Citation for the published paper:
Wiik, L., Ewaldz, T. (2009) Impact of temperature and precipitation on yield and plant diseases of winter wheat in southern Sweden 1983-2007. *Crop Protection*. Volume: 28 Number: 11, pp 952-962.
http://dx.doi.org/10.1016/j.cropro.2009.05.002

Impact of temperature and precipitation on yield and plant diseases of winter wheat in southern Sweden 1983-2007

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Abstract

Weather factors are driving forces in plant disease development and differ between years and locations. Results from long-term fungicide field trials 1983-2007 and disease surveys 1988-2007 in winter wheat in southern Sweden were used to evaluate relationships between yield, the yield increase obtained by fungicide treatment, thousand grain weight (TGW), disease severity and disease incidence, and the independent variables air temperature and precipitation as monthly means. These two weather variables explained more than 50% of the variation between years regarding yield increase, TGW, LBDs (Leaf Blotch Diseases, including Septoria tritici blotch, Stagonospora nodorum blotch and tan spot), brown rust, yellow rust and eyespot, but less than 50% of the variation in yield and powdery mildew. Precipitation in May was the factor most consistently related to LBD disease intensity, and adding another two weather factors further improved the degree of explanation. Weather factors in the preceding growing season influenced growth stage, powdery mildew and brown rust. Mild winters and springs favoured the biotrophics such as powdery mildew, brown rust and yellow rust. Statistically significant correlations between incidence and severity were found for LBDs, brown rust and eyespot, but not for yellow rust and powdery mildew. Regression models with disease incidence as dependent variable generally had a higher degree of explanation and lower P-value than models with disease severity as dependent variable. Our results confirm that weather data can be successfully used in wheat disease prediction models.

Keywords: climate, weather, rain, *Septoria tritici*, fungicide, disease prediction, forecasting.

1. Introduction

Plant disease is governed by a number of factors, some of which can be controlled by farmers (Campbell and Madden, 1990). Resistance breeding against fungal diseases of wheat can give significant results (Bockus *et al*., 2001). However, the varieties currently in use are not resistant to all important diseases. Furthermore, fungi normally adapt to new varieties and overcome resistance. The impact of disease can be reduced by agricultural practices such as crop rotation and sowing date, but cannot be fully controlled in epiphytotic situations. Many important diseases of winter wheat are effectively controlled by fungicides and fungicide use has therefore been standard procedure in many countries for decades (Cook and Thomas, 1990). Fungicide use needs to take into account the crop protection requirements of the farmer and the environmental aspirations of society at large. Both are met if fungicide use can be restricted to clearly justifiable situations.

Disease prediction can help in decisions on whether fungicide treatment is worthwhile and, if so, when and how fungicides should be used (Milne *et al*., 2007). As weather factors are driving forces in plant disease development they are essential in plant disease prediction, including the effect of weather on different parts of the disease cycle – dormancy, reproduction, dispersal and pathogenesis (Polley and Clarkson, 1978; De Wolf and Isard, 2007). The influence of the weather on diseases of winter wheat has been the subject of a great many studies, but further studies are needed to carefully evaluate relationships and provide information useful to farmers (Coakley *et al*., 1988; Pietravalle *et al*., 2003; Gladders *et al*., 2007; Te Beest *et al*., 2008). Prediction accuracy will probably be improved if disease intensity is included in the models proviso sampling and methods of measurement are appropriate (Polley and Clarkson, 1978). Disease intensity has to be measured in some way, and as incidence is less tedious and faster to measure than severity, incidence would probably be preferable unless severity is a much better predictor (McRoberts *et al*., 2003).

