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Clubroot control with "safe" chemicals

A report prepared for

NZ Vegetable & Potato Growers' Federation Inc.

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1 EXECUTIVE SUMMARY

Clubroot remains an important disease for today's growers of vegetable brassicas, despite more than 120 years of research. Controlling clubroot presents many difficulties and some of the most effective control methods use expensive, highly toxic, and/or persistent pesticide chemicals. In the present climate of concern about the effects of pesticides on human health and the environment, there is an increasing need to develop safer methods of controlling clubroot.

This report describes clubroot and the causative pathogen, summarises the latest information on controlling the disease, and reviews chemical control methods that are regarded as "safe" (i.e. unlikely to cause harm to humans, to beneficial and desirable organisms, or to the environment).

"Safe" chemical control methods that have been shown to reduce clubroot severity include applying salts, plant nutrients, composts or waste materials to soil, or adding soil amendments. Surfactants, disinfectants and antibiotics have also been shown to reduce the severity of the disease. Several of these chemicals have been particularly effective when combined with more traditional fungicides. However, none of these methods gives complete protection against the disease. The best prospect for clubroot control in intensive vegetable brassica production is likely to be an integrated management strategy that combines the use of chemical controls, with cultural methods and disease resistant cultivars. This approach provides sustainable control, and also lessens reliance on potentially harmful pesticides.

2 INTRODUCTION

Clubroot continues to be the most important disease of cultivated crucifers throughout the world. In New Zealand the disease poses serious problems for vegetable producers where it can cause severe economic losses in brassica crops by reducing marketable yields, or sometimes completely destroying brassica crops, e.g. cabbage, cauliflower, broccoli, Brussels sprouts, turnip, Chinese cabbage and related vegetables. In some areas of highly intensive vegetable production, values of horticultural land have diminished because of clubroot infestation (Dixon 1988). The costs of controlling the disease have usually been high, requiring either long crop rotations with non-cruciferous plants, or expensive chemical applications.

This review has been undertaken to assist growers to develop effective, low-pesticide methods of clubroot control, and to provide background information to guide research on clubroot control. First, we describe the disease, and review the history of research on clubroot and the causative pathogen as the findings of early studies are still relevant to the control of clubroot in modern vegetable production. Then, because growers are under increasing pressure to use more environmentally friendly methods of disease control, we review "safe" chemicals for clubroot control, i.e. chemicals that are not likely to be harmful to humans, to beneficial organisms, or to the environment.

3 CLUBROOT

3.1 The disease and causative pathogen

The first symptom of clubroot in vegetable brassica crops may be wilting of leaves of infected plants on warm days. Affected plants recover overnight, so this symptom can easily be mistaken for lack of water. As clubroot progresses, leaves of infected plants turn yellow and plant growth is stunted. Infected plants may survive for the life of a crop, but are unlikely to produce marketable vegetables. In severe cases, infected plants wither and are eventually killed by the disease (Karling 1968; Biggs 1994) because clubroot damages root systems. Infected roots become distorted in shape and form galls. Swollen roots are the characteristic symptom of clubroot (Figures 1 and 2) and in severe cases, roots may be very enlarged and swollen. Heavily infected roots eventually decay, reducing the capacity of plants to obtain nutrients and water from the soil (Karling 1968; Biggs 1994), and thus lowering yields drastically.

