effective in Israel (Katan and others 1976; Grinstein and others 1979; Jacobsohn and others 1980) and California (Pullman and others 1979).

Soil solarization for the control of clubroot has been evaluated in southern Australia. Solarization for at least 4 weeks caused a significant reduction in the number of viable clubroot resting spores in the upper 10 cm of soil, as determined by bioassay, at two locations (Porter and Merriman 1983, 1985). Disease development was monitored at one of the two sites and clubroot severity was significantly reduced for the first 6 weeks of the crop. An increased yield from 0 to 14 t/ha of Chinese cabbage was associated with solarization; however, this figure is well below that which would be expected from a commercial crop.

Porter and others (1991) evaluated a range of fumigants in combination with soil solarization as a means of providing more consistent results. The extent of disease control was influenced by soil type and inoculum density. In heavy clay soils, soil solarization in combination with low rates of fumigants gave significantly better control than any of the treatments used alone. However, on sandy soils, which were less severely infested with *P. brassicae*, either dazomet or solarization used alone was as effective as the combined treatment.

There have been a number of factors that have prevented Australian brassica growers from adopting soil solarization as a means of clubroot control. The most important of these has been the cost and difficulties of using plastic and the timing of solarization. Dazomet has also not been adopted because it is extremely expensive to apply at dosage rates effective for clubroot control. Cheaper and more reliable treatments are used for clubroot control in cool climate regions.

Chemical Control

The increase in the amount of literature on the chemical control of *Plasmodiophora brassicae* in the last 50 years is due to the growth of the agrochemical industry, which occurred in the mid-to-late 20th century. Recently, changes to government policy concerning human health and environmental safety have led to the restriction or deregistration of a large number of previously useful active ingredients (for example, methyl bromide, mercurous chloride) reported in older literature. Strict registration procedures and the relatively small size of the vegetable brassica industry in any country have further limited the availability of useful compounds. For example, there are currently no pesticides approved for use against clubroot in the EU (Oxley 2007).

Partial Soil Sterilants

In general, this group of chemicals is highly volatile, has low water solubility, and is active against a range of soil microflora and fauna (White and Buczacki 1977). Many of these products, including formaldehyde, ethylene dibromide, and methyl bromide, have been banned for health

and environmental reasons. Of those remaining, virtually all have been threatened with severe use limitations, including outright bans (Seiber and others 1996).

In a comprehensive review of the use of soil partial sterilization to control clubroot, White and Buczacki (1977) report that of the ten partial soil sterilants reviewed, only two (chloropicrin and dazomet), apart from methyl bromide (now banned worldwide), gave consistently good control of clubroot in both field and small-scale tests. Buczacki and White (1979) and Ahmad (1994) reported that rates of dazomet applied at 200–400 kg/ha provided substantial control and significantly increased the mean head weight of cabbage and Chinese cabbage by at least 15 and 360%, respectively. Due to the high cost of this product, however, use of dazomet is low worldwide and the preferred fumigant is the cheaper methyl *iso*thiocyanate (MITC)-generating product, metham sodium.

Metham sodium is sold as Metham^{TM} or Vapam^{TM}, varying from 32.7 to 42.3% aqueous solutions of the sodium salt of N-methyldithiocarbamic acid. In their review of the use of metham sodium for clubroot control, White and Buczacki (1977) comment that field experiments had produced erratic and inconsistent results, with only one of the treatments reviewed giving complete control of a natural infestation of clubroot. The method of application of this product has been the subject of scientific debate and government regulation. Cetas (1958) reported complete control of clubroot on Chinese cabbage using a drench application of metham sodium (0.12 L/m^2) sealed with 2.5 cm of water. This method was more effective than blade or shank applications of the same rate of metham sodium sealed either mechanically or using water. Cetas (1958) suggested band application of metham sodium as the most promising method for field application following trials in which infection was reduced to 6.5, 3.2, or 33.4% of plants using doses of 0.02, 0.04, or 0.06 L/m of row, respectively. Similar trials conducted by Wiggell and others (1961) failed to reproduce these results, reporting instead only a minor reduction in disease index at harvest following application of 102 ml/m^2 of either a 2.6% solution to whole plots or a 6.25% solution to a 30-cm-wide band.

