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Fungicide use reduction in apple production—potentials or pipe dreams?

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Abstract

Reduction in pesticide use in response to consumer pressures is seen as a major issue in many crops. Fungicides comprise the greater proportion of pesticides applied to apples. Potential methods to reduce their usage have been available for a considerable period of time. These are examined under five broad areas: epidemiological (manipulation of current practices), non-conventional fungicides, biological control with microorganisms, disease-resistant varieties, and isolation. The application of these concepts to commercial horticulture in Australia and the economics and social aspects of reduced-input disease control are discussed. The most likely chance for successful adoption of practices to reduce fungicide usage probably lies with manipulation of current practices. These include a reduction in dose rates associated with inoculum suppression and cessation of apple scab treatments at the end of the primary infection period where good control of the disease has been maintained. Biological control offers promise in the control of post harvest diseases. Disease resistant apple varieties offer scope for niche markets demanding reduced pesticide growing systems. The impediments to reduced fungicide usage are seen as both sociological and financial. The benefits of decreased pesticide usage are largely public, whilst the risks of loss are private. Unless these risks can be compensated for, perhaps with a price premium for low-fungicide fruit, it is unlikely that growers will implement such strategies. The variation in the amount of fungicides used successfully by different growers does, however, give scope to bring total usage by the industry down to a practical minimum.

Keywords: Fungicide reduction; IPM; Apples

1. Introduction

Since Millardet discovered the effects of copper and lime mixtures on reducing disease loss in grapes in the 1880s, the aim of researchers and farmers has generally been to increase the level of disease control. If extra fungicide applications were required to approach closer to 100% control, then this was generally accepted. However, in recent years community attitudes to pesticides and other chemicals has meant a re-assessment of the use of pesticides in agriculture. In response to consumer concerns, the Australian Apple and Pear Growers' Association in 1991 (Anonymous, 1991) signed an agreement with consumer and environmental groups committing growers to the goal of reducing pesticide use by 50% by 1996 and 75% by the year 2000. Several European and Scandinavian countries are also pursuing similar goals (Evans and Rowland, 1993). However, integrated pest management programs (IPM) which reduced pesticide use are far from being universally adopted even when available and validated (Zalom, 1993).

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Table 1
Principal fruit and foliage diseases of apples in Australia

Disease	Pathogen	Importance
Scab	*Venturia inaequalis* (Cke.) Wint.	Major
Powdery mildew	*Podosphaera leucotricha* (Ell. & Ev.) Salmon	Major in some varieties
Sooty blotch	*Gloeodes pomigena* (Schwein.) Colby	Minor, sometimes a problem in wet seasons
Flyspeck	*Schizothyrium pomi* (Mont. & Fr.) Arx	Minor, sometimes a problem in wet seasons
Bitter rot	*Glomerella cingulata* (Stonem.) Spauld. & Shrenk	Serious in some coastal warm, wet areas
Brook's disease	*Cylindrosporium pomi* C. Brooks	Rare, but troublesome in a few coastal orchards
Postharvest		
Blue mould	*Penicillium expansum* Link. and *Penicillium solitum* Westling	The major postharvest rot problems
Grey mould	*Botrytis cinerea* Pers.	Minor
Transit rot	*Rhizopus nigricans* Ehrenb.	Minor
Mucor rot	*Mucor piriformis* E. Fischer	Sometimes troublesome

Fungicides comprise the greater proportion of pesticides applied to apples (Bower et al., 1993) yet until recently almost all research on supervised pest and disease control for integrated pest management has addressed insecticides and insect problems. This has in part been due to less concerns over fungicides which are generally less acutely toxic than insecticides (Anonymous, 1983) but also because of the low economic thresholds of diseases in high value crops, such as apple scab. The short generation time and the large number of propagules produced by the apple scab fungus mean that an epidemic develops so quickly as to make the economic threshold, which is near zero, unworkable.

In this paper the avenues for reducing fungicide use in apples are reviewed and the impediments to the introduction of these techniques into commercial, market driven horticultural practice are examined. The emphasis is on apple production in Australia, but the comments are broadly applicable to other apple growing regions.

1.1. Apple diseases and their control

Apples grown in most geographic areas are attacked by a range of major and minor diseases (Table 1). The principal apple disease in Australia is apple scab, caused by *Venturia inaequalis* (Cke) Wint., which infects leaves, leading to a decline in tree vigour and, more importantly fruit, leading to disfigurement. Many commercial cultivars are susceptible to some degree (Aldwinkle, 1974), the major Australian cultivars ('Delicious', 'Granny Smith') being moderately to highly susceptible. Around 12 fungicide sprays are required to control this disease where springs are wet.

The second important disease is powdery mildew caused by the fungus *Podosphaera leucotricha* (Ell. and Ev.) Salmon. Powdery mildew causes russet on fruit, but since fruit is only susceptible for a few weeks after blossoming, the principal concern is leaf and shoot infection which causes tree debilitation. Fungicides are applied around flowering when young fruit are susceptible, but may be required later in the season when susceptible leaf tissue is produced. Some of the fungicides used for mildew control are specific mildewicides, but modern curative fungicides used for scab control also control mildew.

A number of so-called summer diseases (bitter rot, sooty blotch and flyspeck) (Table 1) are troublesome in areas where the summers are wet and warm. If specific control of summer diseases is required, it is usually accomplished using dithiocarbamate fungicides (Thwaite et al., 1993).

Surveys (Bower et al., 1993) have shown that the number of fungicide sprays applied varies widely from grower to grower even within the same district, although about eight to 12 sprays per season could be taken as typical in Australia.

2. The avenues for reduction in fungicide use in apples

The avenues to reduce fungicide use are examined under five broad areas: (1) epidemiological—a reduction in the number of conventional fungicide treatments applied, or in the dose rates of those fungicides based on epidemiological studies of the disease; (2) adoption of non-conventional chemical fungicides; (3) biological control by microorganisms; (4) disease-resistant varieties; (5) isolation, quarantine and a climate unfavourable for disease.

