Fungal Disease Management in Environmentally Friendly Apple Production – A Review

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Abstract Many pesticides are used very effectively against fungal diseases in crop protection. However, the widespread use of synthetic pesticides in conventional fruit production clearly indicates that pesticides have several limitations and serious harmful effects on the environment and on human health. This prompted a serious need for a more environmentally benign view in the practice of fruit growing and particularly in plant protection, which also strengthened the concept of environment-friendly approach for apple. In this review article, the present status, possibilities and approaches towards fungal disease management for organic and integrated apple production systems, which are the most prominent environmentally friendly production systems of apple, are reviewed. The review focuses on the control of five important apple diseases: apple scab (*Venturia inaequalis*), apple powdery mildew (*Podosphaera leucotricha*), European canker (*Nectria galligena*), brown rot (*Monilinia* spp.) and the disease complex of flyspeck and sooty blotch. The first section of this study provides background information and basic features of current disease control in both apple production systems. Then, in the second section of this study, details of novel aspects of non-chemical control approaches against apple fungal diseases, including agronomic measures, mechanical, physical and biological control options as well as essential features of apple cultivar resistance to fungal diseases are given. The overview on five groups of agronomic measures: (1) cropping system and cover crop, (2) plant material and planting, (3) pruning and canopy management, (4) orchard floor management and (5) nutrient supply and harvest, and another five groups of mechanical and physical control methods: (1) pruning, (2) removal of inoculum sources, (3) shredding of leaf litter, (4) burying of inoculum sources and (5) flaming of leaf litter, showed that these non-chemical control measures are one of the most essential approaches for reducing the infection potential of inoculum sources in apple orchards. However, most of these methods

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are not widely spread in the apple-growing practice due to their high labour costs and/or time limits during the season. We showed that expert-system-based automatisation in the future may greatly enhance the effective integration of these methods into apple growing. We also described almost 30 biological control options, including antagonists, extracts/oils of plants and composts, which were explored recently against fungal diseases of apple, though only few of them are commercially available for the apple-growing practice. Most of these biological control options are suitable only for organic apple growing, as their effectiveness against the key fungal diseases is not able to fulfil the requirements for integrated apple orchards or they are not substantially cost-effective. Developing an effective biological control against polycyclic fungal diseases of apple will be a great challenge in the future for preharvest disease management programmes. In our literature analyses, host resistance, based on breeding programmes for multiple disease resistance, was evaluated as the greatest potential in the effective disease management of environmentally friendly apple production systems. Theoretically, aiming for complete host disease resistance would result in eliminating one of the basic elements of the epidemic triangle and omission of chemical control approaches from disease management of apple.

In the third section of this study, developments in chemical control options for individual diseases are described presenting recently explored knowledge on approved fungicidal products in integrated and organic disease management. Efficacy evaluations of fungicidal products coupled with recent developments on disease-warning systems as well as season-long spray schedules for each disease are discussed for both integrated and organic apple orchards. In addition, the main features of six inorganic chemical compounds, copper, lime sulphur, elemental sulphur, bicarbonates, hydrated lime and kaolin, are described for organic apple production. Then in the fourth section of this study, non-chemical and chemical control approaches are integrated into a multiple management tactic across all fungal diseases and are specified for integrated and for organic apple production systems. Here it was shown that in the past 20 years continued developments of disease-warning systems and host resistance to fungal pathogens, as well as incorporation of some non-chemical control options into fungal disease management of apple resulted in a considerable reduction in the number of fungicide sprays of the season-long disease management programmes. In the final section, suggestions and future trends are given for further improvements in fungal disease management for the two environmentally friendly apple production systems. Finally, it was concluded that the challenge for apple integrated pest management (IPM) programmes in the twenty-first century is to complete the fourth, final IPM level, which supplements IPM level 3 with cultural, social and political realms. While in organic apple orchards, the most essential task is to develop effective non-chemical control options that are practically feasible and can be incorporated easily into the orchard management practices.

Keywords Apple scab · Brown rot · Copper · Sulphur · DMI · QoI · Disease control · European canker · Flyspeck · Integrated · *Malus* × *domestica* · Organic · Apple powdery mildew · Sooty blotch · Sustainable agriculture

Abbreviations

AUDPC	=	area under the disease progress curve
BCA	=	biological control agent
CLW	=	cumulative leaf wetting
cv.	=	cultivars
CWE	=	compost water extract
DMI	=	demethylation inhibitors
EBI	=	ergosterol-biosynthesis inhibitors
FRAC	=	Fungicide Resistance Action Committee
GSE	=	grapefruit seed extract
IFOAM	=	International Federation of Organic Agriculture Movements
IPM	=	integrated pest management
LWD	=	leaf wetness duration
MPH	=	mono-potassium phosphate
PAD	=	potential ascospore dose
PBC	=	potassium bicarbonate
PF	=	petal fall
QoI	=	quinone outside inhibitors
SBC	=	sodium bicarbonate
SMS	=	spent mushroom substrate

1 Introduction

In the 1960s, after not more than a decade of the widespread use of the first non-phytotoxic and highly effective synthetic pesticides in conventional agriculture, it became obvious that they have several limitations and serious harmful effects on the environment and on human health. This prompted a serious need for a more environmentally benign view in the practice of agriculture and particularly in plant protection which strengthened the concept of environmentally friendly approach for agriculture. By the end of the 1970s after a long period of development (started long before the introduction of the above-mentioned synthetic pesticides), environmentally friendly production systems emerged in apple production and later two directions became known worldwide: the integrated and organic production systems (e.g. Sansavini, 1990, 1997; Sansavini and Wollesen, 1992; Reganold et al., 2001; Bellon et al., 2001; Ferron and Deguine, 2005; Lancon et al., 2007).

By now, the rules and several tools for fungal disease management are well-defined and most of them are successfully implemented for the two environmentally friendly production systems in apple (e.g. Anonymous, 1989; Cross and Dickler, 1994; Zalom, 1993). Disease management practices in integrated and organic apple production differ markedly from those in conventional production. Synthetic products are restricted in integrated and banned in organic apple production. In organic apple growing, only natural products such as compost, suspendable rock powder, sulphur and copper compounds, fungicidal and botanical soaps, traps and biological methods are permitted against fungal diseases according to IFOAM (International Federation of Organic Agriculture Movements) standards (Anonymous, 2000), while many synthetic pesticides can be used in conventional apple production. Via the application of these management options, disease management may be less effective in integrated, and especially in organic, apple production than in conventional production with the consequence that production risks are likely to be higher in such systems.

Integrated pest management (IPM) was introduced in apple production in the second half of the twentieth century with the aim of integrating pest management tactics in order to reduce pesticide use. The general acceptance of the apple IPM concept in disease management was the result of some highly forcing elements in fungicide use. First, in apple disease management programmes, narrow-spectrum systemic fungicides are usually combined with broad-spectrum protectant fungicides in order to increase efficacy and minimise fungicide resistance of pathogens. However, the registration of broad-spectrum fungicides is jeopardised due to the zero-risk standard (NRC, 1987; Merwin et al., 1994) with the result that less and less broad-spectrum protectant fungicides are/will be available for disease management. Second, in spite of the fungicide combination or rotation tactics, some apple diseases, mainly apple scab (*Venturia inaequalis*) and apple powdery mildew (*Podosphaera leucotricha*), became resistant to several highly important narrow-spectrum fungicides. For instance, resistance to dodine of the apple scab fungus, *V. inaequalis*, has been known since the late 1960s, to benzimidazoles since the early 1970s, to demethylation inhibitor (DMI) fungicides since the mid-1980s, to anilinopyrimidines since the late 1990s, and such resistant strains frequently occur all over the world (e.g. Szkolnik and Gilpatrick, 1973; Wicks, 1974, 1976; Stanis and Jones, 1985; Köller, 1988; de Waard, 1993; Köller et al., 1997, 2005; Küng et al., 1999; Köller and Wilcox, 2000). *V. inaequalis* also showed reduced sensitivity recently to kresoxim-methyl, a member of the more recently introduced quinone outside inhibitor (QoI) fungicides (Sallato and Latorre, 2006; Jobin and Carisse, 2007) though this has yet only local importance. The really damaging effect on apple disease management programmes is caused by resistance to DMI, anilinopyrimidine and QoI fungicides, as they are the principal classes of fungicides used in the post-infection control of apple scab and other less important fungal diseases. Furthermore (i) the high cost of developing new classes of fungicides, (ii) strict rules of registration, and (iii) the risk of resistance to these new site-specific fungicides have been directing on the way that the future availability of synthetic fungicides for tree-fruit diseases has become increasingly uncertain (e.g. Merwin et al., 1994; Holb et al., 2006). All the above reasons have created a great interest in and priority of other, non-chemical disease management strategies in spite of the fact that these are more expensive and biologically not so effective against the fungal pathogens as compared to synthetic fungicides.

Organic production has its origins in Germany starting at the beginning of the twentieth century (Vogt, 2000) though its worldwide establishment and regulation started in 1977 when the first IFOAM congress was held in Sissach, Switzerland (Weibel, 2002). Industrialised organic apple production started only in the late 1980s in Europe (Weibel and Häseli, 2003). Presently, the organic apple production area is still small (a few thousand hectares in Europe) compared to integrated production but it is continuously growing year by year. The major problem of fungal disease management in organic apple production is the lack of effective fungicides or natural products against the most damaging apple diseases such as apple scab and European canker. Therefore, organic apple growers have to rely strongly on integration of direct and indirect non-chemical control options, which often result in 15–50% yield loss caused by fungal diseases (e.g. Weibel, 2002; Holb, 2005a, 2008b).

More than a hundred pathogens cause diseases of apples (Biggs, 1990) but only three of them (apple scab, apple powdery mildew and fire blight) have worldwide importance in disease management of environmentally friendly apple production. Out of several other diseases, cankers, fruit rot, flyspeck, sooty blotch and rust can also be highlighted with different levels of importance in a regional scale. In this review, an attempt is made to review the recent fungal disease management options in the two environmentally friendly apple production systems: integrated and organic. More specifically the aims of this review were first, to evaluate each non-chemical management approach for fungal diseases of apple with emphasis on apple scab, apple powdery mildew, European canker, brown rot, flyspeck and sooty blotch; second, to show recent developments in chemical control options for individual diseases; and third, to integrate non-chemical and chemical control approaches into a multiple management tactic across all fungal diseases separately for integrated and organic apple production. This study reviews only preharvest, not post-harvest, disease management of apple.

2 Non-chemical Control Approaches Against Fungal Diseases of Apple

Non-chemical control options are of basic interest for both integrated and organic apple production, which include indirect (orchard management practices) and direct (e.g. physical and biological) control measures. In this section, recent developments in non-chemical control options are listed and then their efficacy is evaluated on fungal diseases of apple, focusing on apple scab, apple powdery mildew, European canker, brown rot, flyspeck and sooty blotch (Table 1).

2.1 Orchard Management Practices

Orchard management practices in apple production include several options (e.g. cropping system, planting, pruning, orchard floor management, nutrition supply and harvest) that affect fungal disease management. Orchard management practices are applied in order to provide the best conditions for tree growth as well as to improve yield and fruit quality. This indicates that orchard management has more general aims than just to protect the crop from fungal diseases. Thus, an impact of a particular orchard management practice may have a more indirect

Table 1 Some reviewed aspects of non-chemical control approaches used against scab, powdery mildew, European canker, brown rot, flyspeck and sooty blotch in preharvest disease management of apple

	Fungal disease				
Non-chemical control approaches	Apple scab	Apple powdery mildew	European canker	Brown rot	Flyspeck and sootyblotch
Orchard management practices					
Cropping system and cover crop	Tall grass (reduces ascospore escape)	–*	–	Tall grass (increases sporulation on dropped infected fruit)	–
Plant material and planting	–	–	Infected young nursery tree	–	–
Pruning and canopy management	Effect on canopy microclimate and fungicide coverage	–	–	–	Effect on canopy microclimate and fungicide coverage
Orchard floor management	Mulching, tillage	–	–	–	–
Nutrient supply and harvest	Effect of harvest in rainy days on storage scab	Effect of nitrogen supply on shoot infection	–	Effect of late harvest on post-harvest damage	–
Mechanical and physical control					
Dormant pruning	Woody-shoot, bud	Woody-shoot, bud	Infested twig, leaf scars	Mummified fruit	–
Removal of alternate host	Wild apple, hawthorn, mountain ash, firethorn, locquat	–	–	Rosaceous hosts	Blackberry

Table 1 (continued)

Non-chemical control approaches	Fungal disease: Apple scab	Apple powdery mildew	European canker	Brown rot	Flyspeck and sooty blotch
Removal of crop debris	Fallen leaf; against primary sexual inoculum	–	–	Dropped fruit; clustered fruit against asexual inoculum	Clustered fruit; against asexual inoculum
Shredding of leaf litter	Against primary sexual inoculum	–	–	–	–
Burying of inoculum	Against primary sexual inoculum	–	–	–	–
Flaming of leaf litter	Against primary sexual inoculum	–	–	–	–
Biological control					
Antagonists	Against leaf and fruit infection as well as ascocarp in leaf litter	Against shoot infection	Against leaf scar and pruning wound infection	Against fruit infection	Against fruit infection
Extracts of plants	Against leaf and fruit infection	Against shoot infection	–	–	Against leaf and fruit infection
Plant oils	Against leaf and fruit infection	Against shoot infection	–	–	–
Composts	Against leaf and fruit infection	–	–	–	–
Host resistance	Genetic resistance of cultivars	Genetic resistance of cultivars	Age-related wound resistance, host physiology	Dependent on insect damage and growth cracking	Dependent on fruit skin colour, maturity date, epicuticular wax

*– not investigated for the pathogen in detail in scientific studies.

effect on pathogen populations and, subsequently, on disease severity by affecting the host or modifying the environment. However, these effects on fungal diseases cannot be simply classified and in most cases it is difficult to establish a straightforward cause-and-effect relationship between orchard management practices and disease development. On the other hand, several orchard management practices also have direct effects on the pathogen such as providing an increased food base or physically placing the fungal spores nearer to an infection court. Some orchard management practices have received more attention and are used as direct control measures against fungal diseases of apple such as pruning, nitrogen fertilisation in autumn or host resistance. Some of these specific measures, therefore, will be described in the appropriate section for mechanical, physical control or host resistance.

2.1.1 Cropping System and Cover Crop

Cropping system is not a widely used approach in fruit production due to the long establishment of the crop; therefore, there are limited possibilities for using crop rotation or a multiple cropping system, such as are widely used in arable crops (e.g. Bernoux et al., 2006; Anderson, 2007). However, cover crops are used in apple production, especially in organic orchards; some leguminous crops in a mix with grass are suggested to cover orchard floor space within and between rows in order to protect soil from erosion, loss of nutrients and water, and to support beneficial insects (e.g. Haynes, 1980; Anonymous, 2000; Cross and Dickler, 1994). The effect of cover crop on apple disease management has received little attention and only limited information is available on both the negative and positive effects of cover crops in apple disease management. Aylor (1998) showed that wind speed near the ground of an apple orchard with a tall *Festuca arundinacea* grass alley was only 11% of that in an orchard without a grass alley. Consequently, the presence of a grass alley significantly reduced the escape of *V. inaequalis* ascospores from infected leaf litter at ground level. This might also suppress the escape of other pathogenic fungal spores from the alley which are produced on the ground-level of infected leaf litter. On the other hand, ground cover could also increase the incidence of Phytophthora crown and root rots due to enhanced moist microclimatic conditions at ground-level and in the soil (Merwin et al., 1992). These ground-level moisture conditions can also help the sporulation of *Monilinia* spp. on dropped infected apple fruit, which can be an early summer source of inoculum for infection of fruit on the tree (Holb and Scherm, 2008). From another aspect, an increased population of antagonistic fungi, bacteria and actinomycetes resulting from the application of cover crops may suppress indirectly the parasitic activity of plant pathogens resulting in less disease (e.g. Sumner et al., 1981; Rickerl et al., 1992; Sumner et al., 1995), although this has not yet been proven experimentally for tree-fruit disease management. It is also necessary to emphasise that the advantages of cover crops against fungal diseases have to be viewed with respect to the insect and weed management practices of apple orchards.

2.1.2 Plant Material and Planting

Certified and disease-free plant material is a basic issue for both integrated and organic apple production systems. Vigorous, healthy plant materials grow faster and have more resistance to environmental stresses and less susceptibility to fungal pathogens. However, infected young plant materials can have a large negative effect on the productivity of the young orchards. For instance, McCracken et al. (2003) demonstrated that canker development in young apple orchards, that can cause death of the young trees, could partly be associated with infected nursery material. Also, root and trunk wounds can enhance Phytophthora collar rot development in young trees, especially in humid growing regions (Merwin et al., 1994). Inappropriate planting time, planting rate and planting depth have been shown to increase susceptibility of crops to fungal diseases (Palti, 1981), though this has not been widely studied in apple orchards.

2.1.3 Pruning and Canopy Management

Pruning of apple trees enables management of tree shape, an increased growth of fruiting spurs and improved fruit colouration. Selective removal of branches also increases air movement within the tree canopy, which facilitates quicker drying of plant surfaces and a more uniform application of pesticides (e.g. Latham and Hollingsworth, 1973; Sutton and Unrath, 1984; Childers et al., 1995). Pruning was shown to reduce the abundance of tree canopy, which resulted in a lower incidence of sooty blotch (e.g. Ocamb Basu et al., 1988; Williamson and Sutton, 2000) and apple scab (Holb, 2005a).