PLATE 29

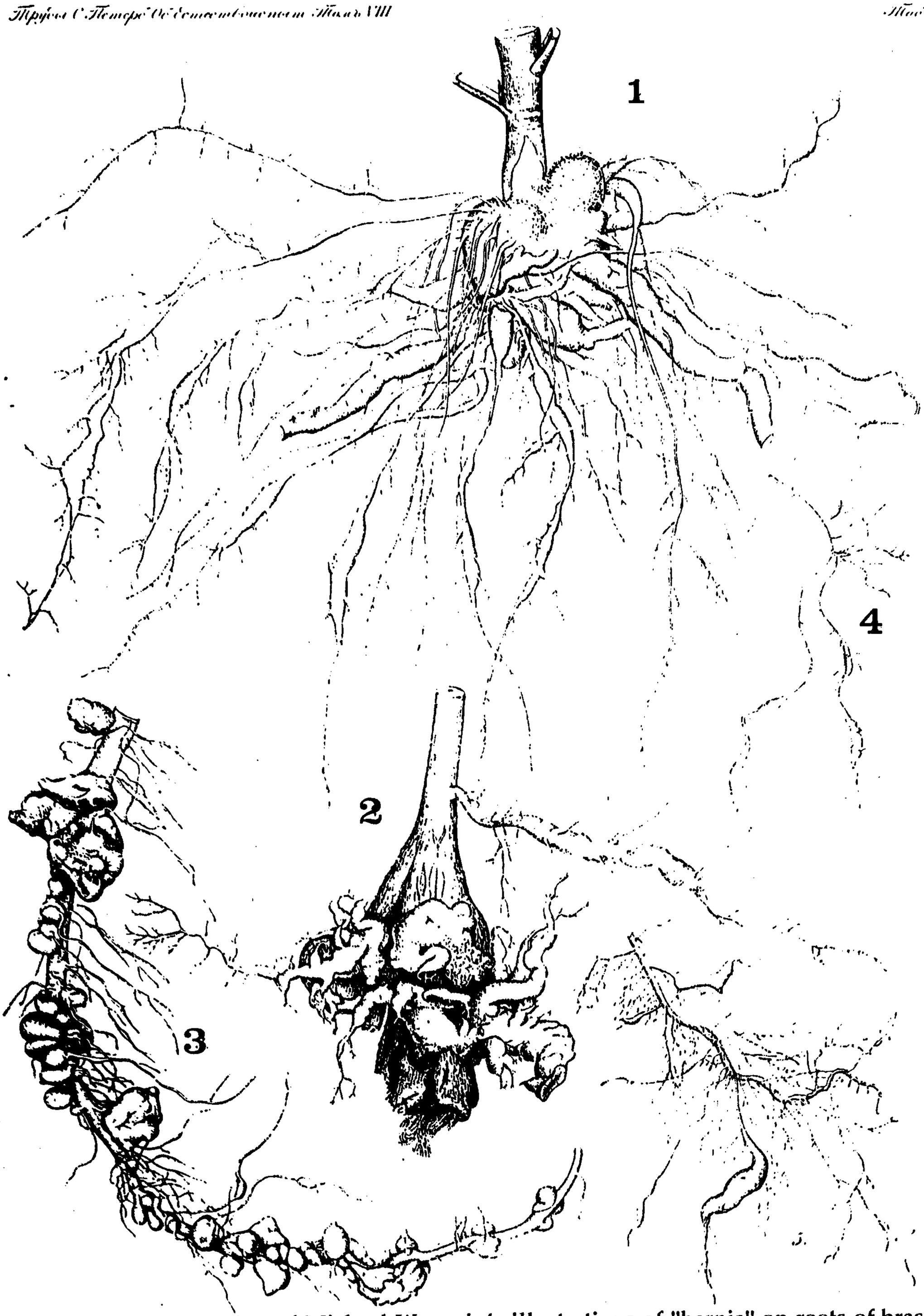

Figure 1: **Reproduction of Michael Woronin's illustrations of "hernia" on roots of brassica plants, published in 1878. "Plate 29. Fig. 1. Roots of a young cauliflower plant covered with hernia swellings. ..... Figs 2 & 3. Hernia swellings on common (white) cabbage. Figs. 4 & 5. Beginning of hernia swellings on roots of young cabbage plant. (All illustrations on this plate are natural size)." (From Chupp 1934).**

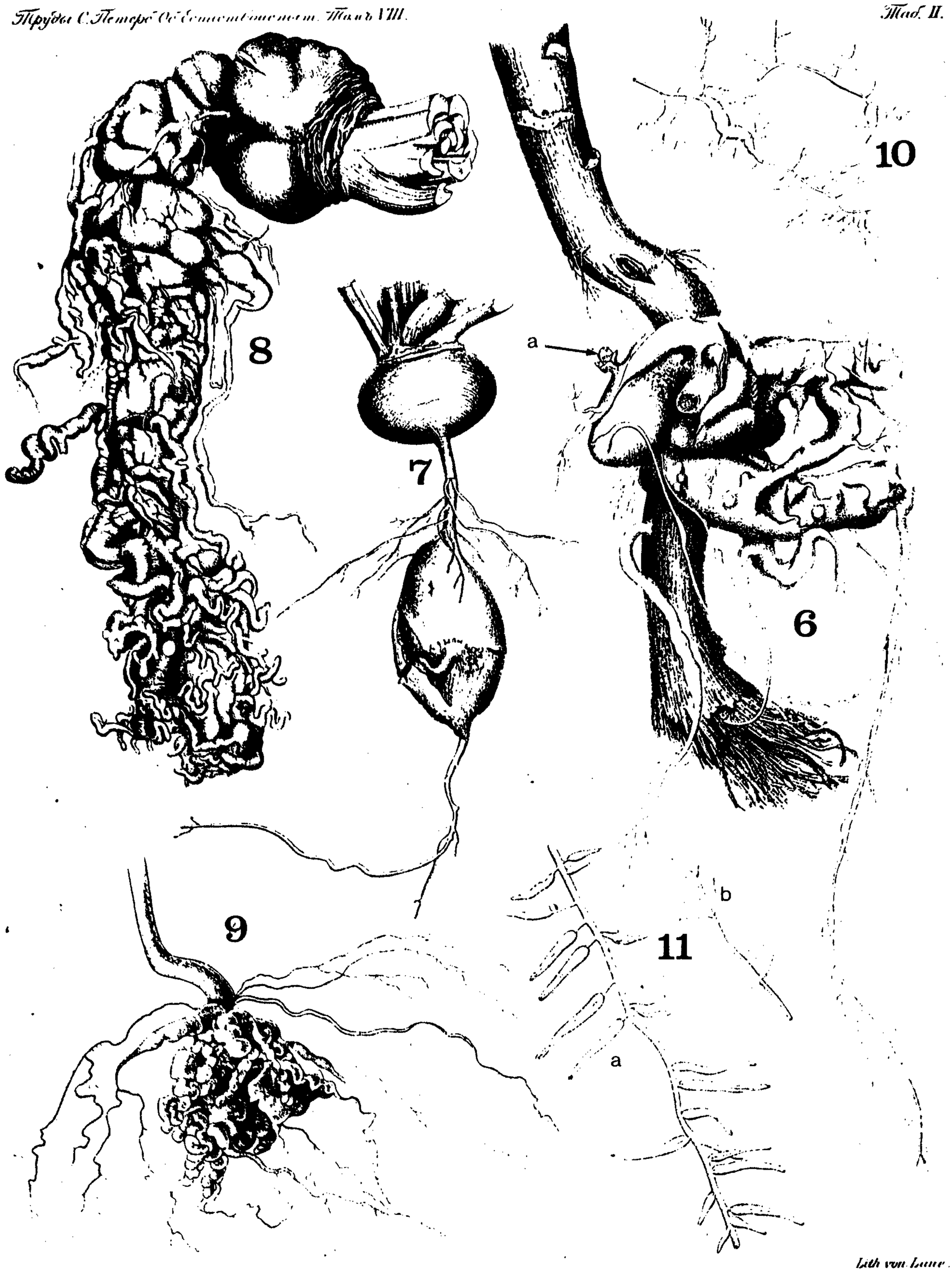

Figure 2: **Reproduction of Michael Woronin's illustrations. "Plate 30. Fig. 6. Hernia swellings on common (red) cabbage, (a) adventitious leaf buds; natural size. Figs. 6 & 8. Swellings on common turnip. Nat. size. Fig. 9. Hernia root swelling on *Iberis umbellata*, natural size. ..... Fig. 10. Beginning of hernia on roots of ordinary (white) cabbage. Nat. size. Fig. 11. Commencement of clubbing on the young roots of cabbage seedlings, grown in pots and artificially infected with spores of *Plasmodiophora*. (A) Nat. size; (b) observed under low magnification of a hand lens." (From Chupp 1934)].**