The key to reduction in fungicide use in apples for most areas is control of apple scab. This disease has the greatest potential for economic loss and consequently has been the basis of fungicide programs. Powdery mildew and, to a lesser extent, some of the other fungal diseases are controlled by the fungicides applied for scab. Summer diseases (bitter rot, sooty blotch and flyspeck) are of consideration in some areas, especially where summers are warm and humid.

2.1. Epidemiological

An understanding of the disease cycle, weather conditions favouring infection and sources of inoculum give potential leads for research on improved disease control, and perhaps some avenues for reduction of fungicide usage.

2.1.1. Post infection (curative) spraying based on weather and climate

W.D. Mills at Cornell in the 1940s (Mills, 1944) elucidated the infection requirements of surface wetness and temperature for apple scab infection and showed that apple scab has an infection period from infection to symptoms (and sporulation) of around 10–15 days, depending on temperature. With this knowledge and the availability of fungicides with curative action, it has become possible to control scab by application of fungicides after infection. This technique has been refined both in the infection model (MacHardy and Gadoury, 1989) and in the instrumentation used to detect when infection criteria have been met (Jones et al., 1980, 1984).

The applicability of this technique to reduce the number of fungicides applied will depend on the spring weather which is typical of the location. Successful reduction in sprays has been achieved in some areas (Zuck and MacHardy, 1981; Ellis et al., 1984). In Australia, initial work showed there were potential savings of sprays to be made in some seasons (Washington, 1980, 1981; Penrose et al., 1985) but a detailed analysis of the climatic parameters in two major Australian apple growing areas showed that infection periods requiring a curative treatment averaged less than 2 weeks apart (Penrose, 1992). Few sprays would be saved by adopting a purely curative approach to control (Penrose, 1989), since the protectant sprays are also applied at similar intervals. In seven field trials over four seasons, Beresford and Manktelow (1994) found apple scab incidence was consistently greater in treatments where fungicide use was reduced by timing sprays with weather information compared to standard calendar based treatments.

In Ohio, Funt et al. (1990) showed that curative spraying gave a saving of 26 sprays over 7 years, with a cost saving of \$62.84 ha^{-1} annually. In New Zealand, monitoring of infection periods could improve disease management through better timing of curative sprays but in some areas there was little scope to deviate from the standard program of 7–10 day application of protectant fungicides because the expected interval between infection periods is less than 7–10 days (Beresford et al., 1989).

The length of the infection period can also affect the applicability of the technique. Penrose (1992) found that the average length of the infection period was around 30 h in two major Australian apple districts. Assuming that the whole orchard could be sprayed within 24 h after the cessation of the infection period and the rain, a curative fungicide with over 2 days' kickback would be required. The extreme variation recorded in the length of the infection period (up to 103 h) means that even a curative fungicide with a 4 day kickback period may not be adequate to provide control in some seasons.

Using historical weather data for scab, rust and frog-eye leafspot simultaneously, Aurauz et al. (1990) found that in five out of ten seasons more applications were required when spraying curatively compared with a typical calendar based program. Reductions could only be achieved in dry location/year combinations. They point out that growers have to address more than one disease, and found in field tests that control of summer diseases, especially fruit rots, was poor with the curative program.

The physical problems brought about by prolonged weather unfavourable for spraying due to rain, wind, or waterlogged soil conditions making machinery access impossible, makes a curative approach risky. Further, the curative treatments available are mostly ergosterol biosynthesis inhibiting fungicides. Exclusive use of this type of chemical may lead to the development of resistance to the fungicides. The applicability of postinfection (curative) disease control is dependent on the climate. Only in areas experiencing relatively dry springs could diseases, especially apple scab, be reliably controlled with postinfection spraying. Although some savings might be made in some wetter areas in some seasons, prolonged wet periods could lead to failure in disease control.

2.1.2. Timing the start and finish of the spray program

Protectant fungicides can be saved by delaying the date of application of the first spray and ceasing spraying at the end of the primary infection period. MacHardy et al. (1993) found that, where the inoculum level present in the orchard was low, the release of significant numbers of ascospores was delayed and consequently the application of the first spray could be delayed without increase in disease levels. The period of delay was determined by the potential ascospore dose (Gadoury and MacHardy, 1986), which is a measure of disease carryover from the previous season. In many cases fungicide application could be delayed until the tight cluster to pink stage of fruit bud development. MacHardy and Gadoury (1985) developed a forecast model for maturation of ascospores of *Venturia inaequalis*. Using degree day accumulations, they were able to forecast the beginning and end of the primary infection period and suggest adapting fungicide strategies accordingly.

The spraying schedule can be terminated early in some situations with consequent reduction in fungicide use. If scab is difficult to find at the fruitlet stage, spraying can be discontinued (Dale et al., 1970). In trials in Australia over three seasons (Penrose and Dodds, 1994), scab did not significantly increase in orchards with low levels of scab ($<0.1\%$ fruit infection) at the end of the primary infection period, even though no sprays were applied up until harvest.

Very early season control of scab (Wilcox et al., 1992) by four applications of sterol demethylation inhibitor fungicides (at tight cluster, pink bud, petal fall and 10 days after petal fall) resulted in a saving of sprays compared with usual schedules. Success of this approach depended on low inoculum levels (fruit scab $< 1\%$ in the previous year) and the risk of development of resistance and the need for good coverage require consideration.

Commercial field experience with delaying the start of protective schedules and their early termination in relation to disease pressure (inoculum levels and weather) will determine if these techniques offer real scope for a reduced fungicide program.

2.1.3. Reduction in application rates

In South Australia, apple scab has been controlled adequately with as low as 25% of recommended fungicide rates in some seasons when applied in low volumes (100 l ha^{-1}) (Wicks and Nitschke, 1986). However, control was better in some seasons that others (Wicks and Granger, 1989). Similar results have been reported from the UK (Cross and Berrie, 1990), although it is suggested that commercial success with greatly reduced dose (and volume) rates (25% of recommended rate) requires careful orchard monitoring, coupled with a flexible management strategy to adjust the choice of pesticide, frequency of application and dose volume rate to suit prevailing conditions. The reduction in rates of fungicide approach is being adopted in The Netherlands (Shenk and Wertheim, 1992).

