The economics of fungicide use in winter wheat in southern Sweden

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Abstract

In southern Sweden, fungicide treatment of winter wheat is prevalent and recommended almost routinely against leaf blotch diseases. However, yield increases and hence the resulting net returns from fungicide use are highly variable within and between years. These variations raise questions about whether, when and how fungicides should be used. To help answer these questions, a thorough economic evaluation of fungicide use was carried out, based on results from untreated plots and fungicide-treated plots in trials in farmers' fields, 1983-2007. Scenarios with varying grain prices and costs of fungicide treatment were evaluated and examined. Doubling and tripling the grain price led to the largest impact on the net return from fungicide treatment, followed by increasing cost of the fungicide. Other costs were of minor importance. The mean net return from fungicide use was no more than 12 € ha^{-1} over the 25 years (2008 grain prices and costs used in calculations). Furthermore, the mean net return was negative in 10 years and less than 50% of the entries were profitable to treat in 11 years. Changes over time and changes in controllable factors (e.g. fungicide and cultivar choice, crop rotation, techniques) and uncontrollable factors (e.g. emerging and new diseases, price relations) influenced the profitability of fungicide use. Fungicide use was in fact more profitable (mean net return 21 compared with 3 € ha^{-1}) during the latter part of the period (1995-2007) than in the earlier part (1983-1994). Improved decision support systems in a holistic framework based on sound economics are urgently needed.

Keywords: plant disease, net-return, profitability, integrated pest management, *Septoria tritici*.

1. Introduction

Many important diseases of winter wheat such as Leaf Blotch Diseases (LBDs, including Septoria tritici blotch – the major leaf blotch disease in Sweden, Stagonospora nodorum blotch and tan spot), powdery mildew, brown rust and yellow rust are effectively controlled by fungicides and fungicide use has therefore been a standard procedure in many countries for decades (Cook and Jenkins, 1988; Wiik, 2009). In southern Sweden (Scania), fungicides are used by most farmers in winter wheat, especially against LBDs. According to actual official recommendations: 'With present grain prices fungicide input is most often profitable in the southern and central Sweden, but the optimal dose strongly fluctuates due to differences in disease intensity between years.' (SCB/SJV, 2008; SJV, 2008).

In their review on the economic basis for protection against plant diseases, Ordish and Dufour (1969) declared the economics of diseases to be a somewhat neglected theme. Some years later Carlson and Main (1976) found economic models of biological systems to be too simple compared with the complex nature of such systems. Since then, the economic importance of plant diseases and the net return from control measures have been estimated now and then, (Cook and King, 1984; Zadoks, 1984; Cook and Jenkins, 1988; Priestley and Bayles, 1988; Cooper and Dobson, 2007; Fabre *et al*., 2007). However, in our opinion the subject has still not been studied sufficiently to provide a good base for limitation and optimisation of control measures. Sundell (1980) made a rough estimate of crop losses in agricultural crops in Sweden during the late 1970s and evaluated the possibilities of reducing these losses and the economic consequences of different restrictions. He found host plant resistance to be the most profitable measure in the controlling of a number of fungal diseases, but he also found a considerable short-term potential for increased use of fungicides and a marked increase in net production costs when the use of pesticides was stopped. In a later evaluation by the Royal Swedish Academy of Agriculture and Forestry, the economic losses caused by total omission of fungicides and a 50% decrease of herbicides in cereals was estimated at 77 € ha^{-1} (KSLA, 1989). More specifically, in winter wheat Wiik (1991) found fungicide treatment to be decreasingly profitable at increasing cost levels (calculated in dt grain ha^{-1}); 81% at cost level 1 dt ha^{-1} and 33% at cost level 6 dt ha^{-1} for 167 field trials in southern Sweden, and 68% and 13% respectively for 96 field trials in central Sweden.

The profitability of fungicide use in field trials carried out during 1983-2007 in southern Sweden was evaluated in a more thorough economic analysis than usual, supplemented with scenarios with different grain prices and fungicide treatment costs expected to be relevant in future assessments. The aim of the evaluation was to highlight economic considerations in wheat production and to examine the profitability of a single fungicide treatment at GS 45-61 in winter wheat.

2. Materials and methods

2.1. Field trials

Data from 446 field trials on winter wheat carried out in 1983-2007 in southern Sweden were used (for details of fungicides, dates etc. see Wiik, 2009; Wiik and Ewaldz, 2009). Yields measured as dt ha^{-1} (dt = metric deciton = 100 kg) at 15% water content in untreated and fungicide-treated plots were used in the economic analyses. We chose to evaluate a single fungicide treatment just before and during heading because it had given the greatest yield increase in studies on treatment strategies performed by Wiik (2009). In the fungicide-treated plots a single fungicide treatment was applied in growth stages (GS) 45-61, i.e. from boots swollen to beginning of anthesis of a crop stand according to the description of the principal and secondary growth stages (00-99) by Tottman and Broad (1987). Hectolitre weight (HLW, g/L), grain protein content (%) and Hagberg falling number (s) for untreated and fungicide-treated plots were not used in the evaluation of the data but are considered in the discussion. The field trials were carried out on farms using different cultivars and agricultural practices, e.g. fertiliser dose. All interventions except fungicide treatment were carried out by farmers. The field trials, which comprised four replicates, were carried out by staff at the Rural Economy and Agricultural Societies according to a precise protocol that included instructions on choice of field (level surface, representative of the region), choice of fungicides (most used on the market broad spectrum such as morpholines, azoles and strobilurins), timing of treatment (GS 45-61), dose (normal recommended), spraying technique (best available), harvesting etc. During 1983-1994 and 2006-2007, each entry (N, see Tables 2, 4 and 5) represents one experimental treatment in a field trial. During 1995-2005 more than one entry or experimental treatment was taken at times from a field trial, e.g. if a single fungicide treatment was tested on more than one cultivar or if there were different nitrogen levels in the same field trial. Mean is usually given as mean of years, but in some cases also as mean of entries (Tables 3 and 6). Results from the latter period are based on more entries than the earlier period.

2.2. Study site

The county of Scania (55°23’-56°25’N, 12°50’-14°31’E) is the southernmost part of Sweden. Scania is a lowland area with more than 40% arable land bordered by coastline to the south, west and east. In general, slightly more than 25% of the Swedish winter wheat acreage of about 275 000 ha was grown in Scania during 1983-2007 (www.sjv.se, accessed February

2009). Cultural practices, cultivars used and the impact of weather are presented in earlier papers (Wiik, 2009; Wiik and Ewaldz, 2009).

