Yield and disease control in winter wheat in southern Sweden during 1977-2005.

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Abstract

Fungicides are routinely used to prevent yield losses in winter wheat in southern Sweden. Yield and 1000 grain weight (TGW) data from 432 trials in farmers' fields were evaluated to review long-term yields (1977-2005) and control of eyespot and Leaf Blotch Diseases (LBDs, including Septoria tritici blotch, Stagonospora nodorum blotch and tan spot), powdery mildew, brown rust and yellow rust. Regression analyses revealed that control of LBDs explained 74% of the yield increase achieved by fungicide treatment at GS 45-61, followed by powdery mildew (20%), brown rust (5%) and yellow rust (1%). Yield of both untreated and fungicide-treated plots increased from approx. 6000 to 12000 kg ha^{-1} over the period 1983-2005. Single eyespot treatment improved yield by ~320 kg ha^{-1} yr^{-1} during the period 1977-2002, mainly due to occasional years with severe eyespot. Single leaf disease treatment at GS 45-61 increased mean yield by 10.3% or 810 kg ha^{-1} yr^{-1} (9.9% or 660 kg ha^{-1} yr^{-1} for 1983-1994 and 10.7% or 970 kg ha^{-1} yr^{-1} for 1995-2005) due to increased TGW and grain numbers, especially in high yielding stands. Additional extra early treatment at GS 30-40 against LBDs increased yield by ~250 kg ha^{-1} yr^{-1}. Estimated variance in yield and TGW was higher between years than within years, while that in yield increase and plant diseases was lower between years than within. The results confirm potential and limits of fungicides and the need for supervised control strategies including factors affecting disease, yield and interactions.

Keywords: 1000 grain weight, yield components, plant disease, *Septoria tritici*, fungicides.

1. Introduction

Since 1980, the total area of arable land in southern Sweden has been decreasing, but the mean acreage of winter wheat has increased from 50 000 ha to 90 000 ha, representing more than 25% of the total winter wheat acreage in Sweden (SCB, 1983-2006).

Leaf blotch diseases (LBDs) on winter wheat caused by *Mycosphaerella graminicola* (anamorph *Septoria tritici*), *Pyrenophora tritici-repentis* (anamorph *Drechslera tritici-repentis*) and *Phaeosphaeria nodorum* (anamorph *Stagonospora nodorum*), are the most serious cereal pathogens in Sweden (Wiik *et al*., 1995; SJV, 2008). Other diseases such as powdery mildew (*Blumeria graminis*), brown rust (*Puccinia triticina*) and yellow rust (*Puccinia striiformis*) also contribute to yield losses due to the destruction of green leaf area, in particular on the two top leaves (Shaw & Royle, 1989a) and ears. Eyespot caused by the sibling fungal species *Oculimacula acuformis* and *O. yallundae* (earlier described as one fungus with the anamorph *Pseudocercosporella herpotrichoides*), is important and sometimes requires fungicide treatment (SJV, 2008).

As in other countries, results from field trials have been used in Sweden to give recommendations on fungicide products, timing and dosages (e.g. Cook & Thomas, 1990). In recent decades, a fungicide treatment against LBDs just before/during heading [growth stage (GS) 47-55 according to Tottman, 1987] has been profitable in most years and is now routine for many farmers in southern Sweden (SJV, 2008). When tan spot caused by *D. tritici-repentis* is a problem, a split application at GS 37-39 and GS 55-59 is recommended. However, in years when LBDs are inhibited due to dry conditions, the use of fungicides has been questioned (Wiik, 1993). For many diseases such as the LBDs, eyespot, powdery mildew and rusts, the use of threshold values or warning forecasts aid decisions regarding treatment. Winter wheat diseases, treatments and yield levels have been regularly studied in field trials and reviewed (e.g. Andersson *et al*., 1986 and Wiik *et al*., 1995). However, there are few scientific studies of the impact and dynamics of diseases on yield and yield loss over longer periods of time.

This study evaluates the results from field trials 1977-2005 for eyespot and, 1983-2005 for leaf diseases. The objectives were to examine the relationships between fungicide treatments and yield and multiple diseases and yield, and to determine variations in yields and diseases within and between years.

2. Materials and methods

Data were obtained from 432 trials in winter wheat fields on farms in southern Sweden (55°23’-56°25’N, 12°50’-14°31’E) in the period 1977-2005. The trials investigated different treatment strategies and fungicides applied at GS 30-61 in different cultivars and at different nitrogen levels and were carried out by staff at the Rural Economy and Agricultural Societies.

2.1 Cultural practices in commercial fields and cultivars

In general, sowing, fertilisation, weed and insect pest control were performed by farmers, the field trials included. The field trials were predominantly situated on good agricultural soils with a mean content of 17% clay and 3.3% organic matter and an adequate supply of phosphorus and potassium. Mean sowing date for winter wheat was 18 September (range 11 September – 3 October) and mean harvest date was 23 August (range 5 August – 25 September). The period from sowing to harvest was 340 days (range 314-375 days). Mean mineral nitrogen (N) applied during the period was 155 kg N ha^{-1} and mean total N including estimated available soil N from the preceding crop and from manure was 177 kg N ha^{-1}. The preceding crop was oilseed rape (54%), cereals other than wheat (17%), leguminous plants

(9%), wheat (7%) and other crops (13%). The most common cultivars in the field trials 1977-1982 were Solid (49%), Holme (20%), Helge (17%), Folke (7%), Hildur (5%) and Walde (2%) and in the field trials 1983-2005 Kosack (33%), Folke (13%), Ritmo (10%) and Kris (7%). The cultivars Holme, Kraka, Konsul, Meridien, Bercy, Bill and Marshal represented 2-3% respectively, while another 17 cultivars represented less than 2% each. Folke predominated 1983-1986, while Kosack was used in over 60% of trials 1987-1994. Ritmo predominated 1995-2000 and Kris 2001-2005. Field trials 1977-1994 used 2-4 cultivars per year, while field trials 1995-2005 used 5-8 cultivars.

2.2 Field trial design

The trials were randomised in a block design with four replicates. The number of treatments per trial differed during the period but each usually included about 10 treatments and an untreated control. Plot size was usually 4 x 12 m and harvested area (excluding border rows) was 2 m x 10 m, i.e. 20 m^2 per plot.