Reduction in application rates has been attempted recently in an IPM program in Batlow, Australia (Bower et al., 1993). The basis for this approach was that: (1) a reduction in rate, if unsuitable, may lead to an increase in disease but probably not total crop loss; (2) modern fungicides are highly efficient and recommended rates have a substantial safety factor built in; (3) disease levels in well managed orchards are currently low and therefore disease pressure is low; (4) the availability of curative fungicides means that to some degree treatment can be applied, and infection and sporulation reduced, after the event; (5) scab warning services being run in many apple growing areas give a good indication of the occurrence of infection conditions.

Fungicides were recommended to be applied at 80% of the recommended rate. No differences were found in scab levels between orchards where the 80% rate was used compared with control orchards (Bower et al., 1993). However, problems were encountered in gaining grower acceptance of reduced rates in some situations (Penrose and Bower, unpublished results, 1993).

It is common for higher field rates of fungicide to be recommended by manufacturers for situations where disease pressure is high. The corollary of this is that it may be possible to recommend lower dose rates where disease pressure is less. Inoculum reduction techniques as outlined below may permit the adoption of reduced rates if a relationship between inoculum levels, weather conditions and fungicide rates can be established.

2.1.4. Reducing disease inoculum carryover

Eradication of overwintering inoculum was seen as a way of reducing apple scab infection many years ago (Keitt and Palmiter, 1937). The commercial use of this technique became established in Australia when Hutton (1954a) showed scab could be eradicated using mercury compounds. Later work showed that urea was also effective (Burchill et al., 1965). Reduction in inoculum carryover, resulting in reduced disease pressure in the spring, permitted the number of sprays applied to be reduced (Burchill and Cook, 1975).

Fall treatments with benomyl (Penrose, 1970; Burchill, 1972) and ergosterol inhibiting fungicides (Gadoury et al., 1989) have been shown to be highly effective in reducing inoculum carryover but concern over potential fungicide resistance problems have limited their use.

The use of urea has remained in common use in Australia to reduce inoculum pressure after a season of high scab levels, but it also offers scope to reduce disease pressure in relatively clean orchards so that other techniques may be introduced.

Dormant season sprays with non-ionic surfactants were found to eradicate apple powdery mildew, (*P. leucotricha*) (Hislop et al., 1978). However, although the yield of fruit from most sprayed trees was greater than from controls, the best mildew eradicants did not produce the greatest yields, perhaps indicating phytotoxic effects. The technique does not appear to have been pursued in later years.

2.1.5. Past success with disease control

Past performance of control measures for sooty blotch and flyspeck has been used as a guide as to whether to spray for these diseases (Gold and Sutton, 1988). A decision analytic model was used to estimate, from disease levels in previous seasons, whether the proportion of fruit of fresh market grade was likely to be high enough to warrant the costs of sooty blotch and flyspeck control. The value of this information on past disease level in terms of saving sprays was found to be zero for orchards consistently producing high quality fruit but was \$180 ha^{-1} for orchards producing consistently low quality fruit. This technique appears to have little scope for determining control strategies for these diseases in orchards seeking premium quality fruit, but may be applicable for production aimed entirely at processing.

2.2. Non-conventional chemical fungicides

A range of plant extracts and other non-conventional compounds have been assessed for apple scab and powdery mildew control. Root extracts of *Rumex obtusifolium* significantly reduced powdery mildew infections under greenhouse conditions, but were less effective in the field (Bosshard et al., 1987). Extracts of ivy (*Hedera helix* L.) leaves inhibited conidial germination of *V. inaequalis* and showed preventative activity against scab and powdery mildew infection of apple seedlings (Bosshard, 1992).

Plant oils were effective in providing partial control of *P. leucotricha* when applied 1 day before or 1 day after inoculation, and emulsified canola oil was comparable to dinocap when applied up to 7 days after inoculation (Northover and Schneider, 1993). However, only slight prophylactic activity occurred against *V. inaequalis*. Mineral oil was found to enhance the efficacy of benomyl against a number of diseases. Control of apple scab with half the recommended rate of benomyl, plus superior oil, was found to be as effective as the full rate of fungicide alone (Gilpatrick and Smith, 1973; Zehr, 1974) but was associated with yield reduction in some varieties (Spotts et al., 1975).

Calcium hydroxide has recently been shown to control apple scab (Wong et al., 1993) and pear scab (*V. pirina*) (Washington and Appleby, 1993) in the field in Australia. Work by the author (Penrose and Dray, unpublished, 1994) suggests that about 95% control may be achieved in the field, but Wong et al. (1993) point out that the effectiveness of calcium hydroxide treatments is inversely dependent on the disease pressure.

Another avenue for the use of alternative chemicals for disease control is to revert to materials which have been surpassed in the past 40 years but are acceptable to organic fruit production. These compounds include sulphur and copper (as 'Bordeaux mixture'). Lime sulphur was the standard fungicide for apple scab control in New South Wales from about 1910 (Anonymous, 1951) until the advent of the dithiocarbamate fungicide thiram (Hutton, 1954b). Early work on these materials indicates low efficacy of disease control and problems with phytotoxicity. Research at that time largely attempted to balance the rate required for efficacy against acceptable phytotoxicity levels (Parry Brown, 1940).

In the postharvest situation Hendrix (1991) removed sooty blotch and flyspeck symptoms using chlorine dips. The technique is seen as a means of overcoming poor control of these diseases using integrated pest management techniques for apple production. It may be possible to reduce the need for postharvest fungicide treaments for rot control by enhancing the calcium content of apple fruit (Conway et al., 1992) or by storage in atmospheres supplemented with carbon monoxide (El Goorani and Sommer, 1979).

