

Chapter 2

Managing crop disease through cultural practices

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2.1 Introduction

Methods used to control plant disease vary depending on the host plant, the type of pathogen, the interaction between the two, as well as a range of other factors including environmental conditions. Most control methods are aimed at protecting crops against pathogens rather than curing them once they have been infected. Cultural control falls into this category, since it aims to prevent contact with the pathogen, to create environmental conditions unfavourable to the pathogen or at least to avoid favourable conditions, or to reduce the amount of pathogen inoculum available to infect crop plants. Methods used for cultural control include host eradication, crop rotation, sanitation, irrigation, tillage and improving crop growth conditions, for example through appropriate fertiliser use. Cultural control provides the foundation for disease control in crops and yet its importance is often overlooked. This chapter aims to provide an overview of the various cultural methods used to control crop disease and to highlight the importance of these methods in improving crop health and productivity.

2.2 Reducing the amount of pathogen inoculum

2.2.1 Host eradication

Host eradication, or roguing, refers to the removal and disposal of whole infected plants. This method is used routinely in nurseries, greenhouses and fields to prevent the spread of pathogens, since it eliminates the infected plants that act as a source of inoculum. In potato cultivation, pathogens can overwinter in infected tubers left in the field and give rise to infected plants (known as volunteers) in the spring. These volunteers can act as sources of inoculum and their removal from the field and subsequent destruction will reduce levels of pathogen inoculum. Eradication has also been used on a somewhat larger scale to stop the spread of destructive pathogens. Continual vigilance is required, however, since the pathogen may reappear. For example, *Sharka* disease caused by the *Plum pox virus* (PPV) was first detected in Switzerland in 1967. By the end of the 1970s, PPV was thought to be successfully eradicated through a combination of survey work

and destruction and disposal of infected trees. However, PPV was detected again in 2004, leading to a new campaign of survey and eradication (Ramel *et al.*, 2006).

If a pathogen requires two hosts to complete its life cycle, control is possible by eradication of the less important host. The wheat stem rust fungus, *Puccinia graminis* f. sp. *tritici*, is a case in point. It requires two hosts, wheat and barberry, to complete its life cycle and until the 1950s was the most important pathogen of wheat in the United States (Leonard, 2001). Since the 1950s, however, stem rust has declined in importance in the United States, due in part to the successful eradication of its alternate host, common barberry (Campbell & Long, 2001).

2.2.2 Sanitation

Sanitation refers to eliminating or reducing the amount of inoculum present by various means, including removal of infected plant parts and plant debris. Destroying crop residues is an important practice, but how it is performed depends upon the type of crop and the type of pathogen. Burying crop debris (see Section 2.3.1) can destroy certain pathogens, particularly if the residues are ploughed in deeply enough, while burning crop residue is a common practice for cereal crops in some parts of the world and will destroy many pathogens. However, burning has some drawbacks, particularly, loss of nutrients and increased soil erosion.

Removal of infected plant parts by pruning has been recommended for the control of fungal pathogens of perennial crops, for example, black Sigatoka disease during the establishment phase of plantains (Emebiri & Obiefuna, 1992), while pruning of infected plant parts and removal and destruction of plant debris form an integral part of the management of *Botrytis* in greenhouses (Hausbeck & Moorman, 1996). Field sanitation is also recommended for control of late blight in potatoes (Sherf & Macnab, 1986; Cohen, 1987). Removal of plant debris by burning was shown to reduce severity of tan spot (*Pyrenophora tritici-repentis*) in wheat and to increase yields (Carignano *et al.*, 2008), while burning of chickpea stubble minimised stubble-borne inoculum of *Ascochyta rabei* (Gan *et al.*, 2006). However, some workers consider that burning has limited utility for plant disease control, since elevated soil temperatures are unlikely to be uniformly intense enough at the soil surface and throughout the upper soil profile where pathogen survival structures are found (Felton *et al.*, 1987). Thus, burning crop residue in Saskatchewan was shown to increase the incidence of plants infected with the common root rot pathogen, *Cochliobolus sativus* (Ledingham *et al.*, 1960) and although burning wheat residue in Brazil reduced the population of *C. sativus*, disease severity was not reduced (Reis & Abrao, 1983; Reis *et al.*, 1990).

2.2.3 Crop rotation

Crop rotation is an ancient cultural practice and a form of crop rotation is described in *Leviticus* 25:3–5, whereby fields were not to be sown and vineyards not to be pruned once every seven years, as a means of providing complete rest for the land (Howard, 1996). Indeed, the benefits of crop rotation include maintenance of soil structure and organic matter, and a reduction in soil erosion that is often associated with continuous row crops (Janvier *et al.*, 2007). The main purpose of rotating crops in conventional arable rotations

is to reduce the incidence of diseases, pests or weeds that are difficult to control with pesticides and for this reason, short rotations of two to three crops are usually employed. In the United States, for example, the majority of the maize crop is grown on a two to three year rotation, while in the United Kingdom, barley and wheat usually form the main part of the rotation, with breaks of oilseed rape, beans, peas or potatoes (Ball *et al.*, 2005).