2.3. Economics

Fungicide treatment distinctly increases the costs of production by more than the obvious cost of the fungicide. The economic model used was:

$$U = [(Y - D) * N] - (cF + cS) \qquad \text{(equation 1)}$$

$$N = Z - (cP + cK + cH + cT + cA) \qquad \text{(equation 2)}$$

where U (€ ha^{-1}) is the net return (income minus costs), Y (kg ha^{-1}) is the yield increase due to a fungicide treatment at GS 45-61, D (kg ha^{-1}) is the yield loss due to wheel damage caused by spraying, N (€ kg^{-1}) is the net value per kg kernel, and cF (€ ha^{-1}) and cS (€ ha^{-1}) are the costs (c) of fungicide (F) and spraying (S). The net value N in equation 1 is given by equation 2, where Z (€ kg^{-1}) is grain price per kg, and cP (€ kg^{-1}), cK (€ kg^{-1}), cH (€ kg^{-1}), cT (€ kg^{-1}) and cA (€ kg^{-1}) are the costs (c) per kg kernel of phosphorus (P) losses from the field, potassium (K) losses from the field, harvest (H), transport (T) and artificial drying (A).

Cost calculations were based on data from www.agriwise.org (accessed March 2009), the Swedish Rural Economy and Agricultural Societies and the Swedish Board of Agriculture (www.sjv.se, accessed March 2009) and adjusted estimations of damage owing to fungicide application reported by Folkesson (1992). All calculations were made in Swedish crowns (SEK) and converted to euro (€) at an exchange rate of 10 SEK to 1 €. The net return was calculated for 21 scenarios, seven scenarios each at three grain prices, 10, 20 and 30 € dt^{-1} (Table 1). In the scenarios, four different fungicide prices (0, 30, 40 or 60 € ha^{-1}), three costs of spraying (0, 6 or 12 € ha^{-1}) and three costs of damage owing to spraying (0, 4 or 8 € ha^{-1}) were used in the calculations (Table 1). Two digits designate each scenario; the first digit 1, 2 and 3 represents the grain price (10, 20 or 30 € dt^{-1}, respectively) and the second digit 0, 1, 2, 3, 4, 5 or 6 an ascending total cost of a fungicide treatment (0, 46, 50, 56, 60, 76 or 80 € ha^{-1}), respectively. This means that the second digit describes the same costs in three scenarios, e.g. for scenarios 13, 23 and 33 the treatment cost is 56 € ha^{-1} but the grain price differs. One more scenario (12b) was included to consider the net return of a mean optimal fungicide dose during the latter period (1995-2007) of the study (optimal dose (od) = cost of fungicide at the dose giving highest net return). Results from 36 field trials with different doses of Amistar (two or more of 0.25 L ha^{-1}, 0.50 L ha^{-1}, 0.75L ha^{-1} and 1.00 L ha^{-1}, active ingredient azoxystrobin 250 g L^{-1}) carried out during 1998-2002 were used to estimate the mean optimal dose (Wiik, unpublished). The functions used were based on available entries without taking different varieties, nitrogen levels etc. into consideration. Fungicide resistance to strobilurins had probably not evolved in Sweden at that time (Jørgensen and Thygesen, 2006). In scenario 12b, yield increase was corrected according to the dose-response found.

An overview of the net return is also given for the three grain prices and three fungicide treatment cost levels (low, medium and high), i.e. 33 € ha^{-1}, 67 € ha^{-1} and 100 € ha^{-1}, respectively (Table 2a and Table 2b).

The increase in harvesting costs was fixed at 0.2 € dt^{-1}, transport costs 0.5 € dt^{-1} (30 km) and drying costs 1.0 € dt^{-1}. Phosphorus (3 kg ton^{-1} grain) and potassium (5 kg ton^{-1} grain) were removed from the field due to the grain yield increase achieved by the fungicide treatment (Bertilsson *et al*., 2005). The resulting financial loss was estimated to be 0.6 € dt^{-1} (P) and 0.3 € dt^{-1} (K) at fertiliser prices of 200 € dt^{-1} and 60 € dt^{-1}, respectively. In total, the increase in the costs of harvest, transport, drying and losses of P and K was estimated at 2.6 € dt^{-1}. Grain price and producer price are used synonymously in the following and net return refers to the producer price minus the above-mentioned costs.

2.4. Statistical methods

ANOVA and regression (SPSS ver. 17.0) were used to analyse the results and boxplots to show the variability (Hawkins, 2005). Following ANOVA, the Student-Newman-Keuls (SNK-test) and Tukeys multiple range test were used to compare means.

3. Results

3.1. Fungicide treatment and yield increase

A mean yield increase due to a single fungicide treatment at GS 45-61 was achieved each year during the period 1983-2007 (Figure 1). In 13 years out of 25 this mean annual numerical yield increase ranged between 10-19 dt ha^{-1} and was statistically significant, but in other years the yield increase was very small, 3 dt ha^{-1} and below, and not statistically significant.

The mean annual standard deviations in yield did not differ greatly between fungicide-treated plots and untreated plots (11.9 and 11.6 respectively) (Figure 1).

3.2. Grain price and profitability

The variation in net return in the 771 entries during 1983-2007 was very large. For example, with a grain price of 10 € dt^{-1} at a low fungicide treatment cost (33 € ha^{-1}), the best 10% of entries gave 113-218 € ha^{-1} and the worst less than -20 € ha^{-1} (Table 2a). With the same grain price (10 € dt^{-1}) and at three treatment cost levels (low, medium and high), it was profitable to treat 77, 50 and 28% of the 771 entries, respectively, corresponding to a required yield increase of 4.5, 9.1 and 13.6 dt ha^{-1}, respectively (Table 2b). Furthermore, at double and triple the grain price, the corresponding fraction of profitable entries obviously increased. The maximum treatment costs (calculated as means of years) while still giving a positive net return increased by a factor of about 2.3 at grain price 20 € dt^{-1} and a factor of about 3.7 at grain price 30 € dt^{-1} compared with grain price 10 € dt^{-1} (Table 3).

Calculated as a mean over years at the chosen three ascending grain prices the net return of a single fungicide treatment at GS 45-61 was positive if the total treatment cost was less than 61, 143 and 226 € ha^{-1}, respectively. Calculated as a mean over all entries it was 74, 175 and 275 € ha^{-1} respectively (Table 3).