None of the non-conventional fungicides has achieved widespread use in current apple growing, principally because of an efficacy level which is less that that which has come to be expected from modern fungicides. The acceptance of infection levels of 5–10% infected fruit, especially associated with organic fruit production, could provide a role for these compounds.

2.3. Biological control of diseases by microorganisms

Biological control of apple disease has been investigated for apple scab, powdery mildew and post harvest diseases. *Chaetomium* spp. were found to reduce scab and powdery mildew infections on apple seedlings in some experiments by Bosshard et al. (1987). They also found that primary infections of *P. leucotricha* were severely parasitised by *Ampelomyces quisqualis*, but the delayed spread of this hyperparasite reduced its efficacy in controlling infections.

Control of *V. inaequalis* in the saprophytic stage by a basidiomycete has been demonstrated. Ascospore production of *V. inaequalis* was prevented when naturally infected leaves were inoculated in the fall with *Athelia bombacina* Pers. (Heye and Andrews, 1983). In later experiments (Young and Andrews, 1990) the fungus was found to spread only slowly and not across 1 cm gaps between leaves. Thus, to achieve good colonization, inoculum would have to be applied extensively to leaves. Because of a lack of survival over the summer, the fungus would need to be applied annually. The role of this fungus in commercial disease control does not seem to have been elucidated.

Control of crown and root rot of apple trees caused by *Phytophthora cactorum* was achieved using *Enterobacter aerogenes* in conjunction with the fungicide metalaxyl (Utkhede, 1987). The use of the bacterium was seen as a means of delaying the development of resistance to the fungicide and providing a practical approach to control the disease.

Biological control of postharvest diseases of pomefruit has been found effective in small scale trials in Australia (Anonymous, 1993). Postharvest control of *Penicillium* sp. and *Botrytis* sp. in apples has been obtained elsewhere with yeasts and bacteria (Janisiewicz, 1987, 1988; Janisiewicz and Roitman, 1988). Promising work with apples and other crops (Jeffries and Jeger, 1990) suggests that a commercial application may be possible in the future.

Jeffries and Jeger (1990) point out that some biocontrol agents work via nutrient competition, and others through production of antibiotics. Consequently, the production of antibiotics may well need the same sort of toxicological and environmental testing as any conventional agrochemical.

2.4. Disease resistant varieties

The situation with scab resistant apple varieties has recently been reviewed. (Merwin et al., 1994). A number of resistant varieties have been available for sometime, but it is only the more recently bred varieties (e.g. 'Liberty', 'Goldrush', 'Enterprise') that are likely to achieve commercialization. However, Merwin et al. (1994) point out that the saving in fungicide costs by using scab resistant varieties only represents 3% of the crop value and could easily be offset by differences in productivity or market prices. The susceptibility of some of these varieties to summer diseases (Warner, 1991) may also be a problem in some areas or seasons when fungicide treatments are reduced. They suggest that the relative strengths and weaknesses of these varieties will need to be evaluated to facilitate their acceptance by growers and the general public. The discovery of a new race of *V. inaequalis* (Race 6) which overcomes the *Vf* resistance gene (Parisi et al., 1993) present in many of the scab resistant cultivars may limit the geographical usefulness of these cultivars.

2.5. *Isolation, quarantine and a climate unfavourable for disease*

The advantages of isolation, choice of geographical location and prevention of entry of diseases should not be overlooked when considering pesticide reduction. Western Australia, because of its isolation, has been free of apple scab until recently. Strict quarantine has maintained this position for the past century or more, with few outbreaks. Scab was detected several times from 1930 to 1947 and eradicated (Cass Smith et al., 1948). Scab was detected again in 1990, and is the subject of a vigorous eradication campaign. Producing apples in an area free of scab will require only very minimal amounts of fungicide to be used for other diseases, such as powdery mildew. Selection of a location for apple growing with a dry climate during the spring and summer offers scope for reduction in fungicide use, provided other agronomic requirements for winter chilling and irrigation can be met.

3. Application to current commercial horticultural practice

For mainstream horticulture, the most likely chance of successful adoption of practices to reduce fungicide usage probably lies with manipulation of current practices using conventional fungicides. This approach has several advantages. Any slight shift in current practice is more likely to be acceptable to commercial growers than a radical change to totally different materials or concepts. Growers are not keen to give up what may work in exchange for something which may or may not (McDonald and Glynn, 1994). A conservative approach, adopting a stepwise reduction in fungicide rate or in program timing in conjunction with measurement of disease pressure, for example, is unlikely to result in major losses if the strategy should fail. The properties and limitations of the fungicides are well understood and the influence of weather and season appreciated. No radical change in varieties with the associated lag time in production is required. Manipulations of current practices can be quickly introduced.

The adoption of non-conventional chemicals as a part of a conventional fungicide program holds promise, but extensive research will be required, not only on efficacy, but also on toxicology, integration into other pest and disease practices and environmental effects.

The niche for biological control seems to be in the postharvest situation, since the problems of establishment of competitors and hyperparasites in the field before the disease causes fruit damage precludes their use in the near future as part of a regular field program. The selection of fungicide tolerant competitors or hyperparasites which would tilt control in favour of reduced rates of fungicides may be an option. The use of biocontrol agents in postharvest situations is favoured by the potential to control the treatment conditions and may be available in the near future.

The role of disease resistant varieties of apples at the moment seems to be limited in main stream orchards since there are problems with changing consumer attitudes to known varieties (Merwin et al., 1994). However, there must be considerable scope for niche markets where these varieties can be promoted because of the requirement to use less fungicide. Their susceptibility to summer diseases may preclude their production with a total absence of fungicides (Merwin et al., 1994).

4. Integration of reduced fungicide techniques and measurement of fungicide usage

As Stoner et al. (1986) point out, for integrated pest management programs (and pesticide reduction) to be adopted, biological knowledge is not enough. The context in which these programs operate must be understood. Reduction of pesticide use for some pests and diseases of apple not subject to high risk (e.g. powdery mildew) is quite feasible whilst pesticide reduction for those problems which require almost 100 percent control (e.g. apple scab) are extremely difficult to achieve (Wearing, 1982).

