

Plasmodiophora brassicae in its environment

Article

Accepted Version

Dixon, G. R. (2009) *Plasmodiophora brassicae* in its environment. *Journal of Plant Growth Regulation*, 28 (3). pp. 212-228. ISSN 0721-7595 Available at <https://centaur.reading.ac.uk/66432/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

Publisher: Springer

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Chapter 3:

Plasmodiophora brassicae in its environment

Geoffrey R Dixon, Centre for Horticulture & Landscape, School of Biological Sciences, Whiteknights, The University of Reading, Reading, Berkshire RG6 6AS, United Kingdom.

Anderson (1855)** “Mr Hunter of Haugh limed part of a field..... at the rate of sixty bolls per scotch acre and the turnips that were afterwards grown on this portion were free of disease..... Yet there are many reports where this failed to happen”. This early comment presages the confusion in our understanding of the interaction of this microbe¹ and its environment which has continued for 150 years.

ABSTRACT

Plasmodiophora brassicae Wor., is viewed here from the stand point of being a highly evolved and successful organism, well fitted for the ecological niche that it occupies. Physical, chemical and biological components of the soil environment are discussed in relation to their effects on the survival, growth and reproduction of this microbe. It is evident that *P. brassicae* is well equipped by virtue of its robust resting spores for survival through many seasonal cycles. Germination is probably triggered as a result of signals initiated by root exudates. The resultant motile zoospore moves rapidly to the root hair surface and penetration and colonisation follow. The short period between germination and penetration is one of greatest vulnerability for *P. brassicae*. In this phase survival is affected at the very least by:- soil texture and structure, its moisture, pH, calcium, boron, nitrogen content and the presence of active microbial antagonists. These factors influence the inoculum potential (*sensu* Garrett, 1956) and its viability and invasive capacity. There is evidence that these effects may also influence differentially the survival of some physiological races of *P. brassicae*. Considering the interaction of *P. brassicae* with the soil environment from the perspective of its biological fitness is an unusual approach, most authors consider only the opportunities to destroy this organism. The approach adopted here is borne of several decades spent studying *P. brassicae* and the respect that has engendered for it as a biological entity. This review stops at the point of penetration, although some of the implications of the environment for successful colonisation are included since they form a continuum. Interactions with the molecular and biochemical cellular environment are considered in other chapters in this Special Edition.

¹ The term microbe is used as a short hand reference for *Plasmodiophora brassicae* reflecting its confused taxonomy

Keywords: *Plasmodiophora brassicae*, clubroot, environment, inoculum potential, biological, chemical and physical interactions

Plasmodiophora brassicae Wor., the microbe causing Clubroot Disease² of the *Brassicaceae*, is very well fitted for successful life on three counts. Firstly, the robust, well protected and apparently long lived, soil borne resting spores allow this organism to withstand adverse conditions and yet these dormant structures appear to be capable of responding speedily once a compatible host arrives. Secondly, when that host is available the primary zoospores emerging from the perennating spores possess efficient and effective locomotion, penetration and invasive capacities. These features enable *P. brassicae* to exploit the soil environment and its interface, the rhizosphere, with the host to best advantage. Thirdly, once within the host environment the reproductive cycles of *P. brassicae* are shielded from adverse external conditions, allowing the production of multitudinous new resting spores that eventually rebuild the soil inoculum potential (*sensu* Garrett, 1956). During this phase the pathogen appears to have the capability of altering the host's metabolic activities to its own advantage (see chapter 4).

For only short times and across minute distances in the soil are the primary zoospores exposed to hostile and adverse conditions. While in this soil phase the delicate and vulnerable single walled, zoospores equipped with twin flagellae swim through the soil moisture films from germinated resting spores to the outer surfaces of root hairs. This is the singularly most vulnerable part of the entire life cycle of *P. brassicae*. Yet, this phase has not received the scientific attention it deserves, probably because the tools needed for such study are either lacking or too crude. There are a few sign posts indicating the effects of chemical and physical soil components on *P. brassicae* itself, mostly these have been gathered through attempts to construct highly adverse conditions and hence stop host invasion thereby controlling the disease. Little is known of how *P. brassicae* interacts with its biological environment apart from a few studies of microbes that might offer elements in strategies for control. Indeed even Karling's monograph (Karling, 1968) is sparse on this topic. Perhaps this goes some way towards explaining why effective control of Clubroot Disease has proved so difficult to achieve. This Chapter outlines what is known and attempts to indicate why large gaps exist in our knowledge and how these might be filled. Comprehending the biological fitness of *P. brassicae* is the focus of this Chapter, elsewhere, for example Chapter 9, others have considered manipulating such understanding to the disadvantage of *P. brassicae*.

² The term Clubroot is reserved solely for the host symptoms resulting from infection by *Plasmodiophora brassicae*

Resting Spores

The resting spore of *P. brassicae* is an obvious point to commence considering environmental interactions. The structure of resting spores is described in Chapter 2. These robust spores have the purpose of providing long term survival and perennation for *P. brassicae* and consequently they have evolved to retain viability in the soil despite exposure to many seasons of adverse weather. Field studies indicate they have a half life of at least 3.6 years and some spores may exist for at least 18 years in the absence of suitable hosts before spore populations are eroded to undetectable levels (Wallenhammar, 1996). Apparently long term resting spore longevity perplexed early researchers such as Gibbs (1939), not least because of reports that cruciferous crops grown on land previously carrying permanent grassland leys could become rife with Clubroot Disease after one or two years of arable cropping with brassicas, frequently swedes (*Brassica napus*) grown for stock feed. Temperature, moisture content and position in the soil profile will influence spore longevity (Monteith 1924; Fedorintschik (1935). Soil pH apparently affects the rate of production of primary zoospores, numbers increased in acidic compared with alkaline soils (Bochow (1961) but without much change in total germination. Spore dormancy and the need for external stimulants form elements in the initial relations between *P. brassicae* and the environment (for example see Honig, 1931). Only a few spores on release from rotten roots germinate immediately (Ogawa and others 2001), forms of external stimulus (Ohi and others 2003; Hata and others 2002) could be needed to initiate the process. The readiness for germination of spores released from host roots was examined by a consecutive string of researchers, for example by:- Humphrey, 1892; Chupp, 1917; Naumov, 1925; Honig, 1931; and Colhoun, 1958; generally they concluded that bacteria and other organisms disintegrate the diseased host tissues and ‘condition’ spores for more effective germination. But these secondary microbes are not essential for the germination process itself. Unknown mechanisms present within the resting spore initiate germination and control its speed. It appears that these mechanisms within individual spores operate quite separately from other spores since not all spores germinate in synchrony.

Rain and flood water disseminate *P. brassicae* over quite substantial distances especially on sloping land. Wind disperses spores that are collected with light, dry, dusty soil particles over even greater distances. Earthworms (Gleisberg, 1922) and possibly moles, root nematodes and insects may be vectors (Chupp, 1924; Eriksson, 1936) for *P. brassicae* in soil. Spores are spread in manure (Gibbs, 1931b) and on farm animals themselves being capable of withstanding the gut environment. Farm animals and their food supplies sailing with European colonists to the New World and Australasia were probably vehicles for *P. brassicae* infesting virgin territory. The worldwide survey of physiological races completed by Toxopeus and others (1986) indicated a predominance of virulences for *B. napus* in these regions. At the more micro-geographical level it is thought likely that the pathogen was introduced into the previously uninfected soils of

intensively cropped vegetable holdings in Lincolnshire (UK) as a result of importing sheep to 'clean-up' unharvested broccoli (*B. oleracea* ssp *italic*) (P Corfield, personal communication). Dirty machinery, wheels, boxes and stillages all provide potential means for the spread *P. brassicae*. Wild and weedy members of the *Brassicaceae* and infested crop transplants harbour, spread and perpetuate the pathogen (see Chapter 8). Once established in a soil profile subsequent distribution is related to soil textural and structural properties and the frequency and intensity of husbandry operations. Soil compaction and panning by rototilling reduced the movement of spores into the subsoil as did a large 'A' horizon of top soil with an active rhizosphere (Murakami and others 2003). The population density of resting spores decreased at increasing soil depths, more than 97 % of the total of *P. brassicae* inoculum was present in the surface soil (0-5 cm depth) and few resting spores were found below 40 cm deep soil (Kim and others 2000). Since the density of resting spores is affected by soil type, pH and host susceptibility a combination of these factors determines intensity of the inoculum potential at a particular site. It follows that after germination in a specific environment the inoculum potential of *P. brassicae* produces dose-response curves (Murakami and others 2002) unique to that particular site.

At germination the resting spore volume increases as vacuoles enlarge and the walls thicken becoming more transparent (Woronin, 1878; Favorski, 1910; Chupp, 1917). A single swarm zoospore is liberated from each resting spore leaving behind residual cytoplasm. Germination is characterised by a loss of refractile globules characteristic of stored reserves in dormant spores and probably indicating the enzymic mobilisation of these resources. Immersion of spores in water may encourage germination (Chupp, 1917, Bawden 1948). Ayers (1944) obtained germination in 1 to 10 days using tap water and speed of germination appeared to be dependent on spore maturity. The absolute need for a host stimulus could be questionable as Honig (1931) induced germination below 21⁰ C in the absence of seedling roots. Optimal temperature for resting spore germination was established as 24 °C and pH 6.0–6.7 with an upper lethal temperature of 45 °C and with visible light inhibiting germination. Spores may be stored as dense suspensions at 3-4°C for 3 years without loss of viability (Macfarlane, 1958) apparently withstanding anaerobic conditions and are not killed by exposure to -20 °C for 3 days. It is standard practice to store galls at -20 °C for several years as stock inoculum (Dixon, 1976). These few fragments of information are sufficient to identify the resting spores of *P. brassicae* as being very robust, capable of coping with very adverse conditions. Comparative experiments aiming to establish the effects of temperature on resting spore germination, motility and host infection require that spore maturity, age and hydrogen ion concentration in the immediate vicinity of the host-microbe interaction are known, standardised and reproducible. All too frequently this has not been the case.