3.3. Differences between years

Net return differed substantially between years. For example, at grain price of 10 € dt^{-1} the maximum treatment costs while still giving a profitable mean annual net return varied between 18 € ha^{-1} (1992) and 137 € ha^{-1} (1987) (Table 3). The variability in net return was large, not only between years but also within years (Figure 2). Three years, representing different intensities of fungal disease and mean yield increases achieved by a single fungicide treatment at GS 45-61, differed in the percentage of entries it was profitable to treat. At three ascending fungicide prices (low, medium and high, scenarios 11, 13 and 15) 52, 45 and 27% respectively of the entries during 2001 were profitable to treat, while during 2002 with severe attacks of LBDs the corresponding entries were 93, 92 and 84%, and in a year with low disease pressure (2005) only 16, 10 and 6% (not shown in Tables or Figures).

3.4. Costs and profitability

Mean annual net return was negative in scenarios 15 and 16 and positive in all other scenarios (Table 4). Negative mean net returns were frequent in several years in scenarios 11-16, less frequent in scenarios 21-26 and rare in scenarios 31-36. At grain price 10 € dt^{-1} and three ascending fungicide treatment costs (scenarios 11, 13 and 16) fungicide treatment was profitable in 16, 14 and 7 years out of 25, respectively. With the same three ascending treatment costs as above and at double the grain price (scenarios 21, 23 and 26) fungicide treatment was profitable in 22, 20 and 17 years out of 25, respectively, and at triple the grain price (scenarios 31, 33 and 36) in 25, 25 and 20 years out of 25, respectively (Table 4). In scenarios 11-16 the number of profitable entries was below 50% in 10-18 years out of 25 (Table 5) and no entries at all were profitable in two years, 1992 and 1994. At doubled the grain price (scenarios 21-26) the number of profitable entries was below 50% in 3-9 years out of 25, while at triple the grain price (scenarios 31-36) it was below 50% in at most 4 years out of 25.

3.5. Optimal dose

Mean maximum yield increase was achieved by using a mean dose of 0.9 L ha^{-1} Amistar (e.g. $y=-1464x^2+2658x+13$, $R^2=0.98$, mean of four doses; y=yield increase, x=dose). However, mean maximum net return was achieved by using a mean dose of 0.55-0.66 L ha^{-1} Amistar (e.g. $y=-923x^2+1219x+9$, $R^2=0.93$, mean of four doses; y=mean net return, x=dose). In scenario 12b, when mean optimum dose and estimated yield increase were considered, the mean net return during 1995-2007 was 24 € ha^{-1}, and of these 13 years three gave a negative mean net return.

3.6. Relationships between net return and number of profitable entries

In each scenario, the relationship between the mean annual net returns (Table 4) and the mean annual number of profitable entries (Table 5) was strong. These relationships showed a good fit, especially at grain price 10 € dt^{-1}, with a second degree equation, e.g. scenario 11 gave the equation $y=-0.01x^2+1.4x+46.1$ (y=no. of profitable entries and x=net return, $R^2=0.94$, N=25). Profitable entries were present even in years with low mean net returns.

3.7. Quality factors affecting payment to the farmer

Fungicide treatment resulted in an increase in mean HLW of more than 10 g L^{-1} in 12 years out of 25, of which six had a statistically significant mean increase of about 20 g L^{-1} (Table 6). Increased HLW as a result of a single fungicide treatment at GS 45-61 positively affected payment to the farmer in 16% of the entries, i.e. when HLW exceeded 740 g L^{-1}. In three years (1987, 2002 and 2007), HLW of 740 g L^{-1} was exceeded in more than one-third of the entries. Fungicide treatment significantly increased HLW calculated as a mean of entries, but not if calculated as a mean of years. In a mean over 18 years, protein content decreased slightly (~2%, 10.3 to 10.1% protein content) as a result of a single fungicide treatment, but the decrease was only statistically significant in one of those years. In a mean over 15 years the Hagberg falling number decreased by almost 17% as a result of a single fungicide treatment, of which the mean annual decrease was statistically significant in three years, with the largest decrease (48 s) in 1998. The decrease in protein content and Hagberg falling number due to fungicide treatment affected payment to the farmer negatively in 6% and 4% of the entries, respectively, i.e. when protein content fell below 10.5% and Hagberg falling number below 200 s. Fungicide treatment did significantly decrease protein content and Hagberg falling number when calculated as a mean of entries, but not when calculated as a mean of years.

Discussion

Doubling and tripling the grain price was the most important factor for the outcome of the net return in our calculations, especially compared with the relatively low impact of costs of fungicide application, crop harvest, transport, drying and loss of plant nutrients (P and K). After grain price, the cost of fungicide had the next largest impact on the net return. We consider the grain prices and costs chosen in the different scenarios to be relevant for future assessments of the profitability of fungicide input, e.g. the grain price was about 10 € dt^{-1} up to 2006 and since then has fluctuated peaking at almost 30 € dt^{-1} in early 2008, which is in agreement with our choice of 10, 20 and 30 € dt^{-1}. The cost of fungicide control is well in line with estimations by the National Board of Agriculture (SJV, 2008; www.agriwise.org, accessed March 2009).

To examine whether fungicide application in winter wheat at GS 45-61 in southern Sweden is profitable to the farmer from a strictly economic point of view, scenario 12a can be used as an example of the past and present time (SJV, 2008; www.agriwise.org, accessed March 2009). The mean net return was 12 € ha^{-1} during the 25 years of this study. This is not a conclusive result, and in several years the mean net return was negative and less than 50% of the entries were profitable to treat. However, changes occur over time that has an impact on the outcome. The mean yield increase during 1983-1994 was 660 kg ha^{-1} compared with 970 kg ha^{-1} for 1995-2005, a difference probably explained by the change from azole to strobilurin fungicides (Bayles, 1999; Wiik, 2009) and to the so far effective active ingredient prothioconazole since 2005. In our chosen past and present time scenario 12a, mean annual net return was higher in the latter period compared with the earlier period, i.e. 21 € ha^{-1} compared with 3 € ha^{-1}. In this study, we used all available entries in field trials with one single fungicide treatment in winter wheat during a limited growth period (GS 45-61), shown to be the most important GS for LBDs in Sweden (Wiik, 2009). However, in some varieties, at high infection pressure and other situations a double treatment might be needed, and the economics of more intense use also need to be evaluated. As the field trials are based on different soil types, different wheat varieties and a range of agricultural practices, our results only demonstrate a mean of the results from entries with different backgrounds and do not show the effect of different means of production, e.g. the profitability for a specific variety or at a specific nitrogen level. Such influences will be evaluated in a coming article. Consequently, changes over time in agricultural practices influence the profitability of fungicide use, such as the introduction of more active fungicides as well as fungicide resistance and fungicides more adapted to the actual disease situation. In addition, changes other than the inherent fungicidal effects can almost certainly affect the profitability of fungicide use; e.g. climate change leading to increased or decreased pesticide costs in winter wheat (Chen and McCarl, 2001), increased use of cultivars with better plant disease resistance (Priestley and Bayles, 1988; Marasas *et al*., 2003), new diseases and disease interactions (Anderson *et al*., 2004; Bearchell *et al*., 2005), new cropping systems (Duveiller *et al*., 2007) and price relations (Nail *et al*., 2007).