Continuous cropping with the same susceptible host plant will result in the establishment of a soil population of pathogenic microbes. Crop rotation avoids this and is often associated with a reduction in crop diseases caused by soil-borne pathogens (Janvier *et al.*, 2007). Using non-host or less susceptible crop plants for the rotation can lead to a decline in the specific populations of plant pathogens in the soil and is best suited for biotrophs, since they require the presence of the specific living host for survival, or pathogens with low saprophytic ability (Bailey & Duczek, 1996; Peters *et al.*, 2003). Crop rotation is less suitable for controlling root-inhabiting pathogens that survive saprophytically or can exist for long periods in soil, for example, pathogens with tough survival structures such as *Rhizoctonia solani*, *Sclerotinia sclerotiorum* and *Pythium* spp. (Sumner, 1982; Umaerus *et al.*, 1989). *S. sclerotiorum* is among the most non-specific and successful plant pathogens and can attack a wide range of crops including oilseed rape (canola), sunflower, flax, pea, bean, clover and potato (Morrall & Dueck, 1982). The number of viable sclerotia of *S. sclerotiorum* in soil was unchanged after three consecutive barley crops following canola (Williams & Stelfox, 1980), suggesting that the four-year rotation between susceptible crops recommended to control sclerotinia stem rot might be ineffective (Kharbanda & Tewari, 1996). In contrast, rotation involving at least three years between canola crops is usually associated with a reduction in severity of blackleg caused by *Leptosphaeria maculans* (Petrie, 1986). Although *L. maculans* can survive in stubble for more than five years, its viability decreases with age and most damaging infections arise from inoculum produced on two- to three-year-old stubble (Kharbanda & Tewari, 1996). Indeed, in South Australia, *L. maculans* was not detected in soils three or more years after a canola crop (Sosnowski *et al.*, 2006) and in this region a two-year rotation between successive canola crops is encouraged (Gladders *et al.*, 2006). With the barley leaf scald pathogen *Rhynchosporium secalis*, the amount of primary inoculum available for initiating epidemics can be decreased by rotation (Shipton *et al.*, 1974), whereas short rotations and reduced tillage which leave infected debris on the soil surface could lead to severe epidemics of *R. secalis* in crops exposed to more primary inoculum (Zhan *et al.*, 2008).

2.3 Reducing pathogen spread within the crop

The rate of pathogen spread within a crop can be reduced by altering the environment within the crop, for example, by manipulating crop density, humidity and moisture levels.

2.3.1 Tillage

Tillage has indirect effects on pathogen spread and can also be used to reduce pathogen inoculum in the soil. Conventional tillage uses primary and secondary cultivation to prepare a seed-bed for planting and results in considerable soil disturbance, while reduced

tillage uses a single cultivation, or even no cultivation (no-tillage, zero tillage, direct drilling), and as a result leads to minimal soil disturbance. Minimum tillage and no-tillage practices can be grouped together under the generic term conservation tillage (Sturz *et al.*, 1997).

Tillage can bury pathogens deeper in the soil where they are less likely to become a problem. It can alter soil texture, aeration, temperature, moisture and density, and can also influence nutrient release in the soil with benefits to the crop (Ball *et al.*, 2005). Tillage also leads to clear fluctuations in microbial activity and biomass in the soil (van Bruggen *et al.*, 2006). Reduced tillage or no-tillage is often associated with higher microbial biomass and activity in upper soil layers compared to regular tillage (ploughing) (van Diepeningen *et al.*, 2005). This concentration of crop debris in the top layers of the soil can promote the over-wintering and survival of numerous pathogens and has prompted concern that increased disease and decreased yields will be the inevitable result of using conservation tillage practices. Although this has proved to be the case under some conditions, there have also been reports of decreases in the incidence of soil-borne diseases (Sturz *et al.*, 1997). As suggested by Sturz *et al.* (1997), such contradictory reports may reflect differences in root development and soil microbial biomass and activity under different regimes. Thus, conservation tillage practices can lead to pathogen inoculum concentrations several orders of magnitude greater than those found under conventional tillage (Khan, 1975; McFadden & Sutton, 1975) and, as a result, plant roots growing in the upper soil layers might be more prone to pathogen infection (Sturz *et al.*, 1997). In contrast however, increased microbial biomass and activity in the top soil layers can give rise to greater root density and root activity (Lynch & Panting, 1980; Carter & Rennie, 1984), which may offset the damaging effects of disease on yield, and might also provide a highly competitive soil environment with resulting disease-suppressive effects (Chen *et al.*, 1988).

In the United States, in the 1990s, losses of wheat and barley as a result of infection by *Fusarium graminearum* (the cause of ear blight, head blight or scab) were nearly \$3 billion (Windels, 2000). These losses were blamed, in part, on the use of conservation tillage, allowing pathogen inoculum to survive on crop residues, although the evidence for increased disease severity under minimum tillage has not always been clear cut (Bateman *et al.*, 2007). Thus, minimum tillage was identified as a risk factor for *F. graminearum* infection in wheat in mid-western USA, if the preceding crop was wheat or maize (Dill-Macky & Jones, 2000). In Germany, the risk of *F. graminearum* infection in wheat was not clear cut following no tillage, if maize, and not wheat, was the previous crop (Yi *et al.*, 2001). In the United Kingdom, there is evidence that minimum tillage and maize cropping increase the risk of infection of wheat ears by *F. graminearum*, although the risk depends on the effects of weather conditions on, for example, infection and inoculum accumulation (Bateman *et al.*, 2007).