An indirect, positive control effect of pruning on flyspeck and sooty blotch has been known for a long time (Brooks, 1912; Colby, 1920) and has a long tradition among recommendations for managing these summer diseases (Williamson and Sutton, 2000). Hickey (1960) clearly demonstrated that pruning created an environment less favourable for the diseases and also allowed improved fungicide coverage. Latham and Hollingsworth (1973), Ocamb-Basu et al. (1988) and Cooley et al. (1997) provided more quantitative data to support the value of pruning. Latham and Hollingsworth (1973) showed that severe pruning could reduce the incidence of sooty blotch and flyspeck by up to 30%. Ocamb-Basu et al. (1988) demonstrated a significant reduction in incidence and severity of sooty blotch after dormant pruning in a non-sprayed orchard, but flyspeck could not be reduced consistently by pruning. They found that improved fungicide coverage could be associated with the improved sooty blotch control. Cooley et al. (1997) found a strong positive correlation between summer pruning (early July) and reduced incidence of flyspeck. The reduction was up to 50% during a 2-year study in which fungicides were not applied. The authors concluded that at least two mechanisms contribute to decreased flyspeck incidence and severity in summer-pruned apple trees: summer pruning decreased the number of hours of relative humidity in the canopy by 63%; and led to increased spray deposition in the upper two-thirds of the tree canopy. A more recent study on apple scab showed that cultivar susceptibility can affect the efficacy of dormant pruning on disease incidence; therefore, a combination of both measures was studied (Holb, 2005a). The results showed that if the cultivar was scab-susceptible and the pruning was severe then pruning had a significant suppressing effect on disease development during summer in organic apple orchards. The pruning-cultivar effect was more consistent on the foliage than on the fruit. The author concluded that improvement in spray penetration in the tree and modification of in-canopy microclimate are the main mechanisms of the indirect control effect of dormant pruning on apple scab.

Finally, it should be emphasised that pruning of apple trees enables the management of fungal diseases not only indirectly by modifying microclimate and/or spray deposition, but also directly by the removal of diseased shoots, stems or dead wood that can harbour pathogens (more details in Section 2.2.1).

2.1.4 Orchard Floor Management

Orchard floor management can include cover crops (mentioned above), mulching and tillage systems. Mulching can have similar positive and negative effects on fungal diseases as was shown for cover crops, though it has the great advantage that it can be used both temporarily and permanently; therefore, the negative effect of live cover cropping can be reduced by removal of, for example, overmoist mulch. Tillage can have a large effect on the compaction of soil, which can occur during any technological operation such as cultivation, pesticide application and harvest. Soil compaction restricts for instance plant rooting and soil aeration, which may be stressful for the tree causing it to become more susceptible to soilborne diseases. Tillage changes the soil environment, which has a great effect on population dynamics of plant pathogens and may affect infection of trees (e.g. Sumner et al., 1981; Boosalis et al., 1986). Tillage can also directly affect sources of inoculum of fungal diseases by cutting and/or burying diseased plant debris, which is described in detail in Section 2.2.4.

2.1.5 Nutrient Supply and Harvest

Properly balanced nutrition is a critical factor for realising the full yield potential. Macro- and micronutrients have long been recognised as being associated with changes in the level of fungal diseases. Here, the effects of each element on apple diseases are not detailed; it is noted only that there are two major objectives of nutrient applications to crops for protection from fungal pathogens. First, nutrition should be applied to satisfy apple requirements and, second, nutrients should be manipulated to be advantageous for plants and disadvantageous for diseases (e.g. Palti, 1981; Nesme et al., 2006). It is known that an overdose of nitrogen supply can increase apple shoot growth during the season and, as a consequence, these shoots will be more susceptible to infections of powdery mildew and/or apple scab.

Harvest also has an impact on fungal diseases of apple and especially timing of harvest can have a great influence on post-harvest diseases such as on Monilinia fruit rot. By delaying harvest until the crop is fully ripe, the fruit may become more susceptible to post-harvest diseases. Mature fruit also becomes more susceptible to mechanical damage, which in turn also predisposes them to post-harvest diseases. In addition, unharvested fruit may become potential inoculum sources for the following years (Byrde and Willetts, 1977). Environmental conditions may also influence storability of fruits; for instance, frequent rain events a few weeks before and during harvest will significantly increase pinpoint scab symptoms on stored fruit caused by *V. inaequalis*.

2.2 Mechanical and Physical Control

Mechanical and physical methods of control of apple diseases is aimed to reduce or eliminate inoculum sources and to suppress disease spread. Mechanical and physical control can be achieved by several means including pruning of infected plant parts; removal, shredding, burying and flaming of inoculum sources located in aboveground parts (Table 2).

For any of these methods, some general rules need to be followed in the field to avoid disease spread. First, treatments should be applied to less severely infected fields first, followed by more severely infected ones; second, treatments should not be made in wet foliage; third, all used equipment should be cleaned of soil, debris and disinfected; and fourth, all removed plant material and crop debris need to be removed from the orchard and destroyed, or if it is not possible then cut into as small pieces as possible and plough into the soil as deep as possible (Palti, 1981). Though, it needs to be emphasised that the handling of removed plant material depends on the pathogen. For example twigs infested with primary powdery mildew do not have to be removed from the orchard or to be ploughed.

2.2.1 Pruning

Pruning of apple trees enables direct management of several fungal diseases of apple by the removal of diseased shoots, fruit, stems or dead wood that can harbour pathogens. Dormant pruning has been shown to reduce the number of overwintered conidial inoculum of *apple scab* that overwintered in association with budscales (Holb et al., 2004, 2005a). A threshold of 40% autumn scab incidence was determined, which predicted the need for control against overwintered conidial inoculum in the following spring. The authors showed that most conidia overwintered in buds could be found in the upper two-thirds of terminals in early spring. Based on these, a control strategy was suggested: if autumn scab incidence on leaves was above 40%, winter pruning of the upper two-third of terminals may need to be performed before bud break to eliminate overwintered conidia associated with buds. This control measure was able to suppress the contribution of asexual inoculum to early scab epidemic significantly (Holb et al., 2005a).

Dormant season pruning was also shown to reduce primary inoculum of *apple powdery mildew* as the fungus mycelium overwinters in buds (e.g. Csorba, 1962;

Table 2 Summary of some mechanical and physical control methods against scab, powdery mildew, European canker, brown rot, flyspeck and sooty blotch in preharvest disease management of apple

Target organism	Studied plant part	Reasons for control	Control method	References
Pruning				
V. inaequalis	1-year-old woody shoots	Overwintering conidia	Dormant pruning	Holb et al. (2004, 2005a)
P. leucotricha	Terminal shoots	Overwintering mycelia	Dormant and seasonal pruning	Csorba (1962); Yoder and Hickey (1983); Hickey and Yoder (1990); Holb (2005b)
N. galligena	Terminal shoots and twigs	Overwintering canker	Dormant pruning	Kennel (1963); Swinburne (1971)
N. galligena	Pruning cuts and leaf scars	Infection site	Modified pruning shears fungicide treatment, canker paint	Seaby and Swinburne (1976); Cooke (1999)
M. fructigena	Mummified fruit	Overwintering stromata	Dormant and seasonal pruning	Wormald (1954); Leeuwen et al. (2002)
Removal of inoculum sources				
Monilinia spp.	Wild rosaceous hosts	Inoculum reservoir	Removal of alternate host	Byrde and Willetts (1977)
*Zygophiala jamaicensis**	*Rubus* spp.	Inoculum reservoir	Removal of alternate host	Sutton (1990a)
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Raking of leaf litter	Curtis (1924); Louw, (1948)
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Collection of leaf litter by flail mower	Holb (2006, 2007b)
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Leaf sweeping	Gomez et al. (2007)
M. fructigena	Summer-dropped fruit, naturally or by hand thinning	Summer inoculum source	Drop-removal	Holb and Scherm (2007)

Table 2 (continued)

Target organism	Studied plant part	Reasons for control	Control method	References
*Peltaster fructicola, Geastrumia polystigmatus, Leptodontium elatus, Z. jamaicensis**	Clustered fruit	Favourable microclimate for disease development	Removal of clustered fruit by hand thinning	Sutton (1990b)
V. inaequalis	Clustered fruit	Incomplete fungicide coverage	Removal of clustered fruit by hand thinning	Holb (this review)
M. fructigena	Clustered fruit	*M. fructigena* infection via fruit-to-fruit contact	Removal of clustered fruit by hand thinning	Leeuwen et al. (2000); Xu et al. (2001)
M. fructigena	Clustered fruit	Codling moth damage via fruit-to-fruit contact	Removal of clustered fruit by hand thinning	Holb and Scherm (2008)
Shredding of leaf litter				
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Leaf shredding	Sutton and MacHardy (1993); Sutton et al. (2000); Vincent et al. (2004); Holb (2007b)
Burying of inoculum sources				
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Ploughing of leaf litter	Curtis (1924); Louw (1948)
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Disc cultivation for reducing leaf litter	Holb (2007b)
Flaming of leaf litter				
V. inaequalis	Fallen leaves in autumn	Overwintering of pseudothecia	Flaming of leaf litter	Earles et al. (1999)

**Peltaster fructicola, Geastrumia polystigmatus* and *Leptodontium elatus* are the causative agents of sooty blotch, and *Zygophiala jamaicensis* is the causative agent of flyspeck.

Yoder and Hickey, 1983; Hickey and Yoder, 1990; Holb, 2005b). Removal of infected terminal shoots during winter pruning is a generally recommended control practice which enhances the efficacy of chemical control measures (Hickey and Yoder, 1990). In Central Europe, removal of mildew-infected terminals reduced primary mildew incidence from 60 to 13% on the highly mildew-susceptible cultivar 'Jonathan' (Csorba, 1962). In the United States, research revealed that the removal of powdery mildew primary inoculum may be valuable and economically feasible in orchards with moderate-to-low numbers of primary infections per tree and might lead to less need for fungicides (Yoder and Hickey, 1983; Hickey and Yoder, 1990). A recent study in integrated and organic apple orchards showed that dormant pruning had no significant effect on primary mildew incidence on slightly susceptible cultivars such as 'Gala', 'Rewena' and 'Liberty'. However, primary mildew incidence was significantly lower in moderatelysusceptible cultivars 'Elstar', 'Pilot' and 'Jonica' in both production systems, but the severity of pruning did not cause significant differences in mildew incidence (Holb, 2005b). Studies also emphasise that seasonal disease development of powdery mildew can greatly be reduced by removal of infected shoot not only in dormant bud stage but during the season when primary infestation is manifested on unfolded young shoots (e.g. Csorba, 1962; Yoder and Hickey, 1983; Hickey and Yoder, 1990).

Dormant pruning also successfully reduces *European canker* (*Nectria galligena*). Removal of infested twigs reduced the spread of twig death within the tree and also reduced the inoculum that could spread and infect new twigs (Kennel, 1963; Swinburne, 1971). On the other hand, pruning cuts coupled with leaf scars are important sites for infection, which need to be protected against infection (Kennel, 1963; Swinburne, 1971). Heinrich (1982) showed that pruning wounds are more susceptible to *Nectria* than leaf scars. The incidence of canker lesions caused by *N. galligena* was shown to be greater following the inoculation of fresh pruning cuts than older cuts (Marsh, 1939; Saure, 1962; Seaby and Swinburne, 1976). High inoculum dose and young pruning wounds resulted in short incubation periods as well as a high incidence of canker (Xu and Butt, 1996). Wounds on woody trees become increasingly resistant to infection by *N. galligena* as they age (Krähmer, 1980; Doster and Bostock, 1988a,b; El-Hamalawi and Menge, 1994). This type of resistance is related to the wound healing process, which leads to the formation of boundary zone tissue and wounds periderm (Mullick, 1975, 1977; Krähmer, 1980). Therefore, all cuts needs to be treated by using infection-suppressing methods such as using modified pruning shears (Seaby and Swinburne, 1976), fungicide treatment and wound-treatment with an effective canker paint (Cooke, 1999).

Removal of mummified fruits by pruning is also a generally recommended practice to reduce primary inoculum sources of *brown rot* (Wormald, 1954; Leeuwen et al., 2002). This practice will disrupt the primary inoculum source in spring, which is released from these mummified fruits attached to the trees. During the season, this practice needs to be followed with all infected fruit, which will reduce sporulation and the number of airborne conidia in the orchard.

2.2.2 Removal of Inoculum Sources

Removal can be performed for at least two purposes: one is removal of alternate hosts of the pathogens and the other is removal of infected crop debris such as infected leaves, dropped fruit and clustered fruit.

Most apple diseases have numerous reservoirs or *alternate hosts*. Removal of these hosts would aid in reducing the inoculum. In the case of apple scab, wild *Malus* spp., hawthorn (*Crataegus* spp.), mountain ash (*Sorbus* spp.), firethorn (*Pyracantha* spp.) and loquat (*Eriobotrya japonica*) should be removed in a 5 km radius from the orchard. This option is rarely followed in practice because most of the inoculum comes from the neighbouring apple orchards and alternate hosts have little importance in most regions. *Monilinia* spp. also have several rosaceous hosts; therefore, it is recommended to remove wild hosts near the orchard and to keep ornamental bushes under surveillance to prevent introduction of inoculum from outside (Byrde and Willetts, 1977). Sutton (1990a) demonstrated that patches of blackberry (*Rubus argutus*) have provided large numbers of inoculum for flyspeck infection on apple trees. He recommended mowing *Rubus* spp. in ditch banks near the orchard or along orchard borders to reduce inoculum levels.

Removal of *crop debris* is of primary value when the inoculum is located on the above-ground parts. For instance, the sexual stage of the apple scab pathogen (*V. inaequalis*) overwinters on leaf debris and produces abundant ascosporic inoculum in the spring. The earliest scab studies (Curtis, 1924; Keitt, 1936; Louw, 1948) already demonstrated that leaf removal greatly reduced the primary inoculum source of apple scab in the following spring. Curtis (1924) and Louw (1948) suggested 62–73 and 83% reduction of scab, respectively, in spring by raking of leaf litter. Recent studies (Holb, 2006, 2007b) also demonstrated that leaves collected by flail mower in orchards reduced ascospore production by 56–79% but reduction in spur-leaf scab incidence in spring was lower (18–57%) in integrated and organic apple orchards compared to earlier studies. The variation in the scab-reduction effect of leaf removal might be associated with differences in scab-susceptibility of the cultivars, disease pressure in spring, spray schedules applied during the season and environmental conditions of the orchards. As leaf removal is generally a good sanitation method against apple scab, this method is strongly advised in both integrated and organic orchards in order to reduce scab risk potential in the following spring. Leaf removal in autumn can be performed in combination with other orchard management activities, using a leaf collector adapter, which is commercially available for most tractors or using a flail mower. An alternative to leaf removal, leaf sweeping, is also successfully used to reduce scab primary inoculum sources in organic apple orchards (Gomez et al., 2007).

Removal of dropped fruit has been shown to be an effective approach to reduce summer inoculum of apple diseases such as *M. fructigena*. Recently Holb and Scherm (2007) demonstrated that the early summer fruit dropped either naturally or by hand thinning serves as a bridge between sporulation from overwintered fruit mummies in the spring and the first fruit with sporulating lesions in the tree in mid-summer. The authors showed that removal of these dropped fruits from the orchard floor resulted in a significantly lower disease incidence on fruits in the tree. Though the treatment was more effective in organic orchards than in integrated ones, drop-removal was suggested as a useful brown rot management practice in both types of environmentally friendly apple orchard.

Removal of clustered fruits was shown to be an effective control option against *sooty blotch and flyspeck*, because clustered fruits provide a more favourable micro-climate for disease development than single fruit, and tightly clustered fruits are difficult to cover thoroughly with sprays (Sutton, 1990b). Incomplete fungicide coverage on clustered fruit can affect negatively the control of other airborne apple diseases such as apple scab and brown rot. Brown rot management in particular showed a relationship with fruit-to-fruit contact among fruits in a cluster. A positive significant correlation was demonstrated between brown rot development and clustered patterns of fruit (Leeuwen et al., 2000; Xu et al., 2001). The disease spread within a fruit-cluster is probably due to physical contact and/or insect damage among the members of the cluster (Leeuwen et al., 2000; Xu et al., 2001, Holb and Scherm, 2008). Within the insect pest group, codling moth showed the strongest correlation with brown rot development (Holb and Scherm, 2008). In a fruit-cluster, codling moth larvae could easily infest all members of the fruit-cluster throughout the contact points. Moth larvae could carry fungal spores and avoid insecticide spray as well, as spray coverage in the contact points of the fruit-cluster can be incomplete (I.J. Holb unpublished). Due to this process, brown rot development can frequently occur in organic orchards where neither codling moth nor brown rot control are sufficient; therefore, a more effective moth control, combining several control methods such as removal of infected fruit and clustered fruit is suggested (Holb and Scherm, 2008).

2.2.3 Shredding of Leaf Litter

Leaf shredding has been widely studied since the 1990s in several apple orchards, and because of its high (from 45 to 85%) efficacy in reducing primary scab infection, it is a widely recommended sanitation method in integrated orchard management practices (Sutton and MacHardy, 1993; Sutton et al., 2000; Vincent et al., 2004). Based on this, Sutton et al. (2000) developed a sanitation action threshold method in order to reduce early-spring application of fungicides in integrated apple orchards. In a recent study, Holb (2007b) showed that leaf shredding applied alone resulted in less reduction of spur-leaf scab incidence (from 25 to 36%) in organic apple orchards compared to those in integrated orchards. He concluded that although large disease pressure in spring and the low efficacy of approved fungicides in organic apple production can greatly lower the efficacy of leaf shredding, it could be a useful sanitation method against apple scab in organic orchards.

2.2.4 Burying of Inoculum Sources

Burying can be a useful element of crop debris removal if the orchard floor is not covered by grass, where leaf removal by flail mower can be difficult to perform.

In these orchards, covering crop debris by soil can help in degradation of infested leaf litter and in reducing inoculum sources. Ploughing and disc cultivation can be used for this purpose. In early studies, Curtis (1924) and Louw (1948) showed that ploughing the leaf litter into the soil resulted in a 66% reduction of scab incidence in the following spring. However, a recent study by Holb (2007b) showed that disc cultivation resulted in only a 7–26% reduction in scab incidence in spring in organic apple orchards. This study also demonstrated that disc cultivation buried the fallen leaves with 50–58% efficacy. The author concluded that this leaf-burying proportion is not sufficient for a significant reduction of spur-leaf scab incidence in commercial organic apple orchards; therefore, the leaf-burying efficacy of disc cultivation needs to be improved. This is likely to be done by soil cultivation deeper than 200 mm, by selecting suitable soil moisture conditions for disc cultivation and by adjusting the disc-tiller to greater rotating ability. Holb (2007b) summarised that applying improved disc cultivation would be an advantageous indirect control option against apple scab for organic growers as it is a general soil-maintaining practice in orchards with bare soil between rows, and therefore it does not represent additional costs. However, the author also indicated that efficacy of disc cultivation in reducing scab incidence would probably be greatly increased by combining it with other non-chemical control options.