Evidence for an impact of the host on resting spore germination is provided by Niwa and others (2008) who reported a significant increase in the percentage of germinated spores (lacking a nucleus) in rhizospheres where the host *B. rapa* var. *perviridis* (neep

greens) was present. The involvement of root exudates as stimulants for resting spore germination was postulated and eventually confirmed by:- Chupp, (1917); Hooker and others, (1945); Macfarlane & Last, (1957), Bochow, (1963, 1965) and Macfarlane, (1970). Substantial studies by Kowalski & Bochow (1996) concluded that the stimulant effect for germination is non-specific and could come from exudates emanating of many species and is not confined solely to those from hosts of *P. brassicae*. This was supported by the evidence of Craig (1989) who found that root exudates from both calabrese and perennial ryegrass stimulated spore germination. Some specific stimulants effects were suggested by Ohi and others, 2003 and Hata and others, 2002. Greatest germination (75%) was found to be induced with root exudates from susceptible cabbage hosts. Suzuki and others, (1992) established that an abiotic stimulant could be present in root exudates particularly those from susceptible and resistant Chinese cabbage cultivars. Complex carbohydrate compounds found in the exudates of cabbage stimulated germination (Mattey & Dixon, unpublished) *in vitro*. Possibly several factors may sequentially influence germination, Yun and others, (2007). Yano and others, (1991) established that a release of calcium ions from spores induced their germination. Host plant exudates stimulated resting spore germination which in turn released a second stimulatory factor, encouraging further activity. The environment in which the host plant grows affects the composition of exudates, drought for example, encourages a release of amino acids. Page (2001) identified calcium as a factor in generating soil suppressiveness to *P. brassicae* and hence adversely affecting germination but recognised that this element does not operate in isolation from the effects of soil microbial flora. Similar findings were reported by Stewart (2007) who used a comparable range of calcium sources. The number of resting spores present was adversely affected by adding highly calcareous converter furnace slag to soils in Japan (Shinoda and others, 2005). Direct evidence that the inhibition of spore germination is a primary cause of pathogen suppression under neutral pH comes from Niwa and others (2008). Numbers of germinated resting spore in soil correlates with levels of root hair invasion. When soil calcium declined so did the number of germinated spores and level of root hair invasion. It seems therefore, that not only do host exudates affect germinability but the numbers of spores available for germination in the first instance relates in some way to calcium availability in soil. Potentially calcium and pH may affect the longevity and viability of the resting spore *in situ* in soil. Calcium-rich compost or calcium carbonate changing soil pH from 6.0 to 6.9 and 6.2 to 7.1 respectively significantly reduced the percentage of germinated spores in the rhizosphere and the number of root-hair infections. This research provides direct evidence that spore germination and subsequent root-hair colonisation is retarded by the presence of calcium and alkaline pH values. Earlier Niwa and others, (2007), found the addition over 15 years of large amounts of organic matter raised soil calcium concentration, changed pH to alkaline values resulting in previously clubroot disease conducive soil becoming suppressive. Organic matter suppressed infection by *P. brassicae* and the finer particle fractions (< 5 mm) changed pH most effectively. Calcium hydroxide, calcium carbonate and potassium hydroxide also suppressed

infection with potassium hydroxide being the least effective (see also Webster, 1986). Adding sulphuric acid to a suppressive soil promoted infection by acidifying it. It is concluded that soil pH has major influence on the processes of infection and calcium contributes separately to these influences with both factors operating in unison. Resting spores from 'unnatural' sources such as callus cultures are less capable of germination than those from galls from whole plants (Matsumiya., 1989, quoting the late T. Naiki, personal communication). This may result from such spores differing physiologically from those grown under natural conditions perhaps as a result of the callus culturing system as suggested by D S Ingram (personal communication). Resting spores have been estimated by the methods of Shinoda and others (2003) and this topic is further explored in Chapter 8. Resting spore numbers per diseased plant increased with low values of disease severity but thereafter, remained almost constant for plants with category '3' symptoms and beyond (Dixon & Doodson, 1970, 1971, Dixon 1977, 1984b). Mean numbers of resting spores per diseased plant ranged from 9^3 to 10^9 regardless of the value of the disease index having apparently passed a saturation threshold. When resting spore load in soil reaches even modest concentrations disease severity increases (Murakami and others 2004).

Zoospore Motility and the Processes of Invasion

Direct knowledge of the movement of zoospores is very limited relating as it does to behaviour after liberation from the resting spore to the point of encystment on root surfaces within soil. This could be termed *Colhoun's Dilemma* (Colhoun, 1958) since *in vivo* studies are obscured by soil and *in vitro* studies are limited by the problems associated with culturing a minute biotrophic microbe which defies axenic culture. The *Dilemma* continues to restrict knowledge even 50 years after Colhoun's labours. Possibly flagellae are those parts of the zoospores primarily affected by soil pH, moisture, calcium, temperature and interactions with other microbes. The motility of other flagellate organisms is known to be affected by such factors, but little information is available for *P. brassicae*. There is a helpful treatment for some other flagellate organisms in Amos & Duckett (1982), while de Weger and others (1987) confirmed that removal of flagellae from the bacterium *Pseudomonas fluorescens* impaired subsequent colonisation of potato roots. Attributing a combined function of locomotion and location to the flagellae of *P. brassicae* is supported by Dick (1997). Less environmental specialization was suggested in the primary zoospores as compared with secondary stages Dixon (1984b).

Soil Moisture

Soil moisture was from the earliest studies of *P. brassicae* viewed empirically as the medium by which the host is reached. In practice of course, the impact of seasonal water supply varies, thus while clubroot is regarded as a disease of wet soils there are many reports of its severity increasing during dry seasons or on dry sites. This perhaps reflects a loss of productive root systems which renders foliage highly susceptible to

water stress in periods of soil deficit. Clubroot disease is however, considered as associated with low lying, poorly drained soils and disease is severest after wet weather. For this reason soil moisture is classed as a dominant environmental factor in interactions with *P. brassicae*. This contention is supported by only limited serious scientific experimentation.

Colhoun at variance to Monteith (1924), Naumova (1933) and Larson and Walker (1934), obtained infection up to pH 8.2 where moisture content was at 70% maximum water holding capacity (Colhoun, 1952, 1953). Thereby, he demonstrated that plants grown under alkaline conditions were vulnerable to clubroot disease when other environmental factors are weighted heavily in favour of the pathogen. In support of this contention, infection developed in 10 to 18 hours with an excessively moist soil (Wellman, 1930). Hence, when soil moisture content rises above 50% soil water holding capacity disease develops very quickly demonstrating indirectly the speed at which primary zoospores travel. Variations in the effects of soil moisture content may well reflect differences in the textures of soil used by differing researchers. Texture could affect the motility of *P. brassicae* zoospores as suggested by Samuel & Garrett (1945) since in their experiments sand–soil mixtures produced the highest levels of infection. Infection developed at moisture levels as low as 9% in mineral soils whereas 60% was necessary with organic soils (Hamilton & Crête, 1978). Where soil moisture rises from 50% of maximum water holding capacity up to saturation (Dixon, 1981, 1984b) disease severity escalates. Lange & Olson (1983) emphasised the dependence of zoosporic microbes on free water existing between the soil crumbs for the movement of zoospores. Free water is critically important for the formation, discharge and dispersal of zoospores and may influence the encystment and penetration processes at the root-hair surface. The distances travelled by soil borne zoospores are relatively short, probably between 10–20 mm judging by information for *Olpidium brassicae* or *Synchytrium endobioticum* both relatives of *P. brassicae*. Invasion of root hairs occurred up to 75mm from the source of *P. brassicae* infection in soils where water mass movements were minimised (Watson, 1967). Mathematical modeling by Yang and others (2004) demonstrated a relationship between soil moisture and host invasion.

Temperature

Temperature has been regarded as a factor of lesser importance than soil moisture affecting the successful movement and invasion of *P. brassicae*. Its study has produced conflicting results in a similar manner to soil moisture and for comparable reasons. Severe infection developed in acidic soils at air temperatures of 16.6 °C, when alkaline soils are used disease expression was less severe. Disease development was more favoured when working with alkaline soils by air temperature of 23 °C and fluctuations around the mean (Colhoun, 1953). As with soil moisture Colhoun's results showed that providing conditions where a cardinal environmental factor greatly favoured the pathogen allowed disease development despite other apparently disadvantageous factors. Previously, temperatures below 20 °C were thought to present a barrier to

clubroot disease development (Chupp, 1917; Gibbs, 1931a). But, Monteith (1924) showed that symptoms developed throughout the range 9 to 30 °C and was supported in this contention by Wellman (1930). In New Zealand Ayers, (1944) identified the minimum temperature for root hair infection of swede at 12-14 °C. Studies by Johnson in the 1960s at the Welsh Plant Breeding Station [now The University of Wales, Aberystwyth] (Johnson, *personal* communication) showed that the early stages of root hair infection immediately following inoculation required temperatures > 22.5 °C. Once root-hair invasion was completed then he believed that lower and fluctuating temperatures were sufficient to support symptom formation. Growth analysis studies by Buczacki and others (1978) suggested that temperature is most significant as a regulatory factor in the second week after inoculation, this is when root hair colonisation reaches its peak and zoosporangia are forming.

It is possible that the predominance of individual environmental factor alters according to the stage in the life cycle under consideration. Webster (1986) postulated: “that when one factor limits disease expression (such as pH) another may significantly modulate their levels (such as temperature)”; this implied that one factor sets an actual limit while another interacts establishing a frequency or intensity. This argument is consistent with Colhoun’s previous contentions. Wallenhammar (1999) citing C. Williamson suggested that galling could develop at 7 °C with diurnal fluctuations in temperature and increases of 8 to 12 hours in day length. Certainly rising spring temperatures were associated with infection and disease expression in Swedish oil seed rape (*B. napus*) crops Wallenhammar claimed as daylength increases and host growth accelerates. Interactions may go further and relate to effects on the constitution of the host since Robak & Gabrielson (1988) found that temperature influenced the expression of host resistance, a finding not uncommon with foliar invading microbes but not frequently suggested for soil borne organisms. He suggested that cauliflower cvs resistant at 15 °C could show susceptibility at 20 °C with high inoculum potentials.

Light Intensity

Since this is a soil borne microbe it would not be expected that light has any significant impact on growth. But Colhoun (1961) showed that light intensity had marked effects on the relationship between spore load and the number of plants that develop clubroot disease. Consequently, Grainger (1962) was able to relate clubroot development with his C_P/R_S ratio system where C_P = the weight of total carbohydrate in the whole plant and R_S = the residual dry weight of the shoot. Webster (1986) commented that “light may influence disease expression via an effect on host photosynthetic efficiency and hence on energy reserves available to fuel clubbing”. Light may also regulate the balance between shoot and root growth. Rausch and others (1981) showed that low light intensities gave a greater reduction in root growth in infected compared with control plants.

Soil Texture and Structure

Some early workers associated clubroot disease expression with light soils (Colhoun, 1958), others expressed a contrary view (Milburn, 1855; Russell, 1859; Eriksson, 1930). In controlled experiments Palm & McNew (1956) demonstrated infection happened more readily in mixtures of soil and sand or of clay and sand or in undiluted soil as compared with pure sand cultures. Soil compaction and consequent water logging caused by animals or machinery is associated with increased disease severity around headlands and gateways (Anderson, 1855, Russell, 1859, Somerville, 1895). By contrast Anderson (1855) associated the disease with loose open soils and Somerville (1895) associated the disease on turnips (*B. rapa*) with soil aeration caused by hoeing during winter and Larson & Walker (1934) contended that aerating alkaline soil favoured infection. Light, sandy, humus-rich and clayey soils are thought most disease prone. As with the interaction of clubroot and acidity or alkalinity there is a dearth of rigorously tested science-based evidence concerning disease development and soil characteristics. Soil type was shown by Tinggal (1980) to influence the disease causing abilities of physiological races of *P. brassicae* (as defined by the European Clubroot Differential Series, ECD). Clay and loam soils are prone to compaction and may also be calcareous resulting in interactions between conducive and suppressive effects moderated by factors such as inoculum potential thereby determining disease expression. Soils of high water holding capacity such as silts are likely to encourage this pathogen. Soil type interacting with calcium and pH are considered by Campbell & Geathead (1996) as factors determining disease intensity.