In some recent work, severity of tan spot in wheat was found to increase under no-tillage conditions, but was reduced following reduced tillage (Carignano *et al.*, 2008). To control blackleg (*Leptosphaeria maculans*) on canola (oilseed rape), it is recommended that crop debris is buried in the autumn and a non-host crop be direct seeded the following spring to avoid re-exposing the buried residue (Gladders & Musa, 1980; Kolte, 1985). Recent research suggests that inoculum production by *L. maculans* decreased with increasing duration of stubble burial in the field over 10 months, before stopping completely

(Naseri *et al.*, 2008). This effect may be due to the mycobiota associated with the buried stubble and these workers suggest that it might be possible to manipulate the population of saprophytic microbiota present on oilseed rape stubble to facilitate the decline of *L. maculans* (Naseri *et al.*, 2008).

2.3.2 Sowing practices

Altering sowing practices such as time of sowing, sowing depth and crop density can help to protect crop plants from pathogens they are susceptible to at particular stages of their development.

2.3.2.1 Time of sowing

Altering the time of sowing to avoid high levels of pathogen inoculum or conditions conducive for development of a particular disease can lead to reduced severity of several crop diseases. For example, in the United Kingdom, sowing winter oilseed rape in August rather than September exposes the earlier sown crop to inoculum from stubble of the previous crop, resulting in more severe *Alternaria* infection on pods. In contrast, the risk of infection is reduced in the later sown crop because the stubble is buried by tillage (Humpherson-Jones, 1992). Late sowing may also be recommended for autumn-sown barley crops, in order to decrease exposure of newly emerging seedlings to inoculum of *R. secalis* produced on previous barley crops in the area (Zhan *et al.*, 2008). In Turkey, rainfall during spring increases the risk of infection of chickpea by the ascochyta blight pathogen, *A. rabei*, while severe drought conditions from late April onwards can lead to reduced crop yields (Dusunceli *et al.*, 2007). Therefore, determining the best time to sow chickpeas requires a balance between the resistance rating of the chickpea cultivar and the weather conditions. Thus, it is recommended that susceptible varieties are sown later, in late March to early April, since this will avoid the precipitation required for *A. rabei* infection and development, while resistant varieties can be sown early (Dusunceli *et al.*, 2007).

2.3.2.2 Depth of sowing

Sowing depth can influence the risk of infection, since the pre-emergence stage of the seedling, which is usually more susceptible to pathogen infection, is longer when seeds are sown deeper. In *Brassica rapa*, for example, rapid emergence of seedlings reduces pre-emergence damping-off because the period of contact between the emerging seedlings and *R. solani* in the soil is reduced (Nuttall, 1982). Thus, significantly higher seedling emergence was reported for several cultivars of *B. rapa* sown at a depth of 1.5 cm compared to 3.0 cm (Nuttall, 1982).

2.3.2.3 Crop density

Crop density can exert considerable influence over disease incidence due to the ease with which pathogen inoculum can be transferred between closely spaced plants and alterations in crop microclimate. In densely planted crops, temperatures are more uniform,

humidity is increased and leaves are wet for longer time, all of which provides favourable conditions for pathogen infection and subsequent development. Crop density can be manipulated in various ways, for example, sowing, pruning and fertilisation.

Reducing the sowing density of barley can decrease severity of *R. secalis* epidemics (Hoad & Wilson, 2006), probably by decreasing the density of the crop canopy, thereby altering microclimate and ensuring inadequate leaf wetness for germination of *R. secalis* conidia (Davis & Fitt, 1994). A similar effect can also be achieved in barley by reducing nitrogen applications (Hoad & Wilson, 2006), mediated possibly by altered microclimate, although there might also be effects of reduced nitrogen on the pathogen (Zhan *et al.*, 2008).

2.4 Soil amendments and mulching

2.4.1 Mulching

Mulches are used to conserve organic matter and moisture and to reduce soil erosion. A variety of materials can be used as mulches, including straw, manure, plastics and paper. Mulching can lead to water retention and nutrient enrichment in the soil and can decrease soil temperature, all of which can influence pathogen infection and disease development in plants. Although mulching can reduce the spread of splash-dispersed pathogens, by altering the environment, it could lead to increased severity of some diseases. Further, if crop residues are used in mulching, disease incidence could increase, since the residues could be used as a food source by a range of pathogens.