Clubroot is caused by the protozoan pathogen, *Plasmodiophora brassicae*. This organism was first recognised and named as the cause of clubroot by the Russian naturalist, Michael Woronin, in a classical research paper (Chupp 1934; see Figures 1 and 2). Before Woronin's pioneering study, clubroot had been attributed to a number of causes including insects, worms, grubs, syphilis, unfermented dung in the soil, poor soil preparation, or lack of caustic lime or common salt in soil (Chupp 1934; Karling 1968). Woronin noted that "cabbage hernia" had caused serious losses to vegetable gardeners in many Russian communities. Karling (1968) described how clubroot has been recognised as a significant problem for brassica growers for many centuries, with reports of the disease causing problems in Roman times, and in the thirteenth and fifteenth centuries.

Woronin classified *P. brassicae* as belonging to the kingdom Protista, later described as a grouping of organisms that are "non-plant, non-animal and non-fungal" (Margulis 1990). Since Woronin's time, biologists have debated the position that *P. brassicae* and related pathogens (the Plasmodiophorales) occupy in the hierarchy of living organisms. Karling (1968) noted that this group 'has been bandied back and forth by protozologists and mycologists for three quarters of a century'. More modern systems of classification (Corliss 1994; Braselton 1995) place *P. brassicae* and related plant pathogens in the Protozoa.

3.2 Occurrence of clubroot

Woronin noted that clubroot was known to be widespread throughout Europe, Russia, Scandinavia, the UK and the USA (Chupp 1934). *Plasmodiophora brassicae* is now found throughout the world wherever brassicas are grown (e.g. Europe, Norway, Sweden, UK, Australia, New Zealand, Japan, Taiwan, USA, and Canada), and clubroot disease is widespread in home gardens as well as in commercial crops (Kirk 1894; Karling 1968; Reyes et al. 1974; Yoshikawa 1983; Hsieh & Yang 1984; Porter et al. 1991; Wallenhammar 1996).

Plasmodiophora brassicae has been recorded on more than 300 host plant species and varieties, including 61 genera of Crucifers and nine non-cruciferous species (Karling 1968), which emphasises its wide host range.

Clubroot is becoming increasingly important for producers of vegetable brassica crops (Karling 1968; Crute et al. 1980; Datnoff et al. 1984; Dixon 1988) because crops are now being grown more intensively to satisfy year-round demand for fresh vegetables. Brassica production is on a larger scale and crops occupy a higher proportion of vegetable-producing land than previously. Rotations between crops have been shortened or eliminated so on some land brassicas are grown continuously. Clean land has been infested by infected transplants, or by contaminated machinery or irrigation

water. All these factors have increased the importance of the disease, contributing to reduced yields and economic returns from brassica production, and in some countries (e.g. Japan) reducing land values in vegetable-producing areas (Dixon 1988).

3.3 Life cycle of *Plasmodiophora brassicae*

After more than 100 years of scientific research, there is still a lack of detailed knowledge of the life cycle of *P. brassicae* (Buczacki 1979; Jones et al. 1982a; Scott 1985; Crute 1986; Toxopeus et al. 1986). Incomplete understanding of the pathogen cycle (Fig. 3) makes it difficult to develop fully rational clubroot control strategies. It is generally accepted that primary zoospores released from resting spores of the pathogen infect root hairs of host plants. These infections develop into zoosporangial plasmodia in host root cells, then later develop into secondary zoospores which on release probably induce secondary infection cycles. Zoospores may also act as gametes which after fusion may initiate a sexual reproductive cycle. This may result in the development of resting spores which proliferate in the gall tissue of infected plants. Resting spores, which are released passively into soil as infected host tissue decays, can survive for as long as 20 years (Karling 1968; Biggs 1994), and may also be widely transmitted by wind and water, on machinery or footwear, on infected transplants, or in the soil in which they have been raised (Buczacki 1979). Resting spores release primary zoospores to infect new generations of host plants. Naturally occurring resistance to *P. brassicae* is rare in host plant germplasm, and the nature or genetics of this resistance is not well understood (Crute et al. 1980; Voorrips 1995). The life cycle of *P. brassicae* has been described in several publications (Tommerup & Ingram 1971; Ingram & Tommerup 1972; Dylewski 1990; Mithen & Magrath 1992).

3.4 Pathogenic variation in *Plasmodiophora brassicae*

Plasmodiophora brassicae exists as a number of different races/pathotypes that exhibit differential pathogenicity to host plants. A multiplicity of pathotypes occur in different countries, within regions and even within individual fields (Dobson et al. 1983b; Lammerink 1986; Chiang & Crête 1989; Falloon et al. 1996a; Some et al. 1996). Research using single spore isolates obtained from identified pathotypes has shown that resulting populations are heterogeneous, with several different and distinct pathotypes originating from the original (Haji Tinggal & Webster 1981a; Jones et al. 1982b; Scott 1985; Voorrips 1995). Thus, field populations of *P. brassicae* are likely to express continua of pathogenicity rather than distinct pathotypes.

A system for characterising *P. brassicae* pathotypes has been devised using the European Clubroot Differential (ECD) host set (Buczacki et al. 1975). However, several problems have been encountered with this system, including indistinct host reactions (Toxopeus et al. 1986), lack of genetic uniformity, and lack of knowledge of the genetic makeup of the differential hosts (Crute et al. 1980; Jones et al. 1982a; Scott 1985; Crute 1986; Toxopeus et al. 1986; Voorrips 1995). The ECD set may also not adequately differentiate mixed populations of *P. brassicae* (Jones et al. 1982a, b; Scott 1985).