Spore Load

A relationship between root hair infections and cortical clubbing could be expected from epidemiological theory (van der Plank, 1975) and was investigated by Naiki and others (1984) using the ECD series of genotypes and 54 common Japanese crucifers. Despite detailed recordings of root hair infection in susceptible and resistant types, disease frequency could not be related to subsequent clubbing reinforcing the results of much earlier studies such as those by Naumov (1925). Nonetheless, spore load is accepted as seminally important in determining the intensity of subsequent disease especially at low concentrations. Key studies by Samuel & Garrett (1945) where number of infected root-hairs increased concomitantly with spore density and Macfarlane (1952) who related rising spore load and percentage of clubbed plants laid early foundations to knowledge in this area. But importantly Macfarlane's (1952) association broke down at very high inoculum levels when he postulated that an early supply of nutrients was available. There are interactions with spore maturity such that older spores appeared more capable of causing infection compared with younger ones in what Colhoun (1958) termed 'infective power'. Under less than optimal environments spore load related to the number of diseased plants thus with alkaline soils he found a direct relationship between spore load and number of diseased plants.

The conditions under which resting spores are stored affected their viability (Macfarlane & Last, 1957) while germination was encouraged and the proportion of germinated spores was increased by the presence of host root exudates. Interacting factors such as:- moisture, temperature, pH, light intensity, and internal factors including spore size, age and nutritional status affected the overall outcome of the interaction between host and parasite. "Inoculum pressure is modified by environment" noted Webster (1986), she concluded that under environmentally unlimiting conditions, and below the threshold level of infection needed for maximum disease expression, severity of clubbing is proportional to increasing inoculum concentration and total root hair infection. Above this threshold level, however, increasing spore concentration may generate higher root-hair infection levels but not relate to increased disease severity. Webster's 'threshold' is effectively a saturation point beyond which the physiological and biochemical processes (see chapter 5) governing symptom development within the host cannot be affected by inoculum load. Saturation itself is not a fixed and immutable value since Webster's work supported the view that only a low percentage of spores in an inoculum are capable of causing successful infection or invasion at any one time. Saturation of the root hair space within an observed section of root, distribution of spores around susceptible root-hairs and distances over which they can travel are all factors influencing the chances of an additional spore being able to establish an infection and proceeding to cause clubroot disease. The two stage life cycle of *P. brassicae* inevitably means that only a limited number of invading zoospores can ultimately proceed to incite symptoms. Not least there may be competition for root-hair space by different physiological races of *P. brassicae* as suggested by Jones (1980). Both antagonistic and synergistic relationships between races of *P. brassicae* may affect relationships between physiological forms (Dixon, 1979, 1980, Jones and others, 1981, Dixon and others, 1981). Within any population of *P. brassicae* spores there may be a range of vigour or infective capacities such that some on establishing infection proceed more rapidly through the life cycle than others. Jones (1980) reported that more than one physiological race of *P. brassicae* may occur within a population or within a spore suspension prepared from a single gall. Jones and others (1981) and Dixon and others (1981) further demonstrated competition between physiological races in experiments using inocula composed of mixed races. Races varied in 'vigour' or 'aggressiveness' as indicated by the intensity of differential reactions between races and hosts using the ECD series. For example, inoculum from *B. napus* cv Marian clubs has been shown to generate a higher disease index on cv. Wilhelmsburger than on cv Nevin, but the reverse was the case for inoculum from cv Acme clubs (Dixon and others 1981). Recently, Tanaka and others (2006b) suggested that there is a suppression of plasmodial development during secondary colonisation in *B. rapa* ssp *pekinensis* cv Kubai 70 which occurs differentially when using a range of isolates of *P. brassicae*. How differences in vigour, aggressiveness or infective capacity are derived and when they come into action are questions yet to be answered.

Host resistance may be considered as an environmental component affecting the success of *P. brassicae*. In that perspective it becomes an additional sink for the energy expended by invading spores. The process of breaching host resistance may be a function of the biological fitness of successive waves of invasions by zoospores both primary and secondary and diminishing general resistance in the host. Ultimately, successful infections are established in the root-hairs of resistant cultivars. It appears that specific resistance is expressed against the secondary phase of the *P. brassicae* life cycle. Hence during that phase more energy may be expended by *P. brassicae*, fruitlessly where robust resistance is present but more successfully when this is not the case. In view of the highly polygenic nature of some forms of resistance to *P. brassicae* especially in *B. oleracea* these events might go some way towards explaining the lags in time between invasions which result in less advanced states of infections on assessment days where plants are subjected to lower inoculum concentrations. As a result infection numbers fall below an observable threshold and in practice are not counted in assays used to determine the value of resistant genotypes. These phenomena have generated much discussion of what constitutes observable or phenotypic resistance to *P. brassicae* (Toxopeus and others, 1975).

Calcium

Possibly the most vexed issue relating to clubroot disease is soil calcium content and the associated hydrogen-ion content (pH) of soil. Calcium emerges as a fundamental factor in the life cycles of both *P. brassicae* and its hosts. Datnoff and others (2007) summarised the involvement of calcium in host metabolism, physiology and signalling of many host-pathogen interactions indicating a relationship with expression of resistance. From the earliest studies of *P. brassicae* and clubroot onwards the disease was associated with acidic soils and claims that it was alleviated by the use of various forms of agricultural lime. Much of the work is, however, contradictory in terms of the forms of lime used, their sources, rates applied, date of application, recipient soil types and the measurement of efficacy. It is now possible to conclude that clubroot disease incidence is not limited at pH 7.0 as is still claimed especially in much farm advisory and home gardening literature. As commented by Colhoun (1958):- “results obtained by field experimentation show the difficulty encountered in determining the *exact upper limit* (my italics) of the soil pH at which infection can (*still*) occur”. This begs the question as to whether there is an *exact upper limit*. Colhoun goes on to argue that “observations have been made without due attention to the variety of other factors which also influence infection” are of little if any value. He advocated the use of potted seedling tests which could be completed in ‘controlled’ conditions. As he also indicates pot tests have been undertaken at high soil moisture content but have failed to control spore load for example and they are much affected by seasonality. Glasshouse experiments running through a winter are far less acceptable because of the weaker host growth compared with those made in spring or early autumn, while summer time experiments are likely to suffer from excessive lifts in air temperature. The chemical

and physical forms and quantities of calcium used also affect the results and add further levels of variables to each experiment. Here again Colhoun (1958) reinforces, as with moisture and temperature, lessons from the classical studies of Samuel & Garrett (1945) related to the impact of spore load, inoculum potential and intensity. Theirs was one of the earliest scientific validations that the effects of pH and of calcium could be separated and quantified individually as factors influencing the environmental success of *P. brassicae*.

Subsequent to Colhoun (1958) practical studies indicated that the impact of the balance of nutrients in the soil is significant while the actual content of individual ions is still important. For example, Myers & Campbell (1985) suggested that clubroot disease expression depends on the balance between pH and the amounts of calcium and magnesium in the soil. While Dobson and others (1983) concluded from their work using roughly and thoroughly mixed limed soils that if roots and spores occur within small pockets of low calcium and / or low pH, invasion is possible despite high overall soil calcium and pH estimations. Fletcher and others (1982) achieved greatest effects of clubroot disease with field applications of calcium carbonate and calcium nitrate which increased pH to 7.9 and 8.3 respectively. They also concluded that although pH was a major factor in reducing disease expression, some other factor than pH possibly the Ca^{++} (calcium) ion itself was involved. Using controlled conditions Hamilton & Crête (1978) formed similar conclusions. These results still however, beg the question of “where and when is *P. brassicae* influenced by the presence of calcium and by pH value?” There is a tendency to assume that these factors affect the microbe while in the soil but since *P. brassicae* spends most of its life cycle within the host it could be fair to suggest that calcium and pH also affect these environments. A role for calcium in the post-infection development of *P. brassicae* is supported by the demonstration that incorporation into roots is pH-dependent (Myers & Campbell, 1985) also Campbell & Greathead (1996) contended that *P. brassicae* is affected at more than one point in the life cycle between spore germination and the completion of resting spore formation in the cortical cells by pH and calcium concentration. Detailed long term experimentation of:- Webster (1986), Dixon & Webster (1988), Webster & Dixon (1991), Dixon and Page (1998) and Page (2001) has confirmed this. It is evident that the greatest impact of calcium is when it is present in the period between spore germination to post-penetration of root-hairs. The latter appears to be when root-hair infection has the biggest impact on subsequent gall formation. There may apparently be separate mechanisms since the periods 0-3 and 0-7 days post-penetration seem to be separated in the extent of their influence on subsequent disease development. The expression of effect seems to be cumulative since it took longer when a $30 \text{ me l}^{-1} \text{ Ca}^{++}$ solution was used as compared with one containing $55 \text{ me l}^{-1} \text{ Ca}^{++}$ in order to achieve similar final results. The host-pathogen response varies also with pH however, that is a separate factor. But it is worth recording here that calcium at pH 7.2 needed to be present by day 14 in order to suppress root-hair infection or alter the progress of galling. The pathogen may be affected by the calcium environment in the root-hair and this alters subsequent

behaviour in the cortical cells. The work of Webster (1986), Dixon & Webster (1988), Webster & Dixon (1991), Dixon and Page (1998) and Page (2001) is supported by results of Donald and others (2004), Donald (2005) in Australia (see Chapter 9). Of major significance is the finding that high concentrations of calcium at pH 6.2 or 7.2 reduce total numbers of root-hair infections and the rate of maturation through plasmodial, sporangial and zoosporangial stages as compared with the controls. Raised concentrations of calcium completely inhibit the later stages of *P. brassicae* development in the root-hair even where high inoculum doses are applied. The calcium effect commences in the soil since Dixon & Page (1998) showed that the germination of resting spores, motility of zoospores and the composition of benign microbial flora around roots are altered. High concentrations of calcium could possibly reduce flagellar action as Satir (1982) and Sleigh & Barlow (1982) reported that changes in calcium of the order of 10^{-6} to 10^{-4} M affected the action of demembrated flagellae, whether this would hold for the flagellae of *P. brassicae* requires to be determined.