Working on capsicum, Stirling & Eden (2008) found that damage from Pythium root rot was more severe with plastic mulches than mulches of plant residue, probably because the organic mulch reduced soil temperatures by roughly 12°C. However, mulching increased losses from cutworms and increased the severity of infection by *Xanthomonas campestris* pv. *vesicatoria* and moreover, the organic mulch reduced fruit yield, mainly due to nutrient leaching from the soil. These workers suggest that mulches have the potential to reduce losses from soil-borne pathogens in vegetable crops, providing crop nutrition is managed adequately (Stirling & Eden, 2008). UV-reflective mulch was found to be much more effective than black polythene mulch in reducing colonisation of tomato by thrips and subsequent infections by tomato spotted wilt virus (Momol *et al.*, 2004). In some years, virus incidence was reduced further by use of the mulch and application of the plant activator acibenzolar-S-methyl (Momol *et al.*, 2004). In fact, the use of reflective mulches to delay the onset of infestations of whitefly and associated viruses is well documented (e.g. Summers & Stapleton, 2002; Summers *et al.*, 2004).

2.4.2 Fertilisers

Adequate mineral nutrition is central to crop production. However, it can also exert considerable influence on disease development (Datnoff *et al.*, 2007a; Walters & Bingham, 2007). Fertiliser application can increase or decrease development of diseases caused by different pathogens, and the mechanisms responsible are complex, including effects of nutrients on plant growth, plant resistance mechanisms and direct effects on the pathogen (Walters & Bingham, 2007). The effects of mineral nutrition on plant disease and the

mechanisms responsible for those effects have been dealt with comprehensively elsewhere (Datnoff *et al.*, 2007a; Walters & Bingham, 2007). The sections below will deal briefly with the influence of nitrogen, phosphorus, potassium, calcium and silicon on plant disease. The effects of sulphur on plant disease, in particular the phenomenon of sulphur-induced resistance, is dealt with in Chapter 11.

2.4.2.1 Nitrogen

Nitrogen fertiliser applied above the recommended rates can result in increased disease incidence and lesion area. This has been demonstrated for biotrophic fungal pathogens such as powdery mildews and rusts (e.g. Mascagni *et al.*, 1997; Hoffland *et al.*, 2000) and necrotrophic pathogens such as *Magnaporthe grisea*, the cause of rice blast (Talukder *et al.*, 2005). It is commonly thought that application of nitrogen fertiliser can increase disease severity via effects on crop canopy development. Thus, large canopies with high shoot densities may be more conducive to spore transfer and pathogen infection than sparse canopies. For example, nitrogen has been shown to increase the severity of *Fusarium* head blight in wheat, and it has been suggested that this might be the result of a nitrogen-induced increase in canopy size, leading to an altered microclimate (Lemmens *et al.*, 2004). In contrast, work on yellow rust on winter wheat suggested that the impact of nitrogen on disease was the result of effects of nitrogenous substances in wheat leaves on pathogen growth, rather than effects on canopy growth and microclimate (Neumann *et al.*, 2004).

However, nitrogen fertilisation is not always associated with increased disease. Several studies have reported no effect of nitrogen on disease severity (e.g. Buschbell & Hoffmann, 1992; Olesen *et al.*, 2000), while Hoffland *et al.* (2000) found that the effect of nitrogen depended on the type of pathogen. Thus, nitrogen increased susceptibility of tomato to the powdery mildew pathogen *Oidium lycopersicum* and the bacterial pathogen *Pseudomonas syringae* pv. *tomato*, while it had no effect on susceptibility to the vascular wilt pathogen *Fusarium oxysporum* f. sp. *lycopersici* (Hoffland *et al.*, 2000). In contrast, tomato plants were more susceptible to *Botrytis cinerea* when grown under low nitrogen conditions (Hoffland *et al.*, 1999). These results do not support the view that nutrient-limited plants are better defended (Bryant *et al.*, 1983; Herms & Mattson, 1992). Indeed, nitrogen limitation has been found to severely compromise the ability of *Arabidopsis thaliana* to express induced resistance to pathogen infection (Dietrich *et al.*, 2004, 2005). It is clear therefore that generalising about the effects of nitrogen on plant disease is unwise and practically, although manipulation or assessment of crop nitrogen status might be used as part of disease control strategies, the approach adopted will depend on the crop and the pathogens from which it is most at risk (Walters & Bingham, 2007).

2.4.2.2 Phosphorus

In an analysis of some 2440 studies of the effects of fertiliser on more than 400 diseases and pests, Perrenoud (1990) found that, in general, phosphorus fertilisation tended to improve plant health, with reductions in disease recorded in 65% of cases. Nevertheless, phosphorus fertilisation increased disease and pest problems in 28% of the cases examined

(Perrenoud, 1990). As with nitrogen, the effects of phosphorus on plant disease may be the result of direct effects on the pathogen, host plant metabolism, leading to effects on pathogen food supply, and effects on plant defences (Walters & Bingham, 2007). Indeed, foliar application of phosphate salts has been shown to induce resistance to pathogens in a range of crop plants, including cucumber (Mucharromah & Kuc, 1991), broad bean (Walters & Murray, 1992), grapevine (Reuveni & Reuveni, 1995), maize (Reuveni *et al.*, 1994) and rice (Mandahar *et al.*, 1998).