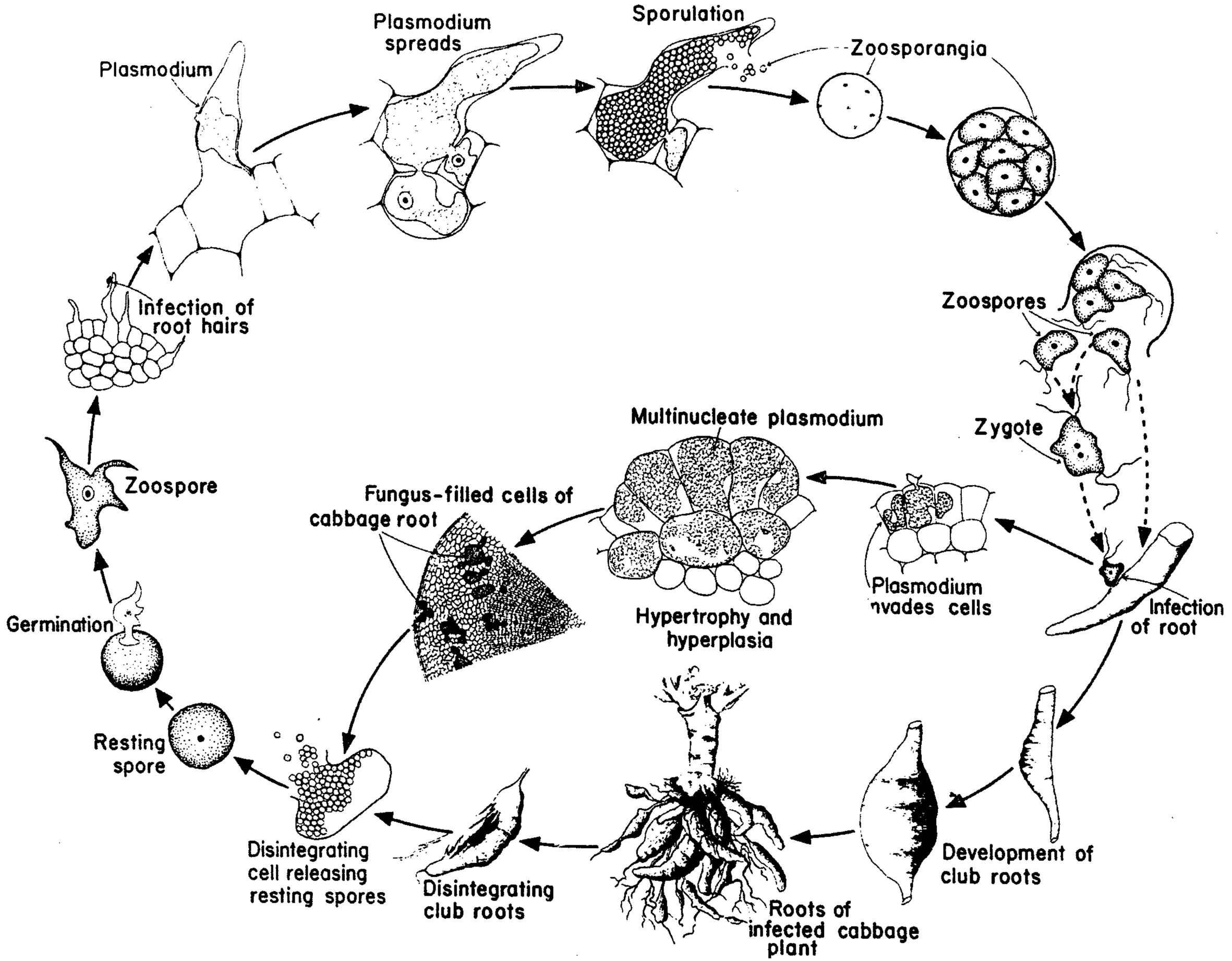

Figure 3: Disease cycle of clubroot of crucifers caused by *Plasmodiophora brassicae* (Agrios 1969).

4 CONTROL OF CLUBROOT

In 1878 Woronin asked, "Is it possible to control the disease? If this is not wholly attainable, is there some means of appreciably lessening the development of *Plasmodiophora* and thereby reducing the injury to the cabbage plant?" His own opinion was "...the absolute eradication of hernia on the cabbage plant is impossible. It is unthinkable that any substance should kill the plasmodium and spores of *Plasmodiophora* and at the same time preserve the protoplasm tissue of the cabbage root in which the *Plasmodiophora* is parasitic. This substance, whatever it might be and in whatever manner it might be applied, would destroy the cabbage plant when it killed the *Plasmodiophora*." (Chupp 1934). Although this statement was made before the advent of systemic pesticides, it is still relevant, as adequate chemical control of clubroot remains an elusive goal. Numerous methods for alleviating the disease have been reported but none is totally effective.

Woronin suggested three methods for 'checking the development of *Plasmodiophora*' (Chupp 1934): burning cabbage stumps and roots after harvest; carefully sorting seedlings before planting to remove infected plants; and rotating crops. He also mentioned the English practice of applying soot to cabbage-growing soil, and dipping transplant roots in a soot/water mixture before planting. Other practices he suggested as possible clubroot controls included removing the clubs on diseased roots, or applying guano, saltpetre, salt, bone-meal or wood ashes to the soil.

The use of pesticides, some of which are highly toxic and persistent, is the most commonly advocated chemical method for controlling clubroot. The effectiveness of fungicides, herbicides, and experimental compounds has also been widely tested. Compounds that have been shown to reduce clubroot severity in glasshouse and/or field trials include the pesticides benomyl, captafol, chlorothalonil, dichlorophen, fosetyl-Al, mancozeb thiabendazole, thiophanate-methyl, thiram, tolclofos-methyl, and trichlamide (Karling 1968; Kroll et al. 1984; Dixon & Wilson 1984a, b; Vanachter et al. 1985; Doyle & Clancy 1986a, b; Dixon et al. 1987; Humpherson-Jones 1993; Nott et al. 1995a, b; Falloon et al. 1996a, b). More recently released pesticides that have shown promise in controlling clubroot include fluazinam (Humpherson-Jones 1993; Nott et al. 1995a, b; Falloon et al. 1996a, b) and flusulfamide (Dixon et al. 1994; Nott et al. 1995a, b; Falloon et al. 1996a, b).