According to the Swedish recommendations a fungicide treatment is habitually required, but in some years the dose can be reduced (SJV, 2008). The fungicides evaluated in the present study were generally at full dose, but using results from field trials evaluating dose-response we were able to consider the economic outcome of reduced doses. Many fungicides are very potent and a dose reduction usually does not impair the efficacy and resulting yield increase greatly due to the non-linear shape of the dose-response curve. Wiik *et al*. (1995) reported that half dose of Tilt Top (0.5 L ha^{-1}, a.i. fenpropimorph 375 g L^{-1} and propiconazole 125 g L^{-1}) resulted in only about 15% less yield increase, while the efficacy against LBDs, brown rust, yellow rust and mildew was 82, 90, 84 and 78%, respectively compared with the full dose. Similarly, a reduction in the dose of Amistar from 1.0 L ha^{-1} and 0.5 L ha^{-1} resulted in only 19% less yield increase, and the efficacy against LBDs, brown rust, yellow rust and mildew was 85, 100, 97 and 102%, respectively (Wiik, unpublished). With these and other results in mind it is not surprising that reduced doses are being considered in plant protection (Milne *et al*., 2007; Bürger *et al*., 2008). By using an optimum dose of Amistar (0.66 L ha^{-1}) compared with a recommended standard dose (0.8 L ha^{-1}) during 1995-2007, the farmer would have gained 3 € ha^{-1} (24 instead of 21 € ha^{-1}) according to our calculations.

Scenario 25 may describe a most likely possible future, a scenario with double the producer price compared with scenarios 10-16 and a 52% increase in the costs owing to fungicide use compared with our past and present time scenario 12a. The mean net return of this scenario during all 25 years was 65 € ha^{-1}. However, divided into the earlier and later periods mentioned previously, both the net return and the percentage of profitable entries were higher in the later period than in the earlier period, i.e. 86 € ha^{-1} compared with 43 € ha^{-1}and 78% compared with 58%, respectively. In another scenario, scenario 16, with the same low grain price as in the past and present time scenario 12a but with a 60% increase in the cost of fungicide use, the mean net return during the 25 years of study was negative (a loss of 16 € ha^{-1}) and only 30% of the entries were profitable to treat with a fungicide.

The Official Statistics of Sweden (SCB/SJV, 2008; Agneta Sundgren, pers. comm., 2009) show that fungicides with active ingredients such as prothioconazole, pyraclostrobin, propiconazole, azoxystrobin, fenpropimorph and cyprodinil were used on 99% of the winter wheat acreage in southern Sweden during 2006. However, the present study shows that a routine single fungicide input at GS 45-61 against LBDs in southern Sweden was questionable from a strictly farm economics point of view in almost one-third of the entries during 1995-2007, and probably higher in central Sweden (Wiik, 1991). On the other hand, part of the total accumulated profit of 328 € ha^{-1} to 198 € ha^{-1} (scenarios 11-13) in southern Sweden during 1995-2007 would be somewhat at risk unless entirely reliable decision support systems are available. Accordingly, thorough economic analyses and probabilities must be allowed to play a vital part in decision support systems (Headley and Lewis, 1967; Rossing *et al*., 1994; Fabre *et al*., 2007). No true decision support system is in use for LBDs in Sweden. Although existing recommendations take account of precipitation, infection pressure, fungicide, fungicide dose, soil type and cultivar, fungicides against LBDs are used almost routinely in southern Sweden (SJV, 2008).

In this study, grain type (bread, starch or feed), HLW, protein content and Hagberg falling number and some other factors upon which producer price were not used in the economic calculations because they have not been routinely recorded. Whether the farmer aimed at bread or feed grain is not unimportant, but the producer price difference was only about 7% higher for bread grain in costing calculations 2000-2008 (www.agriwise.org, accessed March 2009). Fungicide treatment affected HLW positively and in exceptional years protein content and Hagberg falling number negatively, but probably without major economic consequences to the farmer, even if weather and choice of cultivar can be decisive (Ruske *et al*., 2004; Gooding, 2007; Wang *et al*., 2008). Nitrogen fertilisation affects yield, quality parameters and the yield increase achieved by fungicide treatment (Dimmock and Gooding, 2002; Walters and Bingham, 2007). For example, in Swedish field trials carried out during 2001-2003 a single fungicide treatment during heading of winter wheat cultivar Ritmo at three fertiliser levels of 120, 170 and 220 kg N ha^{-1} gave yield increases of 10.6, 12.6 and 16.1 dt ha^{-1} and improved kernel protein content from 9.9 to 10.8 and 11.7 %, respectively (Wiik and Pålsson, 2004). In the present study, which did not permit direct comparisons between nitrogen levels, the range of nitrogen fertilisation was 84-230 kg N ha^{-1}. The protein content in our study changed due to amount of nitrogen fertilisation, as in the study by Wiik and Pålsson (2004), with the yield increase due to a single fungicide treatment being statistically significant between nitrogen levels at high amounts of nitrogen fertilization (>180 kg N ha^{-1}). About 20% of the field trials in our study were fertilised with more than 180 kg N ha^{-1} and thus nitrogen fertilisation will influence the net return, but we omitted the most likely influence of nitrogen from the present economic analysis.