2.2.5 Flaming of Leaf Litter

Flaming is generally used against weeds in orchards though it also has good effect against ascocarps of *V. inaequalis* in leaf litter (MacHardy, 1996; Anderson, 2007). A torch-directed flame works not by burning the leaf litter but rather by searing it and causing cells to rupture. For efficacy, leaf litter on the orchard floor should reach a minimum of 70°C during the treatment; otherwise, it does not have a detrimental effect on the initials of *V. inaequalis* ascocarps. The autumn flaming treatment can reduce ascospore production by 70% in the next spring (Earles et al., 1999). Flaming is not widespread in orchard management, neither as a weed management nor as a sanitation practice against *V. inaequalis*, due to its cost which is two to four times higher than other sanitation or chemical control methods.

In summary, although mechanical and physical control methods are one of the most basic approaches for reducing infection potential of inoculum sources in apple orchards, most of these methods are not widely spread in the apple-growing practice due to their high labour costs and/or time limits during the season. In addition, it is hard to justify the cost-effectiveness of some mechanical and physical control treatments compared to chemical fungicide use. In the future, expert-system-based automatisation may greatly enhance the effective integration of mechanical and physical control methods into apple growing.

2.3 Biological Control

Although field application of biological control agents (BCAs) has received great attention, there are only a few commercially applied biological control products against fungal diseases of apple. There are several reasons which do not allow the widespread use of biological control but the two major ones are first, biological products against phylloplane pathogens reduce diseases rather than completely control them and second, market potential of commercialised bioproducts is lower compared with that of conventional fungicides (Andrews, 1990, 1992). Here, research which has revealed promising biologically important antagonists and plant extracts against key fungal pathogens of apple is described (Table 3).

2.3.1 Antagonists

Apple scab biocontrol related to antagonists has a three-decade history. Field success of apple scab antagonism was achieved, first, by spray application during preharvest season, second, by reducing ascocarp development of the fungus on infected leaf litter during off-season and, third, by decomposing leaf litter.

Chaetonium globosum was the antagonist of *V. inaequalis*, which showed promising efficacy by spray application during the preharvest season against the asexual phase of the pathogen's life cycle (Andrews et al., 1983; Cullen et al., 1984). Studies demonstrated that spray application of ascospores of *C. globosum* reduced significantly the number of lesions and lesion sizes of apple scab in the field. *C. globosum* also reduced conidial production of *V. inaequalis* effectively. The antagonistic effect was due to antibiosis, nutrient competition and high colonisation activity. In spite of the successful in vitro and in vivo studies with *C. globosum*, the antagonist has never become a commercial product due to the commercially unfeasible field application.

Suppressing the ascocarp development of *V. inaequalis* on infected leaf litter received the largest attention and has been investigated most extensively. Zuck et al. (1982) found that *Cladosporium* spp. sporulated on pseudothecia of *V. inaequalis* on fallen apple leaves and no asci or ascospores were found in the parasitised ascocarp. *Cladosporium* spp. received no further attention as a biocontrol option against *V. inaequalis*. Heye and Andrews (1983) found that *Athelia bombacina* reduces ascospore production of *V. inaequalis* by 40–100% on overwintered leaf discs. Detailed investigation of the antagonist's mode of action (Young and Andrews, 1990a,b) showed that the pathogen inhibits the pseudothecial development in the infected leaf disc. The antagonistic fungus has also a cellulotic activity on the leaf litter; therefore, the leaves became much softer under the treatment. The fungus also caused nutrient competition and promoted decomposition of leaf litter by earthworms (Heye and Andrews, 1983).

C. globosum was also shown to reduce the number of ascospores by about 30% when sprayed on detached leaves and held in the field to overwinter (Heye, 1982; Heye and Andrews, 1983). However, the orchard application of the fungus did not result in effective control against ascospores of *V. inaequalis*. The reason was that the antibiotics produced by *C. globosum* diffuse to the leaf surface but are degraded very quickly and lose their activity against ascospores of *V. inaequalis*.

More recent studies showed that *Microsphaeropsis* spp. (later *M. ochracea*) were able to reduce the pseudothecium number on leaf litter and ascospore production

Table 3 Summary of some biological control agents (BCAs) against scab, powdery mildew, European canker, brown rot, flyspeck and sooty blotch in preharvest disease management of apple

Target organism and life cycle phase	Biological control agent (BCA)	Exposure system	References
V. inaequalis sexual phase	*Pseudomonas* spp.	Field study, fallen apple leaves; leaf decomposition	Ross and Burchill (1968)
V. inaequalis sexual phase	*Lumbricus terrestris*	Field study, fallen apple leaves; leaf decomposition	Raw (1962); Niklaus and Kennel (1981)
V. inaequalis sexual phase	*Cladosporium* spp.	Field study, fallen apple leaves	Zuck et al. (1982)
V. inaequalis sexual phase	*Chaetonium globosum*	Field study, fallen apple leaves	Heye (1982); Heye and Andrews (1983)
V. inaequalis asexual phase	*C. globosum*	In vitro, agar plate, laboratory study, field study, apple leaves	Andrews et al. (1983); Cullen et al. (1984)
V. inaequalis sexual phase	*Athelia bombacina*	In vitro, laboratory study, field study, fallen apple leaves, leaf decomposition	Heye and Andrews (1983); Young and Andrews (1990a,b); Miedtke and Kennel (1990)
V. inaequalis sexual phase	*Microsphaeropsis* spp. (later *M. ochracea*)	Field study, fallen apple leaves	Carisse et al. (2000); Vincent et al. (2004); Carisse and Rolland (2004)
P. leucotricha sexual phase	Ampelomyces mycoparasites	Apple shoot	e.g. Sztejnberg et al. (1989)
N. galligena sexual and asexual phases	*Bacillus subtilis*	Apple twig	Swinburne (1975); Swinburne et al. (1975); Corke and Hunter (1979)
N. galligena sexual and asexual phases	*Trichoderma viridae*	Fruit brown rot	Byrde and Willetts (1977)
P. fructicola, G. polystigmatus, L. elatus, Z. jamaicensis sexual and asexual phases	*C. globosum* strain NRRL 6296	Field study	Davis et al. (1991)
P. fructicola, G. polystigmatus, L. elatus, Z. jamaicensis sexual and asexual phases	*Trichoderma harzianum* strain T-22	Field study	Kiyomoto (1999)

by 75% in autumn application compared to untreated control (Carisse et al., 2000; Vincent et al., 2004). In a comparative study, *M. ochracea* was more effective against apple scab fungus than *A. bombacina* (Vincent et al., 2004). *Microsphaeropsis* spp. were capable of penetrating into *V. inaequalis* hyphae and parasitising them through their enzymes and antibiosis. This resulted in reduced growth of the hyphae of *V. inaequalis* and finally cell death of the hyphae. In field studies, it was concluded that *M. ochracea* should be applied in August or September, which results in 61–99% reduction of ascospore production (Carisse and Rolland, 2004). Presently, this fungus is the most promising BCA against the sexual stage of apple scab. Recently, commercialisation of this antagonist has started and trials have been conducted with the pre-commercial product in several European countries (W.E. MacHardy, personal communication).

Leaf decomposition by soil organisms is an indirect way of biological control against apple scab, which includes decomposition by *Pseudomonas* spp. (Ross and Burchill, 1968), *A. bombacina* (Heye and Andrews, 1983; Miedtke and Kennel, 1990) and *Lumbricus terrestris* (Raw, 1962; Niklaus and Kennel, 1981). *Lumbricus* spp. was also shown to consume fruiting bodies of different fungi including *V. inaequalis*(Niklaus and Kennel, 1981). Extensive details of leaf decomposition by soil organisms are given by MacHardy (1996).

Pycnidial fungi belonging to the genus Ampelomyces are the most common natural antagonists of *powdery mildew*s worldwide (Sztejnberg et al., 1989). On apple trees, Ampelomyces mycoparasites overwintered as resting hyphae in the dried powdery mildew mycelia covering the shoots and in the parasitised ascomata of *P. leucotricha* on the bark and the scales of the buds. Although commercialised products of Ampelomyces mycoparasites are available against powdery mildew species, there is low practical potential for effective biological control of apple powdery mildew by products prepared from Ampelomyces mycoparasites (Sztejnberg et al., 1989).

Antagonistic microorganisms such as *Bacillus subtilis* strains were investigated as BCAs against *N. galligena*. The bacterium was an effective option against both leaf scar and pruning wound infection (Swinburne 1975; Corke and Hunter, 1979). First, Swinburne (1975) was able to detect that *B. subtilis* has an inhibitory effect on *N. galligena* on branches of apple trees. Later studies in Northern Ireland (Swinburne et al., 1975) showed that two antibiotic-producing strains of *B. subtilis*, sprayed at 10 and 50% leaf fall, provided about 50% higher protection of apple leaf scars against infection of *N. galligena*. Both strains could be recovered from leaf scars during the dormant season and next spring until the end of April, suggesting that the antibiotic strains were able to multiply and grow during winter. However, the protection was not effective in May when the protective layer was shed. Corke and Hunter (1979) also used autumn application of *B. subtilis* to protect pruning wounds in apple trees against infection by *N. galligena*. Their research showed that the number of *N. galligena* conidia, released during the 12 months following treatments of *B. subtilis*, was 96% lower in the *B. subtilis* treatment compared with the untreated control. For the past three decades, no further research has been performed and no commercialised bioproduct has been available against *N. galligena*.

Biological control options of *M. fructigena* have received little attention in the preharvest apple-growing practice. An early study of Byrde and Willetts (1977) showed that *Trichoderma viridae* might have a reducing effect on *M. fructigena* infection of fruit. However, no further studies have investigated biological control efficacy under orchard conditions.

Little progress has been made in biological control against *flyspeck and sooty blotch*. Field sprays of two BCAs showed success against both diseases. A hydrolised, colloidal, cellulose-based formulation of *C. globosum* (NRRL 6296), applied with an oil-based sticker, reduced the number of flyspeck colonies by 63% compared to an untreated control (Davis et al., 1991). The same treatment also controlled sooty blotch as effectively as a standard conventional fungicide (Davis et al., 1991). *T. harzianum* strain T-22 was also tested against both diseases in 7- or 14-day applications from mid-August until harvest (Kiyomoto, 1999), but the fungus did not significantly reduce either flyspeck or sooty blotch incidence compared with the untreated control. None of the above agents were commercialised for control of flyspeck and sooty blotch.

2.3.2 Extracts/Oils of Plants and Composts

Extracts/oils of plants and composts are widely recommended by IFOAM standards for organic fruit growers (Anonymous, 2000). These materials are considered as alternative fungicides against fungal diseases of apple in organic growing and can be sorted into three groups: plant extracts, plant oils and compost extracts (Table 4).

Plant extracts are one of the promising potential sources for environmentally friendly production, as much of the plant kingdom still remains unexplored for possible materials of biological control (Cutler and Cutler, 1999). Most plant extracts contain several active components against fungal diseases from which the most widely studied ones are extracts of *Yucca schidigera*, *Cocos nucifera*, *Inula viscose*, *Hedera helix*, grapefruit seed extract (GSE) and root bark of *Morus alba*.

Yucca extract, made from dried stems of *Y. schidigera,* is reported to have a high content of steroid saponins and to contain polyphenolic compounds (Cheeke, 2001). Heijne et al. (2007) showed that Yucca extract at a higher dose (0.75%) has a similar efficacy against apple scab as standard schedules of elementary sulphur of 0.4% on cluster leaves. However, these tendencies were no longer visible on leaves from extension shoots. Yucca extract is commercially available in Europe such as Norponin BS Liquid (Nor-Natur Aps, Denmark).

Coconut soap, prepared from *C. nucifera*, has been shown to be efficient against sooty blotch and apple scab. Fuchs et al. (2002) evaluated 1% of coconut soap against sooty blotch in a 2-year study in organic apple production. Six applications of the soap, from early July to early September in 10- to 14-day schedules, significantly reduced disease incidence compared to non-treated control; however, the efficacy was not sufficient under high disease pressure. The efficacy of coconut soap treatment was similar to that of four treatments of lime sulphur at 1% dosage. The authors concluded that coconut soap could be effective against sooty blotch if the disease pressure is low. Tamm et al. (2007) evaluated 0.5% of coconut soap

Table 4 Summary of some extracts/oils of plants and composts against apple scab, apple powdery mildew, European canker, brown rot, flyspeck and sooty blotch in apple orchards

Target organism	Extracts/oils of plants and composts	Exposure system	References
Plant extracts			
V. inaequalis	*Hedera helix*	Field study, apple leaf	Bosshard (1992)
P. leucotricha	*H. helix*	Field study, apple shoot	Bosshard (1992)
V. inaequalis	*Cocos nucifera*	Field study, apple leaf and fruit	Tamm et al. (2007); Kunz et al. (2008)
Sooty blotch	*C. nucifera*	Field study, apple leaf and fruit	Fuchs et al. (2002); Tamm et al. (2007)
V. inaequalis	Grapefruit seed extract	Field study, apple leaf	Spitaler et al. (2004); Trapman (2004)
V. inaequalis	Root bark of *Morus alba*	In vitro, laboratory study	Rollinger et al. (2006, 2007)
V. inaequalis	*Inula viscose*	Field study, apple leaf	Tamm et al. (2007)
V. inaequalis	*Yucca schidigera*	Field study, apple leaf	Heijne et al. (2007)
Plant oils			
V. inaequalis	Oil of sunflower, olive, canola, corn, soybean and grapeseed	Field study, apple leaf and fruit	Northover and Schneider (1993, 1996)
P. leucotricha	Oil of sunflower, olive, canola, corn, soybean and grapeseed	Field study, apple shoot	Northover and Schneider (1993, 1996)
Extracts from compost			
V. inaequalis	Compost water extract (CWE)	Laboratory study, fruit scab	Träckner and Kirchner-Bierschenk (1988)
V. inaequalis	Compost water extract (CWE)	Laboratory study, leaf and fruit scab	Gross-Spangenberg (1992)
V. inaequalis	Spent mushroom substrate (SMS)	In vitro, laboratory study	Yohalem et al. (1994); Cronin et al. (1996)
V. inaequalis	Spent mushroom substrate (SMS)	Field study, apple leaf	Yohalem et al. (1996); Earles et al. (1999)

against apple scab and the soap significantly reduced leaf scab incidence compared to untreated control on cultivars ‘Resista’ and ‘Topaz’. The soap was recommended against apple scab in organic apple production though it had lower efficacy than copper compounds (Tamm et al., 2007; Kunz et al., 2008). Coconut soap is available as a commercialised product, for example, in Switzerland and Germany (Biofa Cocana, Biofa AG, Münsingen, Germany).

Strong fungicidal activity of the extract of *I. viscose*, a perennial crop native to the Mediterranean Basin, was reported against plant pathogens of vegetables and grape (Cohen et al., 2002). The authors revealed seven lipophilic compounds of the Inula extract with fungicidal activity. Fungicide treatments with 0.5% of *I. viscose* extract showed significantly lower leaf scab incidence on cultivars 'Resista' and 'Topas' compared to untreated control (Tamm et al., 2007). 0.5% Inula extract was significantly more efficient against apple scab than coconut soap (1%) or potassium bicarbonate (PBC) (0.5%) treatments. The authors evaluated this plant extract as one of the most promising compounds against apple scab in organic production. The commercialised Inula extract is available, for example, in Switzerland (Inulex, Basel, Switzerland).

The plant extract of *H. helix* has been shown to reduce incidence of apple scab and powdery mildew (Bosshard, 1992). Treatments of the extract showed consistently lower apple scab and mildew incidence than untreated control plots (Bosshard, 1992), but no commercialised product of *H. helix* is currently available.

GSE, a plant derivative, decreased infection of apple scab in organic production but had significantly lower efficacy against the fungus than chemical fungicides (Spitaler et al., 2004; Trapman, 2004). A powerful antimicrobial activity of GSE was reported (e.g. Harich, 1999; Von Woedtke et al., 1999); however, considerable amounts of preservatives were detected in all commercial GSEs investigated so far (e.g. Takeoka et al., 2001; Spitaler et al. 2004). GSE is considered to be a potential plant protection material against apple scab.

Rollinger et al. (2006, 2007) showed that methanol extract of Morus root bark revealed distinct *V. inaequalis*-inhibiting qualities. A bioguided fractionation of the extract resulted in metabolites of moracins M (1), O/P (2), kuwanon L (3) and sanggenons D (4), B (5), G (6), O (7), E (8) and C (9). All the Diels–Alder adducts (3–9) showed an antifungal activity against apple scab with IC_{50} values between 10 μM and 123 μM. The in vivo activity of these fractions also confirmed a distinct antifungal activity against *V. inaequalis*. The authors suggested Morus root bark extract as a potential material against apple scab in organic growing.

Previous studies (Martin and Salmon, 1931, 1933; Calpouzos, 1966) demonstrated the role of *plant oils* in the control of plant diseases in general. In the case of apple diseases, Northover and Schneider (1993, 1996) tested the prophylactic and therapeutic activity of three low-linoleic acid oils (sunflower, olive and canola) and three high-linoleic acid oils (corn, soybean and grapeseed) against apple scab and powdery mildew. All six oils were equally effective against *P. leucotricha*, providing 99% control of the disease. The control efficacy against *P. leucotricha* was comparable to that of dinocap treatments. The six oils in ten applications at 6- to 10-day intervals also decreased scab incidence of fruit and leaf by 81 and 66%, respectively. The efficacy of oils against *V. inaequalis* was significantly lower than that of the standard use of captan. Plant oils are recommended mainly against insect pests (e.g. aphids, mites, scales and codling moth) in the organic and the integrated production guidelines (Anonymous, 2000; Cross and Dickler, 1994) though their use during the season can be considered mainly for organic apple production.