Soil fumigation, using chemicals such as chloropicrin, dazomet, formaldehyde, mercury compounds, methyl bromide, and quintozene, was widely accepted as the most effective method of clubroot control (Karling 1968; White & Buczacki 1977; Porter et al. 1991). *Plasmodiophora brassicae* has been shown to develop tolerance to mercury compounds (Haji Tinggal & Webster 1981b). Currently, soil fumigation is rarely used

to control clubroot because the practice is expensive, the effective chemicals are highly toxic to humans, and their residues have harmful environmental impacts. Several fumigation chemicals (e.g. methyl bromide) are no longer approved for control of soilborne diseases, or are likely to be withdrawn from use in the near future.

5 "SAFE" METHODS OF CONTROLLING CLUBROOT

Considerable advances have been made in recent years in developing chemicals to control plant disease which are less toxic to humans and animals, have less impact on the environment, and require low use rates giving nil or negligible food residues. These new formulas are also compatible with integrated pest management programmes. Much of this progress has been made in response to growing public demand for these characteristics in pesticides (James et al. 1993; Knight et al. 1997). The intractable nature of clubroot, however, has meant that some of the most effective methods for controlling clubroot involve partial soil sterilisation, often with expensive, highly toxic and/or persistent pesticide chemicals.

There is already a considerable body of research-based information on clubroot controls that do not rely on pesticides and here we outline alternative methods of control that could be used by the horticultural industry. These include applying calcium compounds, trace elements or other minerals, composts and surfactants to the soil, and using clubroot-resistant brassica varieties.

5.1 Calcium compounds

Calcium compounds—lime, calcium carbonate, calcium hydrate (slaked lime) calcium oxide (ground lime, quicklime, burnt lime), calcium cyananide, gas lime, calcium chloride, calcium nitrate, calcium hypochlorite—have been the most commonly used soil additives for control of clubroot, and Karling (1968) reviewed the extensive early literature on their use. The level of control achieved with these materials has been variable, however, ranging from nil to excellent (Karling 1968). Results have apparently been affected by factors such as *Plasmodiophora brassicae* inoculum levels, soil moisture, soil type, temperature, the type of calcium, lime particle size, application of additional chemicals and fertilisers, and the timing of applications (Karling 1968; Hamilton & Crête 1978; Dobson et al. 1983a; Campbell et al. 1985).

Several more recent studies have examined the effects of calcium compounds on clubroot. Welch et al. (1976) and Campbell et al. (1985) achieved excellent control of the disease in California for periods of up to three years with applications of calcium carbonate at rates between 5 and 33 t/ha. Campbell et al. (1985) found that lime applications were more effective than quintozene or calcium cyanamide in controlling clubroot.

In recent years, detailed research has broadened understanding of the complex effects of calcium compounds on clubroot, which were originally thought to be due mainly to soil ph effects. Hamilton and Crête (1978) investigated the influence of soil moisture, soil pH, and liming sources on clubroot incidence in both an organic and a mineral soil, and found that a reduction in clubroot depended more on liming source than on soil pH. Fletcher et al. (1982) investigated the effects of applying calcium carbonate, sodium carbonate or calcium sulfate to a mineral soil infected with *P. brassicae*. They showed that calcium carbonate did not affect soil pH but drastically reduced clubroot severity compared with untreated soil, and concluded that a factor other than soil pH influenced the level of clubroot.

Myers and Campbell (1985), using a nutrient solution/sand culture system, showed that calcium or magnesium affected *P. brassicae* but their effects were pH-dependent. Increasing the calcium or magnesium content of plant nutrient solutions decreased the number of root infections and amount of clubroot on plants. The amount of these cations needed to prevent clubroot was smaller as pH increased from 6.2 to 7.2. They concluded that the degree to which clubroot is controlled may depend on the balance between pH and the concentration of calcium and magnesium cations. The pH of soil is probably the most important factor influencing disease development, but high concentrations of calcium and magnesium may give control at pH less than 7.2. Similarly, low concentrations of these cations may allow disease development at pH greater than 7.2. The balance of nutrients influences host/pathogen development, and pH can play a significant role in controlling this balance in the crucifer/*P. brassicae* relationship.

In summarising research on the effects of calcium and pH on clubroot, Dixon and Webster (1988) drew several definitive conclusions:

- The relationship between pH and calcium concentration in the control of clubroot is not direct, as calcium supplements reduce disease severity at both low and high pH.

- The form of calcium used for clubroot control is important. The most effective control is achieved with calcium salts which increase soil pH.

- High pH and calcium concentrations, achieved using calcium carbonate, act by reducing the number of infections in host roots and by inhibiting secondary zoospore development. Calcium salts which generate low pH (e.g. calcium sulfate) may also inhibit later stages of clubroot development.

A subsequent study by Webster and Dixon (1991a) investigated the effects of calcium, pH and *P. brassicae* inoculum concentration on different stages of primary infection of host seedling roots by the pathogen. Increasing calcium concentration reduced

numbers of infections and symptom expression, the degree of effect depending on the inoculum pressure. Calcium at low concentrations inhibited development of sporangia, while at high concentrations, sporangial opening and release of secondary zoospores was inhibited. Alkaline pH reduced root hair infections and their rate of maturation. High pH and high calcium concentration in combination enhanced uptake of the cation. Donald et al. (1997) also demonstrated that products that raise soil pH and have high levels of cations (particularly calcium and magnesium) and boron, improved control of clubroot and increased the yields of broccoli. Calcium salts (carbonate and hydroxide) that increased calcium and raised pH controlled clubroot better than treatments that only affected pH.