For decades, fungicides have been an important means of production in winter wheat in many countries and unfortunately or fortunately not just an optional extra (Eyal, 1981; Cooper and

Dobson, 2007). Our calculations were carried out from a strict farm production economics perspective but as fungicides may have adverse effects on the environment and human health, approval based on risk-benefit analysis has long been regulated by public authorities (Headley and Lewis, 1967). The economics of pesticide usage are complex and influenced by market prices and involvement from the authorities (Zilberman *et al*., 1991; Serra *et al*., 2005). Taxes on pesticides instead of bans may better fulfil environmental goals (Zilberman *et al*., 1991) and reduced price support or a decreased producer price will impede the use of pesticides (Serra *et al*., 2005). Regev *et al*. (1997) showed that fungicides were not risk-reducing at low levels of rainfall and we found no evidence of lower crop variability in fungicide-treated plots than in untreated plots. Subsequently, fungicides did not increase cropping reliability, a fact that is also noteworthy in an economic perspective. In the different scenarios we indirectly showed the effect of market change through the different grain prices selected, and the effects of taxes on pesticides and fuel through the different costs of production. Changes are difficult to predict but scenarios like ours based on real facts are valuable as a baseline for future discussions and recommendations.

The profitability to farmers of using a single fungicide treatment in winter wheat in southernmost Sweden during 1983-2007 was found to be doubtful rather often, although it improved during the latter part of the study due to more effective fungicides becoming available. Producer price and different costs obviously influenced the farm profits. Manageable and non-manageable changes and variations within and between years highlights the need for valid, economically sound and risk/uncertainty-derived decision support systems, preferably based on a more holistic concept than those of today.

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Table 1. Designation and economics of 22 scenarios with different grain prices (€ dt^{-1}) to the farmer and different treatment costs associated with spraying (€ ha^{-1})

Designation of scenarios at three grain prices			Fungicide price	Cost of spraying	~Cost of damage [a]	Treatment cost
10 € dt^{-1}	20 € dt^{-1}	30 € dt^{-1}	€ ha^{-1}	€ ha^{-1}	€ ha^{-1}	€ ha^{-1}
10	20	30	0	0	0	-
11	21	31	30	12	4	46
12a	22	32	40	6	4	50
12b	-	-	od [b]	6	4	od[b]
13	23	33	40	12	4	56
14	24	34	40	12	8	60
15	25	35	60	12	4	76
16	26	36	60	12	8	80

[a] Mean cost at 0.4% damage in the crop due to spraying was ~4 € ha^{-1}, and at 0.8% ~8 € ha^{-1} depending on yield level.

[b] In scenario 12b, the cost of Amistar at optimal dose (od) was included to consider the net return when a mean optimal fungicide dose was used during the latter period of the evaluation period (1995-2007).

Table 3. Maximum total cost (€ ha^{-1}) of a single fungicide treatment at GS 45-61 in southern Sweden 1983-2007 that still gives a profitable net return at three grain prices (scenarios 10 , 20 and 30)

Year (N[a])	Grain price 10 € dt^{-1}		Grain price 20 € dt^{-1}		Grain price 30 € dt^{-1}		Tukey[a]
	Max. cost	Std. dev.	Max. cost	Std. dev	Max. cost	Std. dev	
1983 (13)	46	28	109	66	172	104	cdef
1984 (16)	60	23	141	54	221	85	cdef
1985 (13)	32	18	76	42	120	66	def
1986 (7)	34	44	80	103	126	162	def
1987 (7)	137	41	323	97	508	153	a
1988 (5)	62	13	145	31	229	49	cdef
1989 (12)	19	24	44	57	70	89	f
1990 (9)	95	51	224	119	353	187	abc
1991 (11)	64	23	150	53	237	83	cdef
1992 (6)	18	11	43	26	67	41	f
1993 (3)	24	24	56	56	89	88	ef
1994 (12)	20	12	46	29	73	45	f
1995 (47)	36	26	84	61	133	96	def
1996 (65)	75	50	176	118	277	186	bcdef
1997 (63)	88	38	206	90	324	141	abcd
1998 (36)	101	41	237	95	374	150	abc
1999 (34)	90	46	211	109	332	172	abcd
2000 (37)	58	33	137	79	215	124	cdef
2001 (93)	53	41	124	95	195	150	cdef
2002 (107)	132	54	311	127	490	201	ab
2003 (94)	81	30	191	71	301	111	abcde
2004 (36)	67	42	158	99	249	155	cdef
2005 (31)	24	25	57	59	91	92	ef
2006 (6)	36	19	84	45	132	70	def
2007 (8)	72	24	169	55	266	87	cdef
Mean[b]	61	34	143	79	226	124	
Mean[c]	74	50	175	119	275	187	

[a] Valid in max. cost columns at all three grain prices. Group size is unequal. Harmonic mean of group sizes is used. Type I error levels are not guaranteed. [b] Mean of years (N=25). [c] Mean of all entries (N=771).

Table 4. Different scenarios and mean annual profitability (€ ha^{-1}) for a single fungicide treatment at GS 45-61 in southern Sweden 1983-2007. Shaded areas represent annual means with negative profitability

Year	Net return (€ ha^{-1}), annual mean 1983-2007 of 18 scenarios																	
	11	12a	13	14	15	16	21	22	23	24	25	26	31	32	33	34	35	36
1983	3	-1	-7	-9	-27	-29	63	59	53	49	33	29	123	119	113	107	93	87
1984	16	12	6	3	-14	-17	93	89	83	78	63	58	171	167	161	153	141	133
1985	-12	-16	-22	-24	-42	-44	29	25	19	14	-1	-6	70	66	60	52	40	32
1986	-10	-14	-20	-22	-40	-42	33	29	23	17	3	-3	76	72	66	57	46	37
1987	93	89	83	82	63	62	276	272	266	262	246	242	459	455	449	443	429	423
1988	17	13	7	5	-13	-15	98	94	88	82	68	62	178	174	168	159	148	139
1989	-25	-29	-35	-37	-55	-57	-3	-7	-13	-17	-33	-37	20	16	10	3	-10	-17
1990	51	47	41	38	21	18	176	172	166	160	146	140	301	297	291	281	271	261
1991	20	16	10	7	-10	-13	103	99	93	88	73	68	187	183	177	168	157	148
1992	-26	-30	-36	-38	-56	-58	-4	-8	-14	-19	-34	-39	18	14	8	0	-12	-20
1993	-20	-24	-30	-33	-50	-53	9	5	-1	-7	-21	-27	38	34	28	19	8	-1
1994	-25	-29	-35	-37	-55	-57	-1	-5	-11	-16	-31	-36	22	18	12	4	-8	-16
1995	-9	-13	-19	-21	-39	-41	36	32	26	20	6	0	81	77	71	62	51	42
1996	30	26	20	17	0	-3	127	123	117	111	97	91	220	221	215	205	195	185
1997	43	39	33	30	13	10	157	153	147	141	127	121	272	268	262	251	242	231
1998	56	52	46	43	26	23	189	185	179	172	159	152	321	317	311	300	291	280
1999	45	41	35	32	15	12	162	158	152	145	132	125	279	275	269	258	249	238
2000	13	9	3	0	-17	-20	87	83	77	70	57	50	162	158	152	140	132	120
2001	8	4	-2	-5	-22	-25	75	71	65	58	45	38	142	138	132	120	112	100
2002	87	83	77	74	57	54	262	258	252	245	232	225	437	433	427	415	407	395
2003	36	32	26	23	6	3	142	138	132	125	112	105	248	244	238	227	218	207
2004	22	18	12	9	-8	-11	109	105	99	91	79	71	195	191	185	174	165	154
2005	-21	-25	-31	-35	-51	-55	7	3	-3	-11	-23	-31	35	31	25	12	5	-8
2006	-9	-13	-19	-22	-39	-42	36	32	26	19	6	-1	80	76	70	60	50	40
2007	27	23	17	14	-3	-6	121	117	111	104	91	84	214	210	204	194	184	174
Mean [a]	16	12	6	4	-14	-16	95	91	85	79	65	59	174	170	164	155	144	135