2.3 Fungicides and fungicide treatments

Different types of fungicides and fungicide combinations containing active ingredients such as benzimidazoles, aromatics, morpholines, azoles, amides, strobilurins and pyrimidines were used in the field trials. Standard products at recommended dosages were generally used, e.g. 0.5 L ha^{-1} Tilt 250 EC, a.i. propiconazole 250 g L^{-1}; 0.8-1.0 L ha^{-1} Tilt Top 500 EC, a.i. propiconazole 125 g L^{-1} + fenpropimorph 375 g L^{-1}; 0.5-1.0 L ha^{-1} Amistar, a.i. azoxystrobin 250 g L^{-1}. Calibrated field crop sprayers with fan nozzles at a pressure of 300 KPa pressure and 200 L water ha^{-1} were used as described in standard operating procedures of the Swedish GEP system.

Growth stages (GS) according to Tottman (1987) were used: Stem elongation [ear at 1 cm (pseudostem erect) (GS 30) to flag leaf ligule just visible (GS 39)]; Booting [flag leaf sheath extending (GS 40) to first awns visible (GS 49)]; Inflorescence (ear/panicle) emergence [first spikelet of inflorescence just visible (GS 50) to emergence of inflorescence completed (GS 59)]; Anthesis (flowering) [beginning of anthesis (GS 60) to anthesis complete (GS 69)]; Milk development [caryopsis (kernel) water ripe (GS 70) to late milk (GS 79)].

In addition to an untreated control, one or more of the following four treatments were included in trials: 1) A single early treatment at GS 30-33 (mean GS 31 May 17) with fungicides effective primarily against eyespot, 1977-2002; 2) a single treatment with fungicides against LBDs, mildew, yellow rust and brown rust just before/during heading at GS 45-61 (mean GS 53 June 14), 1983-2005; 3) a split treatment with fungicides against leaf diseases including an early treatment at GS 31-40 followed by one at GS 45-61 and 4) a split treatment with an early treatment at GS 30-33 primarily against eyespot, followed by a treatment at GS 45-61with fungicides against leaf diseases. In early years, eyespot was primarily treated with benzimidazoles and LBDs with azoles, but also amides and a conazole-morpholine mixture. In later years, pyrimidines were generally used against eyespot and strobilurins, conazoles and morpholines against leaf diseases, often in different combinations.

2.4 Disease assessment

The severity of leaf diseases on the top leaves was usually assessed before treatment and 3-5 weeks after last treatment (EPPO Standards, 2004) as percentage damage to flag leaf or top leaf, leaf 2 or the leaf below the flag leaf, leaf 3 or the leaf below leaf 2 and leaf 4 or the leaf below leaf 3. The necrotrophic LBDs caused by *S. tritici*, *St. nodorum* and *D. tritici-repentis* were assessed as one disease due to mixed symptoms. If needed, disease severity at GS 55 on leaf 3 and GS 75 on leaf 2 was estimated by additional assessments. The formula y=0.42 * xii [y=grain yield loss (%) and xii=disease (%) on leaf 2 (flag-1) in the range 0-45%] (Thomas *et al*., 1989; Cook *et al*., 1991) was used to estimate yield loss caused by LBDs. Fungicide efficacy was calculated as reduction in LBD-infected leaf area (%) in treated plots compared with untreated. An eyespot index was calculated from assessments on samples taken during GS 65-77 as (% weakly attacked tillers)/4 + (% moderately attacked tillers)/2 + (% severely attacked tillers)/1, modified from Scott & Hollins (1974).

2.5 Yield

The field trials were harvested with plot combines, mostly Hege and Sampo. Samples of 1 kg from each treatment were analysed for water content and 1000 grain weight (TGW). Yield and TGW were reported at 15% water content and grains m^{-2} were estimated from yield and TGW. Degree of lodging (0-100, 0=upright stand and 100=totally lodging) was graded just before harvest.

Actual yield responses due to a fungicide treatment at GS 45-61 for five disjunctive disease severities were studied at high and low yield levels (high yield level >9250 kg ha^{-1} and low yield level <9250 kg ha^{-1} based on yields for fungicide treatment at GS 45-61; and high yield level >8250 kg ha^{-1} and low yield level <8250 kg ha^{-1} based on yields in untreated plots).

2.6 Statistical methods

Pearson-correlation, ANOVA, regression and variance component were analysed using SPSS (ver. 13.0) (Hawkins, 2005). The Student-Newman-Keuls procedure with multiple range tests was used to compare means. Variance component analyses (Restricted Maximum Likelihood Estimation, REML) were used with year as random factor [GLM, var(year) and var(error)] to differentiate effects within and between years for different variables.

3. Results

3.1 Yield

Yields of both untreated and fungicide-treated winter wheat increased during the period 1983-2005 from ~6000 to 12000 kg ha^{-1} (Figure 1). Mean yield was 8640 kg ha^{-1} in treated field trials and 7830 kg ha^{-1} in untreated. The annual increase in yield over the period was well described by linear regression and was 217 kg ha^{-1} yr^{-1} and 203 kg ha^{-1} yr^{-1} (R^2 = 0.82, P = 0.001 and R^2 = 0.74, P = 0.001) for treated and untreated field plots, respectively. A single treatment against eyespot improved yield by 320 kg ha^{-1} on average, but this was due to a few years with severe eyespot attacks. A fungicide application just before/during heading resulted in an overall mean annual increase of 10.3% or 810 kg ha^{-1} (9.9% or 660 kg ha^{-1} for 1983-1994, 10.7% or 970 kg ha^{-1} for 1995-2005). An additional treatment at GS 31-40 against LBDs improved yield by a further ~250 kg ha^{-1}. The yield increase due to fungicide treatment at GS 45-61 varied considerably between field trials within years and between years during the period (Tables 1 & 2). The yield increases stratified into 250 kg ha^{-1} increments fell into 11 classes within years (Table 2). The distribution of trials with increasing levels of yield increase due to a single treatment at GS 45-61 describes the variation in disease severity between years and also the variation between locations within this relatively limited geographical area. In nine years (eight prior to 1996) out of 23, 50% of trials had yield increases of <500 kg ha^{-1}. In 15 years, 50% of the trials had yield increase of <1000 kg ha^{-1}. Mean annual yield increases of 1000 kg ha^{-1} or more occurred in eight years (1987, 1990, 1996, 1997, 1998, 1999, 2002 and 2003) and were very high in two of these (1987 and 2002). The TGW in untreated plots varied considerably between years (Table 1). The increase in TGW due to fungicide treatment just before/during heading was very small in some years but in a few years with high disease attacks it was as large as 7-9 g. There was a good correlation between yield and TGW within several years and a very high correlation between mean annual yield increase and TGW (R^2=0.92). A 1 g increase in TGW due to a fungicide treatment just before/during heading increased yield by ~200 kg ha^{-1}. The number of grains m^{-2} in untreated plots increased from 14-17 to 20-24 x 10^3 during the period and the return on the seed rate was thus 35- to 60-fold. Fungicide treatment just before/during heading increased grain numbers, but the total yield increase was mainly due to an increase in TGW.