Although the goal of reducing pesticide usage is widely accepted, there has been little effort to differentiate between pesticides when establishing goals or measuring the success of reduction strategies.

The method of measuring fungicide reduction may mask the true facts. The success of a reduction strategy

Table 2
Costs (Australian \$) of disease control in relation to total costs for apple production (cultivar 'Red Delicious') in New South Wales (adapted from Gordon and Walker, 1991)

Total variable costs				\$25552
Total pesticide costs				\$1099
Fungicides (cost ha^{-1} of program)				
Ziram × 5	3.36 kg ha^{-1}	@\$0.76 per 100 l	\$106	
Penconazole × 4	0.56 l ha^{-1}	@\$1.67 per 100 l	\$187	
Copper × 1	11.2 kg ha^{-1}	@\$0.93 per 100 l	\$26	
			\$319	
Fungicide costs as percentage of variable costs				1.2%
Cost savings of reduction in sprays per ha				
1 Ziram			\$21	
1 Penconazole			\$47	

could be measured in reduced number of sprays, or reduction of total weight of fungicide applied. Both have their problems and do not necessarily reflect the desired aim of less impact on the environment. There is an implied assumption in these approaches that pesticides are similar in terms of their toxicity and ecological impact and that there is uniformity across an industry in terms of number of applications and quantity of pesticide applied by the individual growers which comprise the industry. It is, however, likely that the amount of pesticide used and the choice of pesticide will vary with pest or disease pressure, which is in turn a function of weather, location, inoculum levels and plant susceptibility. But also, because of the variability of acceptance of risk, the amount of pesticide also varies between growers with similar pest and disease pressures within the same district (Penrose et al., 1994b). These issues have been addressed by the formulation of an index (Penrose et al., 1994a) in which the properties of a pesticide are rated so that an overall comparison of the pesticide can be made and by the extension of this technique to an accreditation scheme for fruit produced under an integrated pest and disease management scheme.

4.1. The economics of fungicide use reduction

Cost savings are often mentioned as a benefit of pesticide use reduction programs. However, in economic terms the costs of pest and disease control represent only a small proportion of the costs of production. The low cost of chemical control as a percentage of total production costs is a major obstacle for reduction in pesticide use in tree fruits (Wearing, 1988). For apple growing in Australia, the cost of all pesticides and fertilizers represents only 7.5% of the variable cost of production, compared with handling (grading, packing, cool storage) of 45%, marketing (freight, porterage, levies) of 25%, harvesting 11.7%, and other costs (thinning, pruning, etc.) of 7.5% (Gordon and Walker, 1991). Fungicides represent less than one quarter of the chemical costs (Table 2). In New Zealand fungicide costs represent about 8% of total production costs (Beresford and Manktelow, 1994).

The requirements of the market for blemish-free produce is the second major impediment to reduction in pesticide usage. If there is no shortage of supply to a competitive market the requirement for virtually blemish-free produce seems inevitable (Fenemore and Norton, 1985). The price differential between grades means that farmers must ensure the highest proportion of their produce is in the top category (Corbet, 1981). It seems unlikely that consumer attitudes to the overall appearance of fruit will change in the near future. Beresford and Manktelow (1994) found in New Zealand that, when savings from reduced fungicide use (by timing sprays with weather information) were weighed against the increased harvesting and grading costs and revenue losses from increased disease, there is little economic incentive for apple growers to reduce fungicide use. The effect on gross returns of a reduction in the proportion of fruit packed to No. 1 grade is shown

Table 3
Effects of downgrading of apples (cultivar 'Red Delicious') from No. 1 grade to No. 2 grade, on gross returns (Australian $) per ha in New South Wales (adapted from Gordon and Walker, 1991)

Proportion (%) of each grade			Returns per ha ($)	Loss per ha ($)
No. 1	No. 2	Juice		
70	14	16	48664	0
69	15	16	48168	496
68	16	16	47672	992
67	17	16	46680	1488
66	18	16	46184	1984

Assumptions
Yield: 3000 bushels ha^{-1}.
Price: No. 1 grade $21.81 per bushel.
No. 2 grade $5.25 per bushel.
Juice grade $1.37 per bushel.

in Table 3 for Australia. Each 1% downgrading of fruit from No. 1 to No. 2 grade represents a loss of $A 496 ha^{-1}. Southwood (1979) in the UK also pointed out the large economic penalities associated with lower grading of apples.

However, economic models may not adequately explain farmers' behaviour (Mumford and Norton, 1984). Profit maximization is unlikely to be the main goal of decision making and it is more likely that farmers will look for a satisfactory rather than an optimal outcome (Norton and Mumford, 1982). Risk is probably the most important financial obstacle to IPM adoption by growers (Zalom, 1993).

4.2. Sociological considerations

In most cases farmers are risk averse and attempt to reduce variability as much as possible (Norton, 1976). Mumford (1977) points out that it is the farmer's perception of pest hazard and not the actual level of attack which could occur that cause him to apply an insecticide and farmers tend to be more risk averse if they have a larger investment in the crop (Tait, 1978). Using economic threshold models instead of prophylactic approaches requires more knowledge and effort (Corbet, 1981) and is more risky. Because farmers are required to make many managerial decisions it is likely that they will adopt 'standard operating procedures' (Mumford and Norton, 1984) to minimize decision making and the possibility of making a mistake. To some degree this impediment may be overcome by the use of a commercial consultant; however, Norgaard (1976) reported a tentative finding that farmers who use pest management consultants perceive greater risks of pest management and are more risk averse than those who do not use consultants. There is also the problem of risk aversion amongst advisers (Tait, 1978) who must retain their credibility with their clients. A recommendation not to apply a pesticide carries a greater risk than recommending an additional spray which may not be required.