Application of metham sodium through overhead irrigation has been banned in many countries for public health reasons. In spite of application problems, metham sodium remains the most popular of the partial soil sterilants for clubroot control in several countries as it is comparatively less expensive, requires only surface rolling and/or watering rather than polyethylene sheeting to seal the surface, and can be applied by the grower without specialized contract machinery. As more growers seek to incorporate an integrated pest management (IPM) approach into the management of soilborne disease problems, these products are increasingly being used for clubroot only in an effort to eradicate new outbreaks or as a last resort to return levels of soilborne inoculum on severely affected land to a manageable level.

Fungicides

Because *P. brassicae* is not a true fungus use of the term fungicides provides an inadequate and misleading description of the range of chemicals that have been used to control it. Many of these chemicals are fungicidal to a range of fungal plant pathogens, but when used to manage *P. brassicae* a term such as "protozoicide" is a more appropriate description. As this term is not in general use, for clarity and consistency these products have been referred to from this point on simply as "chemicals."

Consistent control of clubroot has been reported for only a small number of chemical actives. Among the most effective and widely used has been mercurous chloride (Calomel^{TM}). The high mammalian toxicity of mercury and the persistence of this chemical in the environment have led to the now almost complete withdrawal of Calomel from the world market. The identification of a safe alternative as effective and reliable as Calomel has been a continuing challenge to clubroot researchers.

Among the most widely evaluated group of chemicals for the control of clubroot are the benzimidazoles and their precursors. In a comprehensive glasshouse evaluation of this group of chemicals, Buczacki (1973) identified four—benomyl, thiophanate, thiophanate methyl, and NF 48—with the potential to control clubroot by soil incorporation. All of these are precursors of the actives methyl benzimidazol-2-ylcarbamate (MBC) and ethyl benzimidazol-2-ylcarbamate (EBC). The efficacy of thiophanate methyl was subsequently confirmed by Doyle and Clancy (1986) who reported that control could be improved by the addition of sulfur at 15 mg/kg.

Incorporation of either benomyl or thiophanate methyl at 100 mg/kg significantly reduced the severity of disease and increased the average head weight of cabbage by 451 and 462, g respectively (Buczacki and others 1976). Results using dipping solutions have been inconsistent (Buczacki and others 1976; Marić and others 1990). Tate and Eales (1982) experimented with a range of application methods and recommended a mechanized transplanting drench, delivering 120 ml of chemical solution per plant, as the most effective method of application of benomyl. Combining root dipping and drenching resulted in the development of symptoms of phytotoxicity that led to depressed yield.

A large number of related chemicals, the alkylene bisdithiocarbamates, are also active against clubroot. Of these, maneb (manganese ethylene bisdithiocarbamate), mancozeb (manganese ethylene bisdithiocarbamate complex with

zinc), and zineb (zinc ethylene bisdithiocarbamate) are among the most effective (Buczacki and Cadd 1976). Zineb has since been used as an alternative to benomyl transplant drenches, the latter chemical proving phytotoxic to cauliflower (Tate and Eales 1982).

Developed in the 1930s, pentachloronitrobenzene (PCNB) was brought to the attention of clubroot researchers by Smieton (1939) who provided the first report of activity against *P. brassicae*. In a review of early evaluations of PCNB and other related compounds, Colhoun (1958) concluded that the chlorinated nitrobenzenes could provide substantial control only under conditions where heavy attacks of clubroot do not occur. Anecdotally, this has been observed in Australia where PCNB remains registered for clubroot control but is rarely used for this purpose. Environmental concern over the accumulation of PCNB and hexachlorobenzene, a technical impurity, in soils (Nishimura and others 1980) has led to the restriction of PCNB in most countries, Japan in particular. The phasing out of PCNB, once widely used in Japan, together with the intensity of Japanese cropping systems, a result of only limited land being suitable for brassica production in that country, has led to a number of new chemicals being developed for clubroot control in Japan by joint private–publically funded development. Of these, trichlamide, flusulfamide, fluazinam, and cyazofamid have been extensively evaluated.