Calcium cyanamide is one of the few compounds reported to successfully control clubroot in most instances where it has been tested (Walker & Larson 1935; Karling 1968; Dixon & Williamson 1984; Dixon et al. 1987; Mappes et al. 1989; Williamson & Dyce 1989; Humpherson-Jones et al. 1992; Cheah 1995; Donald et al. 1997). This compound is not phytotoxic to brassicas unless used at very high rates (Dixon & Wilson 1983; Williamson & Dyce 1989), when its phytotoxicity depends on the structure, texture and water content of the soil.

Calcium cyanamide is a nitrogenous fertilizer with liming, herbicidal and fungicidal properties. Its mode of action against *P. brassicae* is not fully understood. In laboratory experiments (Dixon et al. 1987; Naiki & Dixon 1987) calcium cyanamide suppressed resting spore germination. Breakdown products from calcium cyanamide are also thought to affect *P. brassicae*, either directly or indirectly (Williamson & Dyce 1989). Walker and Larson (1935) demonstrated that urea, a breakdown product of calcium cyanamide, inhibited clubroot. They also demonstrated that the cyanamide anion, produced before complete hydrolysis of calcium cyanamide to calcium hydroxide and urea, may have reduced clubroot.

The amount of calcium cyanamide applied to soil, and the length of time between application and planting, have varied in different studies. A review by Humpherson-Jones et al. (1992) noted that application rates in previous studies had ranged from 450 to 1500 kg/ha. After completing a number of field trials, they concluded that a 14-21 day period between application and planting, and application rates of 1500-1600 kg/ha of 'Perlka' (20% nitrogen, 55% calcium oxide) gave satisfactory control of clubroot and increased cabbage and cauliflower yields. Cheah (1995) showed that a much lower rate (200-300 kg) was effective for controlling disease and increasing yield.

Dixon et al. (1987) demonstrated in glasshouse experiments that adding calcium cyanamide to potting compost at 2 g ai/kg completely inhibited clubroot and primary invasion of root hairs by *P. brassicae*. They also studied the effect of calcium cyanamide on *P. brassicae* resting spores, demonstrating that spore viability was reduced by

increasing both calcium cyanamide concentration and the period of exposure to the chemical.

Calcium cyanamide has also been used in combination with the soil fumigant, dazomet, with good results (Mappes et al. 1989). In a trial with Brussels sprouts and moderate *P. brassicae* inoculum pressure, the incidence of clubroot in untreated soil was 60%; in the calcium cyanamide treatment (800 kg/ha) it was 54%; and in the dazomet treatment (196 kg/ha) it was 37%. No clubroot was found in a treatment which combined both chemicals. When inoculum pressure was high, only the combined treatment reduced the incidence of clubroot. Similar results were obtained in trials with cauliflower and kohlrabi.

5.2 The effectiveness of plant nutrients and trace elements

5.2.1 Boron

When soils are heavily limed, boron deficiency can occur in brassica crops resulting in diseases such as 'hollow head' of cauliflower (Tate & Eales 1982; Tate & Cheah 1983). To counteract these problems, applying boron to the soil was recommended. As well as correcting deficiency symptoms, the treatment also improved clubroot control (Karling 1968; Dixon & Webster 1988). Applications of boric acid, either alone or in combination with other chemicals (benomyl, thiophanate-methyl, zineb, zinc sulfate) have been shown to reduce clubroot in pot and field trials (Antonova et al. 1974; Vytskiĭ 1979; Utkina et al. 1980; Il'ina & Shekunova 1981; Doyle & Clancy 1986a; Dixon & Webster 1988).

In laboratory tests with Chinese cabbage seedlings, boron reduced *P. brassicae* root hair infection and clubroot symptoms, and when boron was applied together with calcium and/or nitrogen the disease was completely inhibited (Dixon et al. 1987). In field trials, however, treatment with either boron alone, or boron combined with calcium cyanamide had little effect on clubroot (Dixon et al. 1987). This result contrasted with the result of a previous field trial where sodium tetraborate controlled clubroot (Dixon & Wilson 1984b). French studies (Shorrocks 1992) gave similar results. In controlled environment experiments with low pH soil (5.0-6.8), incorporated boron had no effect on clubroot, but when pH was raised to 7.8 the severity of the disease was reduced. Boron was more effective in controlling clubroot when it was applied with calcium cyanamide.

Craig and Dixon (1993) investigated the effect of using boron as a pre-planting drench and post-planting spray of summer cabbage. Drenching transplants before planting reduced clubroot in a field trial for up to 44 days. A single spray application of 3.5 kg boron ha^{-1} reduced root hair infection. One application of boron immediately after planting initially gave limited clubroot control, but treated plants later exhibited the

same levels of clubroot as those seen in untreated controls. Applying boron twice, on day 1 and day 8 after transplanting, was found to be the most efficient treatment, reducing colonisation of the roots and pathogen development. No phytotoxicity was observed in any field treatments, but it did occur in glasshouse-grown plants treated with boron solutions containing more than 20 mg l^{-1}.

How boron acts against clubroot is not fully understood (Dixon & Webster 1988; Shorrocks 1992). Webster & Dixon (1991b) demonstrated that boron reduced the maturation rate of root hair stages of *P. brassicae* infections and development of clubroot in root cortices, and that this effect was greater at pH 7.2 than at 6.2. They also noted that intensity of exposure affected the degree to which boron inhibited clubroot.

5.2.2 Sulfur

Karling (1968) noted that a number of studies had tested various sulfur-containing materials against clubroot with conflicting results. Carbon disulfide was first reported to be effective as a seedbed treatment against clubroot in 1887. Sulfuric acid, however, has been shown to increase clubroot severity, and research in the USA and Switzerland also showed that sulfur applications were ineffective. Gibbs (1939) obtained similar results in New Zealand.