Webster (1987) points out that farmers act in their own perceived interests, which may or may not coincide with those farmers' interests as perceived by outsiders. From a social perspective, the need to be seen as a good farmer amongst his neighbours mitigates against accepting higher levels of pest and disease, and an association was found to exist between good conscientious farming and a higher pesticide usage (Norton, 1976).

Penrose and Bower (unpublished, 1993), along with Tait (1977) found that some farmers consistently used more, and others less, pesticides than the average. A feature which emerged from surveys undertaken in New South Wales was the variation in the number of fungicides applied by different growers (Bower et al., 1993) where the total number of fungicides applied varied by over 200%. It is in this area, of the variation between individual orchardists and its relationship to disease control, that significant gains could be made in fungicide use reduction across the apple industry generally.

5. Conclusion

Why have so few of the potential avenues for fungicide use reduction in apples become part of commercial apple production? Whilst the biological information is available in a number of different areas, the adoption of such strategies is dependent on the grower seeing some personal benefit. At the moment, the adoption of fungicide reduction strategies is not without either risk or cost. It does not seem possible to alter current practice without either a reduction in quality or an increase in the risk of failure of pest and disease control. Who is to bear this risk of financial loss? Whilst consumers continue to demand perfect fruit and vegetables, and government regulations enacted over the years to meet community demands prohibit the sale of produce with, in some cases, only superficial blemishes, the grower is left to decide on a disease control strategy which is both environmentally responsible and economically viable. Adoption of reduced pesticide growing systems in a free market system will be driven by that produce receiving a price premium in the market. Fenemore and Norton (1985) found that the main advantages of introducing supervised insect pest control in English apples are environmental and social. In Australia a similar situation exists. The gains from pesticide use reduction are largely public and of benefit to consumers, whilst the risks of loss are private and that of the farmer. Unless farmers can gain a price advantage for fruit produced with less pesticide, over that received by other farmers, there is little incentive to reduce pesticide use. The successful implementation of pesticide reduction strategies will depend on the reduction of the risks of the strategy. Since pest and disease problems vary with weather and climate, implementation of reduction strategies will be more widely adopted in some localities than others. The marketing of fruit produced with less pesticide under a distinctive label, as occurs in parts of Europe, may provide the financial impetus to encourage reduced pesticide use, at least in the short term.

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References

Anonymous, 1951. Lime sulphur for control of black spot in apples and pears. Agric. Gaz., 62: 371–373.

Anonymous, 1983. Poisoning by Pesticides. Division of Occupational Health, Department of Industrial Relations, Sydney.

Anonymous, 1991. Towards a national food policy. In: Pesticides Charter. National Working Group on Food Policy, Australian Consumers' Association, Sydney, p. 21.

Anonymous, 1993. Biological solutions for post-harvest rots. Apple and Pear News No. 28, March 1993. Australian Apple and Pear Growers Association, Melbourne.

Aldwinkle, H.S., 1974. Field susceptibility of 51 apple cultivars to apple scab and powdery mildew. Plant Dis. Rep., 58: 625–629.

Aurauz, L.F., Sutton, T.B. and Pope, L.R., 1990. Simultaneous use of infection criteria for three apple diseases for timing of fungicide sprays. Phytopathology, 80: 1212–1218.

Beresford, R.M. and Manktelow, D.W.L., 1994. Economics of reducing fungicide use by weather-based forecasts for control of *Venturia inaequalis* in apples. N. Z. J. Crop Hortic. Sci., 22: 113–120.

Beresford, R.M., Salinger, M.J., Bruce, P.E. and Brook, P.J., 1989. Frequency of infection periods for *Venturia inaequalis* in New Zealand and implications for fungicide use. Proceedings 42nd New Zealand Weed and Pest Control Conference. N.Z. Weed and Pest Control Society, Palmerston North, pp. 159–164.

Bosshard, E., 1992. Effects of ivy (*Hedera helix*) leaf extract against apple scab and mildew. Acta Phytopathol. Entomol. Hung., 27: 135–140.

Bosshard, E., Schuepp, H. and Siegfried, W., 1987. Concepts and methods in biological control of diseases in apple orchards. Bull. OEPP/EPPO, 17: 655–653.

Bower, C.C., Penrose, L.J. and Dodds, K., 1993. A practical approach to pesticide reduction on apple crops using supervised pest and disease control—preliminary results and problems. Plant Prot. Q., 8: 57–62.

Burchill, R.T., 1972. Comparison of fungicides for suppressing ascospore production by *Venturia inaequalis* (Cke.) Wint. Plant Pathol., 21: 19–22.

Burchill, R.T. and Cook, M.E., 1975. The control of scab and powdery mildew of apple with a reduced number of sprays. Plant Pathol., 24: 194–198.

Burchill, R.T., Hutton, K.E. and Grosse, J.E., 1965. Inhibition of the perfect stage of *Venturia inaequalis* (Cooke) Wint. by urea. Nature, 205: 520–521.

Cass Smith, W.P., Harvey, H.L. and Goss, O., 1948. Apple scab outbreaks season 1947–48, with special reference to the introduction of the disease by infected buds on imported nursery stock. J. Dep. Agric. West. Aust., 25 (Second Series): 129–135.

Conway, W.S., Sams, C.E., McGuire, R.G. and Kelman, A., 1992. Calcium treatment of apples and potatoes to reduce post harvest decay. Plant Dis., 76: 329–334.

Corbet, P.S., 1981. Non-entomological impediments to the adoption of integrated pest management. Prot. Ecol., 31: 183–202.

Cross, J.V. and Berrie, A.M., 1990. Efficacy of reduced volume and reduced dose rate programmes in apple orchards. Crop Prot., 9: 207–217.

Dale, W.T., Knight, B.C. and Croxall, H.E., 1970. Effect of starting date and number of sprays on apple scab control. Plant Pathol., 19: 51–59.

El-Goorani, M.A. and Sommer, N.F., 1979. Supression of postharvest plant pathogenic fungi by carbon monoxide. Phytopathology, 69: 834–838.