N-(1-alkoxy-2,2,2-trichloroethyl)-2-hydroxybenzamides were evaluated by Ohmori and others (1986) as an alternative to PCNB in a greenhouse trial. The C_4–C_6 derivatives of this compound were found to give superior control of clubroot compared with PCNB. Of these, the C_4 derivative [trichlamide, WL 105 305 (NK 483)] was most effective. In a subsequent field evaluation, broadcast incorporation of trichlamide at 30 kg a.i./ha provided control of clubroot equal to that obtained using PCNB (Ohmori and others 1986). Dixon and Wilson (1984) also report a reduction in the severity of disease symptoms using trichlamide. This effect was, however, significant only at 1.5 times the rate recommended by the manufacturer (45 kg a.i./ha). Naiki and Dixon (1987) report that trichlamide has a significant effect on *P. brassicae* 7 days after plants become infected and therefore conclude that this effect must occur during the secondary stage of development of the pathogen within the cortical tissue of hosts.

Developed by Mitsui Toatsu Chemicals Incorporated, Japan, flusulfamide (MTF651, Nebijin™) [4-chloro-N-(2-chloro-4-nitrophenyl)-α,α,α-trifluoro-*m*-toluene sulfonamide] was brought to the attention of clubroot researchers by Dixon and others (1994). These researchers used dust and suspension concentrates of flusulfamide in a series of field trials conducted in the UK. Flusulfamide provided consistently better control of clubroot than thiophanate methyl. The suspension concentrate was the most effective of the two formulations tested; however, there was no significant difference between the three rates used (0.6, 0.9, and 1.2 kg a.i./ha) for either formulation. In contrast, Cheah and others (1998), using a site more severely infested with clubroot than the three sites used by Dixon and others (1994), report that 2.4 kg a.i./ha of flusulfamide was required to cause a significant reduction in clubroot symptoms. Flusulfamide is not directly toxic to *P. brassicae* resting spores; rather it suppresses the development of clubroot by inhibition of germination of *P. brassicae* by adsorption onto the cell walls (Tanaka and others 1999). A number of related compounds, the benzenesulfonanilides, have been evaluated for the control of clubroot by Shimotori and others (1996). None were more active than flusulfamide. Flusulfamide is widely used in Japan and is also registered in New Zealand for control of clubroot in vegetable brassicas.

Fluazinam (Shirlan™ or Omega™) [3-chloro-*N*-(3-chloro-5-trifluoro-methyl-2 pyridyl)-α,α,α-trifluoro-2,6-dinitro-*p*-toluidine], is a pyridinamine fungicide. Fluazinam acts to interrupt the production of energy in fungal pathogens by an uncoupling effect on oxidative phosphorylation (Guo and others 1991). The activity of fluazinam against resting spores of *P. brassicae* and inhibition of subsequent root hair and cortical stages of infection of Chinese cabbage has been demonstrated by Suzuki and others (1995). Field control of clubroot using fluazinam has been reported in Australia (Ransom and others 1991; Porter and others 1998; Donald and others 2001) and New Zealand (Cheah and others 1998). Donald (2005) found that plant dips were the cheapest and simplest method of applying fluazinam to brassica crops; however, this method of application was not pursued because even at the lowest rate used (0.25 g fluazinam a.i./L) some of the seedlings developed blindness (loss of a functional growing tip). Rates lower than 0.5 ml of product/L (0.25 g a.i./L) were considered too small to be delivered accurately in a commercial situation.

A strategic method of application (Donald and others 2001) was developed for fluazinam to overcome problems with existing drench methods, such as poor infiltration and large volumes of water required for plant drenches and phytotoxicity of in-furrow applications (Porter and others 1998). Using this method fluazinam could be incorporated at 1.5 L a.i. per treated ha into the transplant row using small rotary hoes mounted between the tractor and the transplanter. Because the treated area is reduced (to approximately one third the total area), the effective rate (L/treated area) of the fungicide can be increased and the amount of chemical used per hectare (L/visual ha) and hence treatment cost to the grower is reduced. This method of application consistently increased the marketable yield of broccoli and cauliflower. In one trial, banded soil

incorporation increased the marketable yield of both crops by at least 80% compared with the other commercial methods of application currently in use (Donald and others 2001). The volume of water applied was also reduced from 2500 to 500 L/ha.