The use of water *extracts from compost* has been reported against foliar diseases over the past two decades (e.g. Träckner and Kirchner-Bierschenk, 1988; Träckner, 1992; Weltzien, 1991; Yohalem et al., 1994; Zhang et al., 1998; El-Masry et al., 2002). The presence of protease, chitinase, lipase and β-1,3 glucanase (lysogenic enzymes) in compost water extract (CWE) indicates a possible role in fungal degradation (El-Masry et al., 2002) and can induce systemic acquired resistance in plants (Zhang et al., 1998). Träckner and Kirchner-Bierschenk (1988) were the first to test CWE on apple diseases. They reported a reduction in fruit scab lesions from 2.5 to 1.5 lesion/fruit in treatments of manure-straw-soil extract; however, field application of the extract failed to confirm the scab-reducing effect of the controlled study (Gross-Spangenberg, 1992). Yohalem et al. (1994) tested extracts from more than 40 different composts for biocontrol efficacy and extract prepared from spent mushroom substrate (SMS) showed the largest inhibition of conidial germination of *Spilocaea pomi* in an in vitro assay and a reduction of scab symptoms on apple seedlings. Cronin et al. (1996) demonstrated that a major inhibitory principle of the SMS extract is a low-molecular-weight, heat-stable, non-protein metabolite produced by anaerobic microorganisms in the compost. In a 3-year study, anaerobically fermented SMS was applied at weekly intervals from green tip to petal fall and biweekly thereafter (Yohalem et al., 1996). The spray schedule showed significant reduction of leaf scab incidence and severity compared to water-treated control (Yohalem et al., 1996). The authors also demonstrated that the inhibitory effect of the compost was maintained for 13 weeks independently of storage conditions. CWE, also known as compost tea, was also tested against apple scab in organic orchards, and organic production guidelines recommend it as foliar spray against apple scab (Earles et al., 1999).

In summary, recently several biological control options have become known against fungal diseases of apple, though only few of them are commercially available for the apple-growing practice. Most of these products are suitable only for organic apple growing, as their effectiveness against the key fungal diseases is not able to fulfil the requirements for integrated apple orchards or they are not substantially cost-effective. Developing an effective biological control against polycyclic fungal diseases of apple will be a great future challenge for a preharvest disease management programme.

2.4 Host Resistance

In this section, the role of host resistance is described for each disease by giving examples of suitable cultivars for environmentally friendly production systems (Table 5).

The genetic basis of host resistance to *apple scab* has a long tradition in apple breeding (Williams and Kuc, 1969). Monogenic sources of scab resistance in apple breeding are based on six different major genes (Vf, Va, Vr, Vb, Vbj and Vm), which were recently reviewed in detail by Gessler et al. (2006). Vf from *Malus floribunda* 821 is most used in apple breeding programmes throughout the world (Lespinasse, 1989). Vf and the other genes conferring forms of scab resistance have led to the development scab-resistant cultivars (e.g. 'Prima', 'Priscilla', 'Liberty', 'Jonafree', 'Dayton', 'Novamac', 'Priam') which are available for growers (Sansavini, 1997,

Table 5 Examples of apple cultivars showing different levels of susceptibility to apple scab, apple powdery mildew, European canker, brown rot, flyspeck and sooty blotch

	Cultivar susceptibility		
Fungal disease	Genetically resistant	Low to middle	Middle to high
Apple scab	Roughly 100 scab-resistant apple cultivars are available: e.g. ‘Prima’, ‘Priscilla’, ‘Liberty’, ‘Jonafree’, ‘Dayton’, ‘Novamac’, ‘Priam’, ‘Ariwa’, ‘Reanda’, ‘Rebella’, ‘Remo’ ‘Rewena’, ‘Crimson Crisp’, ‘Harmonie’, ‘Topaz’, ‘Brina’, ‘Ariane’, ‘Antares’, ‘Choupette’, ‘Modi’, ‘Golden Orange’, ‘GoldRush’, ‘Topaz’	e.g. ‘Granny Smith’, ‘Jonathan’	e.g. ‘Jonagold’, ‘Jonica’, ‘Gala clones, Idared’, ‘Mutsu’, ‘Elstar’, Golden clones, ‘McIntosh’, ‘Paulared’
Apple powdery mildew	Genetic sources: e.g. ‘White Angel’, ‘David’, ‘Robusta 5’, ‘Korea’	e.g. ‘Golden Delicious’, ‘Winesap’, ‘York Imperial’, ‘Nittany’, ‘Lord Lambourne’	e.g. ‘Jonathan’, ‘Baldwin’, ‘Cortland’, ‘Idared’, ‘Jonagold’, ‘Rome Beauty’, ‘Monroe’, ‘Gravensteiner’, ‘Stayman Winesap’, ‘Cox’s Orange Pippin’, ‘Granny Smith’, ‘Ginger Gold’, ‘Prima’, ‘New Jonagold’, ‘Pink Lady’, ‘Mutsu’
European canker	–*	e.g. ‘Golden Delicious’, ‘Bramley’, ‘Rome Beauty’, ‘Jonathan’, ‘Golden Russett’, ‘Gloster’	e.g. ‘Alkmene’, ‘Gravenstein’, ‘Delicious’, ‘Red Delicious’, ‘McIntosh’, ‘Bismark’, ‘Spartan’, ‘Newtown’, ‘Spitzenburg’, ‘Cox’s Orange Pippin’, ‘Northern Spy’, ‘Idared’, ‘Priam’, ‘Prima’, ‘Priscilla’

Table 5 (continued)

Fungal disease	Cultivar susceptibility		
	Genetically resistant	Low to middle	Middle to high
Brown rot	–		Cultivars with higher susceptibility to insect damages and growth crack show higher susceptibility to fruit rot. Cultivars 'Jonathan' and 'Beauty of Boskoop' are less susceptible to brown rot.
Flyspeck and sooty blotch	–		Commercial cultivars are not resistant and 'Golden Delicious', 'Granny Smith', 'Cox's Orange Pippin', 'Yellow Newton', 'Buckingham' and 'Jonathan' are highly susceptible to both diseases. Symptoms are more visible on light-skinned cultivars, and the diseases tend to be more severe on those cultivars that mature later in the growing season. Differences in disease severity among cultivars might be related to the permeability of the cuticle.

*Genetic aspects of resistance to the causative agents of sooty blotch, flyspeck and brown rot of apple are not known.

1999). Today roughly 100 scab-resistant apple cultivars are available commercially but only a few are used by growers (Gessler et al., 2006; Holb, 2007a). One of the problems is rooted in the relatively easy breakdown of monogenic resistance. By the end of the 1990s, more and more examples justified that resistance genes have been overcome by *V. inaequalis* and it became obvious that the durability of any form of monogenic resistance is questionable. One of the most promising new strategies was using the combination of different resistance genes in the same genotype (pyramiding) which might provide more durable resistance over time (Lespinasse et al., 1999). The term pyramiding is applied also to resistance to different pathogens in a single plant, producing apple cultivars resistant to scab and mildew and tolerant to canker such as cv. ‘Ariwa’ (Kellerhals et al., 2000a,b). More recent evaluations showed that pyramiding combined with quantitative resistance in the same genotype would probably decrease significantly the likelihood of resistance breaching by pathogens (Gessler et al., 2006). For instance, the German breeding programme provided several resistant apple cultivars (‘Re-cultivars’) possessing resistance and/or tolerance against *V. inaequalis*, *P. leucotricha*, *Erwinia amylovora*, *Pseudomonas syringae*, *Panonychus ulmi* and winterfrost (Fischer and Fischer, 1996, 1999). The authors guarantee the possibility that by using these cultivars fungicide spraying can be reduced by 80% or more and suggest them for both organic and integrated apple production. Some of the Re-cultivars, such as cvs. ‘Reanda’, ‘Rebella’, ‘Remo’ and ‘Rewena’, were suggested as donors for multiple resistance breeding (Fischer and Fischer, 1999). An Italian and Swiss survey showed that currently the best resistant cultivars are the red cvs.: ‘Crimson Crisp’, ‘Harmonie’, ‘Topaz’, ‘Brina’ and still under assessment, ‘Ariane’, ‘Antares’, ‘Choupette’, ‘Modi’ and the yellow ‘Golden Orange’, ‘GoldRush’ (Gessler et al., 2006). Currently, the most popular scab-resistant cultivar at a European grower scale is ‘Topaz’ of Czech breeding. It should be noted that severe attacks by other, not commonly occurring, phytopathogenic fungi (such as pathogens of sooty blotch, flyspeck and rust) can be assessed during late summer in orchards where scab-resistant cultivars have not been sprayed with fungicides (Holb, 2008b). Recommendations in Western European countries suggest three to four treatments of scab-resistant cultivars with broad-spectrum fungicides to prevent infection by sooty blotch and flyspeck secondary attacks as well as possible resistance breaching by scab itself (Gessler et al., 2006).

Several studies are available on classifying scab-susceptibility of commercialised apple cultivars (e.g. Aldwinckle, 1974; Norton, 1981; Scheer, 1989; Pedersen et al., 1994; Sandskär and Gustafsson, 2002; Kühn et al., 2003; Dewdney et al., 2003; Quamme et al., 2005). These studies assessed their ratings under unsprayed orchard conditions and suggestions were made mainly for traditional apple production using considerable amounts of fungicide sprays. A recent investigation was aimed to sort 27 cultivars (including scab-resistant, old and popular cultivars) based on their season-long scab reactions under fungicide spray schedules approved for organic or integrated production (Holb, 2007a). The author concluded that popular cultivars (e.g. ‘Jonagold’, ‘Gala’, ‘Elstar’ and Golden clones) were suitable only for integrated apple production and resistant ones (e.g. Re-cultivars) were suitable for organic production.

Despite the large development in scab resistance breeding, established orchards and new planting contain only up to 4% scab-resistant cultivars in European countries. Even many of the organic apple orchards in Europe are planted with popular scab-susceptible apple cultivars, and therefore produce low apple quality. The low acceptance of scab-resistant cultivars is rooted in the poor quality of the first commercialised scab-resistant cultivars. Although many of the later cultivars are appreciably better than their predecessors, these cultivars receive very little marketing promotion now. The future will likely bring better options if molecular identification of major scab resistance genes can be combined with the availability of transgenic R plants. These R genes of apple will allow the option of creating cisgenic apples (Schouten et al., 2006) which may be better accepted by the consumers than transgenic apple transformed with genes not belonging to *Malus*.

In most apple-growing regions, a lower level of *powdery mildew* resistance is more acceptable for a cultivar than that of apple scab resistance. This is due to the fact that low mildew susceptibility of cultivars can already be sufficient to avoid fungicide use. The most known oligogenic resistance sources of mildew are *M. robusta* and *M. zummi* carrying the *Pl1* and *Pl2* resistance genes (Knight and Alston, 1968). *Pl1* and *Pl2* genes have been introgressed into advanced selections and new cultivars (Alston, 1983; Schmidt, 1994; White and Bus, 1999). Other major genes, such as *Pl-w* and *Pl-d*, are in advanced stages of back-cross programmes and genetic markers are being developed (e.g. Evans and James, 2003; James et al., 2005). However, there is a risk of races developing in the pathogen that overcome single-gene resistances, as was experienced with the *Pl-m* gene from ‘Mildew Immune Seedling’ (Korban and Dayton, 1983; Lespinasse, 1983) and recently the *Pl2* gene (Caffier and Laurens, 2005; Caffier and Parisi, 2007). There was a suggestion that the *Pl-w* from ‘White Angel’ may have been overcome by a race of the pathogen, too, as all progenies from this cultivar became infected by the end of one season (Lespinasse, 1989). However, absence of the putative races in both cases in the following season suggests that infection may have been the result of high disease pressure. Present resistance-breeding programmes against powdery mildew focus on multiple resistance of genotypes including other fungal diseases of apple (e.g. Laurens, 1999; Fischer and Fischer, 1999; Gessler et al., 2006).

Apple cultivars have been continuously tested for mildew susceptibility in the past century and cvs. ‘Jonathan’, ‘Baldwin’, ‘Cortland’, ‘Idared’, ‘Jonagold’, ‘Rome Beauty’, ‘Monroe’, ‘Gravensteiner’, ‘Stayman Winesap’, ‘Cox’s Orange Pippin’, ‘Granny Smith’, ‘Ginger Gold’ and ‘Prima’ were considered to be moderately-to-highly susceptible. Less susceptible cultivars include ‘Delicious’, ‘Golden Delicious’, ‘Winesap’, ‘York Imperial’, ‘Nittany’ and ‘Lord Lambourne’ (e.g. Aldwinckle 1974; Norton 1981; Scheer 1989; Hickey and Yoder, 1990; Yoder, 2000). Washington et al. (1998) showed that a number of important commercial cultivars are highly susceptible to powdery mildew (‘New Jonagold’, 23%; ‘Pink Lady’, 18%); however, there were cultivars with high or moderate levels of resistance to powdery mildew (‘Earlidel’, no infection observed; ‘Red Fuji’, ‘HiEarly’ and ‘Redfree’, average incidence of mildew between 3 and 6%). Recently Sholberg et al. (2001) developed a technique for better evaluation of apple cultivars for susceptibility to powdery mildew. The authors grafted the selected cultivars to branches of mature 'Jonagold' trees and then evaluated the cultivars in the summer of the same year and in subsequent years after growth on the host tree. The method provided more reliable assessment of powdery mildew resistance than previous assessment methods.

In apple-growing regions with mild winter and humid weather conditions, resistance against *European canker* is also an essential aim of breeding programmes (Van de Weg, 1989). It is well known that cultivars differ in their susceptibility to *N. galligena*, for instance cvs. 'Gravenstein', 'Delicious', 'McIntosh', 'Bismark', 'Spartan', 'Newtown', 'Spitzenburg' and 'Cox's Orange Pippin' have moderate-to-high susceptibility, while others such as 'Golden Delicious', 'Bramley', 'Rome Beauty' and 'Jonathan' are less susceptible to European canker (e.g. Zagaja et al., 1971, Borecki and Czynczyk, 1984; Van de Weg, 1989; Grove, 1990; Van de Weg et al., 1992; Pedersen et al., 1994; Xu et al., 1998). However, Xu et al. (1998) showed high susceptibility of 'Golden Delicious'. Braun (1997) showed that incidence of European canker was greatest on cvs. 'Red Delicious', 'McIntosh', 'Northern Spy' and 'Idared' (>30%) and significantly lower on cvs. 'Golden Russett' and 'Gloster' (<10%). Susceptibility of apple cultivars to European canker shows quite large variations between studies, which may be due to three main reasons: (i) different disease measures used in the studies, (ii) different infection methods and (iii) different types of entry sites.

Most previous studies use canker size as a resistance criterion, whereas canker incidence and the length of incubation period combined with canker size might be better measures (Braun, 1997), as the relationship between canker incidence, the length of incubation period and canker size may depend on cultivar and experimental conditions. Van de Weg (1989) found a significant difference in the incidence of canker between cultivars, whereas in another study, cultivars did not differ in canker incidence but in size, and the incidence was also not affected by initial incubation temperature while in contrast canker size decreased with increasing temperature (Van de Weg et al., 1992).

Infection methods of some studies were based on natural infection (Zagaja et al., 1971; Pedersen et al., 1994) and others on artificial inoculation (Krüger, 1983; Borecki and Czynczyk, 1984; Van de Weg, 1989). In artificial inoculation studies, some used mycelium as inoculum (Borecki and Czynczyk, 1984) and others used a spore suspension (Krüger, 1983; Van de Weg, 1989; Van de Weg et al., 1992); the duration of the wet period (high humidity), the means of achieving the wet period, and the initial incubation temperature also differed. Van de Weg (1989) revealed that the effects of inoculation techniques on canker incidence result in different incidence values.

In addition, resistance to European canker may also vary with the type of entry site. Most previous studies inoculated fresh wounds around leaf scars or tree trunks, and pruning wounds. Pruning wounds were shown to be a better protocol for screening resistance to *Nectria*, which also incorporates healing rate and tree physiological state (Xu et al., 1998). Xu et al. (1998) also concluded that there were significant interactions between cultivars and ages of pruning wounds on the incidence of canker lesions, which implies that cultivars differ in their rates of wound healing, as shown for other woody species (Biggs and Miles, 1998; Doster and Bostock, 1988a,B). The interactions between age-related wound resistance, cultivar and host physiology may have implications for resistance breeding and canker management. Selection for resistance to *N. galligena* is usually based on incidence and size of cankers following the inoculation of fresh wounds (Borecki and Czynczyk, 1984; Van de Weg, 1989; Van de Weg et al., 1992). Xu et al. (1998) suggested that it might be necessary to improve screening by inoculating wounds of various ages on trees at different physiological stages. In the UK, *N. galligena* spores are present in winter (Swinburne, 1975) and readily germinate at low temperatures (Dubin and English, 1975). It may be advisable therefore to restrict winter pruning to canker-free orchards or cultivars with fast-acting defence mechanisms.

The reviews of Byrde and Willetts (1977) and Batra (1991) noted some of the resistant cultivars to *brown rot* such as cvs. 'Jonathan' and 'Beauty of Boskoop'. Susceptibility of apple cultivars to *M. fructigena* is highly dependent on the presence of wounds. Cultivars with higher susceptibility to insect damages and growth crack show higher susceptibility to fruit rot (Xu and Robinson, 2000; Holb and Scherm, 2008).

Some variations among cultivars were found in their susceptibility to *sooty blotch* and *flyspeck* (Gupta, 1989; Williamson and Sutton, 2000). Commercial apple cultivars are not resistant and 'Golden Delicious', 'Granny Smith', 'Cox's Orange Pippin', 'Yellow Newton', 'Buckingham' and 'Jonathan' are highly susceptible to both diseases (Gupta, 1989). In early studies, differences have been related to skin colour and maturity date (e.g. Colby, 1920; Baines and Gardner, 1932). The authors found that symptoms are more visible on light-skinned cultivars, and the diseases tend to be more severe on those cultivars that mature later in the growing season. Belding (1996) noted that the severity of sooty blotch and flyspeck varied among cultivars and he reasoned that since the fungi involved in the sooty blotch complex grow epiphytically on the cuticle, any difference among cultivars might be due to differences in the components of the epicuticular wax. Although differences were found among cultivars in the five principal components of the epicuticular wax, none of the five components supported in vitro the growth of fungi involved in the sooty blotch complex. If dilute apple juice was added to the treatments, the fungi started to grow using nutrients primarily from fruit leachates. Thus, the author concluded any differences in disease severity among cultivars might be related to the permeability of the cuticle to these leachates. Genetic aspects of resistance to the causative agents of sooty blotch, flyspeck and brown rot of apple are not known and no breeding programmes have been initiated against these diseases.

In summary, host resistance, based on breeding programmes for multiple disease resistance, can be evaluated as the greatest potential in effective disease management of environmentally friendly apple production systems. Theoretically, complete host disease resistance would be one of the best approaches in fungal disease management as this would eliminate one of the basic elements of the epidemic triangle. In addition, if complete host disease resistance would succeed for a long-term period, all other chemical or non-chemical approaches could be eliminated from the disease management of apple.