Ellis, M.A., Madden, L.V. and Wilson, L.L., 1984. Evaluation of an electronic apple scab predictor for scheduling fungicides with curative activity. Plant Dis., 68: 1055–1057.

Evans, G. and Rowland, P., 1993. Improving the efficiency of pesticide use in Sweden, Denmark and the Netherlands. Agric. Sci., 6: 46–48.

Fenemore, P.G. and Norton, G.A., 1985. Problems of implementing improvements in pest control: a case study of apples in the UK. Crop Prot., 4: 51–70.

Funt, R.C., Ellis, M.A. and Madden, L.V., 1990. Economic analysis of protectant and disease-forecast-based fungicide spray programs for control of apple scab and grape black rot in Ohio. Plant Dis., 76: 638–642.

Gadoury, D.M. and MacHardy, W.E., 1986. Forecasting ascospore dose of *Venturia inaequalis* in commercial apple orchards. Phytopathology, 76: 112–118.

Gadoury, D.M., MacHardy, W.E. and Rosenberger, D.A., 1989. Integration of pesticide application schedules for disease and insect control in apple orchards of the northeastern United States. Plant Dis., 73: 98–105.

Gilpatrick, J.D. and Smith, C.A., 1973. Fungicide and Nematicide Tests—Results of 1972. Am. Phytopathol. Soc. Monogr., 28: 16–17.

Gold, H.J. and Sutton, T.B., 1988. Past orchard performance as a guide to decisions on the use of fungicides to control sooty blotch and flyspeck. Crop Prot., 7: 258–266.

Gordon, R. and Walker, S., 1991. Economic issues of apple production—Batlow and District. NSW Agriculture, Murray and Riverina Regions, 43 pp.

Hendrix, F.F., 1991. Removal of sooty blotch and flyspeck from apple fruit with a chlorine dip. Plant Dis., 75: 742–743.

Heye, C.C. and Andrews, J.H., 1983. Antagonism of *Athelia bombacina* and *Chaetomium globosum* to the apple scab pathogen *Venturia inaequalis*. Phytopathology, 73: 650–654.

Hislop, E.C., Clifford, D.R., Holgate, M.E. and Gendle, P., 1978. Eradication of apple powdery mildew (*Podosphaera leucotricha*) with dormant-season sprays of surface-active agents. Pest. Sci., 9: 12–21.

Hutton, K.E., 1954a. Eradication of *Venturia inaequalis* Cooke Wint. Nature, 174: 1017.

Hutton, K.E., 1954b. Control of black spot of apples and pears. Observations on the use of thiram. Agric. Gaz., 65: 161–162.

Janisiewicz, W.J., 1987. Postharvest biological control of blue mould on apples. Phytopathology, 77: 481–485.

Janisiewicz, W.J., 1988. Biocontrol of post harvest diseases of apples with antagonistic mixtures. Phytopathology, 78: 194–198.

Janisiewicz, W.J. and Roitman, J., 1988. Biological control of blue mould and gray mould on apple and pear with *Pseudomonas cepacia*. Phytopathology, 78: 1697–1700.

Jeffries, P. and Jeger, M.J., 1990. The biological control of post harvest diseases of fruit. Biocontrol News Inform., 11: 333–336.

Jones, A.L., Lillevik, S.L., Fisher, P.D. and Stebbins, T.C., 1980. A microcomputer-based instrument to predict primary apple scab infection periods. Plant Dis., 64: 69–72.

Jones, A.L., Fisher, P.D., Seem, R.C., Kroon, J.C. and van de Motter, P.J., 1984. Development and commercialization of an in-field microcomputer delivery system for weather-driven predictive models. Plant Dis., 68: 458–463.

Keitt, G.W. and Palmiter, D.H., 1937. Potentialities of eradicant fungicides for combating apple scab and some other plant diseases. J. Agric. Res., 55: 397–438.

MacHardy, W.E. and Gadoury, D.M., 1985. Forecasting the seasonal maturation of ascospores of *Venturia inaequalis*. Phytopathology, 75: 381–385.

MacHardy, W.E. and Gadoury, D.M., 1989. A revision of Mills's criteria for predicting apple scab infection periods. Phytopathology, 79: 304–310.

MacHardy, W.E., Gadoury, D.M. and Rosenberger, D.A., 1993. Delaying the onset of fungicide programs for apple scab in orchards with low potential ascospore dose of *Venturia inaequalis*. Plant Dis., 77: 372–375.

McDonald, D.G. and Glynn, C.J., 1994. Difficulties in measuring adoption of apple IPM: a case study. Agric. Ecosyst. Environ., 48: 219–230.

Merwin, I.A., Brown, S.K., Rosenberger, D.A., Cooley, D.R. and Berkett, L.P., 1994. Scab-resistant apples for the Northeastern United States: new prospects and old problems. Plant Dis., 78: 4–10.

Mills, W.D., 1944. Efficient use of sulphur dusts and sprays during rain to control apple scab. Cornell Ext. Bull. No. 630.

Mumford, J.D., 1977. Farmer attitudes towards control of aphids on sugar beet. Proceedings 1977 British Crop Protection Conference—Pest and Diseases. British Crop Protection Council, Vol. 1. pp. 263–270.

Mumford, J.D. and Norton, G.A., 1984. Economics of decision making in pest management. Annu. Rev. Entomol., 29: 157–174.

Norgaard, R.B., 1976. The economics of improving pesticide use. Annu. Rev. Entomol., 21: 45–60.

Northover, J. and Schneider, K.E., 1993. Activity of plant oils on diseases caused by *Podosphaera leucotricha*, *Venturia inaequalis*, and *Albugo occidentalis*. Plant Dis., 77: 152–157.

Norton, G.A., 1976. Pest control decision making—an overview. Ann. Appl. Biol., 84: 444–447.

Norton, G.A. and Mumford, J.D., 1982. Information gaps in pest management. Proceedings International Conference Plant Protection in Tropics, pp. 589–597.