Cyazofamid (Ranman™) is a recently developed chemical with specific activity against oomycetes (Takeshi and others 2004). In the oomycetes cyazofamid has been shown to inhibit pathogen development by interfering with the cytochrome bc_1 complex (complex III) by binding to its Q_i center (Mitani and others 2001). Cyazofamid applied at 0.3 mg/L inhibits the germination of resting spores of *P. brassicae* by approximately 80% (Mitani and others 2003). When applied to soil (1–3 mg/kg dry soil), root hair infections and gall formation caused by *P. brassicae* were strongly inhibited. At the highest rate (3 mg/kg dry soil) complete control of clubroot was achieved (Mitani and others 2003). In UK glasshouse trials, a post-transplanting drench (200 ml suspension containing 0.08 g a.i. per plant) completely suppressed clubroot disease. The plug-plant dip (10 ml suspension containing 0.04 g a.i. per plant) also reduced disease severity by 78% (Townley and Fox 2003). Several workers report greater control of clubroot using cyazofamid than fluazinam (Townley 2005; Miller and others 2007). In contrast to fluazinam, phytotoxic effects on brassica plants were not observed for cyazofamid drench or plug-plant dip applications (Townley and Fox 2003).

Consistent control of clubroot in Chinese cabbage and cabbage has also been obtained using AG3 phosphonate as a postplanting drench in greenhouse, microplot, and field trials (Abbasi and Lazarovits 2006). In field trials with bok choy (*Brassica rapa* var. *chinensis*), one (0.07, 0.14, and 0.21% a.i.) or two (0.07% a.i) postplanting drench applications reduced the incidence of clubroot by between 52 and 87%, but this effect was not consistent in a subsequent field trial.

Registration issues continue to restrict the use of many of the chemical products. For example, only two pesticidal actives [quintozene (PCNB) and fluazinam] are registered for the control of clubroot of vegetable brassicas in Australia. In EU countries there are no products registered (Oxley 2007).

Surfactants

A number of surfactant products have been evaluated for their ability to control clubroot (Humpherson-Jones 1989, 1993). In a preliminary glasshouse study in which seven surfactant compounds were evaluated, only the dioctyl sulfosuccinates (Monawet MO-70 and Manoxol OT) and alkyl phenol ethylene oxide (Agral™) provided effective disease control at 500 and 2000 µg/g, respectively. In subsequent studies, use of Agral resulted in the largest consistent yield increase and was the only product that was not phytotoxic to young plants (Humpherson-Jones 1993). In field trials, liquid formulations of several nonionic surfactants were effective as split (root ball soak followed by 0.2% transplant hole application or 0.2% transplant hole application followed by 0.2% surface drench 10 days later) or single applications (0.5% transplant hole application); however, when applied in the absence of disease pressure, all of these treatments were phytotoxic compared with lower rates of application (Hildebrand and McRae 1998). Dixon and others (1997) reported field experiments using boron and Agral. Their work showed that 2% Agral and 15–20 ppm boron applied with the starter fertilizer (75 ml per plant) resulted in a period of approximately 14 days in which the transplant could establish its root system free of infection.

The method of disease control using surfactants is poorly understood. At 5 µg/ml, Agral has been shown to be phytotoxic to zoospores of *Olpidium brassicae* (Woronin) P.A. Dang. (Tomlinson and Faithfull 1979), but the mode of action against *P. brassicae* is unknown. It is possible that these products may be directly toxic or they may act indirectly by interrupting the swimming stage of the pathogen, thereby affecting its ability to reach, adhere to, or infect plant root hairs.

In an alternative approach, Cheah and others (1999) used the adjuvant Silwet™ at 0.1% combined with a chemical soil drench (50 ml/plant) to achieve almost complete control (97%) of clubroot in a heavily infested field site. Addition of the adjuvant significantly reduced symptoms of disease beyond that which was obtained using the chemical (flusulfamide) alone. Although this treatment resulted in significant leaf burn, with some modification of rate and possibly method of application there may be potential for surfactants to be used in this way. As the adjuvant was not used alone in this study, it is not known whether its effect was independent of the chemical and therefore additive, or whether it improved the efficacy of the chemical by improving its retention or adherence to the roots or by some other means.