3.2 Diseases

Eyespot was quite common in some years (Table 1), but caused severe lodging only in exceptional cases. Septoria tritici blotch was frequent in all years, while Stagonospora nodorum blotch and tan spot occurred mainly during the early and latter part of the study period, respectively. Powdery mildew and rust were seen at low levels in many field trials, with the exception of yellow rust in 1988 and 2002, brown rust in 1986, 1987 and 1990 and powdery mildew in the period 2000-2003 (Table 1). In some years, the rusts and powdery mildew were found on specific cultivars, e.g. yellow rust on Kraka 1988, brown rust on Folke and Kosack in the 1980s and powdery mildew on Florida, Bercy, Meridien, Marshal and Ritmo in later years.

In 1992, 1994 and 2004 LBD damage on leaf 2 did not reach 10% severity at GS 75, while in 1997 it was >20% and in 1987 and 2002 39% or more (Figure 2). Fungicide treatment just before/during heading resulted in very high yield increases during 1987 and 2002, moderately high yield increases in 1997 and 2004 and minor yield increases in 1992 and 1994 (Table 1). Mean fungicide efficacy for one treatment against LBDs just before/during heading was 52%, but in some years it was <40% (1983, 1986, 1989, 1991, 1996) and in others >60% (1987, 1988, 1990, 1993, 1994, 1997, 1998) (Table 1). Fungicide efficacy often differed significantly between years, e.g. the very low efficacy in 1996 (18%) and 1989 (23%) was statistically different from all years except 1983, 1984, 1986, 1991, 1992 and 2004.

Disease severity of LBDs on different leaf levels and growth stages was mostly significantly correlated. There was also a correlation between diseases, e.g. yellow rust and LBDs (0.53, P=0.017) and between eyespot and the efficacy of LBD control (-0.49, P=0.018).

3.3 Yield and disease

In two years (1983 and 1996), average eyespot index was >35 and mean yield response to early treatment (~GS 31) with anti-eyespot fungicides was 1050 kg ha^{-1} whereas it was only 190 kg ha^{-1} in years when eyespot index was <10 (1987, 1988, 1992 and 1994).

In regression analyses with the constant omitted and with yield increase due to fungicide treatment as dependent variable and leaf diseases as predictors, LBDs explained 74% of the yield increase (P=0.001), followed by powdery mildew (20%, P=0.021), brown rust (5%, ns) and yellow rust (1%, ns), R^2=0.82. With the formula to predict disease (Cook *et al*., 1991), the mean yield loss due to LBDs was 6.6% in untreated plots in this study (range 0.8-1.7 % in years with very low attacks and 16-19% in years with severe attacks) (Table 1).

The yield increase due to fungicide treatments was correlated to LBD disease severity at later stages, e.g. on leaf 2 at GS 75 (Pearson correlation coefficient 0.596, P=0.003), but not at earlier stages, e.g. on leaf 3 at growth stage GS 55 (0.240 ns) (Figure 3). Disease severity of >5% during GS 55 on leaf 3 (e.g. 1987, 1996, 2002 and 2003) gave a yield increase due to fungicide treatment of 1000 kg ha^{-1} or more. However, in other years (1990, 1997, 1998 and 1999) the yield increase was still >1000 kg ha^{-1} but the severity of attack on leaf 3 at GS 55 was rather low (Figure 3).

LBD severity on both leaf 3 at GS 55 and leaf 2 at GS 75 was significantly negatively correlated with yield level (Table 3). In contrast, powdery mildew was significantly positively correlated with yield level while brown rust showed no significant difference. Actual yield responses due to a fungicide treatment just before/during heading at five disjunctive disease severities and two yield levels based on fungicide-treated yields at GS 45-61 were greater at the higher yield level than the lower (Table 4). In contrast, yield response was lower for the higher of two yield levels based on untreated yields (Table 5).

3.4 Variation within and between years

Variance component analyses for different variables with year as random factor showed that total yield, yield increase, TGW, lodging and all diseases were affected by year (Table 6). The estimated variance of yield and TGW was larger between years than within years, whereas that of yield increase and plant diseases was smaller (Table 6).

4. Discussion

The doubling in actual grain yield 1983-2005 in both untreated and treated plots is probably due to a combination of factors. Grain yield is the outcome of the energy generated by photosynthesis and a multitude of interactions between genotype, various physiological processes, environment, agricultural practices and yield constraints. Yield gain in cultivars released during the latter half of the 20th century is due to some genetic improvements, e.g. shorter cultivars with lodging resistance and high harvest index, more grains per unit area, earlier anthesis and longer grain filling period, higher N use efficiency and disease resistance, and improved agricultural practices (Slafer & Andrade, 1993; Bockus *et al*., 2001; Brancourt-Hulmel *et al*., 2003). In France, 30-50% of the increase in national yield 1956-1999 has been attributed to genetic improvements (Brancourt-Hulmel *et al*., 2003). In China, the eightfold increase in grain yield in cultivars released during 1945-1995 is mostly attributed to cropping practices and not genetic gain (Jiang *et al*., 2003).

Several high-yielding and early maturing modern continental cultivars of wheat were introduced in Sweden during the 1990s due to milder winters. For the period 1995-2005 of this study, when cultivars such as Ritmo and Kris predominated, mean yield in untreated plots

was 9080 kg ha^{-1} compared with 6680 kg ha^{-1} for period 1983-1994, when low-yielding and late maturing bread wheat cultivars such as Folke and Kosack were used. This yield difference can be attributed to a 4.4% increase in TGW and a 29% increase in the mean number of grains m^{-2}. Mean yield per ha in the 1980s was similar to that reported in official statistics for Sweden, but the mean annual increase in yield of ~210 kg ha^{-1} yr^{-1} is much higher than the 81 kg ha^{-1} yr^{-1} in Swedish statistics (SCB, 1983-2006), 110 kg ha^{-1} yr^{-1} in the UK 1948-1997 (Austin, 1999) and 126 kg ha^{-1} yr^{-1} in France 1956-1999 (Brancourt-Hulmel *et al*., 2003). Better soils, cultivars and agricultural practices in the field trials than in wheat crops in general might explain the higher yield increase in this study.
The change from low- to high-yielding cultivars during the mid-1990s corresponded approximately with the change from azole to strobilurin fungicides. The latter probably explains the higher yield increase of 970 kg ha^{-1} achieved by fungicide treatment during the latter period of this study compared with 660 kg ha^{-1} in earlier years. A similar difference between fungicide types was reported by Bayles (1999) in the UK.