[a] Mean of years.

Table 5. Profitability (% of no. of entries) of a single fungicide treatment at GS 45-61 in southern Sweden 1983-2007. Shaded areas represent annual means with negative profitability in Table 3

Year	N	Profitable entries (%), annual mean of 18 scenarios 1983-2007																	
		11	12a	13	14	15	16	21	22	23	24	25	26	31	32	33	34	35	36
1983	13	46	46	38	38	15	15	85	85	77	77	69	62	85	85	85	85	85	77
1984	16	75	75	75	69	25	25	100	94	94	94	75	75	100	100	100	100	94	94
1985	13	15	15	8	8	0	0	85	77	62	62	46	38	92	92	92	92	77	62
1986	7	29	29	29	14	14	14	57	57	57	57	43	29	57	57	57	57	57	57
1987	7	100	100	100	100	86	86	100	100	100	100	100	100	100	100	100	100	100	100
1988	5	80	80	80	80	0	0	100	100	100	100	100	100	100	100	100	100	100	100
1989	12	8	8	8	8	8	8	42	33	33	25	25	17	42	42	42	42	33	33
1990	9	89	89	89	78	67	67	89	89	89	89	89	89	89	89	89	89	89	89
1991	11	82	73	64	64	36	36	100	100	100	100	100	91	100	100	100	100	100	100
1992	6	0	0	0	0	0	0	50	50	33	33	0	0	83	50	50	50	50	50
1993	3	33	33	0	0	0	0	67	33	33	33	33	33	67	67	67	67	33	33
1994	12	0	0	0	0	0	0	42	42	33	33	17	8	75	58	50	42	42	42
1995	47	32	26	19	17	6	6	68	68	64	62	51	40	81	79	79	72	68	62
1996	65	74	71	66	66	52	48	82	80	78	78	77	74	83	83	83	82	80	78
1997	63	86	84	79	78	57	54	97	97	95	95	95	94	98	98	98	97	97	95
1998	36	94	94	92	89	67	64	100	100	100	97	97	97	100	100	100	100	100	100
1999	34	85	79	71	68	56	56	97	97	97	94	94	91	97	97	97	97	97	97
2000	37	62	62	57	51	30	27	86	86	78	78	76	76	89	89	89	89	86	78
2001	93	52	48	45	43	27	26	74	74	74	71	66	60	78	77	75	74	74	73
2002	107	93	92	92	92	84	84	98	98	97	96	93	93	100	100	99	98	98	97
2003	94	87	83	76	73	55	53	100	100	99	98	95	94	100	100	100	100	100	98
2004	36	67	61	58	58	42	39	83	83	81	81	72	69	89	83	83	83	83	81
2005	31	16	13	10	10	6	6	42	39	32	32	29	26	55	55	48	42	39	32
2006	6	17	17	17	17	0	0	83	83	83	83	67	33	83	83	83	83	83	83
2007	8	88	75	75	75	50	25	100	100	100	100	100	100	100	100	100	100	100	100
Mean [a]		56	54	50	48	31	30	81	79	76	75	68	64	86	83	83	82	79	76

[a] Mean of years.

Table 6. Influence of fungicide treatment on wheat grain factors (HLW, protein content, Hagberg falling number) that affect the price received by the farmer. Calculated change between fungicide-treated and untreated field plots deriving from payment threshold values (see footnote d)

Year	HLW g/L				Protein content %				Hagberg falling number s			
	N[a]	Untreat[b]	Treat[c]	Change[d] %	N[a]	Untreat[b]	Treat[c]	Change[d] %	N[a]	Untreat[b]	Treat[c]	Change[d] %
1983	13	785	798	0	-	-	-	-	-	-	-	-
1984	16	789	800	6	-	-	-	-	-	-	-	-
1985	13	809	808	0	-	-	-	-	-	-	-	-
1986	7	821	820	0	-	-	-	-	-	-	-	-
1987	7	754	777	57	-	-	-	-	-	-	-	-
1988	5	826	832	0	-	-	-	-	-	-	-	-
1989	12	829	829	0	7	11.8	12.0	0	7	264	260	0
1990	9	831	833	0	4	10.3	10.7	0	4	270	270	0
1991	11	820	824	0	8	10.6	10.6	0	10	270	270	0
1992	6	827	825	0	3	10.7	10.8	0	3	270	270	0
1993	3	821	823	0	-	-	-	-	3	270	270	0
1994	10	828	827	0	2	12.4	12.1	0	-	-	-	-
1995	41	782	788	0	3	10.8	10.5	67	-	-	-	-
1996	65	743	759*	20	56	10.6	10.3	9	-	-	-	-
1997	49	770	787**	8	28	10.9	10.5	0	-	-	-	-
1998	36	753	768	22	36	11.7	11.3	6	36	329	288*	22
1999	34	710	729	15	32	11.1	10.7	13	32	181	167	6
2000	36	716	721	0	35	12.0	11.9	3	35	254	240	17
2001	71	760	770**	17	72	10.9	10.8	1	68	323	304*	4
2002	98	726	764***	36	98	11.4	10.9***	10	71	353	327*	3
2003	85	739	764***	22	85	12.0	11.7	2	61	364	345	0
2004	36	750	762*	22	36	11.9	11.7	6	12	313	298	0
2005	31	795	800	0	31	10.5	10.6	0	31	349	341	0
2006	5	748	751	0	5	12.4	12.2	0	3	307	313	0
2007	8	740	755	38	8	11.8	11.5	0	4	256	259	0
Mean[e]	771	757	773***	16		11.3	11.1***	6		315	296**	4
Mean[f]	25	779	789 ns			11.3	11.2 ns			292	281 ns	

[a] Number of entries, field trials (1983-1994, 2006-2007) or experimental treatments (1995-2005), untreated and treated respectively.
[b] Not fungicide-treated plots. [c] Fungicide-treated plots, single treatment during GS 454-61. [d] Change due to fungicide treatment for numbers of N exceeding payment threshold values: HLW ≥740 g/L, protein ≥10.5%, Hagberg falling number ≥200 s. Asterisks (*, **, ***) indicate statistically significant differences. [e] Mean of all entries. [f] Mean of years.