The effect of sulfur on clubroot development in susceptible and resistant brassicas was studied by Pryor (1940) using a nutrient solution culture method. Sulfur deficiency increased the number of plants with clubroot compared with plants grown in full nutrient solution, for both susceptible and resistant hosts. Doyle and Clancy (1986a) found in glasshouse tests that sulfur applications did not reduce disease incidence or severity, but a combination of sulfur and thiophanate-methyl reduced the severity and incidence of clubroot more than either treatment used alone. Sulfur was shown to give moderate control of clubroot when used either in combination with lime as lime sulfur, or on its own (Karling 1968).

5.2.3 Potassium

A number of early workers tested the efficacy of products containing potassium (Karling 1968) and found they gave little or no control of clubroot. Products tested included potassium hydroxide, potassium carbonate, potassium chloride, potassium permanganate and potassium nitrate.

Pryor (1940) investigated the effect of potassium on clubroot using controlled nutrient experiments and found that in susceptible hosts there was a slight increase in the percentage of plants infected with clubroot when there was an excess of potassium. Potassium deficiency reduced clubroot. Similar results were obtained by Walker and Hooker (1945).

5.2.4 *Magnesium*

Early experiments to test the effects on clubroot of materials containing magnesium (carbonate, sulfate or chloride) have given negative results. More recent research (Myers & Campbell 1985), which investigated the effects of pH, calcium and magnesium on clubroot in a nutrient solution sand culture system, showed that increasing magnesium content decreased the amount of clubroot and number of root hair infections on test plants.

5.2.5 *Copper*

Karling (1968) reviewed the reported results of using copper compounds and copper-containing preparations to control clubroot. Bordeaux mixture, copper sulfate, copper carbonate, and copper oxide have all been reported to partially control clubroot. Several other studies, however, have shown no response to these treatments, so the evidence for their efficacy is questionable.

5.2.6 *Nitrogen*

Pryor (1940) investigated the effects of nitrogen on clubroot in a number of brassica varieties, and demonstrated that clubroot developed on susceptible varieties at both low and high levels of nitrogen. Walker & Hooker (1945) found that when nitrogen was omitted from nutrient solutions, cabbage plants developed more clubroot than when adequate nitrogen was supplied. Dixon et al. (1987) found that elevated nitrogen had little effect on clubroot and root hair invasion by *P. brassicae* in seedlings in nutrient culture. However, high levels of nitrogen combined with high levels of either calcium or boron, completely inhibited clubroot development. Furthermore, in a field trial, nitrogen applied as a root dip to cabbage seedlings one day before transplanting reduced clubroot in adult plants.

5.2.7 *Other nutrients*

Barium hydroxide, barium carbonate, magnesium oxide and magnesium carbonate were found by Samuel and Garrett (1945) to almost completely inhibit root hair infection by *P. brassicae* when susceptible seedlings were grown in sand and soil mixtures, while aluminium hydroxide, magnesium chloride and barium chloride were found to have little effect on root hair infection by *P. brassicae*. Applying manganese reduced clubroot in seedlings of susceptible cabbage varieties (Antonova et al. 1974). On the other hand, zinc sulfate, zinc chloride, zinc oxide and aluminum sulfate applied to transplants as liquids have all been shown to be ineffective for clubroot control (Karling 1968).

5.3 Surfactants

Humpherson-Jones (1989, 1993) tested several surfactant materials for activity against *P. brassicae* infection of cabbage in glasshouse and field trials. Alkyl phenol ethylene oxide (Agral) and two formulations of sodium dioctyl sulfosuccinate (Monawet MO-70 and Manoxol OT) effectively controlled clubroot in glasshouse tests. In field trials, the same chemicals, applied to transplants as pre-planting soaks, or as drenches in transplant holes, were very effective in controlling clubroot. For example, alkyl phenol ethylene oxide, applied as 100 ml of 0.1% or 0.2% solutions in transplant holes, reduced clubroot severity and resulted in a yield increase of up to 250%. The surfactant was not thought to be toxic to resting spores of *P. brassicae*, but was probably toxic to zoospores in a manner similar to that observed with zoospores of the lettuce big vein pathogen, *Olpidium brassicae* (Wor.) Dong (Tomlinson & Faithfull 1979).

5.4 Disinfectants

Datnoff et al. (1984) confirmed that irrigation water from ponds and streams could be contaminated with *P. brassicae* resting spores, providing a source of clubroot infection in cabbage fields. Datnoff et al. (1987) demonstrated that adding chlorine to contaminated water reduced clubroot infection of irrigated plants in glasshouse and field trials, although effective levels of chlorine (200 mg /ℓ) were phytotoxic to cabbage plants in the field. Results from this study suggested that chlorine killed resting spores of *P. brassicae*. Koponen et al. (1993) demonstrated in glasshouse trials that clubroot in rape plants grown in *P. brassicae*-contaminated containers was reduced by disinfecting the containers with formaldehyde, iodine, quaternary ammonium compounds, sodium hypochlorite and potassium peroxysulfate.

5.5 Antibiotics

Karling (1968) cited a test of streptomycin for the control of clubroot. Transplant holes were drenched with a 0.25% solution of streptomycin, but the treatment only reduced clubroot on treated plants by 8%. Griseofulvin was tested for efficacy against *P. brassicae* by Last (1956), Potter (1956, 1957), and Macfarlane and Last (1957). Griseofulvin was most effective when there were low populations of *P. brassicae* spores in the soil, but it only reduced the severity and not the incidence of clubroot. Applying griseofulvin two weeks after inoculation of soil was more effective in reducing clubroot than applying it immediately after, or four weeks after inoculation. These workers also tested the effectiveness of griseofulvin as a foliar spray but despite original suggestions that downward translocation of the antibiotic was responsible for clubroot reduction,

they later concluded that runoff from leaves caused the observed responses. Rosser (1957) found that applying griseofulvin to seed beds or using it as a transplant dip was ineffective for controlling clubroot. Conversely, Rich (1957) found that griseofulvin gave good clubroot control when applied to soil, and also demonstrated that it did not translocate to plant roots when it was applied as a foliar spray.