Clearly, an adequate phosphorus supply is important for crop growth and in turn, may well help to reduce disease. However, the regime of phosphorus fertiliser used will depend on a range of factors, including the crop and the pathogens likely to be important. Reuveni & Reuveni (1998) suggested that foliar-applied phosphate might be used as part of an integrated disease control programme, although grower adoption of such an approach will depend on the existence of other effective disease control measures and the economics of disease control in the particular crop.

2.4.2.3 Potassium

In an analysis of 181 papers reporting effects of potassium on plant disease, Prabhu *et al.* (2007) found that 120 (66%) reported reductions in disease, while 49 (27%) reported an increase in disease. Although this suggests that in many cases, potassium is associated with disease reductions, Prabhu *et al.* (2007) point out that inadequate consideration has been given to the effects of associated anions, nutrient balance and nutrient status to allow the definitive role of potassium to be determined. For example, it has been suggested that in some cases, the effects of potassium, applied as potassium chloride fertiliser, might be due to the chloride ion rather than potassium (Fixen *et al.*, 1986). Further, chloride fertilisation has been shown to suppress disease in cereal crops (Engel *et al.*, 1994).

As indicated in the section above, there has been much interest in the application of fertilisers to crop foliage, including the effects of foliar fertiliser application for crop disease control (Reuveni & Reuveni, 1998; Ehret *et al.*, 2002). Foliar-applied potassium chloride has been shown to control *Blumeria graminis* and *Septoria tritici* on wheat in field studies (Cook *et al.*, 1993; Mann *et al.*, 2004), probably due to osmotic effects on the fungal pathogens, disrupting pathogen development and subsequent infection (Kettlewell *et al.*, 2000; Mann *et al.*, 2004).

Application of potassium to deficient soils usually increases plant resistance to diseases (Prabhu *et al.*, 2007). This might be partly related to the effect of potassium in increasing epidermal cell wall thickness or disease escape as a result of vigorous crop growth (Prabhu *et al.*, 2007), although the mechanisms by which potassium affects plant disease are not well understood.

2.4.2.4 Calcium

There are many reports that application of calcium to soils, foliage and fruit reduces the incidence and severity of a range of diseases of crops, including cereals, vegetable crops, legumes, fruit trees, as well as post-harvest diseases of tubers and fruits (Rahman & Punja, 2007). For example, calcium has been shown to inhibit anthracnose (caused by

Colletotrichum gloeosporioides or *C. acutatum*) in apples (Biggs, 1999) and to decrease post-harvest disease development on strawberry (Cheour *et al.*, 1990), while treatment of tomato with calcium carbonate reduced fusarium crown rot disease (Woltz *et al.*, 1992). In contrast, Nam *et al.* (2006) could find no effect of calcium on anthracnose on strawberry. Because calcium increases resistance of plant cell membranes and cell walls to microbial enzymes, increasing calcium concentrations in storage organs could lead to enhanced resistance to pathogens (Conway & Sams, 1984; Biggs & Peterson, 1990). However, the form in which the calcium is applied can influence the mechanism by which calcium affects disease. For example, the addition of lime can affect disease by altering pH, while calcium salts (e.g. propionate) can be directly inhibitory to pathogens (Rahman & Punja, 2007). Making general recommendations for the use of calcium in plant disease control would be unwise due to the range of crops and pathogens affected by calcium application. Instead, the appropriate amount and form of calcium to be applied needs to be determined for individual crop-pathogen interactions. The dwindling availability of fungicides, together with increasing public concern for the environment means that the use of calcium to control plant disease, especially post-harvest, is attracting increased attention.

2.4.2.5 Silicon

Although the effects of silicon in reducing disease severity have been known since 1940 (Wagner, 1940), it was not until the 1980s that more detailed work was carried out in this area. In this work, cucumbers grown in nutrient solutions supplemented with silicon were found to have significantly less powdery mildew infection than plants not receiving silicon supplementation (Miyake & Takahashi, 1983; Adatia & Besford, 1986). Indeed, silicon has been shown to suppress both foliar and soil-borne pathogens in curcubits (Belanger *et al.*, 1995) and to reduce susceptibility of rice to various pathogens (Datnoff *et al.*, 2007b). Wheat grown in soil amended with silicon showed reduced infection by several pathogens, including *B. graminis* f. sp. *tritici*, *S. tritici* and *Oculimacula yallundae* (Rodgers-Gray & Shaw, 2000, 2004).

It has been suggested that the effects of silicon in providing disease control are due to the creation of a mechanical barrier to penetration (Kim *et al.*, 2002). However, this has been disputed by studies which could find no evidence for the creation of a physical barrier following silicon treatment in wheat inoculated with powdery mildew and bitter gourd and tomato inoculated with *Pythium aphanidermatum* (Samuels *et al.*, 1991; Heine *et al.*, 2007). Rather, several studies have suggested that silicon activates defences in plants. For example, in wheat inoculated with *B. graminis* f. sp. *tritici*, epidermal cells of silicon-treated plants were shown to react to attempted infection with specific defences, including papilla formation and callose production (Belanger *et al.*, 2003). In the rice-*M. grisea* pathosystem, silicon-mediated resistance was found to be associated with accumulation of antimicrobial compounds at infection sites, including diterpenoid phytoalexins (Rodrigues *et al.*, 2004). In fact, phytoalexin accumulation occurs in silicon-mediated resistance in both dicots and monocots and since phytoalexins are highly specific to plant species, it has been suggested that silicon might be acting on mechanisms shared by all plant species, for example, those resulting in activation of plant stress genes (Fauteux *et al.*, 2005).