3 Features of Chemical Control for Individual Diseases in Integrated and Organic Apple Production

3.1 General Features and Chemical Control of Apple Scab

3.1.1 Integrated Apple Orchards

Much of the pesticides used in apples are for management of apple scab; therefore, disease components of apple IPM programmes have focused largely on managing apple scab (e.g. Gadoury et al., 1989; Merwin et al., 1994). Chemical control of apple scab has one of the longest and widest histories among plant pathogens and was reviewed in detail by MacHardy (1996). This review, therefore, will emphasise only some of the key elements of apple scab chemical control in integrated apple production (Table 6).

From the end of World War II until the 1970s, growers typically maintained protection throughout a period from green-tip to early fruit set (when fruitlets were approximately 10 mm in diameter) by applying fungicides at approximately weekly intervals (Cooley and Autio, 1997). After this, fungicides were applied at 2- to 3-week intervals during the secondary infection period. A typical fungicide programme before the introduction of IPM involved 15–25 fungicide applications over the growing season in most apple-growing areas (Becker et al., 1982). Generally, growers used fungicides with limited post-infection activity and good protective properties to treat scab. Although the Mills table was available for timing fungicide application after infection, at that time, applying the available fungicides only after a measured infection period had practical limitations.

The first possibility for successful implementation of apple IPM could be achieved by the 1980s when (i) techniques were developed which made it easier for growers to measure Mills infection periods using a modified hygrothermograph (MacHardy and Sondej, 1981), (ii) new findings of apple scab epidemiology were released (e.g. Sutton et al., 1981; Gadoury and MacHardy, 1982, 1986; MacHardy and Gadoury, 1989), and (iii) a new class of fungicides, the ergosterol-biosynthesis inhibitors (EBI), was introduced widely (e.g. Gadoury et al., 1989, 1992; Wilcox et al., 1992; Cooley et al., 1992; Cooley and Autio, 1997). The first use of pathogen monitoring and the Mills infection period table coupled with the post-infection application of EBIs fungicides resulted in a 30–50% reduction in the number of fungicide applications against apple scab. However, the practical use of this system was somewhat complicated as the grower was forced to choose between the optimal timing of post-infection sprays for apple scab and the timing of sprays for other diseases and pests. To solve this contradiction, integration of pesticide application schedules was attempted for disease and pest control in apple orchards (Gadoury

Table 6 Examples of chemical-based fungicides used and/or tested against scab, powdery mildew, European canker, brown rot, flyspeck and sooty blotch in preharvest disease management of apple in integrated orchards

	Fungal disease				
Features	Apple scab	Apple powdery mildew	European canker	Brown rot	Flyspeck and sooty blotch
Common name of fungicide/ Fungicide group	e.g. azoxystrobin, benomyl, bitertanol, captafol, captan, chlorothalonil, copper, cyproconazole, cyprodinil, dichlofluanid, dichlone, difenocnazole, diniconazole, dithianon, dodine, epoxiconazole, fenarimol, fenbuconazole, ferbam, fluazinam, fluquinconazole, flusilazole, folpet, hexaconazole, imibenconazole, kresoxim-methyl, macozeb, maneb, mapanpyrim, methiram, myclobutanil, nuarimol, penconazole, pyrifenox, pyrimethanil, sulphur, tebuconazole, tetraconazole, thiophanate-methyl, thiram, trifloxystrobin, triflumizole, triforine, ziram	e.g. benomyl, bupirimate, Ca-polysulphide, cyproconazole, dichlofluanid, diniconazole, dinocap, epoxiconazole, fenbuconazole, fluqinconazole, flusilazole, hexaconazole, imibenconazole, kresoxim-methyl, mono-potassium phosphate, myclobutanil, nuarimol, oxythioquinox, penconazole, polyoxin B, pyrazophos, pyrifenox, sulphur, tebuconazole, thiophanate-methyl, triadimefon, triadimenol, trifloxystrobin, triflumizole, triforine	e.g. anilinopyrimidines, azoxystrobin, benomyl, bitertanol, bordeaux mixture, captan, carbendazim, copper, dithianon, dodine, fenarimol, fenpropimorph, ferbam, imazalil; kresoxim-methyl, mancozeb, maneb, methiram, myclobutanil, thiophanate-methyl, thiram, triflumizole, ziram	Most fungicides against scab are effective against brown rot on apple, e.g. benomyl, captan, copper, cyprodinil, fluazinam, folpet, iprodion, mancozeb, methiram, thiophanate-methyl, trifloxystrobin	e.g. captan, mancozeb, benomyl, thiophanate-methyl; ziram; kresoxim-methyl, trifloxystrobin, DMI fungicides

Table 6 (continued)

Features	Fungal disease				
	Apple scab	Apple powdery mildew	European canker	Brown rot	Flyspeck and sooty blotch
Key references	e.g. Stanis and Jones (1985); Scheinpflug and Kuck (1987); Hildebrand et al. (1988); Köller (1988); Gadoury et al. (1989, 1992); Wilcox et al. (1992); Cooley et al. (1992); Sholberg and Haag (1993); Merwin et al. (1994); Shirane et al. (1996); Cooley and Autio (1997); Kunz et al. (1997, 1998); Olaya and Köller (1999a,b); Köller and Wilcox (2000, 2001); MacHardy (1996, 2000); Holb and Heijne (2001); Holb et al. (2003a,b); Köller et al. (2004); Fisher and Meuneir (2005); Holb et al. (2005b); de Waard et al. (2006); Grasso et al. (2006); Jobin and Carisse (2007)	e.g. Spotts and Cervantes (1986); Hickey and Yoder (1990); Yoder and Hickey (1995); Sholberg and Haag (1994); Yoder (2000); Reuveni et al.(1998); Reuveni (2000); Reuveni et al. (1998); Berrie and Xu (2003); Lesemann et al. (2006)	e.g. Byrde et al. (1965); Bennett (1971); Swinburne et al. (1975); Swinburne (1975); Berrie (1992); Cooke et al. (1993); Xu and Butt (1996); Lolas and Latorre (1997); Cooke (1999); Latorre et al. (2002)	e.g. Wormald (1954); Byrde and Willetts (1977); Batra (1991); Holb and Scherm (2007, 2008)	e.g. Lewis and Hickey (1958, 1972); Hickey (1960); Brown and Sutton (1986, 1995); Hartman (1995, 1996a,b); Rosenberger et al. (1996a,b, 1997a,b, 1998, 1999); Barden and Marini (1998); Williamson and Sutton (2000); Hernandez et al. (2004); Gleason et al. (1999, 2002); Babadoost (2003); Babadoost et al. (2004); Batzer and Gleason (2005); Cooley and Rosenberger (2005)

et al., 1989; MacHardy, 2000). Three periods were identified for the integration of pesticide applications: (i) prior to pink bud stage, (ii) at petal fall, and (iii) in summer during the secondary infection periods.

Further issues of IPM pesticide application were directed towards reducing fungicide use with the implementation of non-chemical control approaches, which was the so-called advanced apple IPM system (Prokopy, 1993; Prokopy et al., 1994, 1996). In these approaches, chemical control has to be coupled with the use of the potential ascospore dose (PAD) threshold (e.g. MacHardy et al., 1993; Cooley and Autio, 1997), of mechanical sanitation of primary inoculum (e.g. Sutton et al., 2000; Vincent et al., 2004; Holb, 2006, 2007b), and of BCAs against the sexual stage of *V. inaequalis* (Carisse et al., 2000; Vincent et al., 2004).

From the end of World War II until the 1970s, growers typically maintained protection throughout a period from green-tip to early fruit set (when fruitlets were approximately 10 mm in diameter) by applying fungicides at approximately weekly intervals (Cooley and Autio, 1997). After this, fungicides were applied at 2- to 3-week intervals during the secondary infection period. A typical fungicide programme before the introduction of IPM involved 15–25 fungicide applications over the growing season in most apple-growing areas (Becker et al., 1982). Generally, growers used fungicides with limited post-infection activity and good protective properties to treat scab. Although the Mills table was available for timing fungicide application after infection, at that time, applying the available fungicides only after a measured infection period had practical limitations.

Currently, several fungicide groups are registered with preventive or post-infection activities against apple scab all over the world including ftalimides, dithiocarbamates, guanidines, anilino-pyrimidines, benzimidazoles, DMIs and QoIs (Merwin et al., 1994). With this arsenal of fungicides, apple growers follow a combination of pre- and post-infection management strategies against scab using both protectant and curative fungicides. Protectant fungicides are generally used early in the season when there are only few leaves or when infection periods can be forecasted. Curative fungicides are used when a protectant fungicide applied before the infection was washed off by rain, a protectant fungicide was not applied prior to the infection period, or the risk of primary infection was very high (large amount of ascospores, many new unprotected leaves and severe infection period).

DMIs, QoIs and anilinopyrimidines are the principal classes of fungicides used in post-infection management of apple scab in most apple-growing regions. DMI fungicides specifically target C_{14}-demethylation of 24-methylenedihydrolanosterol, disrupting fungal sterol biosynthesis (Scheinpflug and Kuck, 1987; Köller, 1988). DMIs are prone to selecting for development of resistance in microorganims. Resistance mechanisms to DMIs include overexpression of the CYP51A1 gene from the pathogen (e.g. Schnabel and Jones, 2001), as well as efflux mechanisms (e.g. Del Sorbo et al., 1997; Nakaune et al., 1998) and point mutations (e.g. Délye et al., 1997, 1998). DMI resistance in apple scab is well-documented (e.g. Stanis and Jones, 1985; Sholberg and Haag, 1993; Shirane et al., 1996; Kunz et al., 1997; Hildebrand et al., 1988; Köller and Wilcox, 2000, 2001) including practical resistance (e.g. Braun and McRae, 1992; Köller et al., 1997). Resistance to DMIs is quantitatively (e.g. Köller and Scheinpflug, 1987; Smith et al., 1991; Kalamarakis et al., 1991; de Waard, 1993) controlled by more than one gene. Therefore, loss of sensitivity to DMIs by the pathogen is gradual, following a multistep process. The sensitivity of the fungus slowly deviates from the original baseline values and may reach a point at which disease control is affected. However, the critical point of fungicide efficacy loss is hard to identify under field conditions.

As QoIs also have high risk for development of fungicide resistance (e.g. Kunz et al., 1998; Olaya and Köller, 1999a,b; Köller et al., 2004; Fisher and Meunier, 2005; de Waard et al., 2006; Grasso et al., 2006), they are recommended in fungicide alternating programmes as a strategy to slow down fungicide resistance development (e.g. de Waard et al., 2006; Jobin and Carisse, 2007). Strobilurins have been described as being more active against spore germination and host penetration (Gold et al., 1996; Ypema and Gold, 1999). They act as an inhibitor of fungal mitochondrial respiration by binding to the mitochondrial cytochrome bc1 complex subunit and disrupting electron transport (Ypema and Gold, 1999). QoI resistance can be both quantitative and qualitative. In the case of quantitative resistance, a slow decline in disease control can be experienced due to the presence of minor resistance genes that contribute to the avoidance of the intended effects of the fungicide (Grasso et al., 2006). Quantitative shifts can be detected easily with laboratory tests and then can be attributed to the loss of control, which results in a dose-dependent disease control in practice. QoI resistance can also be qualitative, i.e. not showing dose dependence in disease control. In this case, mutational amino acid exchanges can be detected in the cytochrome target site, mostly G143A for *V. inaequalis* (e.g. Olaya and Köller, 1999a,b; Zheng et al., 2000). This mutation is easily detectable with molecular tools but only after resistance has occurred.

Due to the increasing insensitivity of DMIs to apple scab in practice, the use of DMIs is advised to be reduced in several apple-growing areas. Such recommendations may lead to (i) increased use of QoIs and the consequences of possible resistance to QoIs and (ii) increased usage of protectant fungicides which have a higher impact on the environment. This clearly emphasises the essential importance of fungicide antiresistance strategies recommended by the Fungicide Resistance Action Committee (FRAC). Beyond the FRAC recommendation though, the best approach is probably to favour the implementation of integrated tools for apple scab management, such as inoculum reduction by non-chemical approaches, monitoring fungicide resistance and sanitation-improved fungicide timing. Efficacy of these practical management approaches can also be improved by novel disease-warning systems and models (e.g. Seem et al., 1989; Butt et al., 1992; Trapman, 1994; Aalbers et al., 1998; Berrie and Xu, 2003; Holb et al., 2005b). These developments resulted in the creation of more advanced scab management strategies in integrated apple production.

3.1.2 Organic Apple Orchards

One of the key features of chemical disease control in organic apple production is that the effectiveness of approved products is low against the key apple diseases.

Therefore, disease pressure is often high and direct organic disease management often fails especially in humid climatic conditions. Therefore, non-chemical approaches are widely recommended to compensate for the low efficacy of chemical control. According to IFOAM and European standards, only a few chemical products are approved in organic apple production (Anonymous, 2000; EEC, 2000). Most of these inorganic chemical compounds are protectant fungicides providing short-term residual activity. The most widely used compounds are copper, lime sulphur and elemental sulphur in organic apple production; therefore, we focus on the fungicidal features of these compounds. Recently, some other simple inorganic materials, such as SBC and PBC, hydrated lime and kaolin have also received attention and are therefore included in our overview (Table 7).

Copper is one the oldest compounds used in plant protection. Its history started in 1882 when the French botanist Millardet discovered the effectiveness of the mixture of copper sulphate and slaked lime against grape downy mildew. Within a decade, the so-called 'Bordeaux mixture' was also used against apple scab (MacHardy, 1996). The use of copper compounds in traditional crop protection sharply decreased after the development of synthetic fungicides but they remained the leading fungicides in organic production. Copper compounds are considered as protective fungicides with good residual activity (e.g. Hamilton, 1931; Holb and Heijne, 2001). However, a recent in vitro study on apple scab demonstrated that some copper salts ($Cu(OH)_2$ and $CuSO_4$) showed 16 and 40 h post-infection activity and killed primary stromata (Montag et al., 2006). $Cu(OH)_2$ was more effective than $CuSO_4$; however, research also showed that application of $Cu(OH)_2$ under dry conditions did not kill primary stromata. For exertion of the post-infection activity of copper salts, leaves must be wet. As this cannot be guaranteed in the field, a post-infection application of $Cu(OH)_2$ cannot be recommended under orchard conditions.

Regarding the mode of action, research showed that copper salts dissolve in water and copper ions (Cu^{2+}) are released into the spray solution, which are the active component of copper fungicides. Copper ions are capable of penetrating into fungal spores and denature proteins with the inhibition of various enzymes in the cell (Heitefuss, 2000). This hypothesis supposes that water solubility of the copper compounds should be important. However, the solubility of copper alone cannot explain the effectiveness of the slightly soluble copper hydroxide and copper oxychloride as well as the insoluble copper oxide. Copper fungitoxicity is believed to be more complex and at least three additional hypotheses are known for explaining the effectiveness of less water-soluble copper compounds. Dissolution of these compounds might be aided by (i) CO_2 and ammonium ions dissolved in rainwater or dew (Pickering, 1912; Reckendorfer, 1936), (ii) exudates from the plant (DeLong et al., 1930) and (iii) secretion of acids or complexing agents by the spore (Barker and Gimingham, 1911; McCallan and Wilcoxon, 1936; Martin et al., 1942). For instance, in a recent study, Montag et al. (2006) demonstrated that *V. inaequalis* spore exudates react with insoluble copper compounds and form highly toxic copper complexes. These copper complexes were more toxic to *V. inaequalis* than dissolved Cu^{2+} ions in the cell. However, copper ions also affect the plant and may

Table 7 Some features of the most widely used inorganic materials against apple scab, apple powdery mildew, European canker, brown rot, flyspeck and sooty blotch in preharvest disease management of apple in organic orchards

	Inorganic materials					
Features	Copper	Lime sulphur	Elemental sulphur	Bicarbonates	Hydrated lime	Kaolin
Fungicide compounds	Copper sulphate Copper oxychloride Copper (I)oxide Copper hydroxide	Calcium polysulphide with calcium thiosulphate	Micronised and non-micronised sulphur	Sodium bicarbonate (SBC) Potassium bicarbonate (PBC)	Calcium hydroxide	Components of stone powder
Target disease in organic apple orchards	Apple scab, brown rot, European canker, flyspeck and sooty blotch	Apple scab, powdery mildew; brown rot, European canker, flyspeck and sooty blotch	Powdery mildew, flyspeck and sooty blotch; apple scab; brown rot	Apple scab	Apple scab	Apple scab, sooty blotch and flyspeck
Fungicide action	Protectant; in vitro 16–40 h post-infection activity against scab	Protectant; in vitro and in vivo 16–72 h post-infection activity against scab	Protectant	Protectant	In vitro and in vivo 16 h post-infection activity against scab	Protectant
Mode of action	Multi-site toxicity, toxic to fungal spores by complex mechanisms	Multi-site toxicity, toxic to fungal spores by complex mechanisms	Multi-site toxicity, toxic to fungal spores by complex mechanisms	–	Kills conidia and germ tubes of *V. inaequalis*	–
General application schedule in organic apple orchards	Early spring spray until early tight cluster, 10–14 days application schedule after the end of June, fallen leaf treatment	Dormant spray, 7–14 days application schedule during the season, fallen leaf treatment	Replacing copper sprays and supplementing elemental sulphur spray, 7–14 days application schedule during the season	Supplementing copper and sulphur sprays, 7–14 days application schedule during the season	Supplementing copper and sulphur sprays, 7–14 days application schedule during the season	Not recommended for season-long spray schedules

Table 7 (continued)

Features	Inorganic materials: Copper	Lime sulphur	Elemental sulphur	Bicarbonates	Hydrated lime	Kaolin
Phytotoxicity and side effects	Phytotoxic to leaves and fruit, toxic to some carabid species	Phytotoxic to leaves and fruit, toxic to predatory mites	Phytotoxic above 20°C, toxic to predatory mites	Not phytotoxic to apple fruit at the recommended dose	Not phytotoxic to apple fruit at the recommended dose	Not phytotoxic to apple fruit at the recommended dose
Environmental impact	Toxic to earthworms, heavy metal soil and water pollution	Natural compound with little or no environmental concern	Non-toxic to human and warm-blooded animals	Low mammalian toxicity may increase soil sodium level	Not investigated for apple	Not investigated for apple
Key references in apple	e.g. Hamilton (1931); Byrde and Willetts (1977); Ellis et al. (1994, 1998); Lolas and Latorre (1997); Heitefuss (2000); Holb and Heijne (2001); Holb et al. (2003a,b) (2005a,b); Montag et al. (2006); Jamar and Lateur (2007); Holb (2008a)	e.g. Hamilton (1931); Mills (1944, 1947); Byrde and Willetts (1977); Tweedy (1981); Kelderer et al. 1997 (2000); Heitefuss (2000); Tate et al. (2000); Holb and Heijne (2001); Holb et al. (2003a); Montag et al. (2005)	e.g. Wormald (1954); Hickey (1960); Lewis and Hickey (1972); Byrde and Willetts (1977); Ellis et al. (1998); Yoder (2000); Heitefuss (2000); Holb and Heijne (2001); Holb et al. (2003a,b, 2005a,b); Holb and Scherm, (2007, 2008)	e.g. Schulze and Schönherr (2003); Ilhan et al. (2006); Tamm et al. (2006); Jamar and Lateur (2007); Kunz et al. (2008)	Schulze and Schönherr (2003); Montag et al. (2005)	Thomas et al. (2004); Berkett et al. (2005)

retard plant growth and cause russeting of young plant tissues. Slow drying conditions on the plant surface result in an increase of the availability of copper ions and thus retard plant growth and may cause severe plant injury. Therefore, longer wet weather periods with low temperatures after a spray application can be phytotoxic and may cause fruit russeting during bloom and early fruit development (e.g. Ellis et al., 1994, 1998; Holb and Heijne, 2001).