The photosynthetic activity of wheat upper foliage post-anthesis is the main source of assimilates distributed to the grains, but assimilates formed pre-anthesis can later be translocated to grains, e.g. as a buffer against stress if post-anthesis photosynthesis is disturbed (Wang *et al*., 1998). The use of fungicides to control plant disease, especially LBDs, keeps the upper foliage healthy and increases green leaf area duration thus promoting high grain yields (Bryson *et al*., 2000). For example, Gooding *et al*. (2000) showed that the mean grain weight increased by 1.15 % per day when senescence of the flag leaf was delayed. Fungicides applied at flag leaf appearance (GS 39 or T2) have given the best yield gain in the UK (Cook & Thomas, 1990; Hardwick *et al*., 2001). In the present study, yield (particularly yield increase due to a single late fungicide treatment at GS 45-61) was strongly linked to increased TGW, confirming results by e.g. Gooding *et al*. (2000).

In this study, control of eyespot fungi with fungicides was very high in two out of 26 years and in a few field trials where eyespot attack led to lodging. Previous studies in Sweden also indicated that eyespot in wheat at GS 30-32 only repaid labour and fungicide costs in 15-20% of cases (Wiik *et al*., 1995). However, when the eyespot index exceeded 30 in the untreated control at GS 75-77 and led to lodging, fungicide treatment at GS 30-32 was very profitable. Earlier studies show that higher yield increases can be achieved when fungicide treatment suppresses lodging (Scott & Hollins, 1978), but factors other than eyespot attack may also be involved (Wiik, 1986).

Statistical analyses of the influence of single and multiple disease attacks on yield response showed that LBDs damaged leaf area most and gave the highest yield response to fungicide treatment at GS 45-61. Predictions of loss in grain yield proved fairly accurate for average LBD severity on leaf 2 at GS 75 over all years in this study. However, in some years the correlation between the actual yield increase due to fungicides and the estimated yield loss predicted by the formula was fairly low (R^2=0.47, P=0.0003). This may be due to the interaction of other diseases, e.g. in 1983 when severe eyespot attacks masked the effect of the LBDs and in other years when control of the rusts contributed to the yield response. Moreover, the predictions originate from a critical point model, which might oversimplify the damage function (Shaw & Royle, 1989a). Powdery mildew followed the LBDs as the second most important leaf disease overall in this study. Rusts were generally of minor importance most likely due to successful resistance breeding (McIntosh & Brown, 1997), but can have a substantial effect on yield (e.g. Bockus *et al*., 2001). Brown rust and not mildew was the second most important disease after LBDs during the period 1983-1994 of this study.

Stagonospora leaf and glume blotch (*St. nodorum*) caused severe attacks in Sweden during the 1970s, but since the 1980s *S. tritici* has become more important than *St. nodorum* in Sweden and other countries, e.g. England and Wales (Hardwick *et al*., 2001; Shaw *et al*., 2008). In this study Stagonospora nodorum blotch, Septoria tritici blotch and tan spot were assessed together as LBDs although with new methods they can now be separated (Guo *et al*., 2007). Powdery mildew attack has increased and brown rust has decreased in southern Sweden since the 1990s in contrast to England and Wales, probably a result of national choice of cultivars and host resistance to mildews and rusts. For example Ritmo is clearly more susceptible to mildew and Kris is more resistant to brown rust than Kosack (Larsson *et al*., 2005).

As diseases and pests in wheat most often coexist and interact, a multi-disease approach is essential (Kranz, 2005), although the focus must remain on the LBDs. The positive correlation between yellow rust and LBDs found in this study is not in agreement with glasshouse studies where rust development was repressed by the Septoria tritici blotch (Madariaga & Scharen, 1986). Powdery mildew has been reported to predispose plants to *Septoria tritici* infection (Brokenshire, 1974), which might explain the significantly positive correlation between these diseases in this study.

Larsson (2005) demonstrated that the economic threshold for aphids (*Sitobion avenae*) in winter wheat decreased with higher yield. Similarly in the present study the yield increase achieved by a fungicide treatment at GS 45-61 was larger for the higher out of two yield levels based on yields treated with a fungicide at GS 45-61. Conversely at two yield levels based on untreated yields, the yield increase achieved by a fungicide treatment at GS 45-61 was smaller at the higher yield level, as was the LBD severity. Lovell *et al*. (1997) and

Ewaldz (2000) suggested vertical upward movement of *S. tritici* inoculum to be less abundant in a dense canopy, more impenetrable to rain splash than a thin canopy. Based on analysis of field experiments on fungicide treatment at GS 39 during the period 1979-1987 Cook & Thomas (1990) suggested that higher yielding crops were more tolerant to foliar diseases and gave the same absolute yield increase at different yield levels (<6000 kg ha^{-1} to >11000 kg ha^{-1}) but the percentage yield increase decreased with increasing potential yield level.

The recent change in grain prices will improve the profitability of a fungicide treatment for the farmer as long as costs of production do not increase as much as the grain price. In Sweden, treatment with a fungicide or a fungicide mixture against LBDs has to result in a yield increase of between 225 and 680 kg ha^{-1} to be a profitable investment (SJV, 2008), depending on how the costs are estimated (grain price, choice of fungicide or fungicide mixture, field pattern, sprayer equipment, labour, spray tracks or damage during application). In this study, a profitable annual average yield increase was achieved in most years, explaining why treatment just before or during heading has become routine for many farmers in southern Sweden. Fungicide treatment against other diseases such as eyespot, rusts and mildew, normally not so frequent and devastating, is less profitable or not profitable. However, some cultivars and specific conditions may promote attacks of these diseases, and during such circumstances treatment becomes profitable.