2.4.2.6 Crop nutrition and plant disease

The sections above on nitrogen, phosphorus, potassium, calcium and silicon show that, in spite of some inconsistencies, crop nutrition clearly influences disease incidence and severity in a range of pathosystems. Many of the studies suggest that managing crop nutrition through appropriate fertiliser practice could be a useful aid to control plant disease. However, because nutrition will also affect crop yield and quality, a balance needs to be struck between maximising yield and quality and minimising disease. Therefore, the extent to which fertiliser regimes can be modified to enhance disease control will depend on the relative effects of crop nutrition on disease development, the response of crop yield and quality to disease, and the crop's potential yield and quality in the absence of disease.

2.4.3 Organic amendments

Organic amendments cover a range of inputs, including animal manure, solid wastes and composts. These amendments are often used to improve soil quality, usually by contributing to general suppressiveness through enhanced microbial biomass and activity (Janvier *et al.*, 2007). Organic amendments are rich in labile carbon fractions which are an energy source for microorganisms and moreover, they can themselves contain antagonistic microbes. A substantial body of data indicates that organic materials can reduce incidence of diseases caused by a range of plant pathogens (see Bailey & Lazarovits, 2003). Since composts are dealt with in Chapter 5, this section will look at the effects of high nitrogen amendments and manures on plant disease.

2.4.3.1 Animal manures

The impact of animal manures on disease incidence and severity is much less predictable than that of composts. Thus, fresh chicken manure was shown to reduce survival of *Phytophthora cinnamomi* and disease incidence on seedlings of *Lupinus albus*, while cow, sheep and horse manure did not consistently suppress populations of *P. cinnamomi* or disease symptoms (Aryantha *et al.*, 2000). Interestingly, in this work, only chicken manure stimulated populations of endospore-forming bacteria, a factor that was strongly associated with seedling survival. Animal manures have been implicated in increasing the incidence of common scab on potato (Bailey & Lazarovits, 2003). However, Conn & Lazarovits (1999) found that a single application of liquid swine manure reduced the incidence of wilt and common scab in potato and reduced numbers of plant parasitic nematodes for three years after the treatment. Microsclerotia of the wilt pathogen *Verticillium dahliae* were killed by exposure to liquid swine manure (Conn & Lazarovits, 2000), apparently due to the presence of volatile fatty acid mixtures in the manure (Tenuta *et al.*, 2002). Subsequent work demonstrated that in acidic soils, liquid swine manure killed microsclerotia of *V. dahliae* by volatile fatty acids and/or nitrous acid toxicity, while in alkaline soils, microsclerotia were killed by ammonia toxicity (Conn *et al.*, 2005). The authors suggested that for these mechanisms to be operational and effective in practice, the chemical composition of the manure, rate of application and soil characteristics need to be determined in each case (Conn *et al.*, 2005).

In some recent work, Messiha *et al.* (2007) examined the incidence and severity of brown rot in different soil types. They found that cow manure amendment significantly reduced disease incidence in organic Dutch sandy soils, although populations of the bacterial pathogen *Ralstonia solanacearum* were not affected. In Egyptian sandy soils, however, population density of the bacterium was reduced, probably as a result of microbial competition (Messiha *et al.*, 2007). This work indicates that the mechanism of disease suppression of soil-borne plant pathogens may vary greatly depending on the soil type.

2.4.3.2 High nitrogen amendments

There are numerous reports of the efficacy of a range of high nitrogen amendments in controlling a variety of pathogens (see Bailey & Lazarovits, 2003). For example, meat and bone meal and soy meal significantly reduced the incidence of verticillium wilt, common scab and populations of plant parasitic nematodes in potato field trials (Conn & Lazarovits, 1999; Lazarovits *et al.*, 1999). Amendments such as soy meal and blood meal are degraded in the soil leading to the release of ammonia, which is toxic to many organisms, including the resting structures of plant pathogens (Bailey & Lazarovits, 2003). A low level of organic carbon in the soil was found to be critical for the accumulation of ammonia, while high levels of soil organic matter prevents ammonia accumulation (Tenuta & Lazarovits, 1999).

2.4.4 Irrigation

Although an adequate water supply is vital to crop production, irrigation can play a detrimental rather than a beneficial role in managing plant diseases. For example, irrigation water can spread pathogen propagules and under dry conditions can prevent desiccation of such propagules, thereby effectively increasing the level of inoculum in soil. Watering from overhead prolongs leaf wetness, thereby providing favourable conditions for germination and infection by fungal spores. Overhead watering also increases the risk of splash-dispersal of spores, thus increasing pathogen spread. However, irrigation can be used to reduce the level of pathogen inoculum. Thus, the activity of microbes that destroy fungal sclerotia can be increased by alternate wetting and drying of the soil. Generally, drip or trickle irrigation, which delivers water directly to the root zone at a rate insufficient to lead to pathogen spread, is least likely to encourage disease development.