Biological Control

Soils that are suppressive to clubroot exist widely throughout the world. Biological agents associated with the activity of microorganisms are an important factor determining the suppressiveness of some soils (Takahashi 1994; Murakami and others 2000a). Young and others (1991) proposed that a phenolic compound, gentisic acid, is involved in disease suppression. Niwa and others (2007) studied disease suppression in soils that had a 15-year

history of amendment with high rates of organic matter. They concluded that although both calcium and soil biota influence suppression of clubroot, their effect is moderated by soil pH, which is the major factor associated with disease suppression by organic matter. Likewise, Page (2001) found pH, calcium, and soil biota to be responsible for suppression of clubroot in Scottish soils.

Several attempts have been made to control clubroot using soilborne fungi (Djatnika 1991; Cheah and Page 1997; Cheah and others 2000) or bacteria (Einhorn and others 1991; Cheah and others 2000). Reports of field control using these biological organisms are limited (Cheah and Page 1997) and there are no commercial biocontrol products available. In an alternative approach, Arie and others (1998) demonstrated complete control of clubroot in greenhouse tests following application of culture broth of an isolate of *Phoma glomerata* (Corda) Wollenw. & Hochapfel to Chinese cabbage and turnip (*B. rapa*), cabbage and broccoli (*B. oleracea*) hosts. This effect was caused by epoxydon (5-hydroxy-3-(hydroxymethyl)-7-oxabicyclo[4.1.0]hept-3-en-2-one) and may be due to antiauxin properties of this chemical. There is potential for this work to lead to the development of new agrochemical products active against clubroot.

Mycorrhizal fungi, known to inhibit disease development in a number of plant species (Linderman 1996), are rare or absent in the Brassicaceae (Brundrett 1991). Recently, a root endophytic fungus, *Heteroconium chaetospira* (Grove) M.B. Ellis, that was isolated from Chinese cabbage was shown to inhibit clubroot in both sterile and nonsterile soil (Narisawa and others 1998). This was the first successful report of suppression of clubroot using a root endophyte. Teruyoshi and others (2001) report that 18 of 666 rhizoplane fungi caused a significant reduction in symptoms of clubroot in *B. rapa*. Of these, two were isolates of the root endophytic fungus *H. chaetospira.* Further greenhouse and field experiments with this endophyte indicated that it is an effective biocontrol agent against *P. brassicae* in Chinese cabbage at low to moderate soil moisture and at pathogen resting-spore densities at or below 10^5 spores per gram of soil (Narisawa and others 2005).

Bait or decoy crops (for example, radish, leafy daikon) are commercially available. These crops induce spore germination. The bait crop becomes infected; however, the crop is ploughed under before the pathogen completes its life cycle. In this way the number of clubroot spores in the soil is reduced further than can be achieved with other rotation crops (Yamagishi and others 1986; Murakami and others 2000b). In addition to radish, canola and mustard are also suitable bait crops, but Harling and Kennedy (1991) indicate that bait crops are effective only if infection is not too severe and they are used in conjunction with liming. Murakami and others (2004) caution that any reduction in soil resting-spore numbers resulting from the use of bait crops would be lost immediately upon ploughing of clubbed roots in the subsequent crop. The high cost of seed, additional cultivation, and the time that the land is out of production (most bait crops are hoed in 6 weeks after planting), together with an inability to accurately predict soil inoculum load pre- or post-bait crop has limited the use of this method of disease management. Frequently, several radish bait crops are recommended to reduce the soil inoculum load to an acceptable level, further increasing the treatment cost. Another compound, a dry powder extract of *Posidonia australis* Hook. F., a species of seagrass, has recently been shown to stimulate germination of *P. brassicae* and reduce disease severity (Hata and others 2002), but there are no commercially available germination stimulants with proven efficacy against *P. brassicae*.

Host Resistance

Host resistance to clubroot is much sought after by brassica growers. Ideally, complete or at least significant resistance in the host could provide growers with a relatively cheap and reliable control measure to include in an integrated control strategy. In reality, commercial lines with durable resistance to clubroot have proven elusive (see Piao and others, this issue; Diederichsen and others, this issue).