Acidity and Alkalinity

Recently, Wallenhammar (1999) pointed to the uneven distribution of acidic and alkaline areas of soil in individual fields with pH ranging from 5.73-8.45 in localised patches. Mattsson (1995) identified that pH values of the subsoil are frequently more alkaline than the upper horizons in Sweden especially in the calcareous glacier clay region near Uppsala in eastern central Sweden. This modernises aspects of *Colhoun's Dilemma* related to pH. Earlier Palm (1958, 1963) had concluded that the effect of pH is not restricted solely to the establishment of *P. brassicae* as a parasite because the rate of gall proliferation was markedly suppressed by an alkaline condition of the medium after infection in the host tissues. It was suggested that changes in the soil reaction may have more drastic effects on gall development than on the number of infections by zoospores. Using organic buffers Myers & Campbell (1985) adjusted pH and calcium content separately from each other and showed that at $10 \text{ me l}^{-1} \text{ Ca}^{2+}$ and a pH of above 7.1 reduced the numbers of primary zoosporangia in root-hairs thus inhibiting galling. Webster & Dixon (1991) demonstrated that the effects of pH are independent of calcium concentration and found that alkaline pH reduced total root-hair infection number and retarded the maturation of plasmodia, sporangia and zoosporangia. The pH effect on the maturation of root-hair infections is activated by exposure to alkaline pH within 3 days of penetration. Prolonged exposure beyond 3 days gives no additional effect.

There may be a dual effect in that alkaline pH increases sensitivity of the host and / or *P. brassicae* to calcium effects as well as increasing the efficiency of calcium uptake. The effects of pH and calcium are remarkably similar but this does not necessarily mean they are one and the same as has been suggested by some workers. They may regulate the pathogenic potential of an inoculum quite separately. Since pH regulates the response to calcium intracellular function may be modified in addition. A high concentration of H^+ ions in plant tissues is potentially antagonistic to calcium. Membrane permeability is lowered by both alkaline pH and by high calcium. This

environment could affect the growth and reproduction of *P. brassicae* as it proliferates within the host root-hair and epidermal cells or within the cortical cells. Alkaline environments could affect primary and secondary invasions, cortical migration and cell hypertrophy. An involvement of Ca^{2+} ions in the growth and reproduction of *P. brassicae* ultimately leading to induced cell death or hypersensitivity is suggested by Takahashi and others (2006). At the agronomic level promoting high alkalinity linked with continuous cropping is suggested by Shinoda and others (2005) as a means of reducing the soil inoculum load.

Boron

This element has associated with affecting the activities of *P. brassicae* from the 1930s (O'Brian and Dennis, 1936) onwards. One of the first controlled studies was that of Palm (1963) who investigated the effect of boron on *P. brassicae* in sand cultures and recorded maximum root-hair infection at 0.3 me l^{-1} or less. He further demonstrated that in the absence of boron the inhibitory effect of calcium on root-hair infection is suppressed, he suggested that lime may fail to diminish clubroot disease in boron deficient soils. Dixon and Wilson (1983), Dixon (1983), Dixon & Wilson (1984 ab), Dixon 1984 (ab), Dixon & Wilson (1985) Dixon (1985) have achieved significant reductions in disease index with sodium tetraborate applied to acidic granitic soils in three successive years of field studies. More recent studies showed that environments with elevated boron concentration there are significant effects both in the root-hair and cortical phases of *P. brassicae*. Throughout the *in planta* stages of the life cycle of *P. brassicae* boron has an impact on the microbe. There appears also to be a relationship with the quantity of boron in the plant which is moderated by uptake over time and space as determined by the size of the plant root system and its capacity to absorb boron. It is likely that there are interactions with other ions. For example, lime applications in the forms of calcium carbonate or oxide may alter the nutrient environment in soil to the detriment of *P. brassicae* and therefore, make the host-parasite association more affected by other factors such as boron. Alternatively, boron may have a primary effect because Webster & Dixon (1991) found that the effects of boron interact with both the primary and secondary stages of development of *P. brassicae* ultimately affecting the intensity of symptom expression. The environment induced by boron in cells where membrane permeability and wall structure are altered may be to the detriment of *P. brassicae*. It could also make for conditions less conducive for nuclear division by the microbe. Quite possibly boron effects are distinct from those of calcium and pH. Dixon (1991) identified that boron affects the progress of *P. brassicae* by retarding the rate of sporangial maturation. The correlation of diminished intensity of disease expression and boron suppression of root-hair infection and gall formation appears related to host exposure. Long exposures to low concentrations seem to equate with the effects of shorter exposures to higher concentrations. Field and controlled laboratory studies (Craig & Dixon 1993 ab) identified that boron has a substantial effect on the ability of *P. brassicae* to invade root-hairs and establish colonisation in the field. Raising the

boron content of the rhizosphere prior to the availability of a susceptible host to infested soil limited the subsequent ability of *P. brassicae* zoospores to penetrate, colonise root hairs and cause symptoms.

Nitrogen

Nitrogen is reported as influencing host parasite associations (see recent general summary by Datnoff and others, 2007), yet there have been few investigations into its effect on clubroot disease. High concentrations of nitrate (4–6 times standard) consistently suppress disease symptoms and Webster (1986) postulated a two phase response with low concentrations enhancing and high concentrations retarding, as found with other biostimulants (Dixon, 1991). Adding nitrate nitrogen results in the stimulation of cellular free amino acid pools. If this stimulated arginine or lysine rich histones then this could possibly lead to repression of RNA polymerases in the microbe preventing it from making access to the gene products needed for pathogenesis. Webster (1986) postulated that as nitrate concentration increased enzyme sites became saturated with consequent substrate and / or product inhibition and the amino acid moieties being diverted towards forming an environment inhibitory to *P. brassicae*. Nitrate metabolism is regulated by the availability of reduced co-factors NAD(P)H (nicotinamide adenine dinucleotide (phosphate)–reduced) for conversion to the ammonium form (Hewitt, 1970). If under conditions of high nitrate supply all available NAD(P)H were used up, then a shortage of such co-factors could influence the activity of *P. brassicae in planta*. Raising nitrate levels above 20 me^{-1} reduced symptom expression and numbers of infected plants. Results obtained in controlled conditions using split root techniques (Dixon & Khatan, unpublished, 1997) demonstrated the effects of nitrate ions in influencing the rhizosphere environment to the detriment of *P. brassicae*. These results were then supported by glasshouse and subsequent field experiments (Dixon, 2009a). In experiments in India, Bhattacharya & Mandal (2006) found that calcium ammonium nitrate and calcium nitrate significantly reduced the intensity of clubroot disease and supported the results of Page (2001). She showed by detailed laboratory and field studies that calcium nitrate is associated with decreases in *P. brassicae* infection with a subsequent reduction in the severity of symptom expression. During the soil phase of *P. brassicae* the viability of resting spores and the ability of primary zoospores to invade the host are reduced by the presence of calcium nitrate. There may be changes to the fitness of *P. brassicae* as a result of the presence of calcium nitrate. In this compound, calcium is available in a highly soluble form linked to the nitrate ion. Page (2001), also concluded that the presence of calcium nitrate in the rhizosphere may also have been associated with changes to the dominant physiological race of *P. brassicae*.

Interactions between the fertiliser calcium cyanamide, *P. brassicae* and other soil microbes have been studied for well over 70 years. A substantial body of information has been built up (Dixon & Wilson (1983); Dixon & Williamson (1985); Naiki & Dixon (1987); Coulshed & Dixon (1990); Humpherson-Jones and others (1992) and Dixon

(2009b) demonstrating that calcium cyanamide and the products of its degradation, calcium and nitrate nitrogen, are associated with the reduced viability of *P. brassicae*. Much further research is required to elucidate the means by which this effect is achieved, but it is now considered likely that calcium cyanamide alters the balance of biological components in the soil environment surrounding *P. brassicae*. Thereby, the growth and reproduction of soil-borne microbes antagonistic to *P. brassicae* are encouraged. Detailed research worldwide by for example:- Klasse (1999) in Germany; Donald and others (2002 and 2004), Donald (2005) in Australia; Porth and others (2003) in the USA; McDonald and others (2004), Belec and others (2004) Tremblay and others (2005), Manolii and others (2005) in Canada and Murakami and others (2002) in Japan, supports the contention that adding calcium cyanamide to soil infested with *P. brassicae* results ultimately in the reduction in the intensity of clubroot disease (see also chapter 8).

Other calcareous substances such as calcified seaweed (a form of coral), or true extracts of algal seaweed which contain inorganic nutrient ions and organic compounds including plant growth regulators and extracts of composts (Tilston and others, 2002) have been associated with changes to the biological environment of soil to the detriment of growth and reproduction of *P. brassicae*. Recently, particular interest has focused on phosphonate and phosphite formulations. These apparently interact with the secondary disease expression phase but no indication has yet been offered for their role in the soil environment (Abbasi & Lazarovits, 2006 a & b). Sen (2005) comments on effects of molybdenum along with calcium and boron in the root environment in relation to pathogenesis of *P. brassicae* on rapeseed mustard in West Bengal India. Interaction of the nutrient environment, pathogenesis and resistance is discussed by Dixon & Walsh (1998), Huber & Graham (1999), Dixon (2002).

Biological Soil Constituents

Little is known of the relationships between *P. brassicae* and the macro- and microflora and fauna in soil. The free swimming zoospores of *P. brassicae* are undoubtedly at risk from the predatory habits of soil inhabitants. Instances of 'disease suppression' may well relate to the presence of such organisms which could increase in unquantified amounts either naturally or following husbandry activities. Soil suppressiveness to pathogenic organisms resulting from the activities of saprophytic microflora is a well accepted phenomenon (Alabouvette and others, 1996) validated by extensive research. Adding organic or inorganic soil amendments that stimulate the microflora has a significant effect the survival of *P. brassicae*. Bacteria such as *Bacillus* spp. and fluorescent *Pseudomonas* spp. are recognised as affecting the growth of *P. brassicae* (Einhorn and others, 1991). Biotic suppressive soils were identified in Taiwan with pH of above 7.4 and a calcium content of 1210 ppm (Hseih and Wang, 1986). Since the resting spore walls contain chitin it is likely that chitinolytic bacteria could be major antagonists of *P. brassicae* reducing the inoculum potential (Anon 2008). Antibiosis resulting from microbial sources has usually been approached as a means for the

biological control of *P. brassicae* as opposed to developing an understanding of the ecological relationships between organisms.

Extensive studies of soil suppressiveness relating to *P. brassicae* have come from researchers in the Fukushima area of northern Honshū, Japan. Haplic andosol soils were found to be more conducive to *P. brassicae* than low-humic andosols even when high spore concentrations were present in the latter. It was suggested that the suppressiveness of low-humic andosols relates to the presence of biological antagonists (Murakami and others, 2000). Biotic suppression of *P. brassicae* in presence of Chinese cabbage (*B. raopa*) host plants reportedly resulted from the presence of the soil endophytic fungus *Heteroconium chaetospora* (Narisawa and others, 2005). Soil moisture content, pH and spores density significantly affected the level of repression of *P. brassicae*. Crop rotations particularly those containing maize (*Zea mays*) depressed the activities of *P. brassicae* (Yamada and others, 2003). This may be expressed as ecological interaction and biological control as described by Dixon (2003 ab).