Table 2a. Net return (€ ha^{-1}) at three grain prices and three fungicide treatment cost levels [low (33 € ha^{-1}), medium (67 € ha^{-1}) and high (100 € ha^{-1})] estimated for 771 entries in field trials carried out 1983-2007. The net return is divided into 10 % steps in decreasing order of net return.

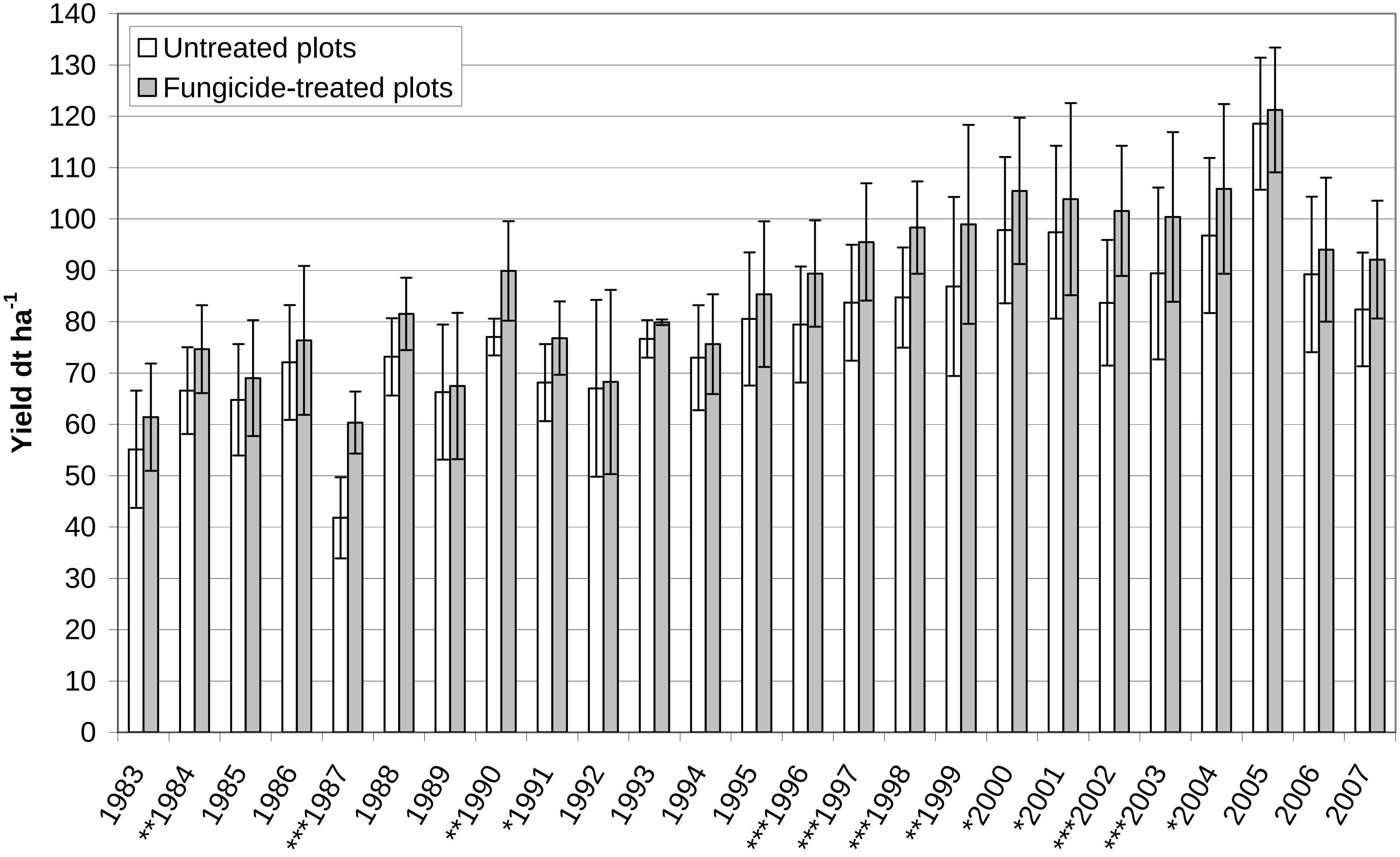
Percent of entries in 10% steps in descending order of net return and at three grain prices	Net return € ha^{-1} at three fungicide treatment cost levels		
	Low	Medium	High
Grain price 10 € dt^{-1}			
0 – 10 %	218 to 113	184 to 79	151 to 46
10 – 20 %	113 to 83	79 to 49	46 to 16
20 – 30 %	83 to 63	49 to 29	16 to -4
30 – 40 %	63 to 48	29 to 14	-4 to -19
40 – 50 %	48 to 34	14 to 0	-19 to -33
50 – 60 %	34 to 23	0 to -12	-33 to -45
60 – 70 %	23 to 8	-12 to -26	-45 to -59
70 – 80 %	8 to -3	-26 to -37	-59 to -70
80 – 90 %	-4 to -20	-38 to -54	-71 to -87
90-100 %	< -20	< -54	< -87
Grain price 20 € dt^{-1}			
0 – 10 %	557 to 310	523 to 276	490 to 243
10 – 20 %	310 to 240	276 to 206	243 to 173
20 – 30 %	240 to 193	206 to 159	173 to 126
30 – 40 %	193 to 158	159 to 124	126 to 91
40 – 50 %	158 to 125	124 to 91	91 to 58
50 – 60 %	125 to 98	91 to 64	58 to 31
60 – 70 %	98 to 64	64 to 30	31 to -3
70 – 80 %	64 to 37	30 to 3	-3 to -29
80 – 90 %	35 to -3	1 to -37	-32 to -70
90-100 %	< -3	< -37	< -70
Grain price 30 € dt^{-1}			
0 – 10 %	896 to 507	862 to 473	829 to 440
10 – 20 %	507 to 397	473 to 363	440 to 330
20 – 30 %	397 to 323	363 to 289	330 to 256
30 – 40 %	323 to 268	289 to 234	256 to 201
40 – 50 %	268 to 216	234 to 182	201 to 149
50 – 60 %	216 to 173	182 to 139	149 to 106
60 – 70 %	173 to 120	139 to 86	106 to 53
70 – 80 %	120 to 77	86 to 43	53 to 10
80 – 90 %	74 to 14	40 to -20	7 to -53
90-100 %	< 14	< -20	< -53