The progression towards higher yields and the variation within and between years is evident in these results, both in yield increase due to fungicidal input and severity of the diseases, and the results show the potential and limitations of fungicides in preventing yield losses. Another example of this variation is the difference in annual average yield increase (1980-1990) due to a fungicide treatment during GS 45-60 between southern Sweden (650 kg ha^{-1} due to a higher disease pressure) and central Sweden (240 kg ha^{-1}) (Wiik, 1991). The variation within and between years is caused by several factors, e.g. characteristics in the fungal populations (Shaw & Royle, 1989b; McDonald & Linde, 2002), weather (Pietravalle *et al*., 2003), climate (Coakley *et al*., 1999), management practices including nitrogen fertilisation level, choice of crop, cultivar and fungicide and site factors (Cook & Thomas, 1990; Simón *et al*., 2003; Arraiano *et al*., 2006; Milne *et al*., 2007). This variation is reported from all over the world and is logical as every field is unique, evidently in its location, and with its own history and prerequisites of presence and prevalence of plant diseases, e.g. *Septoria tritici* and *Stagonospora nodorum* (Leath *et al*., 1993). To improve future crop protection and to take the right measures, e.g. supervised application of fungicides, more has to be learned about these factors (Jeger, 2004; De Wolf & Isard, 2007). A general conclusion from this study is the great value of objective and impartial field trials well executed over consecutive years with comparable treatments and disease assessments, including necessary documentation of actions and further information. Results from such field trials can be used to optimise fungicide use from the perspective of farmers and of public authorities. In countries with similar conditions for wheat growing as in Sweden, treatment with an effective fungicide to protect the upper leaves during grain filling will be of extreme importance unless cultivars with significantly improved resistance and management practices can be developed and applied. An extra treatment against LBDs at GS 31-40 was found to contribute to a yield increase, but in most cases a sole fungicide spray application at GS 39-59 to protect the upper leaves would be sufficient.

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Table 1. Mean annual incidence of eyespot (index) and percentage attack by LBDs (*Septoria tritici*, *Stagonospora nodorum* and *Drechslera tritici-repentis*), powdery mildew, brown rust, yellow rust, 1000 grain weight (TGW, g), no. of grains, actual and estimated yield increase (kg ha^{-1}) in southern Sweden, 1983-2005

Year	Eyespot	LBDs on leaf 2 DC 75 (efficacy[3)])	Mildew max attack	Brown rust max attack	Yellow rust max attack	TGW increase[1)] (untreated TGW)	Rel. increase[1)] in no. of grains (untreated grains m^{-2})	Actual yield increase[1)] (untreated yield)	Yield loss[2)] Cook et al. 1991
	index	%	%	%	%	g	no.	kg ha^{-1}	%
1983	37	41 (37)	0,3	4,2	0,1	2.8 (33.2)	103 (16602)	630 (5510)	17.2
1984	22	15 (40)	2,8	1,1	0,0	2.7 (40.0)	104 (16936)	760 (6770)	6.3
1985	13	9 (51)	0,2	0,7	0,0	0.7 (46.5)	105 (13913)	420 (6480)	3.8
1986	20	15 (33)	0,6	7,3	0,0	0.9 (47.8)	104 (15076)	430 (7200)	6.3
1987	6	47 (82)	1,1	6,4	0,0	9.0 (29.2)	110 (14336)	1850 (4180)	18.9
1988	9	24 (63)	1,2	2,4	4,0	3.1 (42.2)	104 (17348)	840 (7310)	10.1
1989	29	11 (23)	0,3	1,2	0,2	0.8 (42.2)	100 (15772)	140 (6650)	4.6
1990	32	14 (71)	0,3	10,1	1,0	5.9 (41.4)	102 (18223)	1230 (7540)	5.9
1991	30	24 (34)	0,3	0,3	0,0	4.3 (37.8)	101 (18066)	900 (6830)	10.1
1992	4	2 (41)	0,0	0,0	0,2	0.1 (41.8)	102 (16022)	130 (6700)	0.8
1993	14	2 (64)	2,1	2,6	0,0	1.6 (48.3)	101 (15778)	320 (7660)	0.8
1994	7	4 (63)	0,1	2,2	0,0	1.1 (39.8)	101 (18317)	260 (7300)	1.7
1995	28	13 (58)	1,2	0,2	0,0	0.7 (40.4)	104 (19910)	480 (8050)	5.5
1996	38	11 (18)	1,0	0,0	0,0	0.4 (37.0)	111 (19874)	1000 (7950)	4.6
1997	19	23 (69)	0,2	0,1	0,0	4.3 (39.3)	103 (21308)	1180 (8370)	9.7
1998	22	8 (61)	1,0	0,0	0,0	5.6 (41.2)	102 (20541)	1360 (8470)	3.4
1999	24	17 (55)	1,4	0,3	0,9	4.2 (40.7)	103 (21361)	1210 (8680)	7.1
2000	24	7 (56)	13,0	0,0	0,0	3.2 (51.8)	101 (18894)	770 (9780)	2.9
2001	32	8 (58)	2,6	0,4	0,1	2.2 (47.7)	102 (20430)	640 (9740)	3.4
2002	21	39 (57)	5,5	1,1	2,3	6.8 (40.3)	104 (20780)	1790 (8370)	16.4
2003	21	7 (51)	5,6	0,3	0,1	3.3 (39.8)	104 (22453)	1100 (8940)	2.9
2004	22	7 (43)	1,7	0,1	0,0	3.0 (43.1)	102 (22436)	910 (9680)	2.9
2005	22	15 (56)	0,1	0,1	0,0	0.6 (48.9)	101 (24236)	270 (11860)	6.3
Mean	22	16 (52)	1,9	1,8	0,4	2.9 (41.8)	103 (18635)	810 (7830)	6.6

[1)] The increase was achieved by a fungicide treatment just before/during heading.
[2)] Yield loss according to the formula by Cook et al. 1991, y=0.42 * xii [y=percentage loss in grain yield and xii=percentage disease leaf 2 (flag-1), in the range 0-45%].
[3)] Fungicide efficacy, %.