Primary plasmodia were found in the root cultures of both susceptible and resistant cultivars by Takahashi and others (2006) but secondary plasmodia proliferated only in cultures of susceptible hosts. These authors concluded that the alkalinisation of the root culture of resistant cultivars was responsible for this difference. In the rhizosphere (Nicholas, 1965) saprophytic species thrive supported by nutrients in plant root exudates. This is the environment in which the primary zoospores of *P. brassicae* are actively attempting penetration and colonisation of the host root-hairs. This is a dynamic situation in constant flux as the microbial flora changes under the influence of substantial alterations to root activity, for example root-hairs themselves last for only a few hours, and the range of microbial species alters in some instances almost hourly. This situation must have a major impact on the inoculum potential of *P. brassicae*. Ultimately, this potential includes the supply of biological energy needed for penetration and colonisation of a host. It is a function of inoculum density or intensity (mass or units of inoculum per unit of soil), available nutrient (both internal and external to the propagule), environmental factors and genetic capacity of *P. brassicae* itself (extended from Martinson, 1963). For a particular host species, the levels of genetic resistance varying as they may do during its life cycle and interactions with the environment are key factors determining the outcome of encounters with *P. brassicae*. Combining all these factors of host and microbe interacting with their respective environments offers a predictive index for the success of growth and reproduction by *P. brassicae*.

Despite well over a century of study there is little information concerning the life and death of *P. brassicae* in soil. That is now in very marked contrast to our understanding of interactions within the host (see chapters 4, 5, 6, and 7). Dixon & Walsh (1998) showed that while *P. brassicae* only interacts with the soil environment for a short period both in time and space, this period is critical for the success of *P. brassicae* in establishing subsequent growth and reproduction within the host. These authors emphasise that the rhizosphere is not a rigid entity either in its parameters of shape,

content or time. The propagules of *P. brassicae* experience an environment in which there is an irregular distribution of nutrients, water and oxygen. Elements such as calcium which move towards the root surface by mass flow may accumulate in the rhizosphere in quantities larger than required by the plant roots for uptake. As a result surplus ions accumulate in the immediate environs of the rhizosphere and could have immense impact on *P. brassicae* for example; while the rhizosphere around the root apex is acidic that further back can be alkaline with obvious effects on the colonisation and invasion of those areas by this microbe. Important aspects for the survival of soil borne microbes include the conditions prevailing at the time of arrival at the root surface and in the surrounding rhizosphere affecting establishment and penetration (Bowen & Rovira, 1999). This aspect of the infection court has been rarely examined for even a few pathogenic microbes and not at all for *P. brassicae*. Only work such as that of Page (2001) showing that under some circumstances the presence of calcium and nitrate nitrogen can be associated with changes in the virulence spectrum of the pathogen population begins to indicate the powerful forces present in the rhizosphere which impinge on the primary zoospores of *P. brassicae*. It appears that signals could pass out from the host root to the resting spores of *P. brassicae* triggering germination and then the primary zoospore proceed with location finding and flagella motion towards the root surface (see Figure 1). There are suggestions that sugars and / or carbohydrates in root exudates are involved in triggering the germination of *P. brassicae* and subsequent processes. If this is accurate then quite possibly these compounds also offer an external source of energy for the microbe. Location and direction finding by the zoospore is most likely a result of some form of general or specific chemotaxis such as a gradient of compounds such as carbon dioxide, oxygen or a redox gradient. Alternatively, the zoospores may simply be passively swept through the soil water films by physical flow. That might explain why high levels of soil moisture are prerequisite for successful colonisation. Since temperature is also an important factor possibly it regulates the rates of energy release within the zoospore and chemical interactions with soil components.

While *P. brassicae* is germinating and in motion the primary zoospores are subject to attack by other soil inhabitants such as *Bacillus* species. Decoy crops such as the Japanese leafy daikon (*Raphanus sativus*) appear to operate by encouraging resting spore germination and root-hair colonisation but without successful secondary stage colonisation and subsequent symptom expression (Murakami and others, 2000). Presumably such hosts offer sources of energy for germination and colonisation but without an internal environment conducive to the growth and reproduction of the secondary stages of *P. brassicae*. The degree of decomposition of organic matter apparently influences its suppressive effects in soil and could indirectly also influence these processes.

The fungus *Heteroconium chaetospora* inhibited the activities of *P. brassicae* even where soil physical conditions of moisture and pH would have otherwise have been conducive

(Narisawa and others 2005). Chinese cabbage (*B. rapa*) roots became colonised by hyphae of *Heteroconium chaetospora*, but there is no visible evidence of host cell wall degradation, host reactions or invagination of the host plasma membrane around the hyphae (Yonezawa and others 2004). Earlier work by these authors linked the suppressive and electrical properties of soil. Those with negative charges matching similar potential on spores of *P. brassicae* were conducive to development of the microbe while those with positive charges were suppressive (Murakami and others, 2004). Other members of the soil microflora such as *Bacillus* spp., *Pseudomonas* spp. and *Trichoderma* spp. are recorded as reducing the activity of *P. brassicae* (Yeoung and others, 2003) and *Streptomyces* (Cheah and others, 2001; Joo and others, 2004).

The biotic basis for soil suppressiveness to *P. brassicae* was earlier shown to be supported by abiotic factors (Murakami and others, 2000; Murakami and others 2007) reflecting earlier research by Bochow and colleagues (Bochow, 1961, 1963, 1965; Einhorn and others, 1991). The effect of rhizosphere components on the success of *P. brassicae* was emphasised by Belec and others (2004).

Host and Non-Host Plants

Soil environments created by non-host and host plants such as:- leek (*Allium porrum*), winter rye (*Secale cereal*) and perennial ryegrass (*Lolium perenne*) tended in glasshouse studies to reduce the growth of *P. brassicae* but such effects have been less dramatic in the field. There was no species-specific interaction between *P. brassicae* and non-host types (Friberg and others, 2006). Root exudates from *Lolium perenne* stimulated more spore germination than was obtained from other plants (Friberg and others 2005). These differences could not be explained by variations in the composition of the exudates or differences in root activity. But alternatively such an environment could mitigate against *P. brassicae* such that the microbe fails to invade otherwise susceptible hosts such as *Cardamine flexuosa* as reported by Tanaka and others (2006a). Break or rotational crops may alter the soil environment in a manner suppressive to *P. brassicae* (Cheah and others 2006). Studies of the association of *P. brassicae* and hosts other than cruciferous types have attempted to construct rotations which are antagonistic to *P. brassicae*.

The existence of pathotypes of *P. brassicae* is well established. These exist in complex mixtures within galls, fields and more widely as determined by Toxopeus and others (1986). The pathotypes interact and are influenced in these interactions by the surrounding environments (Tinggal, 1980; Jones, 1980). The extent to which such interactions are influenced by host plants remains to be determined.

The success of *P. brassicae* is dependent on the density of resting spores, soil type, soil pH and host susceptibility. Dose response curves vary even where soils are of similar pedological type (Murakami and others, 2002). The impact of edaphic chemistry

including boron, calcium, nitrogen concentrations and pH on the growth and reproduction of *P. brassicae* within host cells are described by Dixon (2002), Dixon & Page (1998), Webster & Dixon (1991 a & b). Their results describe implications for the manner by which resting spores germinate, the motility of primary zoospores, growth and reproductive efficiency of *P. brassicae in planta* and for the expression of forms of host resistance. These topics and their wider implications have been reviewed by Dixon (2009a).

Considerable focus has been placed on factors affecting the life of *P. brassicae* in this Chapter and elsewhere in this volume are discussions of its life within the hosts. But knowledge of the adversities causing the death of *P. brassicae* can only be surmised at by inversion of those factors apparently aiding the microbe. The death of *Plasmodiophora brassicae* apparently occurs logarithmically in soil so that a few propagules persist for a very long time (Macfarlane, 1952). This conforms with Wallenhammar's findings. Possibly even the lowest level of inoculum can be significant for the survival of *P. brassicae* since Ayers (1944) described infection as commencing from a single zoospore. That being so then *Plasmodiophora brassicae* is indeed superbly well evolved and fitted for survival in hostile soil environments.

References

Abbasi, P. A. & Lazarovits, G. (2006a). Reduction in the incidence and severity of clubroot caused by *Plasmodiophora brassicae* on bok choy and cabbage with soil applications of AG3 phosphonate. Canadian Journal of Plant Pathology, 28,342-371 (reports of Annual Meeting of the Canadian Phytopathological Society, 2006).

Abbasi, P. A. & Lazarovits, G. (2006b). Effect of soil application of AG3 phosphonate on the severity of clubroot of bok choy and cabbage caused by *Plasmodiophora brassicae*. Plant Disease, 90 (12), 1517-1522.

Alabouvette, C., Lemanceau, P. & Steinberg, C. (1996). Biological control of Fusarium wilts: Opportunities for developing a commercial product. Chapter 9 In: Principles and Practice of Managing Soilborne Plant Pathogens. (Edit. R. Hall), pages 192-212. American Phytopathological Society (APS), St Paul, Minnesota USA.

Amos, W. B. & Duckett, J. G. (1982). Prokaryotic and Eukaryotic Flagella. Symposium of the Society for Experimental Biology Number 35, Cambridge University Press, Cambridge.

Anderson, A. (1855). Report on the disease of finger and toe in turnips. Transactions of the Highland Agricultural Society of Scotland, July 1853-March 1855, pages 118-140.

- Anon (2008). Chitin against clubroot. *Gemuse*, 44 (2): 26-27.
- Ayers, G. W. (1944). Studies on the life history of the clubroot organism *Plasmodiophora brassicae*. *Canadian Journal of Research, Section C.*, 143-149.
- Bawden, F. C. (1948). Department of Plant Pathology. Report of the Rothamsted Experimental Station for 1947, 49-52.
- Belec, C., Tremblay, N. & Coulombe, J. (2004). Managing soil – borne pathogens: a sound rhizosphere to improve productivity in intensive horticultural systems. *Acta Horticulturae*, 635, 41-46.
- Bhattacharya, T. K. & Mandal, N. C. (2006). Management of clubroot (*Plasmodiophora brassicae*) of rapeseed and mustard by nitrogenous fertilisers. *Anal. of Plant Protection Sciences*, 14 (1), 260-261.
- Bochow, H. (1961). Über die Beeinflussung von *Plasmodiophora brassicae* Wor. durch Mineralsalze. *Phytopath. Zeitschr.* 40, 420-421.
- Bochow, H. (1963). Untersuchungen zur Ökologie und indirekten Bekämpfung von *Plasmodiophora brassicae* Wor. Ein Beitrag zur Klärung von Fragen der Bodenhygiene. *Habilitationschrift, Univ. Rostak*, 1963, 155 pages.
- Bochow, H. (1965). The effect of root diffusates of host and non-host plants on the spore germination of *Plasmodiophora brassicae* Wor., *Plant microbe relationships. Proceedings of a Symposium on the Relationships between soil micro-organisms and plant roots. Prague 1963*, 296-299 Czechoslovak (now the Czech Republic) Academy of Science, Prague.
- Bowen, G. D. & Rovira, A. D. (1999). The rhizosphere and its management to improve plant growth. *Advances in Agronomy*, 66, 1-102.
- Buczacki, S. T., Ockendon, J. G. & Freeman, G. H. (1978). An analysis of some effects of light and soil temperature on clubroot. *Ann. Appl. Biol.*, 88, 229-238.
- Campbell, R. N. & Greathead, A. S. (1996). Control of clubroot of crucifers by liming. Pages 90 – 101 In: *Soil borne Pathogens: Management of Diseases with Macro – and Microelements.* (edit. A W Engelhard), American Phytopathological Society (APS), St Paul, Minnesota USA.
- Cheah, L. H., Gowers, S. & Marsh, A. T. (2006). Clubroot control using *Brassica* break crops. *Acta Horticulturae*, 706, 329-332.
- Cheah, L. H., Kent, G. & Gowers, S. (2001). Brassica crops and a *Streptomyces* sp. As potential biocontrol for clubroot of brassicas. *New Zealand Plant Protection*, 54, 80-83.
- Chupp, C. (1924). Cabbage diseases. *Plant Disease Reporter*, 8, 125-126.