5.6 Composts and waste materials

Composts and other waste materials have been used successfully to control soilborne diseases in China, Japan and other Asian countries for many years (Hoitink & Fahy 1986), and there is increasing interest in the use of these materials in other countries (Pitt et al. 1997). Studies have investigated the effects of applying composts and waste products on the control of clubroot in soils infested with *P. brassicae*, and examined the effects of composting processes on resting spores of the pathogen. Kinoshita et al. (1984) tested the efficacy of composted bark, cattle manure, poultry manure, sewage sludge and composted wool waste for control of clubroot in field grown cabbages. Clubroot severity was reduced with two annual applications of either sewage sludge or composted wool waste. Further trials showed that additional applications of composted wool waste did not reduce disease severity further. Applying a combination of sewage sludge and composted wool waste did not improve disease control compared with single applications of the two composts. Applying a composted wool waste treatment with quintozene further enhanced clubroot control. Adding sewage sludge raised the soil pH and increased total nitrogen and phosphorus content, and exchangeable calcium and magnesium in the soil. Composted wool waste increased only the nitrogen content of the soil. In Poland, Szczech et al. (1993) investigated the efficacy of slurries of commercial earth worm compost as pre-plant root dips for controlling clubroot. The compost was tested as an alternative to the peat commonly used in the dip slurry, which also included thiophanate-methyl. The compost reduced clubroot more than the control treatment of peat. The standard peat/fungicide treatment was most effective in controlling clubroot.

Composting infested plant material has been shown to kill *P. brassicae* resting spores. The high temperatures (60-70°C) reached in the early stages of composting are the likely cause of spore death. The best results are achieved at compost moisture levels of 60-80% in alkaline conditions (Ylimäki et al. 1983; Bollen 1985; Lopez-Real & Foster 1985).

5.7 Soil amendments

Sun and Huang (1985) developed a soil amendment (S-H mixture) containing 4% bagasse, 8% rice husks, 4% oyster-shell powder, 8% urea, 1% potassium nitrate, 13% calcium superphosphate and 61% mineral ash (31% silicon dioxide, 44% calcium oxide, 2% magnesium oxide, 18% aluminium oxide, and 1% ferrous oxide). After successful use of the mixture to control Fusarium diseases in vegetables, it was tested against other soilborne pathogens including *P. brassicae*. In glasshouse tests, S-H mixture at 1% in clubroot-infested soil completely inhibited disease development (Hsieh & Yang 1984; Sun & Huang 1985). Testing the components of the S-H mixture suggested that the mineral ash was the likely active ingredient (Hsieh & Yang 1984; Lin et al. 1990), reflecting Woronin's observations over 100 years ago on using soot for clubroot control. Components of the S-H mixture greatly reduced the number of host root hairs infected with *P. brassicae*, and zoosporangium formation in roots.

Evans (1993) demonstrated that adding chitin to soil infested with *P. brassicae* reduced clubroot in Chinese cabbage plants six weeks after sowing. Reduction in disease was greatest when planting was delayed for one month after chitin had been added to the soil. Some phytotoxicity from chitin amendment was observed.

Chitosan, a polysaccharide derived from deacetylation of crab exoskeletons (chitin), has been tested against *P. brassicae* (Cheah & Page, 1997). A field trial showed that a 2% solution of chitosan used as a soil drench significantly reduced the severity of clubroot in Chinese cabbage, but did not increase the top weight of the plant.

Attempts have also been made to develop biological control of clubroot by using isolates of soil fungi (Djatnika, 1991) and soilborne bacteria (Einhorn et al, 1991; Elsherif & Grossman, 1991), but none of these has proved effective under field conditions. However, Cheah and Page (1997) tested ten isolates of *Trichoderma* collected from root zones of brassica plants. They showed that two of these had reduced the severity of the disease, but did not increase the top weight of the plant. Narisawa et al. (1998) isolated 322 root-colonising fungi and showed that 16 of these almost completely suppressed clubroot in sterile soil. Two (*Heteroconium chaetospira*) of these fungi were also effective in non-sterile soil.

These results indicate that there is a potential opportunity to control clubroot using biological agents isolated from root zones, which can colonise the roots of host plants.

5.8 Other non-pesticide methods of clubroot control

A number of crop management practices may reduce the severity of clubroot in vegetable brassicas by naturally reducing *P. brassicae* inoculum levels in soil, e.g. crop rotations, long fallows between brassica crops, growing bait crops (e.g. resistant turnip, kale, oilseed rape, tomato, cucumber, peppermint, summer savory and thyme), improving soil drainage, and removing weeds (Karling 1968; Yamagishi 1987; Harling & Kennedy 1991; Rod 1994; Robak 1996).

6 CONCLUSIONS

Many different materials, which are probably safe for human health, beneficial organisms and the environment, have been tested for efficacy against *P. brassicae*. Few of these have been shown to eliminate clubroot, and conflicting conclusions have been made about several materials, emphasising that the development of clubroot is affected by many interacting factors in the complex soil environment.

Despite some equivocal results, several materials that have shown promise for clubroot control can be used in intensive brassica production. They include fertilisers containing calcium and boron (particularly calcium carbonate), surfactants, and composts and soil amendments.

A number of materials have been shown to improve clubroot control when used in combination with pesticide chemicals. As advances in pesticide science improve the safety of disease control chemicals, integrated clubroot control strategies that use "safe" methods combined with appropriate chemical applications are likely to become increasingly acceptable. The introduction of vegetable brassica cultivars with durable resistance to clubroot will form a third part of an integrated strategy for clubroot control (Nott et al. 1995a). Combining the use of safe chemicals, resistant cultivars and appropriate agronomic practices (Nott et al. 1994; 1995a; 1995b) offers the greatest likelihood of adequately controlling clubroot in intensive vegetable production.

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