Table 2. Frequency of yield increases from a fungicide treatment during growth stages DC 45-61, classes (I-XI) in 250 kg ha^{-1} steps in field trials in southern Sweden during 1983-2005. Shaded area represents classes with at least 50% of the trials of that year

Year	No.[1)]	I <249 kg ha^{-1}	II 250-499 kg ha^{-1}	III 500-749 kg ha^{-1}	IV 750-999 kg ha^{-1}	V 1000-1249 kg ha^{-1}	VI 1250-1499 kg ha^{-1}	VII 1500-1749 kg ha^{-1}	VIII 1750-1999 kg ha^{-1}	IX 2000-2249 kg ha^{-1}	X 2250-2499 kg ha^{-1}	XI >2500 kg ha^{-1}
		Yield increases from a fungicide treatment during growth stages DC 45-61 during 23 years (1983-2005) and several field trials[1)] each year divided into 11classes (I-XI) in accumulated steps of 250 kg ha^{-1} in yield increase.										
1983	13	2	5	1	3	1	1	0	0	0	0	0
1984	18	0	6	0	8	3	1	0	0	0	0	0
1985	13	2	7	3	1	0	0	0	0	0	0	0
1986	7	3	2	0	1	0	0	1	0	0	0	0
1987	7	0	0	0	1	0	1	1	0	2	1	1
1988	5	0	0	1	3	1	0	0	0	0	0	0
1989	14	8	4	1	0	1	0	0	0	0	0	0
1990	11	1	0	0	3	2	2	1	1	0	0	1
1991	12	0	2	2	3	3	2	0	0	0	0	0
1992	6	3	3	0	0	0	0	0	0	0	0	0
1993	3	1	1	1	0	0	0	0	0	0	0	0
1994	12	7	4	1	0	0	0	0	0	0	0	0
1995	47	13	15	10	6	1	0	2	0	0	0	0
1996	65	12	5	5	8	14	6	7	2	3	1	2
1997	63	2	3	9	12	11	8	9	5	3	1	0
1998	36	0	1	3	8	6	4	4	4	3	3	0
1999	34	1	2	7	5	2	8	3	0	3	2	1
2000	37	4	6	6	9	6	4	1	1	0	0	0
2001	93	24	14	14	15	10	5	8	3	0	0	0
2002	107	2	5	2	6	10	14	8	15	17	8	20
2003	94	0	7	16	16	21	17	9	8	0	0	0
2004	36	6	5	4	4	8	2	2	5	0	0	0
2005	31	16	7	5	1	1	1	0	0	0	0	0
All years	764	107	104	91	113	101	76	56	44	31	16	25

[1)] No. = Number of field trials or different varieties and nitrogen levels within a field trial, treated with a fungicide just before or during heading.

Table 3. Percentage LBDs % (including *S. tritici, S. nodorum, D. tritici-repentis*), powdery mildew and brown rust, 1000 grain weight (TGW, g) and yield increase (kg ha^{-1}) discriminated into five untreated yield levels[1)] 1983-2005. SNK-test[2)] in each column marked by letters, P<0.05

Yield in untreated kg ha^{-1}	LBDs on leaf 3 DC 55 %	leaf 2 DC 75 %	Powdery mildew %	Brown rust %	TGW g	Yield Increase[3)] kg ha^{-1}
3330- 6990	6.4 a	22.0 a	2.0 bc	1.3 a	37.2 d	1010 a
7000- 7990	4.6 ab	17.8 ab	1.7 c	0.8 a	40.7 c	1010 a
8003- 8970	3.4 bc	14.8 bc	3.0 abc	1.3 a	40.9 c	1070 a
9010- 9970	2.3 c	13.4 bc	3.6 ab	0.6 a	43.0 b	1060 a
10020-13520	1.6 c	10.2 c	4.1 a	0.3 a	46.9 a	800 b
P	0.000	0.000	0.001	0.060	0.000	0.005

1) No. of entries in each yield level: ~100 to 150.

2) Student-Newman-Keuls procedure or multiple range test was used to compare different means. Means with different letters within columns differ significantly.

3) Yield increase achieved by fungicide treatment just before/during heading.

Table 4. Actual yield increases (kg ha^{-1}) obtained from a fungicide treatment at GS 45-61 at five disjunctive LBDs disease severities including Septoria tritici blotch, Stagonospora nodorum blotch and tan spot on leaf 2 at GS 75 during 1983-2005 in southern Sweden at two different yield levels based on the yield in fungicide treated plots. N= no. of entries

Severity of LBDs on leaf 2 at GS 75	Yield increase (kg ha^{-1}) in fungicide-treated field plots with yield levels less than 9250 kg ha^{-1}	Yield increase (%) in fungicide-treated field plots with yield levels less than 9250 kg ha^{-1}	Yield increase (kg ha^{-1}) in fungicide-treated field plots with yield levels more than 9250 kg ha^{-1}	Yield increase (%) in fungicide-treated field plots with yield levels more than 9250 kg ha^{-1}	P-value for differences between yield levels
> 0%	860 (N=286)	10.9	1130 (N=312)	10.6	0.0001
> 5%	970 (N=192)	12.3	1230 (N=225)	11.4	0.0001
>10%	1050 (N=141)	13.5	1340 (N=159)	12.6	0.0001
>15%	1130 (N=110)	14.5	1430 (N=106)	13.5	0.0030
>20%	1210 (N= 87)	15.5	1480 (N= 79)	14.1	0.0210

Table 5. Actual yield increases (kg ha^{-1}) obtained from a fungicide treatment at GS 45-61 at five disjunctive LBDs disease severities including Septoria tritici blotch, Stagonospora nodorum blotch and tan spot on leaf 2 at GS 75 during 1983-2005 in southern Sweden at two different yield levels based on the yield in untreated plots. N= no. of entries

Severity of LBDs on leaf 2 at GS 75	Yield increase (kg ha^{-1}) in fungicide-treated field plots with yield levels less than 8250 kg ha^{-1}	Yield increase (%) in fungicide-treated field plots with yield levels less than 8250 kg ha^{-1}	Yield increase (kg ha^{-1}) in fungicide-treated field plots with yield levels more than 8250 kg ha^{-1}	Yield increase (%) in fungicide-treated field plots with yield levels more than 8250 kg ha^{-1}	P-value for differences between yield levels
> 0%	1050 (N=300)	13.2	940 (N=298)	8.9	0.045
> 5%	1180 (N=213)	14.5	1030 (N=204)	9.6	0.041
>10%	1260 (N=167)	15.5	1140 (N=133)	10.5	0.141
>15%	1330 (N=129)	16.4	1190 (N= 87)	11.2	0.173
>20%	1390 (N=105)	17.0	1250 (N= 61)	11.7	0.235

Table 6. Variance component analyses for nine variables, including LBDs (including *S. tritici, S. nodorum, D. tritici-repentis*), with year as random factor[1)]