Chupp, C., (1917). Studies on clubroot of cruciferous plants. Bulletin of Cornell Agricultural Experimental Station, no 387, 419-452.

Colhoun, J. (1952). Factors affecting the incidence of club root disease of Brassicae. Nature London, 169, 21-22.

Colhoun, J. (1953). Observations on the incidence of club root disease of Brassicae in limed soils in relation to temperature. Annals of Applied Biology, 40, 639-644.

Colhoun, J. (1958). Club root disease of crucifers caused by *Plasmodiophora brassicae* Woron. – A monograph. The Commonwealth Mycological Institute, Kew, Surrey, Phytopathological Paper No 3.

Colhoun, J. (1961). Spore load, light intensity and plant nutrition as factors influencing the incidence of club root disease of Brassicae. Transactions of the British Mycological Society (now Mycological Research), 44, 593-600.

Coulshed, K. & Dixon, G.R. (1990). Use of calcium cyanamide and dazomet for the control of clubroot. Proceedings of Crop Protection in Northern Britain Conference, Dundee, 391.

Craig, M A & Dixon, G R (1993a). The influence of boron on the growth of *Plasmodiophora brassicae* in Summer Cabbage. Proceedings Crop Protection in Northern Britain 277-282.

Craig, M A, Dixon G R (1993b). Alterations to the growth of *Plasmodiophora brassicae* Wor. (Clubroot) associated with boron. Proceedings 6th International Congress of Plant Pathology Montreal Poster 3.4.12.

Craig, M. A. (1989). Resting spores of *Plasmodiophora brassicae* as affected by root exudates of hosts and non – hosts. BSc Hons Horticulture Dissertation, University of Strathclyde, Glasgow, 71 pages.

Datnoff, L. E., Elmer, W. H. & Huber, D.M. (2007). Mineral nutrition and plant disease. The American Phytopathological Society, St Paul, Minnesota, USA.

Dick, M. W. (1997). Fungi, flagella and phylogeny. Mycological Research, 101: 385-394.

Dixon, G R (2009a). Husbandry – the sustainable means of controlling soil borne pathogens:- a synoptic review. Acta Horticulturae (in press).

Dixon G R (2009b). Calcium cyanamide – A century of Integrated Control. Plant Protection Science (in press).

Dixon, G R (2003a). Clubroot, a case for integrated control. The Plantsman, 2(3), 179-183.

Dixon, G. R. (2003b). Suppressing *Plasmodiphora brassicae*, the Cause of Clubroot Disease by Biomanipulation. 8th International Congress of Plant Pathology: Solving Problems in the Real World. February 2nd to 7th 2003, Christchurch, New Zealand. Delivered as Oral Poster on Thursday 6th February; Poster Number 20.17, page 275 Abstracts volume 2 - Offered Papers.

Dixon, G. R. (2002). Interactions of soil nutrient environment, pathogenesis and host resistance. *Plant Protection Science (Special Issue)* 38 (1), 87-94.

Dixon, G. R. (1991). Primary and secondary stages of *Plasmodiophora brassicae* (clubroot) as affected by metallic cations and pH. Pages 381 – 386 in *Biotic Interactions and Soil – Borne Diseases*, no 23 in *Developments in Agricultural and Manged Forestry Ecology* (Edits. A. B. R. Beemster, G. J. Bollen, M. Gwerlagh, M. A. Ruissen, B. Schippers & A. Tempel), Elsevier, Amsterdam.

Dixon, G. R. (1985). *Vegetable Husbandry. Research Investigations and Field Trials*, Horticulture Division, Aberdeen School of Agriculture (University of Aberdeen Department of Agriculture and North of Scotland College of Agriculture), Aberdeen.

Dixon, G. R. (1984a) *Vegetable Husbandry. Research Investigations and Field Trials*, Horticulture Division, Aberdeen School of Agriculture (University of Aberdeen Department of Agriculture and North of Scotland College of Agriculture), Aberdeen.

Dixon, G. R. (1984b). Galls caused by fungi and bacteria. Chapter 15 in *Plant Diseases: infection, damage and loss* (Edits. R. K. S. Wood & G. J. Jellis), Blackwell Scientific Publications, Oxford.

Dixon, G. R. (1983) *Vegetable Husbandry. Research Investigations and Field Trials*, Horticulture Division, Aberdeen School of Agriculture (University of Aberdeen Department of Agriculture and North of Scotland College of Agriculture), Aberdeen.

Dixon, G. R. (1981). *Vegetable Crop Diseases*, The MacMillan Press. London & Basingstoke, 404 pages.

Dixon, G.R. (1980). Variation in *Plasmodiophora brassicae*. *Annals of Applied Biology*, 94, 278-280.

Dixon, G.R. (1979). Interactions between host cultivar and *Plasmodiophora brassicae* populations. *Proceedings of Woronin + 100 International Conference on Clubroot*. Published by University of Wisconsin, USA pp. 93-96.

Dixon, G.R. (1977). *Manual of Plant Growth Stage and Disease Assessment Keys* - contains keys developed for the assessment of cluroot of root crops, clubroot-seedling key, Department for Environment, Food & Rural Affairs (Defra) (previously Ministry of Agriculture, Fisheries and Food MAFF), Plant Pathology Laboratory, Harpenden, Hertfordshire now at Central Science Laboratory, York.

- Dixon, G.R. (1976). Methods for testing seedling resistance to clubroot (*Plasmodiophora brassicae*) used in Western Europe and U.S.A. *Plant Pathology*, 25, 129-134.
- Dixon, G.R. & Doodson, J.K. (1970). Clubroot of Brassica Crops. *Agriculture (London)*, 77, 500-503.
- Dixon G.R. & Doodson, J.K. (1971). Assessment keys for some diseases of vegetable, fodder and herbage crops. *Plant Varieties and Seeds. (Journal of National Institute of Agricultural Botany)*, 12, 299-307.
- Dixon G R & Page L V (1998). Calcium and nitrogen eliciting alterations to growth and reproduction of *Plasmodiophora brassicae* (clubroot). *Acta Horticulturae*, 459, 343 – 349.
- Dixon G R & Walsh U F. (1998). Suppression of plant pathogens by organic extracts - A Review. *Acta Horticulturae*, 469, 383 – 390.
- Dixon, G.R. & Webster, M.A. (1988). Antagonistic effects of boron, calcium and pH on pathogenesis caused by *Plasmodiophora brassicae* (clubroot) - A review of recent work. *Crop Research (Horticultural Research)* 28, 83-95.
- Dixon, G.R. & Williamson, C.J. (1985). Factors affecting the use of calcium cyanamide for control of *Plasmodiophora brassicae*. *Proceedings Better Brassicas 1984 Conference, St. Andrews. Published by Scottish Crop Research Institute, Dundee*, 238-244.
- Dixon, G. R. & Wilson, F. (1985). Fungicides applied to propagation blocks and the field to control *Plasmodiophora brassicae*, clubroot on cabbage. *Tests of Agrochemicals and Cultivars no 6 (Supplement to Annals of Applied Biology 106)*, 44-45.
- Dixon, G. R. & Wilson, F. (1984a). Field evaluation of chemicals for control of clubroot (*Plasmodiophora brassicae*). *Proceedings of the Crop Protection in Northern Britain Conference, Dundee*, 400-405.
- Dixon, G. R. & Wilson, F. (1984b). Field evaluation of WL 105305 (NK483) for control of clubroot (*Plasmodiophora brassicae*). *Tests of Agrochemicals and Cultivars no. 5 (Supplement Annals of Applied Biology, 104)*, 34-35.
- Dixon, G. R. & Wilson, F. (1983). Evaluation of calcium cyanamide for control of *Plasmodiophora brassicae* (clubroot). *Tests of Agrochemicals and Cultivars no 4. (Supplement to Annals of Applied Biology, 102)*, 50-51.
- Dixon, G.R., Jones, D.S. & Ingram, D.S. (1981). Studies on the populations of *Plasmodiophora brassicae*. *Proceedings Eucarpia Cruciferae 1981 Conference, Published by Agricultural University of Norway, Aas*, 41-44.

Dobson, R. L., Gabrielson, R. L., Baker, A. S. & Bennett, L. (1983). Effects of lime particle size and distribution and fertiliser formulation on clubroot disease caused by *Plasmodiophora brassicae*. *Plant Disease*, 67, 50-52.

Donald, C. & Porter I. J. (2004). A sand solution culture technique used to observe the effect of calcium and pH on root hair and cortical stages of infection by *Plasmodiophora brassicae*. *Australasian Plant Pathology*, 33 (4), 585-589.

Donald, E. C. (2005). The influence of abiotic factors and host plant physiology on the survival and pathology of *Plasmodiophora brassicae* of vegetable brassicas. PhD Thesis University of Melbourne, Australia, 215 pages.

Donald, E. C., Lawrence, J. M. & Porter, I. J. (2004). Influence of particle size and application method on the efficacy of calcium cyanamide for control of clubroot of vegetable brassicas. *Crop Protection*, 23 (4), 297-303.

Donald, E. C., Porter, I. J. & Lancaster, R. A. (2002). Strategic application of lime, fertilisers and fungicides for improved control of clubroot. *Cruciferae Newsletter* 24: 81-82.

Einhorn, G., Bochow, H., Huber, J. & Krebs, B. (1991). Methodological studies to detect antagonists of the clubroot pathogen *Plasmodiophora brassicae* Wor. *Archiv. Für Phytopathologie und Pflanzenschutz, Archive of Phytopathology and Plant Protection*, 27 (3), 205-208.

Eriksson, J. (1930). *Fungous Diseases of Plants*. 2nd Edition, London, Bailliere Taindall & Co, 526 pages.

Eriksson, J. (1936). *Die Pilzkrankheiten der Kulturgewächse. Handbuch für Pflanzenbauer und Studierende. I. Teil, 2 auf. ; 38-42.*

Favorski, W. (1910). Nouvelle recherche sur le développement et la cytologie de *Plasmodiophora brassicae* Wor. (In Russian), *Mém. Soc. Nat. Kieff.*, 20, 149-183.