In most organic apple orchards, scab is controlled by using copper- and sulphur-containing fungicides. In a common fungicide scheme, one to three sprays of copper are applied in the early spring followed by wettable sulphur sprays until harvest during wet periods (Holb and Heijne, 2001). Copper is more effective during the ascospore season than elementary sulphur (e.g. Cooley et al., 1991; Hamilton, 1931; Holb and Heijne, 2001). Copper fungicides were commonly used in organic apple orchards due to their good protective effects, whether applied alone or in various combinations with sulphur.

The largest concern of copper as a heavy metal is that it has serious environmental impacts, especially on soils and waters. In some European countries, copper levels of some agricultural soils exceed the Dutch limit (Anonymous, 1991) of 36 mg kg^{-1} soil following a prolonged use of copper-based products (e.g. van Rhee, 1976; Flores-Veles et al., 1996; Paoletti et al., 1998). Copper pollution in orchards was shown to negatively impact soil ecology and to have detrimental effects on earthworm populations (e.g. Van Rhee, 1976; Paoletti et al., 1998; Holmstrup et al., 1998; Friis et al., 2004). This poor ecotoxicological profile conflicts with the ecological concepts of organic and integrated apple production. Therefore, attempts are being made in several countries to reduce copper application rates in protective spray schedules (e.g. Holb et al., 2003a; Jamar and Lateur, 2007). In addition, strategies are being developed which help to minimise the number of copper spray applications. For instance, Holb (2008b) demonstrated that for apple scab control the use of orchard sanitation by combination of leaf removal and winter pruning could reduce the PAD below 600 ascospores m^{-2} orchard floor on the moderately scab-susceptible cultivar ‘Jonathan’. Under such conditions, spray applications could be omitted before early tight cluster in Hungarian organic apple production. This results in omitting two copper sprays at dormant bud and green-tip stages. Omitting these copper sprays would be a benefit for those organic orchards in Europe where the use of copper compounds is restricted or banned.

In the last two decades, several countries restricted copper compounds to an annual use of 2–4 kg ha^{-1} (Anonymous, 1997; EEC, 2000) in organic fruit production. Moreover, in the past few years, some European countries, e.g. the Netherlands and Scandinavian countries, have banned copper-based products (Holb et al., 2003a; Tamm et al., 2004). It seems to be a trend that the use of copper will be forbidden in other European countries in organic growing because of the above environmental reasons. This initiates a more comprehensive research for replacements of copper-based products in European agriculture, including organic fruit production.

Lime-sulphur is also one of the oldest fungicides in use. The common formulation contains a mixture of 29% (wt/vol) calcium polysulphide and a small amount of calcium thiosulphate (McCallan, 1967). Lime sulphur is prepared by boiling hydrated lime ($CaO{\cdot}H_2O$) and elemental sulphur with water. The commonly used fungicide application rate is 2%. At this rate, lime sulphur has a pH of 10.0 and constantly releases small amounts of hydrogen sulphide (H_2S) gas. H_2S gas (Tweedy, 1969, 1981) is able to permeate the fungal membrane (Miller et al., 1953; Tweedy, 1981). It then modifies the respiration complexes of mitochondria when it reaches the cytoplasm (Beffa, 1993). Modifications in the respiratory complexes affect the electron flux in the mitochondrial respiratory chain resulting in multi-site toxicity and broad-spectrum efficacy (Beffa, 1993; Beffa et al., 1987).

As a pesticide, lime sulphur was first described in 1802 in England (Tweedy, 1969). By 1850, the present lime sulphur formula was standardised, and by 1900 it was in common use in California for apple scab, powdery mildew, aphids, mites, brown rot and other pests and diseases (Tweedy, 1969). Most research investigations of lime sulphur were made at the beginning of the twentieth century. Results showed that its efficacy and phytotoxicity were similar to those of copper fungicides (e.g. Goldsworthy, 1928; Hamilton, 1931; Mills, 1947). Moreover, Hamilton (1931) and Mills (1944, 1947) demonstrated that lime sulphur gave sufficient control when applied within 30–72 h after inoculation of *V. inaequalis*. Similarly, the studies of Mills (1944, 1947) have shown that lime sulphur prevented apple scab infection when it was applied within 50 h after the beginning of rain. Some years ago, lime sulphur as a fungicide was newly investigated in relation to season-long disease management in organic apple production. Cooley et al. (1991) and Ellis et al. (1994) claimed that reduced rates of lime sulphur gave better scab control during summer than elemental sulphur applied alone. Kelderer et al. (1997, 2000), in their preliminary studies in South Tyrol, showed that application of lime sulphur shortly after a predicted infection period might have good post-infection activity against apple scab in organic apple production. However, in another study conducted in Austria, satisfactory scab control was not achieved by post-infection treatments with lime sulphur (2–5%) (Steffek, 1999). Trapman and Drechsler-Elias (2000) and Trapman (2001, 2002) in the Netherlands revealed that lime sulphur (1.5–2%) applied at 20–30 h after predicted infection periods gave sufficient scab control under field conditions in organic apple orchards. This result was in agreement with later field trial results of Klopp et al. (2004) in northern Germany. Zemmer et al. (2002) showed that lime sulphur could stop the scab infection until the formation of appressorium. However, when the infection proceeded to the formation of primary stroma, the efficacy of treatments with lime sulphur was insufficient. Further in vitro studies (Montag et al., 2005) showed that lime sulphur (1.5%) applied 16 h after infection killed early infection structures and stopped further development of the apple scab fungus. Lime sulphur reduced the percentage of scab mycelium penetration to below 10% even with treatments of 40 h after infection. In a Dutch study, post-infection treatments with lime sulphur (0.75–2%) applied 35–45 h after predicted infection periods were able to stop primary scab infections (Holb et al., 2003a). The authors used a scab-warning system based on this 35–45 h post-infection activity and saved one to two lime sulphur sprays compared to the preventive treatments of lime sulphur during the primary infection period.

Studies on non-target effects of fungicide sprays claimed that lime sulphur is toxic to plant organs (e.g. Cunningham, 1935; Subhash, 1988; Tate et al., 2000). The mechanism of lime sulphur phytotoxicity is insufficiently understood. The soluble sulphide component of lime sulphur is believed to be responsible for plant injury by reducing carbon dioxide assimilation, which appears to be a fundamental factor underlying the phytotoxic effects (Subhash, 1988). An increased phytotoxic effect was noted when relative humidity and/or leaf wetness increased after spraying (e.g. Cunningham, 1935; Subhash, 1988; Tate et al., 2000). These results suggest that low-volume sprays of lime sulphur can be less phytotoxic than high-volume sprays, because the material applied with the low-volume application dries almost immediately upon contact with the leaf. By contrast, it has been found that the curative activity of lime sulphur might be dependent on wet conditions after spraying (Trapman and Drechsler-Elias, 2000; Trapman, 2001). This is based on the hypothesis that the polysulphide component of lime sulphur is the main active ingredient for its curative activity. The polysulphide component of lime sulphur is able to penetrate into the fungus mycelia only in the water phase (Doran, 1922; Goldsworthy, 1928). If the leaf surface dries, lime sulphur has only a protective effect against the apple scab fungus (e.g. Doran, 1922; Goldsworthy, 1928; Tweedy, 1981; Trapman, 2001). In organic apple orchards, Holb and Heijne (2001) and Holb et al. (2003a) demonstrated experimentally that all lime sulphur treatments had greater curative efficacy against apple scab in wet years but they caused significantly higher leaf phytotoxicity compared to dry years. In addition, the authors showed that lime sulphur has potential for replacing copper fungicides though replacing copper with lime sulphur can result in severe phytotoxicity and reduced yield quality under humid climate conditions.

Elemental sulphur as a fungicide has long been used for plant disease control, including apple fungal diseases, but its efficacy is undoubtedly lower than that of modern, conventional fungicides (e.g. Wormald, 1954; Lewis and Hickey, 1972; Ellis et al., 1998; Holb and Heijne, 2001; Holb and Schnabel, 2005; Schnabel et al., 2007). Elemental sulphur is a contact fungicide with only a weak protective activity (e.g. Ellis et al. 1994, 1998; Lewis and Hickey, 1972). In organic apple orchards, Holb and Heijne (2001) found that 0.5% wettable sulphur applied alone showed acceptable protective activity during the season under low disease pressure. In organic apple scab management, wettable sulphur might be applied successfully on a 5- to 7-day protectant schedule depending on the rate of leaf development during the period of ascospore infections, and it can prevent infections on a 10- to 14-day schedule during summertime if the disease pressure is low (Ellis et al., 1994, 1998; Holb and Heijne, 2001). Under high disease pressure in exceptionally wet years, efficacy of wettable sulphur is unacceptably low, and therefore it is risky to be used against apple scab.

Two types of elemental sulphur-based products are available to commercial growers: non-micronised sulphur and finer-ground micronised sulphur with particle sizes of 4–5 μm. Extremely fine, micronised particles of sulphur were found to act quicker and with greater toxicity against fungal spores compared to larger, non-micronised sulphur particles under controlled conditions (e.g. Wilcoxon and McCallan, 1930; Martin and Salmon, 1932; Tweedy, 1981). Therefore, micronised sulphur products may possess superior fungicidal activity compared to non-micronised sulphur. This effect did not seem to consistently influence field performance of the two forms of wettable sulphur (Holb and Heijne, 2001; Holb and Schnabel, 2005; Schnabel et al., 2007). Although micronised sulphur may act faster and be more toxic than non-micronised sulphur, it acts for a shorter period of time as elemental sulphur particles can quickly penetrate into the fungus cell (Tweedy, 1981; Beffa, 1993). Non-micronised sulphur may be less toxic but it may stay longer on the fruit and leaf surface and can penetrate into the fungus cell for a longer period of time. Moreover, very fine particles of micronised sulphur may be washed off more easily from the plant surface compared to the rough particles of non-micronised sulphur (I.J. Holb, unpublished data). Especially during light precipitations, the rougher sulphur particles may even be re-diluted on the plant surface and penetrate into the fungus cell again. These effects may cancel each other out and make the two forms of sulphur equally effective in the field.

Bicarbonates are one of the control options now attracting attention. They are common food additives allowed under European and North American regulations. Sodium bicarbonate (SBC) and potassium bicarbonate (PBC) have been used against plant pathogens (e.g. Homma et al., 1981; Corral et al., 1988; Horst et al., 1992; Ziv and Zitter, 1992; Palmer et al., 1997; Karabulut et al., 2003) including apple scab (e.g. Schulze and Schönherr, 2003; Ilhan et al., 2006; Tamm et al., 2006; Jamar and Lateur, 2007; Kunz et al., 2008). Recently Ilhan et al. (2006) showed that SBC effectively inhibited spore germination and germ tube elongation of *V. inaequalis* in vitro. In field experiments, 1% SBC treatment reduced the scab incidence on apple leaves to 30% compared with 63% in the water-treated control. The efficacy of 1% SBC was comparable with that of the label dose of tebuconazole on leaves and fruit. The authors showed that treatments of SBC were neither phytotoxic to leaves nor did they adversely affect quality parameters of harvested fruit. Ilhan et al. (2006) concluded that SBC should pose a minimal hazard to humans because of its low mammalian toxicity and it is an inexpensive substance, which would be an advantage to farmers with limited resources. A practical concern with SBC treatments is the presence of sodium, whose addition to agricultural soils is usually avoided; therefore, substitution by the more expensive PBC is recommended (Mlikota Gabler and Smilanick, 2001). Jamar and Lateur (2007) demonstrated that PBC significantly reduced apple scab severity on leaves and fruits compared with water control. The level of scab control was similar to that of wettable sulphur applied alone. The authors indicated that PBC is a contact fungicide with only a weak protective activity. PBC is highly water-soluble and can be washed off from the leaves by a small amount of precipitation. Therefore, frequent spray applications of PCB are recommended against scab in apple orchards (Jamar and Lateur, 2007).

Hydrated lime [$Ca(OH)_2$] has been tried as a replacement for copper fungicides against apple scab. $Ca(OH)_2$ at 5 g l^{-1} was recently shown to quickly kill conidia and germ tubes of *V. inaequalis* (Schulze and Schönherr, 2003). Applications prior to inoculation had no effect as $Ca(OH)_2$ is quickly converted to calcium carbonate ($CaCO_3$) and calcium bicarbonate [$Ca(HCO_3)_2$] by reacting with CO_2 from the air. $CaCO_3$ had no fungicidal effect on apple scab. For this reason, $Ca(OH)_2$ is unsuitable as a protective fungicide and therefore only post-infection activity in combination with a scab-warning system can be expected. Montag et al. (2005) showed that a suspension of hydrated lime (5 g l^{-1}) applied 16 h after infection killed early infection structures and stopped further development. Values of pH 12.4 or higher were necessary (Römpp, 1995) to disrupt the spore membranes and kill germinated conidia of *V. inaequalis* and their primary penetration structures. Montag et al. (2005) observed no phytotoxic reactions of $Ca(OH)_2$, neither with fruit nor with leaves. Their results indicated that a strategy with post-infection treatments of $Ca(OH)_2$ to control apple scab has potential and might become an alternative to lime sulphur. The authors suggest that $Ca(OH)_2$ should be applied with overhead irrigation, which would have several advantages: (i) growers could make applications to an entire orchard in a short time; (ii) if necessary, application of $Ca(OH)_2$ suspensions during rain is possible, as the solid particles act as a buffer and the pH of 12.4 can be maintained even during a light rain or drizzle; (iii) compaction of wet soils by heavy machinery is avoided; and (iv) applications can be automated.

Kaolin is used as a potential insecticide against plum curculio in most organic apple orchards. Berkett et al. (2005) showed that kaolin sprays were able to reduce apple scab too. On cluster leaves and fruit, trees regularly sprayed with kaolin had significantly less incidence of scab than non-sprayed trees. In addition, there was no apparent interference of kaolin with the effectiveness of a standard fungicide programme. The authors concluded that a great advantage of kaolin would be the possible integration of disease and pest management in organic apple production.

3.2 Apple Powdery Mildew

3.2.1 Integrated Apple Orchards

The management of apple powdery mildew is partly based on cultivar resistance in integrated orchards (e.g. Yoder and Hickey, 1983; Hickey and Yoder, 1990). Bower et al. (1995) demonstrated that mildew-resistant cultivars could reduce effectively the need for mildewicides in apple production. Recently, the use of mildew-susceptible cultivars has decreased in apple production; therefore, powdery mildew control is usually coupled successfully with apple scab management as most of the scab fungicides also control powdery mildew sufficiently. Therefore, separate fungicide sprays in apple disease management are not usual against apple powdery mildew. However, in some countries, as DMI are no longer effective against apple scab, they are added to protectant sprays only for powdery mildew control (S. Kunz, personal communication).

Fungicides registered for mildew control are sulphur, oxythioquinox, benzimidazoles, bupirimate, nitrothalisopropy, pyrazophos and EBIs in most countries (e.g. Spotts and Cervantes, 1986; Hickey and Yoder, 1990; Sholberg and Haag, 1994).

The primary mildewicides are DMIs and sulphur in apple orchards (Yoder, 2000). The DMIs have been perceived by many growers as being highly effective, but more expensive than sulphur for mildew control (Yoder, 2000). OoI fungicides were also shown to be highly effective in controlling apple powdery mildew (Reuveni, 2000). Trifloxystrobin (at a concentration of 0.01–0.015%) was superior to most DMIs such as penconazole and myclobutanil (Reuveni, 2000). Highly effective mildewicides, such as most DMIs and OoIs, which strongly suppress the disease, provide acceptable control, even on highly susceptible apple cultivars (Sholberg and Haag, 1994; Reuveni, 2000; Yoder, 2000). However, different levels of DMI and strobilurin resistance in apple powdery mildew isolates were detected (e.g. Reuveni et al., 1998; Reuveni, 2000; Lesemann et al., 2006).

The fungus survives the winter in buds, making it difficult to control during the early spring development of apple trees. First sprays against powdery mildew can only be effective after bud burst when budscales open and overwintered mildew mycelia become available for fungicides. A special action threshold level at 20% leaf infection was suggested in the Mid-Atlantic region of the USA (Yoder and Hickey, 1995; Yoder, 2000). Applications of fungicides should be made from the tight-cluster stage until terminal shoot growth ceases in midsummer. The interval between sprays is generally 7 days during the stages of rapid leaf development before petal fall and 12–14 days during the post-bloom period. Disease assessment and forecasting systems along with sprays of DMIs before mildew becomes severe should be highly effective in minimising losses in commercial orchards (Hickey and Yoder, 1990).