Table 2b. Percent no. of profitable entries (net return > 0 € ha^{-1}) and yield increase required to obtain a profitable net return at three grain prices and three fungicide treatment cost levels, low (33 € ha^{-1}), medium (67 € ha^{-1}) and high (100 € ha^{-1}) during 1983-2007.

Grain price	Percentage of profitable entries at three fungicide treatment cost levels			Yield increase (dt ha^{-1}) required to obtain a profitable net return		
	Low	Medium	High	Low	Medium	High
10 € dt^{-1}	77	50	28	4.5	9.1	13.6
20 € dt^{-1}	89	80	69	1.9	3.9	5.8
30 € dt^{-1}	91	86	82	1.3	2.5	3.7

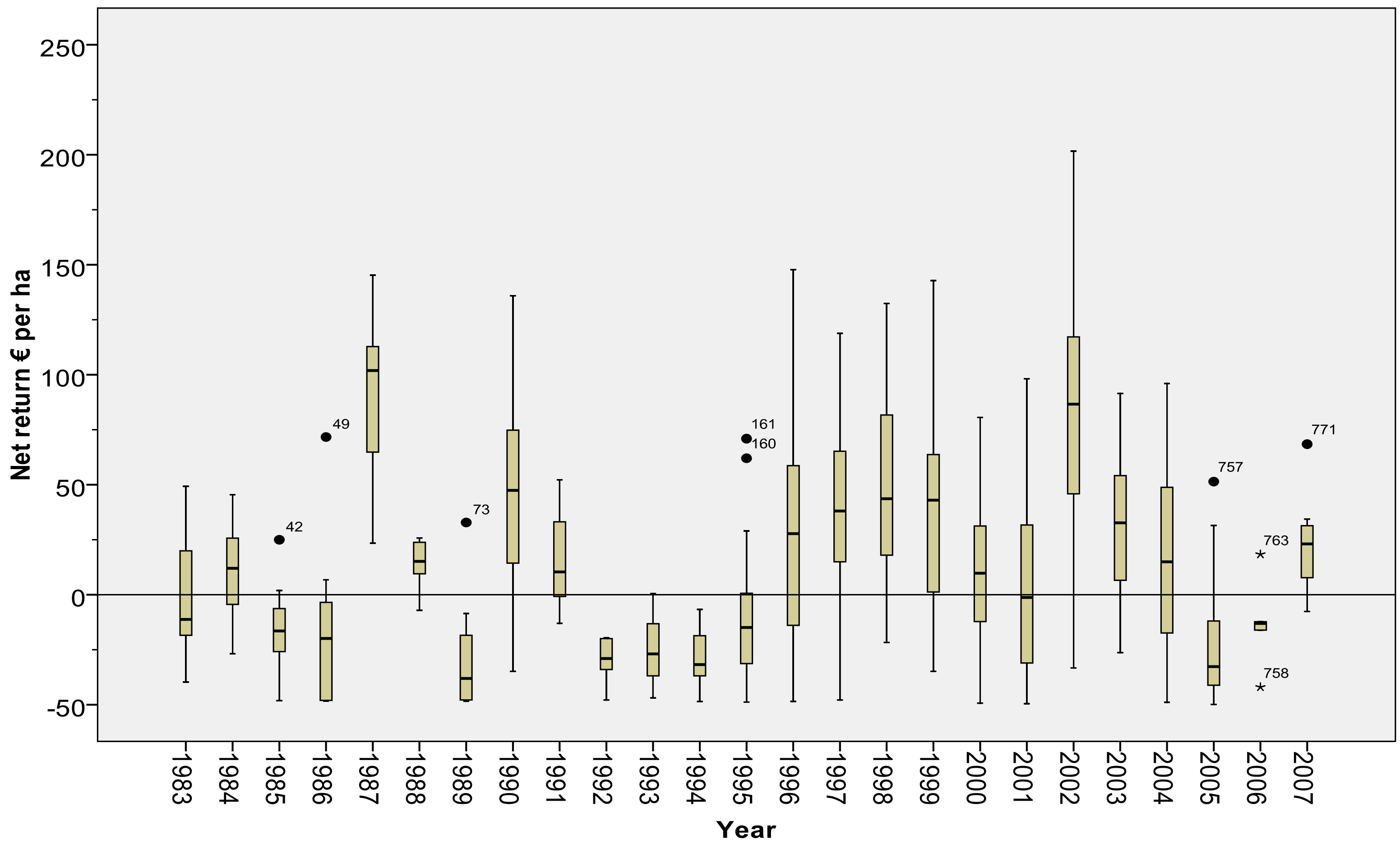
Figure 1. Yield (dt ha^{-1}) in untreated and fungicide-treated (single treatment at GS 45-61) plots in farmers' fields in southern Sweden, 1983-2007. Bars represent standard deviations. Asterisks before years indicate statistically significant differences between untreated and treated plots. Data from Wiik (2009) and Wiik and Ewaldz (2009).

Figure 2. Variability (as boxplots according to SPSS, Hawkins, 2005) in net return (€ dt^{-1}) in scenario 12a during 1983-2007 with 771 entries. Medians are marked as a horizontal line in the boxes with upper and lower quartiles. T-shaped bars indicate the range, with outliers (●) and extreme outliers (∗).



Untreated plots
Fungicide-treated plots
Yield dt ha^{-1}
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
1983
**1984
1985
1986
***1987
1988
1989
**1990
*1991
1992
1993
1994
1995
***1996
***1997
***1998
**1999
*2000
*2001
***2002
***2003
*2004
2005
2006
2007

Figure 1.



250
200
150
100
50
0
-50
Net return € per ha
49
42
73
161
160
771
757
763
758
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
Year

Figure 2.