Fedorintschik, N. S. (1935b). Life history of club – root of cabbage (*Plasmodiophora brassicae* Woron.). (In Russian) *Summary Science Research Wk. Institute of Plant Protection Leningrad, 1935, 69-70.* (abstract in *Review of Applied Mycology*, 16, 10).

Fletcher, J. T., Hims, M. J., Archer, F. C. & Brown, A. (1982). Effects of adding calcium and sodium salts to field soils on the incidence of clubroot. *Annals of Applied Biology*, 100, 245-251.

Friberg, H., Lagerlof, J. & Ramert, B. (2005). Germination of *Plasmodiophora brassicae* resting spores stimulated by a non – host. *European Journal of Plant Pathology*, 113 (3), 275-281.

Friberg, H., Lagerlof, J. & Ramert, B. (2006). Usefulness of non host plants in managing *Plasmodiophora brassicae*. *Plant Pathology*, 55 (5), 690-695.

Garrett, S. D. (1956). *Biology of Root Invading Fungi*. Cambridge University Press, Cambridge.

Gibbs, J. G. (1931a). Club root in cruciferous crops. *New Zealand Journal of Agriculture*, 42, 1-17.

Gibbs, J. G. (1931b). Dissemination of club root in the dung of farm stock. *New Zealand Journal of Agriculture*, 42, 193-198.

Gibbs, J. G. (1939). Factors influencing the control of club root. *New Zealand Journal of Science and Technology*, 20A, 409-412.

Gleisberg, W. (1922). Das Ratsel der Hernieverbreitung. *Nachr. Bl. Pfl'sch'dienst*. Berlin, 2, 89-90.

Grainger, J. (1962). The host plant as a habitat for fungal and bacterial parasites. *Phytopathology*, 52, 140-150.

Hamilton, H. A. & Crête, R. (1978). Influence of soil moisture, soil pH and liming source on the incidence of clubroot, the germination and growth of cabbage produced in mineral and organic soils under controlled conditions. *Canad. J. Pl. Sci.*, 58, 45-53.

Hata, S., Sumi, Y. & Ohi, M. (2002). Dry powder and extract of *Posidonia australis* Hook. F., a species of seagrass, stimulate the germination of the pathogen *Plasmodiophora brassicae* and control clubroot of Chinese cabbage. *Journal of the Japanese Society for Horticultural Science*, 71 (2), 197-202.

Hewitt, E. J. (1970). Physiological and biochemical factors controlling the assimilation of inorganic nitrogen supplies by plants. In: *Nitrogen Nutrition of the Plant*. Leeds, Waverley Press, 78-103.

Honig, F. (1931). Der Kohlkropfereger (*Plasmodiophora brassicae* Wor.). *Gartenbauwiss.*, 5, 116-225.

Hooker, W. J., Walker, J. C. & Link, K. P. (1945). Effects of two mustard oils on *Plasmodiophora brassicae* and their relation to resistance to clubroot. *J. Agric. Res.*, 70, 63-78.

Hseith, W. H. & Wang, J. (1986). Investigation on suppressive soils of clubroot of crucifers in Taiwan. *Plant Protection Bulletin (Taiwan Republic of China)* 28: 353-362.

Huber, D. M. & Graham, R. D. (1999). The role of nutrition in crop resistance and tolerance to diseases. In *Mineral Nutrition of Crops: Fundamental Mechanisms and Implications*. Food Products Press Binghamton USA pages 169-204.

Humpherson Jones, F M, Dixon, G R, Craig, MA and Ann, D M (1992). Control of clubroot using calcium cyanamide - A review. *Proceedings of Brighton Crop Protection Conference - Pests and Diseases 1992* 98-4 p1147-1154.

Humphrey, J. E. (1892). Report on plant diseases etc. With observations in the field and in the vegetation house. Publ. Document Massachusetts Agricultural Experimental Station, no 33, 218-248 (Abstract in Bot. Zbl., 1892, pp 307-309.).

Jones, D. R. (1980). Differential pathogenicity of *Plasmodiophora brassicae* Wor. PhD thesis University of Cambridge.

Jones, D.R. Ingram, D.S. & Dixon, G.R. (1981). Differential pathogenicity of *Plasmodiophora brassicae*. Cruciferae Newsletter, No. 6, 54-56.

Joo, G. J., Kim, Y. M., Kim, J. W., Kim, W. C., Rhee, I. K., Choi, Y. H. & Kim, J. H. (2004). Biocontrol of cabbage clubroot by the organic fertiliser using *Streptomyces* sp AC-3. Korean Journal of Microbiology and Biotechnology, 32 (2), 172-178.

Karling, J. S. (1968). The Plasmodiophorales. Hafner Publishing Company, New York & London.

Kim, C. H., Cho, W. D. & Kim, H. M. (2000). Distribution of *Plasmodiophora brassicae* causing clubroot disease of Chinese cabbage in soil. Plant Disease Research, 6 (1), 27-32.

Klasse, H. J. (1999). Calcium cyanamide – a unique source of nitrogen promoting healthy growth and improving crop quality in vegetables. In Improved crop quality by nutrient management. Kluwer Academic Publishers, Dordrecht The Netherlands, 233-235.

Kowalski, K. & Bochow, H. (1996). Observations on the behaviour of resting spores of *Plasmodiophora brassicae* in the presence of cruciferous and non-cruciferous plant roots. Acta Hort. 407: 419-421.

Lange, L. & Olson, L. W. (1983). The fungal zoospore – Its structure and biological significance. Pages 1-42 IN: Zoosporic Plant Pathogens – A modern perspective (edit Buczacki, S. T.), Academic Press, London & New York.

Larson, R. H. & Walker, J. C. (1934). Soil treatment in relation to clubroot of cabbage. Journal of Agricultural Research, 48, 749-759.

Macfarlane, I. & Last, F. T. (1957). Club root of cruciferous plants. Report of Rothamsted Experimental Station for 1956, 117-119.

Macfarlane, I. (1952). Factors affecting the survival of *Plasmodiophora brassicae* Wor. in the soil and its assessment by a host test. Annals of Applied Biology, 39, 239-256.

Macfarlane, I. (1958). A solution – culture technique for obtaining root – hair or primary infection by *Plasmodiophora brassicae*. Journal of General Microbiology, 18, 720-732.

Macfarlane, I. (1970). Germination of resting spores of *Plasmodiophora brassicae*. Trans. Br. Mycol. Soc., 55, 97-112.

- Manolii, V. P., Strelkov, S. E., Bansal, v. K. & Howard, R. J. (2005). Liming and calcium fertiliser for clubroot control in canola (*Brassica napus*), Canadian Journal of Plant Pathology, 27 (3), 472.
- Martinson, C. A. (1963). Inoculum potential relationships in *Rhizoctonia solani* measured with microbiological sampling tubes. Phytopathology, 53, 634-638.
- Matsumiya, E (1989). *In vitro* system for an obligate parasite *Plasmodiophora brassicae*. Dissertation for Master of Agriculture degree Graduate School of Agriculture, Hokkaido University, Japan, 63 pages.
- Mattsson, L. (1995). Skördevariationer inom enskilda fält. Storlek och tänkbara orsaker. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Soil Fertility. Report 196.
- McDonald, M. R., Kornatowska, B. & McKeown, A. W.. (2004). Management of clubroot of Asian Brassica crops grown on organic soils. Acta Horticulturae 635: 25-30.
- Milburn, M. M. (1855). Experimental investigations on the finger and toe in turnips. Journal of Agriculture, July 1853-March 1855, pages 73-82.
- Monteith, J. (1924). Relation of soil temperature and soil moisture to infection by *Plasmodiophora brassicae*. Journal of Agricultural Research, 28, 549-561.
- Murakami, H., Tsushima, S. & Shishido, Y. (2000). Soil suppressiveness to clubroot disease of Chinese cabbage caused by *Plasmodiophora brassicae*. Soil Biology & Biochemistry, 32 (11/12), 1637-1642.
- Murakami, H., Tsushima, S., Akimoto, T., Kuoryanagi, Y. & Shishido, Y. (2004). Quantitative studies on the relationship between plowing into soil of clubbed roots of preceding crops caused by *Plasmodiophora brassicae* and disease severity in succeeding crops. Soil Science and Plant Nutrition, 50(8), 1307-1311.
- Murakami, H., Tsushima, S., Kuroyanagi, Y. & Shishido, Y. (2002). Reduction in resting spore density of *Plasmodiophora brassicae* and clubroot severity by liming. Soil Science and Plant Nutrition, 48 (5), 685-691.
- Murakami, K., Nakamura, F. & Goto, I. (2007). Effects of *Bacillus subtilis* NB 22 addition to nursery soils on incidence of clubroot disease. Japanese Journal of Soil Science and Plant Nutrition, 78 (4), 387-390.
- Murakami, K., Shinoda, H., Maruta, R. & Goto, I. (2003). Relationship between physical and chemical properties of soil and resting spore density of *Plasmodiophora brassicae* and clubroot disease index in production areas of cruciferous vegetables. Japanese Journal of Soil Science and Plant Nutrition, 74 (6), 781-786.

- Murakami, K., Shinoda, H., Nakamura, F. & Goto, I. (2004). Influence of soil types and soil pH on the incidence of clubroot disease caused by *Plasmodiophora brassicae*. *Japanese Journal of Soil Science and Plant Nutrition*, 75 (3), 339-345.
- Murakami, H., Tsushima, S. & Shishido, Y. (2002). Factors affecting the pattern of dose response curve of clubroot disease caused by *Plasmodiophora brassicae*. *Soil Science and Plant Nutrition*, 48 (3), 421-427.
- Myers, D. F. & Campbell, R. N. (1985). Lime and the control of clubroot of crucifers: effects of pH, calcium, magnesium and their interaction. *Phytopath.*, 75, 670-673.
- Naiki, T. & Dixon, G.R. (1987). The effects of chemicals on developmental stages of *Plasmodiophora brassicae* (clubroot). *Plant Pathology*, 36, 316-327.
- Naiki, T., Tanahashi, K. & Kageyama, K. (1984). The relationship between root hair infection with *Plasmodiophora brassicae* Wor. and subsequent club formation among cruciferous species. *Annals Phytopathological Society of Japan*, 50, 211-215.
- Narisawa, K., Shimura, M., Usuki, F., Fukuhara, S. & Hashiba, T. (2005). Effects of pathogen density, soil moisture, and soil pH on biological control of clubroot in Chinese cabbage by *Heteroconium chaetospora*. *Plant Disease*, 89 (3), 285-290.
- Naumov, N. A. (1925). Contribution to the study of club root of cabbage. II. (In Russian). *Morbi Plant.* 14, 49-73.
- Naumova, Mme N. A. (1933). Contribution to the knowledge of the influence of soil factors on the development of club root in the Cruciferae. (In Russian). *Bull. Pl. Prot. Leningrad, Series II.*, *Phytopath.* 3, 32-52. (Abstract in *Review of Applied Mycology*, 13, 141).
- Nicholas, D. J. D. (1965). Influence of the rhizosphere on the mineral nutrition of the plant. Pages 210-251 IN *Ecology of Soil-Borne Plant Pathogens – Prelude to Biological Control* (edits. K. F. Baker & W. C. Snyder). John Murray, London.
- Niwa, R., Kumei, T., Nomura, Y., Yoshida, S., Osaki, M. & Ezawa, T. (2007). Increase in soil pH due to Ca – rich organic matter application causes suppression of clubroot disease of crucifers. *Soil Biology & Biochemistry*, 39, 778 – 785.
- Niwa, R., Nomura, Y., Osaki, M. & Ezawa, T. (2008). Suppression of clubroot disease under neutral pH caused by inhibition of spore germination of *Plasmodiophora brassicae* in the rhizosphere. *Plant Pathology*, 57, 445 – 452.
- O'Brian, D.G. & Dennis, R. W. G. (1936). Further information relating to control of clubroot in swedes. *Scottish Journal of Agriculture*, 19: 1-18.