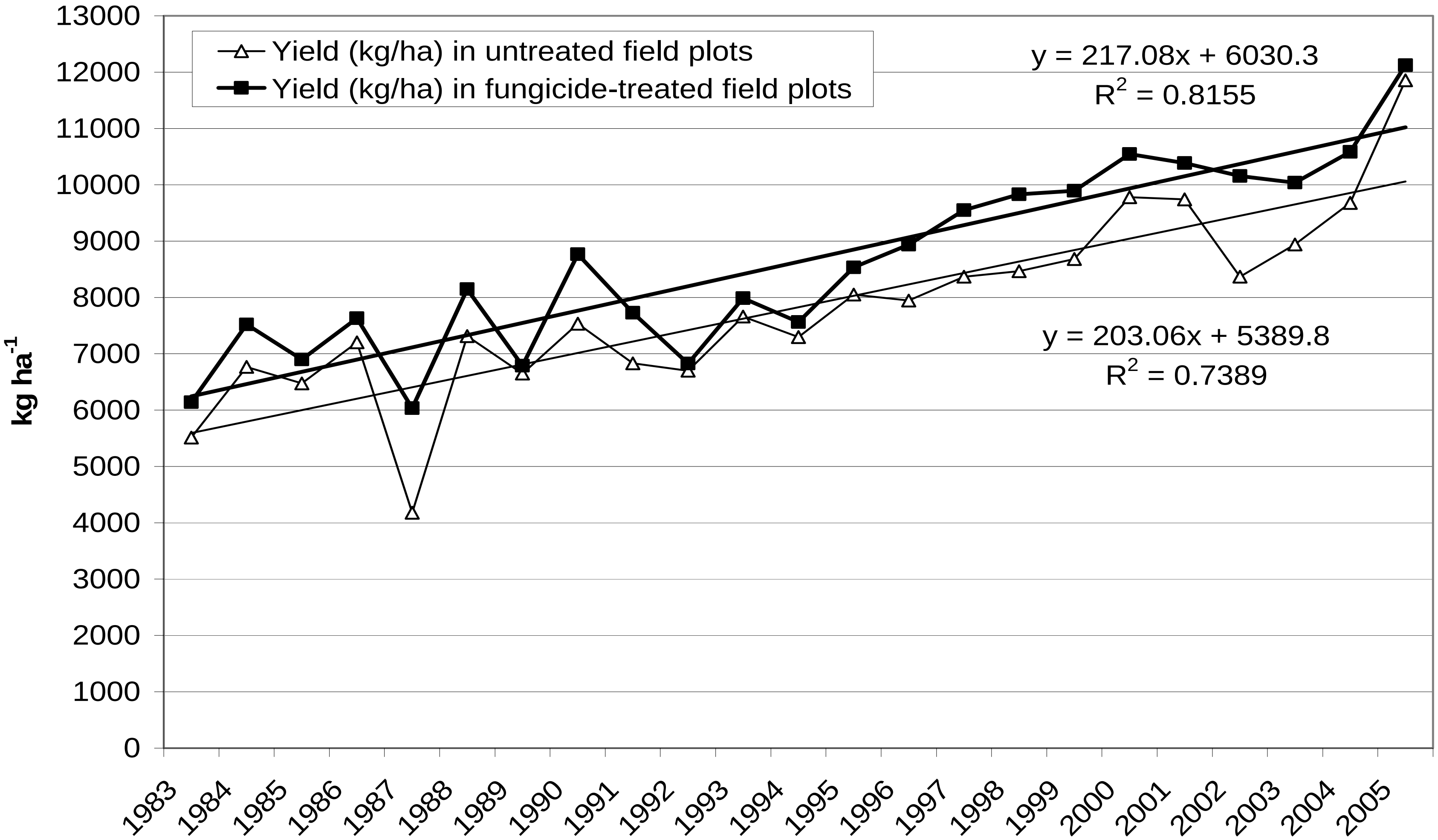
Dependent variables	No. of entries	Var(Year)[2)]	Var(Error)[3)]
Yield	764	57	43
Yield increase	764	40	60
1000 grain weight (TGW)	700	56	44
Lodging	711	18	82
LBDs on leaf 3 at DC 55	593	28	73
LBDs on leaf 2 at DC 75	598	43	57
LBDs, maximal attack	707	39	61
Control of LBDs	707	31	69
Eyespot	131	43	57
Powdery mildew	711	25	75
Yellow rust	514	26	74
Brown rust	563	48	52

[1)] GLM, var(year) and var(error). Method: Restricted Maximum Likelihood Estimation (REML).
[2)] Estimates of the variance (%) attributed to differences between years.
[3)] Estimates of the variance (%) attributed to differences within years.

Figure 1. Yield (kg ha^{-1}) in Swedish winter wheat field trials carried out in southern Sweden during 1983-2005. Yield in untreated field plots marked Δ and yield in fungicide-treated (once GS 45-61) field plots marked ■. Lines show linear estimates of yield from untreated and treated field plots with equations and R^2-values.

Figure 2. LBD (*S. tritici, S. nodorum, D. tritici-repentis*) severity (%) on leaf 2 (flag leaf = leaf 1) at different growth stages (GS) in untreated plots during 1987, 2002, 1997, 2004, 1994 and 1992.

Figure 3. Yield increase (kg ha^{-1}) due to a fungicide treatment at GS 45-61 and percentage attack of LBDs (*S. tritici, S. nodorum, D. tritici-repentis*) on leaf 3 at GS 55 (Δ) and on leaf 2 at GS 75 (■) in southern Sweden, on average for each year 1983-2005. Bars showing standard deviation for yield increase.