In a study of the control of the downy mildew pathogen *Peronospora sparsa* on blackberry, O'Neill *et al.* (2002) found that the use of sub-irrigated sand beds resulted in very low disease incidence, whereas the use of overhead irrigation led to the disease developing in 97% of plants. In southern Israel, less frequent and reduced irrigation was shown to lower the incidence of *Monosporascus cannonballus* on melon and to postpone plant collapse, although yields were reduced (Pivonia *et al.*, 2004). Gitaitis *et al.* (2004) examined the effects of a number of treatments, including irrigation, on centre rot of onion caused by the bacterium *Pantoea ananatis*. They found no effect of drip or overhead sprinkler irrigation on the incidence or severity of centre rot (Gitaitis *et al.*, 2004). *Phytophthora capsici* is a serious soil-borne pathogen of pepper (*Capsicum annuum* L.) and causes significant crop losses worldwide. The pathogen has been shown to spread under high

soil moisture conditions. However, Sanogo (2006) could find no evidence that soil water saturation predisposed pepper to infection by *P. capsici*.

Appropriate treatment of irrigation water can be used to reduce pathogen inoculum, thereby reducing spread of the pathogen. *Phytophthora* root rot is a problem in container-grown hardy nursery stock and the pathogen can be spread by irrigation water. In some recent work, Pettitt *et al.* (2007) examined the efficacy of a non-woven capillary matting fabric (Tex-R® Pro), coated with a latex polymer-based formulation of cupric hydroxide (Spin Out®), in controlling *Phytophthora* root rot in container-grown *Chamaecyparis lawsoniana*. The fabric was used as bed covers and was also cut into discs which were used to cover the tops of the plant containers or were inserted to cover the holes at the bottoms of the containers. Bed covers and disc inserts were found to significantly reduce disease spread, while pot toppers were not effective. In addition to reducing spread of the pathogen in irrigation water, survival of zoospores and zoospore cysts was also significantly reduced by this fabric (Pettitt *et al.*, 2007).

2.4.5 Flooding

Flooding can be used in crop protection, since it reduces weeds as well as numbers of fungal propagules, nematodes and insects in the soil. However, flooding can also spread pathogens and indeed, its success in disease management is variable, depending on the pathogens present in the soil. Thus, Teo *et al.* (1989) found that 65% of sclerotia of *S. sclerotiorum* were destroyed after two years in the field at high moisture (5.9–26.2%) compared with 45% at low soil moisture (0.0–1.7%). As a result, they concluded that incorporating an appropriate irrigation schedule into the crop rotation system might reduce inoculum of *S. sclerotiorum* (Teo *et al.*, 1989). Unfortunately, frequent irrigation could increase alternaria blackspot and root rot (Teo *et al.*, 1988; Saharan, 1992). Interestingly, in a study of the population dynamics of *M. cannonballus*, Beltran *et al.* (2005) found that although ascospore numbers declined in fields that were in fallow and flooded for three years, soil-borne inoculum was viable and capable of infecting muskmelon. Clearly, *M. cannonballus* is well adapted to survive in soils which maintain a high water table or under flooding (Beltran *et al.*, 2005). Eradication of some pathogens can be achieved effectively with flooding, but it is expensive, adversely affects soil structure and its effect in controlling disease is temporary (Kharbanda & Tewari, 1996).

2.5 Suppressive soils

A range of root-inhabiting pathogens, for example, *Pythium* spp., some *Phytophthora* spp. and some *Fusarium* spp., survive saprophytically on soil organic matter or exist for long periods in the soil in the absence of the host plant, making them difficult to control. Interestingly, some soils have the capacity to suppress such pathogens, with the result that crops grown in such soils exhibit less disease, even if other environmental conditions are favourable (van Bruggen, 1995). Baker & Cook (1974) described suppressive soils as those in which disease severity or incidence remains low, despite the presence of a pathogen, a susceptible host plant, and environmental conditions favouring pathogen infection and subsequent disease development. Soil suppressiveness can be the result of different

mechanisms (Baker & Cook, 1974): (a) inability of the pathogen to establish or persist, (b) the pathogen establishes, but causes little or no damage, (c) the pathogen establishes and causes disease, but the disease becomes less important, despite the presence of the pathogen in the soil. Höper & Alabouvette (1996) distinguished between pathogen suppression and disease suppression, the former referring to the ability of the soil to limit the inoculum density of the pathogen and its saprophytic activity, and the latter to the capacity of the soil to restrict disease development even though the host, quantity of pathogen inoculum and the environment appear favourable. Therefore, the capacity of a soil for disease suppression will be determined by its effects on the processes of colonisation and infection by the pathogen, and the subsequent development of disease symptoms. Importantly, pathogen suppression and disease suppression might not necessarily be coupled, and some soils might be pathogen suppressive but not disease suppressive and vice versa (Höper & Alabouvette, 1996).