Ogawa, S., Takahashi, H., Hayakawa, T., Ito, K., Mitsui, T., Hori, H. & Kiso, A. (2001). Enhancement of germination of spores from obligatory plant pathogen, *Plasmodiophora brassicae* which causes clubroot disease. Bulletin of the Faculty of Agriculture Niigata University, Japan, 54(1), 35-43.

Ohi, M., Kitamura, T. & Hata, S. (2003). Stimulation by caffeic acid, coumalic acid, and corilagin of the germination of resting spores of the clubroot pathogen *Plasmodiophora brassicae*. Bioscience, Biotechnology and Biochemistry, 67 (1), 170-173.

Page, L. V. (2001). Studies of components for a potential integrated control system for *Plasmodiophora brassicae*. PhD thesis, University of Strathclyde, Glasgow UK.

Palm, E. T. & McNew, G. L. (1956). A method for determining the incidence of club root infection in nutrient cultures. Contributions of the Boyce Thompson Institute, 18, 333-337.

Palm, E. T. (1958). Effect of mineral nutrition on invasiveness of *Plasmodiophora brassicae* Wor. and the development of club root. Dissertation Abstracts, 19, 425-426.

Palm, E. T. (1963). Effect of mineral nutrition on the invasion and response of turnip tissue to *Plasmodiophora brassicae* Wor. Contributions of the Boyce Thompson Institute, 22, 91-112.

Plank, van der, J. E. (1975). Principles of Plant Infection. Academic Press, New York, 216 pages.

Porth, G., Mangan, F., Wick, R. & Autio, W. (2003). Evaluation of management strategies for clubroot (*Plasmodiophora brassicae* Woron) in Brassicaceae. Proceedings of the Interamerican Society for Tropical Horticulture, 46, 78-80.

Rausch, T., Mattusch, P. & Hilgenberg, W. (1981b). Influence of clubroot disease on the growth kinetics of Chinese cabbage. Phytopath. Z., 102, 28-33.

Roback, J & Gabrielson, R. L. (1988). The effects of inoculums potential in screening for resistance to *Plasmodiophora brassicae* in greenhouse trials. Acta Agrobot. 41, 217-224.

Russell, R. (1859). The cause of finger and toe in turnips. Journal of Agriculture ns., 1857-9, pages 529-544.

Samuel, G. & Garrett, S. D. (1945). The infected root hair count for estimating the activity of *Plasmodiophora brassicae* Woron. In the soil. Annals of Applied Biology, 32, 96-101.

Satir, P. (1982). Mechanisms and controls of microtubule sliding in cilia. In:- Amos, W. B. & Duckett, J. G. Prokaryotic and Eukaryotic Flagella, Cambridge University Press (Symposium of the Society for Experimental Biology, Symposium no XXXV.), 179-201.

- Sen, P. (2005). Antagonistic effect of Ca, B and Mo on club-root disease of rape-mustard. *Indian Agriculturist*, 49 (1/2)13-16.
- Shinoda, H., Murakami, K. & Goto, I. (2003). An improved method for measurement of the resting spore density of *Plasmodiophora brassicae* from infested soils. *Japanese Journal of Soil Science and Plant Nutrition* 74 (3), 287-191.
- Shinoda, H., Murakami, K. & Gotto, I. (2005). Effect of amelioration of soil acidity and continuous cropping of cruciferous vegetables on the incidence of clubroot disease and resting spore density in soil. *Japanese Journal of Soil Science and Plant Nutrition*, 76 (6), 891-896.
- Sleigh, M. A. & Barlow, D. I. (1982). How are different ciliary beat patterns produced? In:- Amos, W. B. & Duckett, J. G. *Prokaryotic and Eukaryotic Flagella*, Cambridge University Press (Symposium of the Society for Experimental Biology, Symposium no XXXV.), 139-157.
- Somerville, W. (1895). Further infection experiments with finger and toe. *Journal of the Royal Agricultural Society*, 3rd Series, 6, 749-759.
- Stewart, K. (2007). Conventional and novel treatments for control of clubroot of Brassicas. PhD thesis, University of Edinburgh. UK.
- Suzuki, K., Matsumiya, E., Ueno, Y. & Mizutani, J. (1992). Some properties of germination-stimulating factor from plants for resting spores of *Plasmodiophora brassicae*. *Annals of the Phytopathological Society of Japan* 60: 699-705.
- Takahashi, H., Ishikawa, T., Kaido, M., Takita, K., Hayakawa, T., Okazaki, K., Itoh, K., Mitsui, T. & Hori, H. (2006). *Plasmodiophora brassicae* induced cell death and medium alkalinisation in clubroot-resistant cultured roots of *Brassica rapa*. *Journal of Phytopathology* 154(3): 156-162.
- Takahashi, H., Takita, K., Kishimoto, T., Mitsui, T. & Hori, H. (2002). Ca²⁺ is required by clubroot – resistant turnip cells for transient increases in PAL activity that follows inoculation with *Plasmodiophora brassicae*. *Journal of Phytopathology*, 150 (10), 529-535.
- Tanaka, S., Mizui, Y., Terasaki, H., Yasuaki, S. & Ito, S. I. (2006a). Distribution of clubroot disease of a cruciferous weed, *Cardamine flexuosa*, in major isolated islands Hokkaido and Okinawa in Japan. *Mycoscience*, 47 (2), 72-77. Enter as 2006a
- Tanaka, S., Mido, H. & Ito, S. (2006b). Colonisation by two isolate of *Plasmodiophora brassicae* on a clubroot-resistant cultivar of Chinese cabbage (*Brassica rapa* L. spp *pekinensis*). *Journal of General Plant Pathology* 72(4): 205-209.

- Tilston, E. L., Pitt, D. & Groenhof, A. C. (2002). Composted recycled organic matter suppresses soil-borne diseases of field crops. *New Phytologist* 154 : 731-740.
- Tinggal, S. B. H. (1980). Physiologic populations of *Plasmodiophora brassicae* Woron. In Devon and Cornwall. PhD Thesis, University of Exeter, UK, 294 pages.
- Toxopeus, H., Gowers, S. & Crête, R. (1975). The problem of 'cut-off points'. Clubroot Newsletter no 4: 6-8.
- Toxopeus, H., Dixon, G.R. & Mattusch, P. (1986). Physiological specialisation in *Plasmodiophora brassicae*; an analysis by international experimentation. *Transactions of the British Mycological Society, (now Mycological Research)*, 87, 279-287.
- Tremblay, N., Belec, C., Coulombe, J. & Godin, C. (2005). Evaluation of calcium cyanamide and liming for control of clubroot disease in cauliflower. *Crop Protection*, 24 (9), 798-803.
- Wallenhamar, A-C. (1999). Monitoring and control of *Plasmodiophora brassicae* in spring oilseed brassica crops. *Acta Universitatis Agriculturae Sueciae, Agraria* 183, Swedish University of Agricultural Sciences, Uppsala, 53 pages.
- Watson, A. G. (1967). The movement of *Plasmodiophora brassicae* in soil. *Phytopathology*, 57, 608.
- Webster, M. A. (1986). pH and nutritional effects on infection by *Plasmodiophora brassicae* Wor. and on clubroot symptoms. PhD thesis, University of Aberdeen, 273 pages.
- Webster, M.A. & Dixon, G.R. (1991). Calcium, pH and inoculum concentration as factors limiting root hair colonization by *Plasmodiophora brassicae* Wor. *Mycological Research*, 95, 64-73.
- Weger, L. A. de., Vlugt, C. I. M. van der, Wijfjes, A. H. M., Bakker, P. A. H. M., Schippers, B. & Lugtenberg, B. (1987). Flagella of a plant-growth-stimulating *Pseudomonas fluorescens* strain are required for colonisation of potato root. *Journal of Bacteriology* 169: 2769-2773.
- Wellman, F. L. (1930). Club root of Crucifers. Technical Bulletin of the United States Department of Agriculture, no. 181, 331pp.
- Woronin, M. (1878). *Plasmodiophora brassicae* Urheber der Kohlpflanzen – Hernie. *JB. Wiss. Bot.*, 11, 548-574. (Translation by Chupp, C. *Phytopathological Classics*, no 4, 1934, American Phytopathological Society.).

- Yamada, M., Asandhi, A. A. & Purwati, E. (2003). Employing one – year rotations with three vegetable combinations to control clubroot damage in the West Java Highlands. Research Highlights published by the Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Japan, 16-17
- Yang, M. Y., Yanf, J. L., Sun, D. W. & Yan, w. Z. (2004). Effects of soil moisture on the incidence of clubroot. Southwest China Journal of Agricultural Sciences, 17(4), 482-483.
- Yano, S., Tanaka, S., Kameya-Iwaki, M. & Katumoto, K. (1991). Relation of Ca²⁺ efflux to germination of resting spores of clubroot fungus. Bulletin of the Faculty of Agriculture, Yamaguchi University 39 : 105-112.
- Yeoung, Y. R., Kim, J. H., Kim, B. S. Young, J. J. & Yoon, C. S. (2003). Effects of beneficial antagonists *Bacillus* sp., *Pseudomonas* sp. and *Trichoderma* sp. On the control of clubroot of Chinese cabbage. Korean Journal of Horticultural Science & Technology, 21 (3), 194-198.
- Yonezawa, M., Usuki, F., Narisawa, K., Takahashi, J. & Hashiba, T. (2004). Anatomical study on the interaction between the root endophytic fungus *Heteroconium chaetospira* and Chinese cabbage. Mycoscience, 45 (6), 367-371.
- Yun, H., Quing, M. S., Qin, L/ X., Jing, W. & Ling, H. X. (2007). Morphology of *Plasmodiophora brassicae* and biological characterisitic of the pathogenic resting spores in rapeseed. Scientia Agricultura Sinica, 40 (7), 1388-1394.