Recent research on control of apple powdery mildew tested spray machines, developed integrated fungicide-fertilizer spray programmes, and improved disease warning. A study by Cross and Berrie (1995) compared axial fan sprayer with the air-assisted tunnel sprayer in integrated apple orchards. The authors concluded that control of powdery mildew was similar when using either sprayer. Approximately 30% of the spray volume applied was collected for recycling with the tunnel sprayer, but the main limitations of the tunnel sprayer were its slow maximum forward speed and the restricted tree size and shape on which it can be used. Other research focused on integrating sprays of mono-potassium phosphate (MPH) fertilizer with systemic fungicides against powdery mildew (Reuveni et al., 1998). Reuveni et al. (1998) showed that the effectiveness of alternating systemic fungicides with a 1% solution of MPH was similar to that of the commercial treatment with the systemic fungicides. In addition, the tank-mix of 1% MPH solution with a half rate of fungicides was as effective or superior to that obtained by the standard fungicide treatment. The authors concluded that the inhibitory effectiveness of MPH fertilizer makes it a potential major component of an IPM programme and the MPH fertilizer can also be useful in mildew resistance management. Recent research also made a great development in forecasting apple powdery mildew. Xu (1999) developed a model to simulate epidemics of powdery mildew on vegetative shoots which generates two types of output: (i) forecasts of disease severity and (ii) indices of the relative favourability of weather conditions on disease development. This model became part of the PC-based disease-warning system, Adem(TM). Field evaluation of Adem(TM) resulted in similar or better mildew control than a routine programme (Berrie and Xu, 2003). In addition, Xu and Madden (2002) argued that the leaf incidence–density relationships for apple powdery mildew may also be incorporated into practical disease management decisions.

3.2.2 Organic Apple Orchards

In organic apple production, mildew resistance of cultivars is a key element of powdery mildew control. The most commonly used fungicide against powdery mildew in organic apple production is elemental sulphur. Of the mildewicides, sulphur was shown to be the least effective but it was demonstrated that increasing the number of sulphur applications from six to eight increased mildew control and yield (Yoder, 2000). Sulphur sprays are also used against apple scab in organic production, and therefore the interval between sulphur sprays is generally 7 days during both the primary and secondary infection periods of powdery mildew. This frequent use of sulphur compounds against powdery mildew fulfils the marketing requirements for organic apple production.

In the last two decades, plant and minerals oils also received attention for control of powdery mildew in order to replace the frequent use of sulphur (e.g. Northover and Schneider, 1993, 1996; Grove and Boal, 1996; Yoder et al., 2002; Fernandez et al., 2006). Sunflower, olive, canola, corn, soybean and grapeseed oils were equally effective in providing over 99% control of *P. leucotricha* when applied to apple foliage 1 day before or 1 day after inoculation (Northover and Schneider, 1993, 1996). The authors also showed that mechanically emulsified canola oil was comparable to dinocap when applied 1, 2, 4 and 7 days after inoculation. Recently, mineral oils were also tested in a three-spray early-season programme targeting apple powdery mildew but the results showed that powdery mildew shoot infestation was suppressed only in 1 year and no differences in fruit damage were found when treatments were compared to untreated control (Fernandez et al., 2006).

3.3 European Canker

Control of European canker is extremely difficult in apple-growing areas where environmental conditions are favourable for the disease such as mild winters and cold summers coupled with high annual precipitation. Removal of infected plant parts is usually not sufficient to control this disease and chemical applications are needed to avoid severe damage (Grove, 1990; Latorre et al., 2002).

Fungicide sprays have already proved effective in preventing canker in early studies (e.g. Byrde et al., 1965; Bennett, 1971). Copper sprays in autumn and/or spring are a general recommendation against the disease, which can be recommended for integrated apple orchards, and the only chemical control option for organic orchards. One to three protective sprays of copper compounds (e.g. Bordeaux mixture, copper oxychloride or copper dioxide) or copper compounds alternated with benzimidazole fungicides (benomyl, thiophanate-methyl or carbendazim) are widely used during leaf fall (Lolas and Latorre, 1997). Benzimidazoles are known to suppress sporulation of the pathogen for prolonged periods (Swinburne et al., 1975) and may thus prevent autumn infection by *N. galligena* without the need for an additional autumn treatment (Cooke, 1999). However, this group of fungicides is now banned for integrated production in several countries. Application timing of fungicides against European canker can be different for apple-growing regions (Swinburne, 1975). In the United States, in the North Pacific Regions, copper sprays are recommended prior to autumn rains and at the onset of leaf fall (Grove, 1990). However, in Northern Ireland Swinburne et al. (1975) showed that spring-summer fungicide programmes caused a greater reduction in canker numbers than autumn fungicides alone. Further investigation in Northern Ireland showed that autumn application of carbendazim gave inadequate control and thiophanate-methyl, bitertanol and fenpropimorph were ineffective (Cooke et al., 1993). According to the above results, spring-summer fungicide sprays were also investigated compared with autumn spray programmes. For instance, Cooke et al. (1993) showed that carbendazim applied as a spring-summer treatment reduced canker development to a similar level to a spring-summer dodine scab programme plus autumn copper oxychloride. Summer carbendazim plus captafol were an outstandingly effective treatment. Berrie (1992) also showed that carbendazim was the only fungicide that reduced numbers of cankers significantly in comparison with captan, dithianon, mancozeb and imazalil. Both Cooke et al. (1993) and Berrie (1992) studies concluded that carbendazim mixed with an effective scab fungicide remains the recommended treatment in an orchard with a serious canker problem. In a more recent study, Cooke (1999) showed also that DMI fungicide programmes during the season including autumn application of copper oxychloride achieved excellent canker control. Curative activities of DMI fungicides were also tested. Xu and Butt (1996) reported that curative fungicide sprays were relatively ineffective in preventing canker development at pruning cuts 48 or 36 h after inoculation with *N. galligena*. The authors showed a dramatic decrease in canker numbers on 1-year-old wood following fungicide treatments, which implied an external source of inoculum rather than the development of cankers from systemic infections. The reason is that the uptake into woody tissue from foliar fungicide sprays is extremely limited and insufficient to produce a fungicidal dose, since their translocation is almost exclusively acropetal (Crowdy, 1977). DMI fungicide sprays are thus unlikely to kill the pathogen within established cankers, to inhibit possible systemic spread via the xylem, and to prevent symptomless systemic infection by *N. galligena* (Cooke, 1999). In addition, not even newer groups of fungicides (such as anilinopyrimidines and the strobilurins) may reduce systemic infection of *N. galligena* with a higher efficacy than other older fungicides.

Efforts were also made to improve canker control by using disease forecasting. As weather conditions are critical, both for inoculum production and infection by *N. galligena*, predictions that use temperature and duration of leaf wetness required for infection have been used for timing fungicide applications on European canker (e.g. Lortie, 1964; Wilson, 1966; Dubin and English, 1974a,b, 1975; Xu and Butt, 1993, 1994). More recently, Latorre et al. (2002) developed a PC-based infection-warning system throughout the analysis of weather parameters and implemented it in the predictive software PatFrut. In the model test, five and six warnings of European canker infection were determined during leaf fall in 2 years, which were associated with rain events and wetness periods. The forecast model showed benefit for canker control. In 1 year, significant differences in disease incidence were obtained reducing disease incidence from 24 to 4.6% when treatments were scheduled according to the model programme (Latorre et al., 2002).

3.4 Monilinia Fruit Rot

Brown rot is rarely a serious problem in integrated apple orchards (Batra, 1991; Holb, 2008a). If fruits are prevented from skin injury then fungicide programmes against apple scab are also effective against brown rot. In the case of specific brown rot problems, fungicides effective against apple scab are also active against brown rot. Sprays applied during bloom reduce blossom blight (in those areas where *M. fructicola* also occurs on apple) and sprays applied 2–3 weeks before harvest help to reduce fruit infection where severe fruit injury is expected (Byrde and Willetts, 1977; Batra, 1991).

In organic apple orchards, brown rot of apple can become a serious disease due to two reasons: first, insect (and especially codling moth) control is insufficient in organic apple orchards, and therefore large numbers of injured fruits are present in the orchards; and second, approved fungicides in organic apple orchards are not effective enough against brown rot. Copper and sulphur compounds were used for brown rot control from the late nineteenth century (Wormald, 1954). Copper fungicides are primarily able to reduce primary inoculum sources produced on mummified fruit (Byrde and Willetts, 1977; Batra, 1991). Sulphur fungicides were widely recommended until the early 1970s, especially against the fruit rot stage of brown rot (Byrde and Willetts, 1977; Batra, 1991). Efficacy of sulphur compounds is based on a reduction of spore germination and spore viability in *Monilinia* spp. (Tweedy and Turner 1966). Over the past 30 years, sulphur has been used against brown rot only in organic apple production, as there is no more effective option against the disease.

3.5 Flyspeck and Sooty Blotch

It can be stated in general that due to the several fungal species associated with the sooty blotch and flyspeck complex, control can be achieved by broad-spectrum fungicides with longer residual activity (Hernandez et al., 2004). However, these fungicides have several harmful effects on the environment; therefore, most of them are banned and no longer used. Research also indicated that fungicide applications from a second cover spray through late August controlled summer diseases more effectively than early-season treatments (Barden and Marini, 1998). The newer site-specific fungicides have narrow-spectrum activities mainly with shorter residual activity, which first, results in a more frequent spray application during summer, and second, not all the fungi associated with sooty blotch and flyspeck complex can be equally controlled. In addition, control of the disease complex with narrow-spectrum fungicides will affect the efficient use of a reduced summer spray programme against scab and probably will limit the omission of the last fungicide sprays against scab in the warm, moist growing areas of the world. All of these will provide a new challenge for scientists and growers in applying chemical control. On the other hand, they provide a clear indication that non-chemical control approaches will play an important role in the successful management of the sooty blotch and flyspeck complex. Recently, a detailed review was published of the current status of sooty blotch and flyspeck control (Williamson and Sutton, 2000); therefore, only the presently available fungicides for integrated and organic apple orchards are discussed here.

3.5.1 Integrated Apple Orchards

Among contact organic fungicides, captan is one of the earliest fungicides which was found to be effective against the sooty blotch fungus, *Gloeodes pomigena,* in in vitro tests and its failure to control sooty blotch in the field was attributed to its short residual activity (Hickey, 1960). Several earlier studies (e.g. Weaver, 1953; Hickey, 1960; Lewis and Hickey, 1958, 1972) led to the development of a spray timing programme similar to the one used today in which the cover sprays are applied every 10–14 days during the summer. Hickey (1977) found that zineb provided up to 60 days residual activity and suggested combinations of captan plus zineb for sooty blotch and flyspeck control for the mid-Atlantic growing region. Brown and Sutton (1986) found that the residual control provided by mancozeb was 20–30 days longer for sooty blotch and 30–50 days longer for flyspeck than that provided by captan. Because of their excellent residual and broad-spectrum activity, these fungicides became widely used from the mid-1960s through to the early 1990s. In the 1980s, the benzimidazole fungicides, benomyl and thiophanate-methyl, were beginning to be inserted into the cover spray programme, often in combination with captan, to improve sooty blotch and flyspeck control. However, most of these fungicides are not allowed to be used in modern integrated orchards anymore. From the 1990s, new fungicides (DMIs and QoIs) with site-specific activity were released and incorporated into the spray programme. This resulted in one or more causative fungi of sooty blotch and flyspeck becoming more important.

Recently, control was also improved via the use of eradicant spray programmes based on forecast models to time fungicide applications. In the first study, Brown and Sutton (1995) monitored hours of leaf wetting (using a DeWit leaf wetness recorder), rainfall and temperature. They noted that the first symptoms of sooty blotch and flyspeck appeared after an average of 273 h of leaf wetting of 4-h duration or greater had accumulated, beginning with the first rain that occurred 10 days after petal fall. They recommended that a threshold of 200–225 h of accumulated wetting should be used to time benzimidazole applications but they suggested that a higher threshold could be used under low-inoculum situations. They indicated also that if the model had been used, the average grower would have saved two sprays each year. The model has subsequently been modified by several researchers. Hartman

(1995, 1996a) and Smigell and Hartman (1998a,b) suggested 175 h of total wetting as a threshold for the insertion of a benzimidazole fungicide in the spray programme in Kentucky. By using the programme, up to four sprays a year have been saved. Hartman (1996b) and Smigell and Hartman (1998a,b) used also their version of the flyspeck and sooty blotch model to time the placement of multilayer fruit bags (used to modify fruit colour for specialty markets) on developing fruit. Gleason et al. (1999), using the Hartman model, compared the accumulation of leaf wetting on-site with an electronic sensor with predicted leaf wetness data. Using the on-site data, they were able to use two sprays less than were used in the protectant programme and one less when using leaf wetness data from the commercial company.

At the same time, a somewhat similar approach was utilised for timing benzimidazole sprays to control flyspeck in New York (Agnello et al., 1999; Rosenberger et al., 1996a,b, 1997a,b, 1998, 1999). The authors reasoned that the last fungicide spray applied to control scab, which typically includes benomyl, thiophanate-methyl, captan or ziram, provided 14–21 days residual activity against flyspeck, depending on the particular fungicide. After the 14- to 21-day period, total hours of leaf wetting are accumulated until 100 h are reached. This 100-h period is referred to as a 'protection gap' and is based on the ability of benzimidazole fungicides to eradicate existing infections during this time period.

More recently, Gleason et al. (2002), Babadoost (2003), and Babadoost et al. (2004) further improved the effectiveness of a disease-warning system and efficacy of reduced-risk fungicides for management of sooty blotch and flyspeck. The authors showed that warning system-timed applications of the second-cover fungicide spray occurred when 175 h of leaf wetness had accumulated; wetness data were derived either from a sensor placed beneath the canopy of apple trees (on-site) or according to remotely sensed estimates. Using sensor measurements as inputs to the warning system saved one to three fungicide sprays per season. The reduced-risk fungicides, kresoxim-methyl and trifloxystrobin provided a control of sooty blotch and flyspeck equal to benomyl or thiophanate-methyl in all trials. Later Batzer and Gleason (2005) also demonstrated that selection of tree canopy sites for leaf wetness duration (LWD) monitoring could profoundly affect the performance of LWD-based disease-warning systems in apple orchards. In addition, Cooley and Rosenberger (2005) revealed that conidia usually do not reach orchards until the cumulative leaf wetting (CLW) from cultivar 'McIntosh' petal fall (PF) reaches 270 h. They concluded that fungicide sprays could be omitted during summer until the time that CLW-PF reaches 300 h. This timing regime should allow growers to omit one to two fungicide sprays during June and July in most years without significantly increasing the risk of flyspeck on fruit at harvest (Cooley and Rosenberger, 2005).

3.5.2 Organic Apple Orchards

Copper, lime sulphur and elemental sulphur can be used against the sooty blotch and flyspeck complex in organic apple orchards. The first report of a fungicide trial for sooty blotch and flyspeck was in 1894, using Bordeaux mixture (Lamson, 1894), and it was reported that Bordeaux mixture could reduce the incidence of disease from 77 to 18%. Bordeaux mixture, applied every 2–4 weeks during the season, was generally recommended during the first decade of the twentieth century to control the diseases (Stevens and Hall, 1910; Ploper and Backman, 1991). By 1910, Bordeaux mixture was being replaced by lime sulphur, which was less phytotoxic (Hickey, 1960). From this time until the late 1940s and early 1950s, Bordeaux mixture and lime sulphur were the principal fungicides used for the control of sooty blotch and flyspeck in commercial apple orchards and in the past 50 years they remained the main fungicides in organic orchards (Trapman et al., 2004). Recently, a disease-warning system is also used against sooty blotch in organic apple orchards based on applications of lime sulphur and copper sprays (Trapman, 2004).

As regards other organically approved fungicide options, coconut soap, prepared from *C. nucifera*, has been shown to be efficient against sooty blotch (Fuchs et al., 2002). Authors showed that effectiveness of six applications of the soap was similar to that of four treatments of lime sulphur at 1% dosage. The authors concluded that coconut soap could be effective against sooty blotch if the disease pressure is low. Kaolin has also been evaluated against sooty blotch and flyspeck in organic apple orchard (Thomas et al., 2004; Berkett et al., 2005). A kaolin-based product, Surround WP (Engelhard Corp., Iselin, New Jersey), was applied at five different rates and frequencies throughout two growing seasons but it was successful at suppressing only flyspeck and only in 1 year.

4 Integration of Multiple Management Tactics Across All Important Fungal Diseases in Integrated and Organic Apple Production

Fungal disease management of apple is based on scab control in both integrated and organic production systems. Management of all other diseases are mainly incorporated into scab management programmes or specific treatments may be attached to scab control schedules such as for the management of European canker, flyspeck and sooty blotch.