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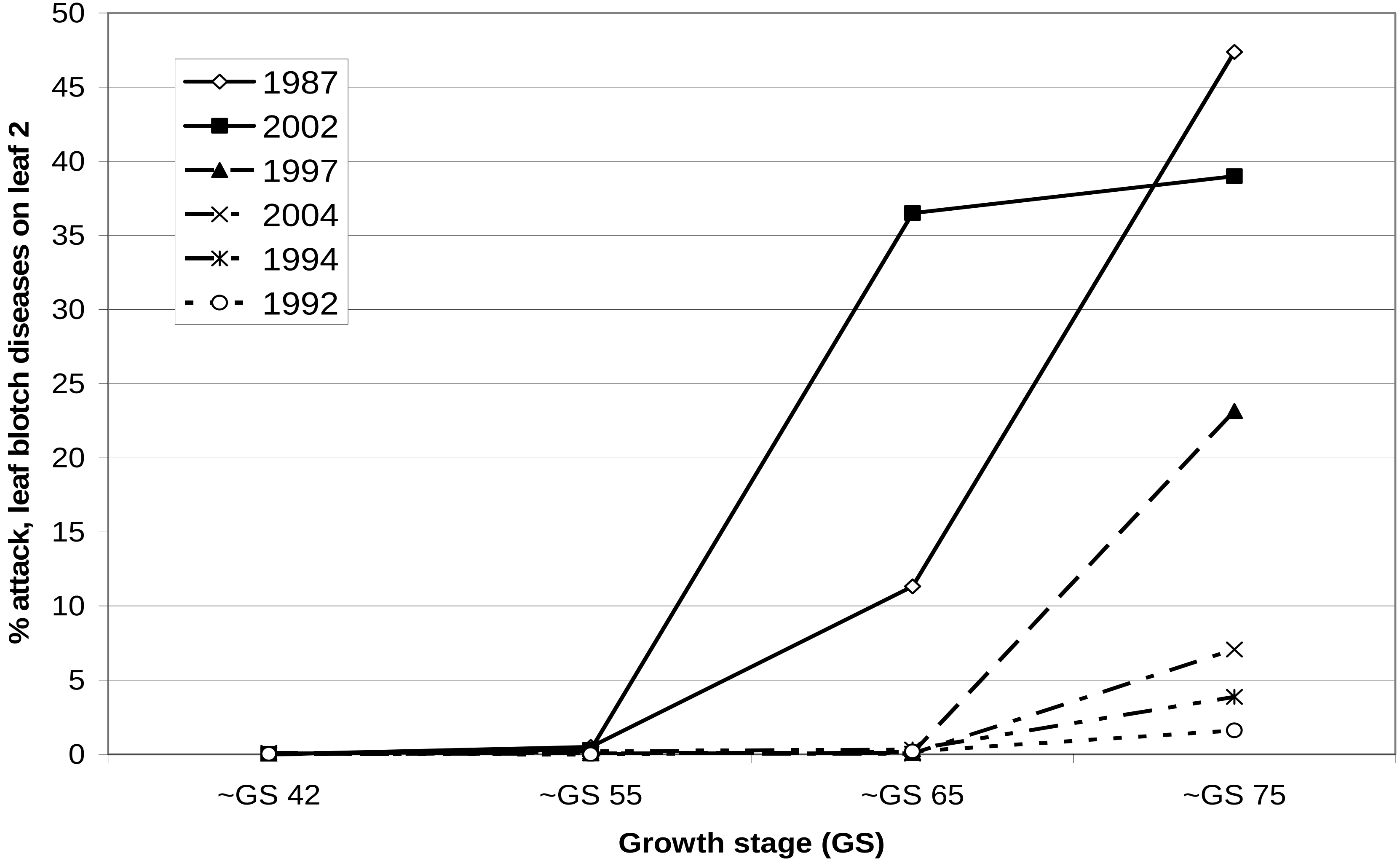

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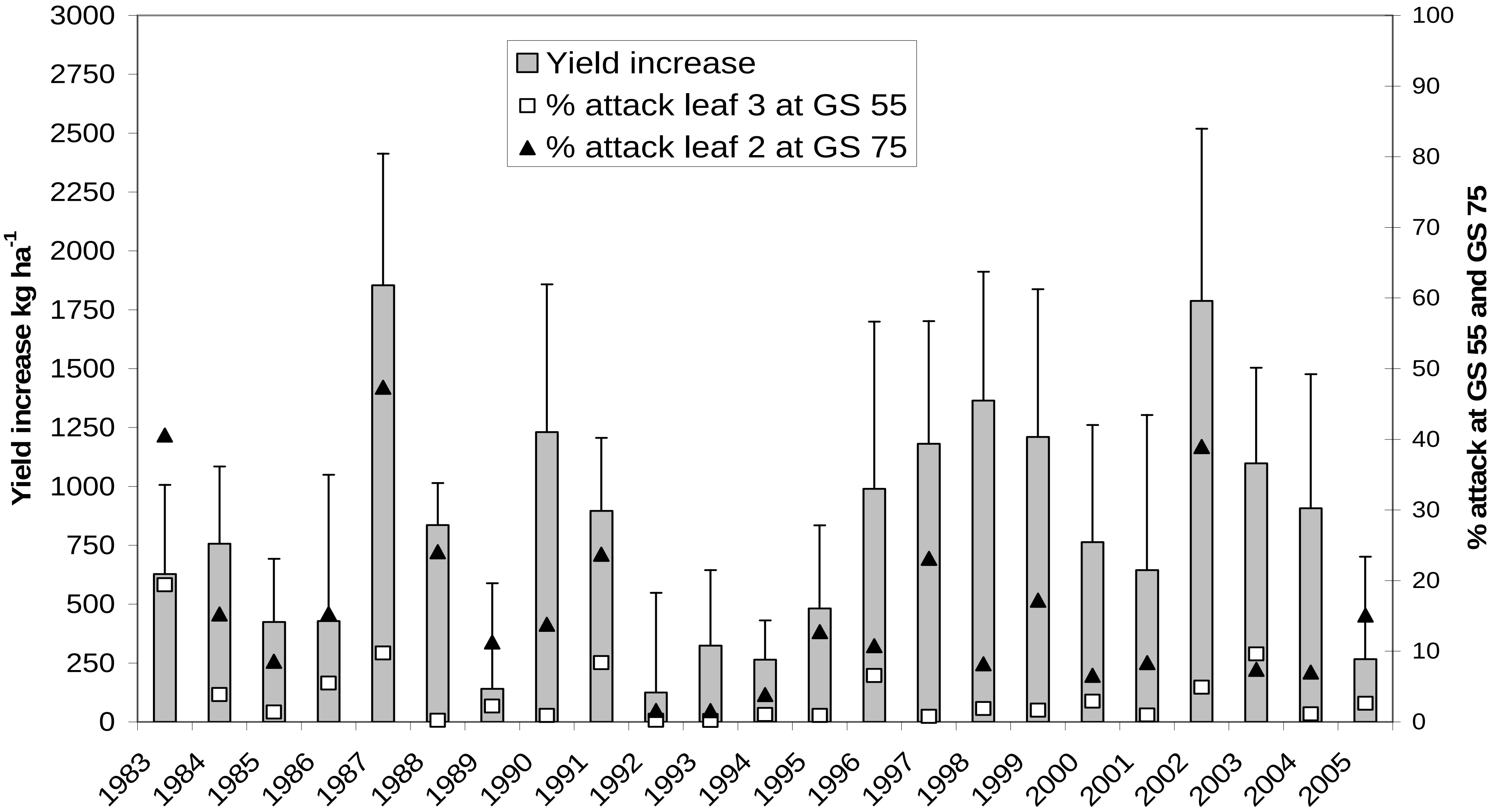

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