Parisi, L., Lespinasse, Y., Guillaumes, J. and Kurger, J., 1993. A new race of *Venturia inaequalis* virulent to apples with resistance due to the *Vf* gene. Phytopathology, 83: 533–537.

Parry Brown, H., 1940. Weaker lime sulphur sprays for black spot of apples and pears. Agric. Gaz., 51: 509–512.

Penrose, L.J., 1970. Prevention of formation of ascospores of *Venturia inaequalis* Cke. Wint. by benomyl. Aust. J. Sci., 32: 476–477.

Penrose, L.J., 1989. A rational approach to apple scab control—the role of disease warning systems and curative spraying. Plant Prot. Q., 4: 115–118.

Penrose, L.J., 1992. The significance of selection of infection model and climatic parameters on the operation and benefits of a primary apple scab warning service. Plant Prot. Q., 7: 12–16.

Penrose, L.J. and Dodds, K.A., 1994. Incidence of *Venturia inaequalis* on apple fruit during the second half of the season under different fungicide and weather regimes. N. Z. J. Crop Hortic. Sci., 22: 251–261.

Penrose, L.J., Heaton, J.B., Washington, W.S. and Wicks, T., 1985. Australian evaluation of an orchard based electronic device to predict primary apple scab infections. J. Aust. Inst. Agric. Sci., 51: 74–78.

Penrose, L.J., Thwaite, W.G. and Bower, C.C., 1994a. Rating index as a basis for decision making on pesticide use reduction and for

accreditation of fruit produced under integrated pest management. Crop Prot., 13: 146–152.
Penrose, L.J., Thwaite, W.G. and Bower, C.C., 1994b. Pesticide use reduction—logical decision making. Proceedings 47th New Zealand Plant Protection Conference, pp. 397–400.
Shenk, A.M.E. and Wertheim, S.J., 1992. Components and systems research for integrated fruit production. Neth. J. Agric. Sci., 40: 257–268.
Southwood, T.R.E., 1979. Pesticide usage: prodigal or precise. Proceedings of the 10th British Crop Protection Council Conference—Pests and Diseases, Vol. 3. British Crop Protection Council Publications, pp. 603–619.
Spotts, R.A., Hall, F.R., Ferree, D.C. and Jones, B.M., 1975. Yield reduction in apples related to benomyl-oil spray applications. Plant Dis. Rep., 59: 541–543.
Stoner, K.A., Sawyer, A.J. and Shelton, A.M., 1986. Constraints to the implementation of IPM programs in the USA: a course outline. Agric. Ecosyst. Environ., 17: 253–268.
Tait, E.J., 1977. A method for comparing pesticide use patterns between farmers. Ann. Appl. Biol., 86: 229–240.
Tait, E.J., 1978. Factors affecting the usage of insecticides and fungicides on fruit and vegetable crops in Great Britain. II. Farmer-specific factors. J. Environ. Manage., 6: 143–151.
Thwaite, W.G., Withey, R.K., Penrose, L.J. and Gordon, R., 1993. Orchard and Vineyard Plant Protection Guide for Inland New South Wales, 3rd edn. NSW Agriculture, Orange, Australia, 108 pp.
Utkhede, R.S., 1987. Chemical and biological control of crown and root rot of apple caused by *Phytophthora cactorum*. Can. J. Plant Pathol., 9: 295–300.
Warner, J., 1991. Field susceptibility of scab-resistant apple cultivars and selections to frogeye leaf spot. Can. Plant Dis. Surv., 71: 165–167.
Washington, W.S., 1980. Scab and powdery mildew control with fungicides applied after scab infection periods, 1979. Fungicide and Nematicide Tests. Am. Phytopathol. Soc. Monogr., 36:40.
Washington, W.S., 1981. Scab control with fungicides applied after infection periods. Fungicide and Nematicide Tests. Am. Phytopathol. Soc. Monogr., 37:34.
Washington, W.S. and Appleby, M., 1993. Calcium hydroxide for the control of pear scab. 9th Biennial Conference, Australasian Plant Pathology Society, Hobart, 1993, abstract 23.
Wearing, C.H., 1982. Integrated pest management—progress and prospects with special reference to horticulture. N. Z. J. Exp. Agric., 10: 87–94.
Wearing, C.H., 1988. Evaluating the IPM implementation process. Annu. Rev. Entomol., 33: 17–38.
Webster, J.P.G., 1987. Decision theory and the economics of crop protection measures. In: K.J. Brent and R.K. Atkin (Editors), Rational Pesticide Use—Proceedings 9th Long Ashton Symposium 1987. Cambridge University Press, Cambridge, pp. 211–223.
Wicks, T.J. and Granger, A.R., 1989. Effects of low rates of pesticides on the control of pests and diseases of apples. Aust. J. Exp. Agric., 29: 439–444.
Wicks, T.J. and Nitschke, L.F., 1986. Control of apple diseases and pests with low spray volumes and reduced chemical rates. Crop Prot., 5: 283–287.
Wilcox, W.F., Wasson, D.I. and Kovach, J., 1992. Development and evaluation of an integrated, reduced-spray program using sterol demethylation inhibitor fungicides for control of primary apple scab. Plant Dis., 76: 669–677.
Wong, J.A.L., O'Loughlin, J., Schupp, J.K. and Williams, W., 1993. High pH on leaf and fruit surfaces as a control strategy for apple scab. 9th Biennial Conference, Australasian Plant Pathology Society, Hobart, 1993, abstract 22.
Young, C.S. and Andrews, J.H., 1990. Recovery of *Athelia bombacina* from apple litter. Phytopathology, 80: 530–535.
Zalom, F.G., 1993. Re-organizing to facilitate the development and use of integrated pest management. Agric., Ecosyst. Environ., 46: 245–256.
Zehr, E.I., 1974. Fungicide and nematicide tests—results of 1973. Am. Phytopathol. Soc. Monogr., 29: 29.
Zuck, M.G. and MacHardy, W.E., 1981. Recent experience in timing sprays for control of apple scab: equipment and test results. Plant Dis., 65: 995–998.