It is thought that the suppressiveness of a soil is determined mainly by its microbial properties, especially since the suppressive effect can be destroyed by sterilisation (Peters *et al.*, 2003). These microbial properties include the presence of rhizosphere and root endophytic bacteria, which disrupt pathogen infection by various means, including production of antibiotics, siderophores, nutrient competition and induction of systemic resistance (Peters *et al.*, 2003; Sturz & Christie, 2003). Other possible mechanisms include predation of fungal hyphae by soil microfauna and competition from arbuscular mycorrhizal fungi (Workneh & van Bruggen, 1994; Knudsen *et al.*, 1995; Azcon-Aguilar & Barea, 1996).

It has been suggested that given the effects of soil structure on soil micro-heterogeneity and microbial activity, suppressiveness is likely to be dependent on soil structure (Ball *et al.*, 2005). For example, a poorly structured soil will restrict the activity and movement of soil organisms, with consequences for predator-prey relationships. This, in turn, will have consequences on pathogen survival, the spread and survival of introduced microorganisms (e.g. biocontrol agents) and infection by fungal pathogens (Rattray *et al.*, 1993; Young & Ritz, 2000; Otten *et al.*, 2001).

van Bruggen *et al.* (2006) argue that healthy soils are more suppressive to soil-borne plant pathogens than biologically impoverished soils. These authors define a healthy soil as a stable soil system with high levels of biological diversity and activity, internal nutrient cycling, and resilience to disturbance. The implication is that microbial fluctuations following a disturbance would dampen more quickly in a healthy than a biologically impoverished soil (van Bruggen *et al.*, 2006). The authors suggest that regular addition of soil organic matter might increase background levels of microbial activity, increase nutrient cycling, lower the concentrations of easily available nutrient sources, increase microbial diversity and enhance natural disease suppression (van Bruggen *et al.*, 2006).

2.6 Intercropping

The simultaneous planting of more than one crop in the same area is called intercropping and is an important feature of cropping systems in the tropics. Intercropping has been reported to provide protection against pathogens in component crops (e.g. Boudreau & Mundt, 1992; Fininsa, 1996), although effectiveness can vary depending on location and

crop variety (Boudreau, 1993; Boudreau & Mundt, 1994; Bulson *et al.*, 1997) and there can be effects on yield. Thus, under-sowing leeks with clover reduced the incidence of rust (*Puccinia allii*) and although quality was improved, crop growth was reduced (Theunissen & Schelling, 1996). Similarly, intercropping tomato with soybean or sesame, in combination with sanitation, limited late blight (*Phytophthora infestans*) development, but taller intercrops reduced tomato growth and production (Tumwine *et al.*, 2002). Interestingly, Kinane & Lyngkjaer (2002) found that in barley–legume intercrops, disease incidence was reduced, irrespective of location, although not always significantly. For example, net blotch (*Pyrenophora teres*) on barley was reduced whenever it was intercropped with grain legumes, while on pea, ascochyta blight (*Ascochyta pisi*) was reduced (Kinane & Lyngkjaer, 2002). In this work, although brown rust (*P. hordei*) on barley was reduced when intercropped with legumes, these reductions were not significant. In some recent work on barley–grain legume intercropping, disease reductions were observed in all intercrop combinations, compared to the sole crop (Hauggaard-Nielsen *et al.*, 2008).

Mechanisms proposed to account for reductions in disease in intercropped systems include alterations in microclimate, competition and induced resistance. Fininsa & Yuen (2002) examined the effects of intercropping bean (*Phaseolus vulgaris*) with maize and/or sorghum in four cropping systems (sole cropping, row, mixed and broadcast intercropping) on common bacterial blight caused by *Xanthomonas campestris* pv. *phaseoli*. They found that intercropping delayed epidemic onset, lowered disease incidence and severity and reduced the disease progress rate, although the magnitude of these effects varied depending on the cropping system. Fininsa & Yuen (2002) suggested that in mixed and broadcast intercropping, where the plants are under the associate crop and not in separate rows, there are likely to be competition and dispersal interference effects. In contrast, in row intercropping competition, microclimate changes and interference effects would be less important (Fininsa & Yuen, 2002). According to these workers, the final effect on disease would depend on the canopy and root structure and tillering capacity of the associate crop.

Intercropping has been shown to enhance and stabilise yields, reduce weeds and plant diseases and improve resource use. However, there is a need for increased understanding of the ecological mechanisms associated with planned spatial diversity, in order to enhance the benefits achieved from intercropping.

2.7 Conclusions

Cultural control can be an effective and sustainable approach to the management of plant disease. Indeed, continuing problems with fungicide resistance and breakdown of host plant resistance, together with increasing concern for the environment means that there is renewed interest in cultural practices for the management of crop diseases. However, the choice and use of cultural practices will depend on the crop and the pathogen, although it might be possible to integrate the management of more than one disease by combining several appropriate cultural practices. In order to maximise the potential of cultural practices in disease control, a sound understanding of the mechanisms by which they exert their effects is required.

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