4.1 Integrated Apple Orchards

In the past three decades, automatised disease-warning systems have been key elements of fungal disease management in integrated apple orchards. Based on this, the number of chemical applications against fungal diseases has been reduced (Fig. 1/A). As numbers of fungicide sprays are still too high, further reduction is needed especially of sprays against scab. The basic market criterion for integrated apple fruit is that final fruit scab incidence must be below 1% (Holb et al., 2003b). This is a strict criterion; therefore, scab control relies mainly on the effectiveness of chemical fungicides to fulfil the 1% scab threshold level at harvest. Based on annual scab control schedules, advanced IPM against fungal diseases identifies two periods

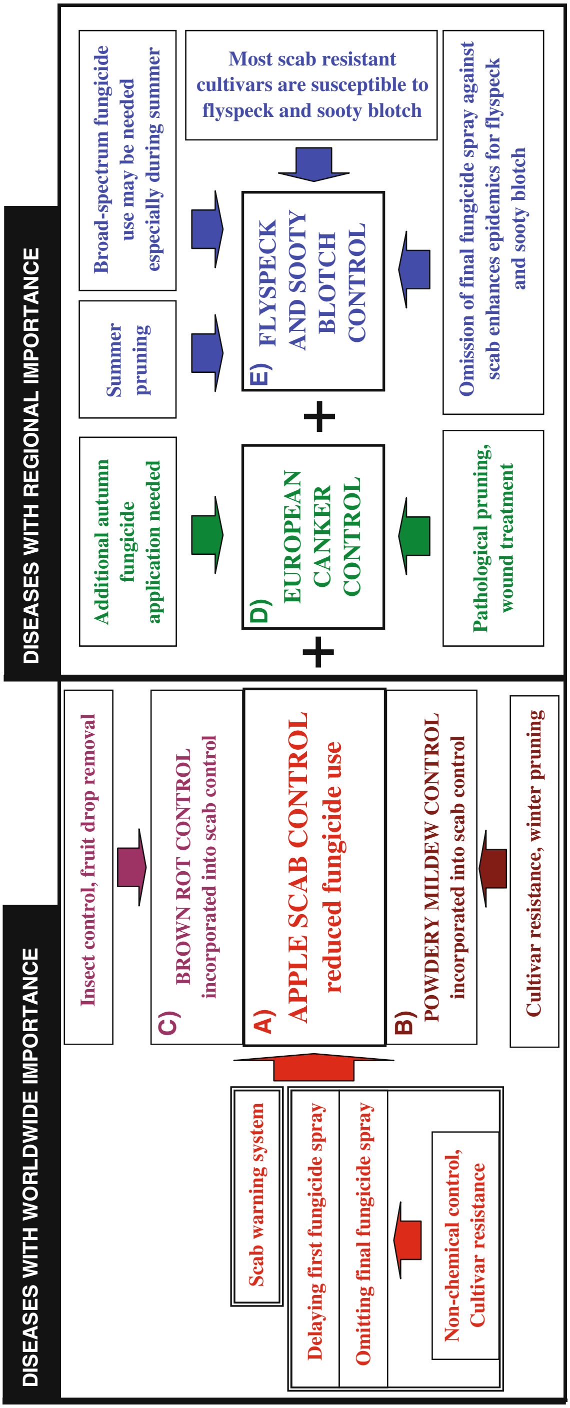

Fig. 1 Summary for integration of management tactics across six important fungal diseases in integrated apple production

for reducing the number of fungicide applications. One is omitting sprays against scab in the beginning of the season by using PAD threshold criteria for delaying first fungicide sprays (MacHardy et al., 1993; Sutton et al., 2000) and the other is omitting fungicide sprays at the end of the season by timing the final spray application against scab (Scheer, 1987; Holb et al., 2003b). Omission of fungicide sprays at the beginning or/and at the end of the season relies on incorporation of non-chemical control options in the disease management schedule, although their biological efficacy and expenses can be highly limiting factors of their use against apple scab (Fig. 1/A). Two options are the most popular in the present apple IPM programmes: one is cultivar resistance and the other is the reduction of primary inoculum by sanitation (Fig. 1/A). Both options presently have limitations. Resistant cultivars are not yet widespread due to low market interest related to their insufficient fruit quality. The reduction of primary sources of scab inoculum is the most effective by leaf removal in the sexual phase and by pruning in the case of the asexual fungal phase. However, the grower attitude is highly dependent on the applicability of these methods, whether it is realistic to omit the first two sprays at the beginning of the season or not (Rosenberger et al., 1996a; Cooley and Autio, 1997).

Control of apple powdery mildew is mainly a question of cultivar susceptibility. The most widely grown cultivars have low-to-moderate mildew susceptibility, which gives a possibility to reduce fungicide use against powdery mildew (Fig. 1/B). This option highly suits to scab control in two aspects: (i) most scab fungicides are highly effective against powdery mildew and (ii) removal of infected shoots during winter pruning is suited to mechanical control of both powdery mildew and scab control (Fig. 1/B). On the other hand, if cultivars are susceptible to powdery mildew (such as 'Jonathan') omitting the first two fungicide sprays against scab until pink bud stage might be impossible as a fungicide spray would be needed against powdery mildew after bud burst. This also indicates that mildew susceptible cultivars cannot be a part of the overall disease management in the future in integrated apple orchards.

Scab fungicides are highly effective against brown rot, though brown rot infection may occur at the end of summer or early autumn when scab fungicide sprays are omitted. However, this late infection is highly correlated with insect injury (Holb and Scherm, 2008); therefore, efficacy of brown rot control is highly dependent on the success of insect control, which is out of the question in a well-managed integrated apple orchard (Fig. 1/C).

Control of European canker during the season is also managed by scab control though it can be more difficult to adjust to scab control than to control of powdery mildew or brown rot (Fig. 1/D). The use of an effective scab control programme based on DMIs and/or non-systemic fungicides such as dithianon should largely prevent canker from becoming established in an orchard as long as the major source of inoculum is external. Supplementing this with two autumn applications of copper oxychloride is worthwhile in wet areas such as Northern Ireland, where it can substantially reduce leaf scar infection (Fig. 1/D). Fungicide spray treatments cannot, however, eradicate existing infections, so if trees are already visibly infected, the programme must be supplemented by cutting out and removing cankers and treating wounds with an effective canker paint (Fig. 1/D).

Control of flyspeck and sooty blotch can be difficult to adjust to scab control in warm and moist growing areas (Fig. 1/E). The major reasons are (i) control of flyspeck and sooty blotch requires broad-spectrum fungicides that might not be used for apple scab for most spray applications; (ii) scab control does not use expensive systemic fungicides at the end of the season due to their cost and fungicide resistance management; (iii) omission of the last fungicide sprays against scab at the end of summer or early autumn might not be applied on flyspeck- and sooty blotch-susceptible cultivars as both diseases build epidemics at the end of summer; and (iv) scab-resistant cultivars receive very few sprays during summer which might allow flyspeck and sooty blotch to cause severe symptoms (Fig. 1/E). Unfortunately, the most favourable scab-resistant cultivars are susceptible to flyspeck and sooty blotch and additional sprays are needed against both diseases during summer. Overall, there is a clear indication that the non-chemical control approach becomes an increasingly essential supplementing option for successful management of the sooty blotch and flyspeck complex. Cooley and Autio (1997) suggested a combination of summer pruning and limited captan use for management of the sooty blotch and flyspeck complex in an advanced IPM programme reducing fungicide use compared to traditional IPM programmes (Fig. 1/E). Although this advanced IPM practice reduced fungicide use, it was also shown that growers were reluctant to incorporate them fully (Cooley and Autio, 1997). Strictly on the basis of expenditures, growers who adopt the advanced IPM programme would save approximately two fungicide applications a year without incurring additional disease damage and would hence save approximately USD 140 ha year^{-1} including application costs (Rosenberger et al., 1996a). Additional costs incurred would include the PAD analysis, estimated at USD 30 ha year^{-1}. Hence, although the advanced IPM methods might save USD 110 ha year^{-1} this would be quickly lost if growers incurred around 1% more than the usual fruit damage (Rosenberger et al., 1996a). As this profit benefit can be lost very easily, growers are reluctant to adopt the advanced IPM programme. This indicates that even if new aspects of the advanced IPM programme are successful, it must be refined to be attractive to apple growers.

4.2 Organic Apple Orchards

In organic apple orchards, there is no efficient chemical control option that could help the low or moderate efficacy of non-chemical disease management. The most effective fungicides are copper and sulphur compounds and their efficacy is below that of the standard synthetic fungicides. Therefore, the risk of disease epidemics is high. To somewhat lower epidemic development, the grower has to use disease-resistant apple cultivars and apply efficient combinations of non-chemical control measures as well. One of the key prerequisites for the successful use of the non-chemical control methods is that the orchard site has to suit to cultivars' optimum, and agronomic measures have to be used to suppress disease development. After this, the frequent use of sulphur and copper fungicides may provide an acceptable disease level and fruit quality for the organic fruit market.

The cultivar planted should possess at least scab and powdery mildew resistance. Cultivar resistance coupled with mixing cultivars within the orchard can be a viable option for reasonable organic apple growing. Most organic apple growers in Europe still use moderately or even highly susceptible cultivars that require large numbers of sulphur and copper sprays, reaching 25–30 sprays per year. This means a weekly fungicide schedule from bud burst until mid-June, then applications at 10–14 days intervals until harvest depending on weather conditions. Due to the restriction of copper fungicides in organic apple production, copper is used in the beginning of the season and the rest of the spray applications contain large amounts of sulphur fungicides, which results in sufficient control of powdery mildew. However, this schedule is not able to control sufficiently other diseases such as apple scab, European canker, flyspeck and sooty blotch. Therefore, cultivar resistance and all previously described non-chemical control options constitute important elements of a successful suppression of apple diseases in organic apple production. All these approaches are very time-consuming and consequently have high labour costs. One of the keys to the success of the non-chemical control options is harmonising management practices during the season based on epidemic features of the pathogen, weather conditions and the efficacy of non-chemical control schemes against the disease. As an example, an option is shown here (Fig. 2) for harmonisation of these elements, which were recently developed to control overwintering conidia of the apple scab fungus in organic apple orchards (Holb et al., 2005b).

In this model, three parameters should be incorporated: (1) Y_{75} as the time for bud closure for cv. 'Jonagold'; (2) previous year autumn scab incidence (40%) as the minimum threshold criterion for overwintering conidia; and (3) minimum values of AUDPC (area under the disease progress curve) and theta (the absolute rate of disease progress) for calculating the present year epidemic intensity until the tree reaches day Y_{75}. The effect of spray application can be modelled based

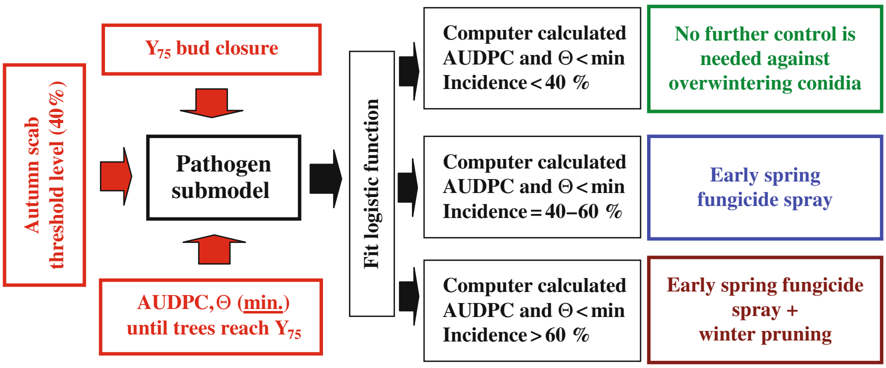

Fig. 2 Possible implications of the most important disease parameters (AUDPC – area under the disease progress curve; theta (Θ) – the absolute rate of disease progress; Y_{75}– the time for bud closure for cv. 'Jonagold'] in apple scab management for the organic production system. Adapted from Holb et al. (2005b)

on the above factors in order to suppress conidial entrapment as much as possible. If the computer-calculated AUDPC and theta are lower than the minimum and until mid-October the orchard has a lower level of scab incidence, less than 40%, then no further control is needed against overwintering conidia. However, if computer-calculated AUDPC and theta are higher than the minimum and autumn scab incidence is between 40 and 60% until mid-October, then an additional copper or lime sulphur spray should be applied at bud burst next spring. Finally, if computer-calculated AUDPCs and theta are higher than the minimum and autumn scab incidence is above 60% until mid-October, then an additional early fungicide spray combined with winter pruning should be applied in order to suppress infections by overwintered conidia.

5 Future Trends

Observing environmentally friendly production in a more general sense, i.e. with regards to the concept of sustainability ('the ability of a system to continue'), most research reveals that integrated production is the future 'sustainable' way to solve crop protection difficulties in arable and tree-fruit production. This is in spite of the fact that, for example, integrated apple production still uses considerable amounts of synthetic pesticides including a large proportion (90%) of fungicides (Penrose, 1995). On the other hand, organic production has received much criticism as to what extent it is sustainable. In fact, researchers believe that there are some basic issues which remain to be solved in order to fully establish the sustainability of organic production. This is due to the fact that the majority of the compounds utilised in crop protection in organic production systems are derived from non-renewable resources and they are not without toxicological hazards to the environment or humans (Edwards and Howells, 2001). Despite these problems, researchers agree that organic farming is more sustainable than conventional production in a bio-physical sense. In summary, both production systems require further development in disease management by improving, for example, warning system, resistance breeding and non-chemical control options.

Current research studies predict that genetic tools are likely to play the most essential role in fungal disease management of apple with the multiple resistance breeding approach if they will be able to produce apples that are not only disease-resistant but also have equally good taste and quality as the susceptible ones. Genetic tools might not be the final approach to solve the fungal disease management as emergence of new pathogen races might break this resistance from time to time. Therefore, other disease resistance mechanisms such as more physiological approaches (e.g. systemic acquired resistance) might be involved in the practice of a successful apple disease management. Either way, the host resistance approach will receive great attention in the future, as basically this seems to be the least costly option for growers and the most environmentally friendly approach for effective disease management.

Often agronomic practices (and also other non-chemical control methods) that are known to reduce disease incidence or severity, even if they are environmentally sound, are not economically feasible. Another problem is that only few of them are absolutes in disease control. For instance, some pathogens are controlled by mulching but others are not or their development is even enhanced by applying mulching. Some diseases can be managed by irrigation, while irrigation makes other diseases worse. In addition, it might be an economic problem if one approach can control only one disease, such as a BCA always has this feature, even if it is effective. In the future, improvement of the present expert systems such as POMME (Travis and Latin, 1991) and their incorporation into precision farming practices for apples might provide the best chance to include agronomic measures and non-chemical control options more efficiently in the current environmentally friendly apple production systems.

As integrated disease management of apple still uses large quantities of chemical-based fungicides, it will undoubtedly benefit from the use of previously discussed non-chemical control methods against fungal diseases. Integration of the novel and more effective non-chemical control methods enables the continuous development of integrated disease management by reducing or replacing fungicides and consequently it will continue in an overall reduction in the use of pesticides. This will result in plant protection schedules gradually approaching the basic concept of the ecologically based production system. The present status of integrated apple production – the combination of chemical, cultural and biological control methods in fungal disease management strategies – is only at the stage of the second level of IPM in the integrated fruit protection. Recently, research programmes have been initiated for the third level of IPM (Prokopy et al., 1994; MacHardy, 2000; Prokopy, 2003), which harmonises scab management strategies with control of other diseases and pests and with other horticultural management practices. The challenge for apple IPM programmes in the twenty-first century is to complete the fourth, final IPM level, which supplements IPM level 3 with cultural, social and political realms.

In organic apple orchards, there are still several efficacy problems in fungal disease management strategies, so further improvements are needed for integrating chemical, cultural and biological control methods in a much more effective way. An urgent task is to develop effective non-chemical control options that are practically feasible and can be incorporated easily into the orchard management practices of organic apple production. These new technological elements must result in acceptable yield and fruit quality parameters. Until these tasks are achieved, an essential change in the current status of organic production cannot be expected.

6 Conclusion

Current fungal disease management in environmentally friendly apple production still relies largely on chemical control. In the past 20 years, continued developments of disease-warning systems and host resistance to fungal pathogens, as well as incorporation of some non-chemical control options into fungal disease management of

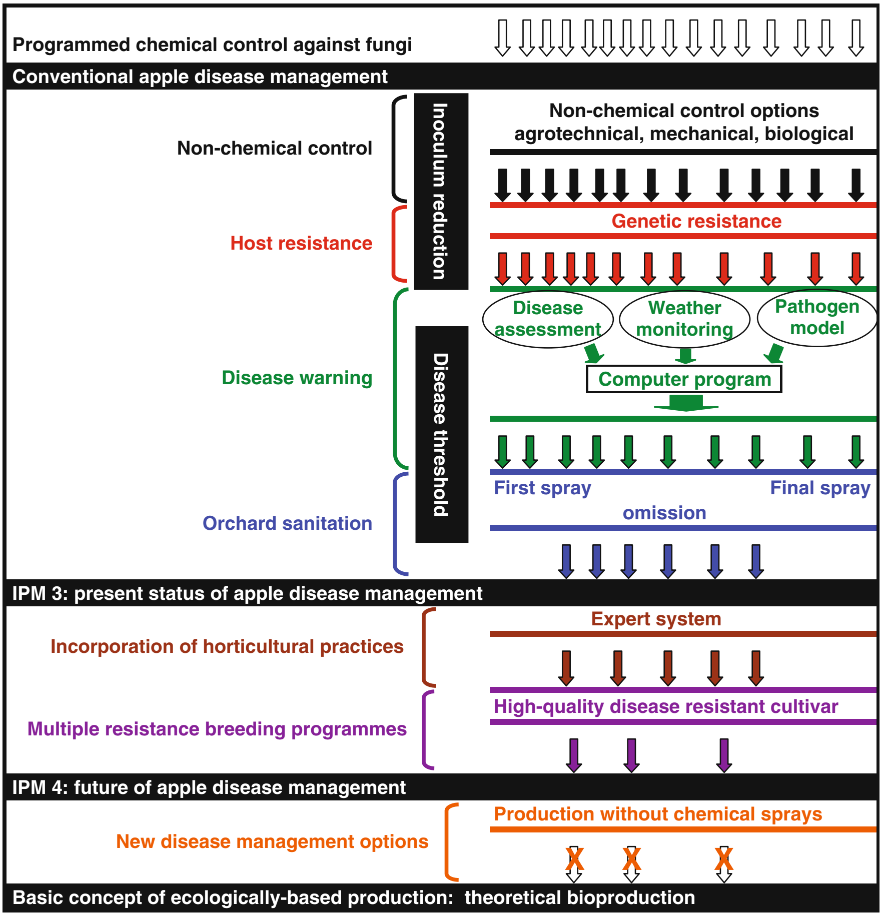

Fig. 3 Basic strategies for reducing chemical-based control against fungal diseases by using several means of non-chemical control approaches in order to reach the basic concept of ecologically based apple production systems. *Arrows* represent fungicide sprays during the season

apple, were able to reduce the number of sprays against fungal diseases considerably (Fig. 3). In addition, the duration of season-long pesticide use was reduced by developing disease threshold levels for omitting fungicide sprays at the beginning or/and at the end of the season (Fig. 3). Despite this, disease management in environmentally friendly apple production still uses large quantities of chemical-based fungicides. Therefore, our future task is to integrate the novel and more effective non-chemical control methods throughout system development. In addition, these methods should be combined with those host resistance components which use genetic tools with multiple resistance breeding approaches. These methods will enable the continuous development of environmentally friendly disease management by reducing or replacing fungicides (Fig. 3). Particularly, the challenge for apple IPM programmes in the twenty-first century is to complete the fourth, final IPM level, which supplements IPM level 3 with cultural, social and political realms. While in organic apple orchards, the most essential task is to develop effective non-chemical control options that are practically feasible and can be incorporated easily into the orchard management practices. Then finally, both environmentally friendly apple production systems may eventually unite into the basic concept of the ecologically based production system (Fig. 3).

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