Numerous resistant cultivars of *B. rapa*, Chinese cabbage and turnip, are currently widely available. The use of these resistant cultivars is an important control measure for clubroot in these crops, but control failures using the older resistant cultivars of Chinese cabbage (for example, cv. Yuki) are widely reported by farmers in Australia. This has forced a return to the use of crop rotation, liming, nutrition, and chemical treatments in these crops. Commercial cultivars of clubroot-resistant *B. oleracea,* the predominant vegetable brassicas, have only recently become available (Anon 2003). Clubroot-resistant white cabbage, cvs. Tekila, Kilaton, and Kilaxy, and cauliflower, cv. Clapton, were introduced to UK and mainland European markets during 2005 (see Diederichsen and others, this issue). In Australia these cultivars, marketed as Syngenta cabbage (cv. Maxfield) and cauliflower (cv. Highfield), were commercially released in 2007. Their impact on the market has not yet been fully realized. Recently, two oilseed rape cultivars (cv. Mendel by NPZ-Lembke and cv. Tosca by Svalöv-Weibull) that show resistance to a number of *P. brassicae* collections have been released (Diederichsen and others 2006). Cultivar Mendel has been commercially available in the UK since 2003 (see Diederichsen and others, this issue). Already there are reports of serious disease outbreaks in cv. Mendel in UK and mainland European crops,

likely a result of close rotation with this cultivar on infested land (Oxley 2007). Genomics of resistance, mechanisms of resistance, and the development and conservation of resistant cultivars are reviewed elsewhere in this issue by Piao and others and Diederichsen and others, respectively. Recent experience with clubroot-resistant cultivars of Chinese cabbage and oilseed rape highlight the importance of integration of resistance as a management tool with a range of other control measures as a means of delivering a more robust management strategy and prolonging the effectiveness of resistant cultivars.

Integrated Control of Clubroot

Integrated control is now a feasible strategy for the management of clubroot in vegetable brassicas (Maruyama and others 1983; Page 2001; Dixon 2003; Porter and others 2004; Donald 2005; Donald and others 2006). Evidence to support the benefits of long rotations, increasing soil pH using lime, application of calcium and boron, and the benefits of strategic application of fungicides, in particular fluazinam and flusulfamide, is overwhelming. Simple and practical hygiene guidelines have been developed. Recently, resistant cultivars of *Brassica oleracea* (cabbage and cauliflower) have also become available, as have molecular and serologic methods that measure soil inoculum and predict yield loss. Together, these are the tools available to manage clubroot. Integrated control does not mean using all of these available tools simultaneously. No doubt this would effectively control clubroot but at what cost?

In field trials conducted in Australia, integration of two or more field treatments was more effective at controlling clubroot than applying any one treatment on its own at acidic pH sites (pH < 7; Donald 2005; Donald and others 2006). On these sites the most effective control strategies were treatments that consisted of combinations of one or two treatments (calcium nitrate, fluazinam, or metham sodium) together with lime (Donald 2005; Donald and others 2006). With only one exception, application of lime with another treatment increased crop profitability by between A$200 and A$6579/ha more than could be obtained using lime alone. By contrast, although the addition of a third treatment to the combination generally added to the control of clubroot, it did not further increase grower profits. Integrated control, therefore, refers to the cost-effective application of the available tools to manage clubroot. Growers of the relatively high-value vegetable brassicas can afford to spend more to protect these crops than can broadacre brassica farmers and, therefore, will have more tools available to them. In practice, on Austrialian vegetable farms with low soil inoculum levels, the most profitable control strategies have been treatments that consist of combinations of calcium oxide lime prior to transplanting and repeated application of calcium nitrate with boron at transplanting and in the weeks post-transplanting. At high inoculum sites, additional treatments of fluazinam or metham sodium are required (Porter and others 2004).

Further advancement in integrated control will rely on cultivar resistance coupled with better reduction of inoculum through manipulation of the nutrient/chemical changes in the soil, rhizosphere, root hairs, and plant cells. An increased knowledge of the modes of action of many chemical interactions within the plant roots and surrounding soils under different pH levels is essential. This will undoubtedly lead to the development of new crop IPM systems, which rely on modification of the soil environment to reduce inoculum of *P. brassicae* or prevent infection. Future sustainable systems must also reduce the use of harmful pesticides or high levels of synthetic fertilizers, which is essential to maintenance of soil and ecosystems health.

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