This study evaluated long-term relationships between yield of winter wheat and temperature/precipitation, and relationships between plant disease attack and temperature/precipitation in southern Sweden, with the aim of providing useful forecasts and warnings on plant diseases of winter wheat and thereby optimising fungicide input. Plant diseases included in the evaluation were Leaf Blotch Diseases [LBDs, including Septoria tritici blotch caused by *Mycosphaerella graminicola* (anamorph *Septoria tritici* – the major leaf blotch disease in Sweden), Stagonospora nodorum blotch caused by *Phaeosphaeria nodorum* (anamorph *Stagonospora nodorum*), tan spot caused by *Pyrenophora tritici-repentis* (anamorph *Drechslera tritici-repentis*)], powdery mildew caused by *Blumeria graminis*, brown rust caused by *Puccinia triticina*, yellow rust caused by *Puccinia striiformis* and eyespot caused by *Oculimacula acuformis* and *Oculimacula yallundae*. In addition, the use of disease severity and disease incidence as predictors was compared and the potential use of weather factors in plant disease prediction was evaluated.

2. Materials and methods

2.1. Weather

Temperature and precipitation data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI, www.smhi.se). Weather stations in the main agricultural areas in southern Sweden (Scania) were chosen, i.e. the same areas in which the field trials and surveys were carried out. Temperature and precipitation data from the following 36 stations were pooled to produce a mean value for each month and year for southern Sweden during 1983-2007: Temperature (position in Scania/SMHI station no): S.W./5223, 5235, 5336; Lund/5343; S.E./5430; N.E./5455, 6402, 6403, 6413; Helsingborg/6203, 6204; N.W./6214, 6218, 6219. Precipitation: Landskrona/5252; Trelleborg/5323; S./5326, 5332, 5340; Skurup 5328; Malmö/5336; Björnstorp/5338 and Vomb/5341; Lund/5343; Stehag/5354 and Svalöv/5356; S.E./5423, 5429, 5430, 5431; N.W./6202, 6203, 6204, 6205; N.W./6209, 6212, 6213, 6214, 6215, 6219; N.E./6401, 6403, 6405, 6408.

2.2. Study site

The county of Scania (55°23’-56°25’N, 12°50’-14°31’E) is the southernmost part of Sweden and comprises 11 035 km^2 in area compared with 410 335 km^2 for the whole country. 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 1/4 of the Swedish winter wheat of about 275 000 ha was grown in Scania during 1983-2007 (www.sjv.se, accessed February 2009). Cultural practices in commercial fields and the varieties used in southern Sweden are presented in an earlier paper (Wiik, 2009).

2.3. Growth stages

In assessment of crop stands, growth stages (GS) according to Tottman and Broad (1987) for a crop stand 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 completed (GS 69)]; Milk development [caryopsis (kernel) water ripe (GS 70) to late milk (GS 79)].

2.4. Surveys

Disease surveys and forecasts were carried out in southern Sweden (Scania) in about 55 winter wheat fields per year during the period 1988-2007. Each field contained an 18-24 m x 25 m marked plot in which no treatment with fungicides or insecticides was allowed but the plot was treated similarly to the rest of the field in every other respect. Crop growth stage (GS) and disease incidence of LBDs (assessed collectively), powdery mildew, yellow rust and brown rust were recorded every week from late April to early July (~GS 24 to ~GS 75). Irrespective of leaf level, disease incidence was assessed on the upper three leaves of 17 randomly collected straws. Due to this method of assessment, disease incidence very seldom reached 100%. If needed, disease incidence and growth stage were linearly estimated. An eyespot index was calculated from assessments on samples taken in July at ~GS 75 as 0.25 x (% weakly attacked tillers) + 0.5 x (% moderately attacked tillers) + 1.0 x (% severely attacked tillers). Each of these approximately 55 plots represented ~1700 hectares of wheat and the varieties in the plots were representative of regional use. In later years, untreated plots in variety trials and in fungicide trials were included in the disease surveys.

2.5. Field trials

In this study, data from 432 field trials of winter wheat in 1983-2005 as reported in an earlier paper (Wiik, 2009) and supplementary data from 14 field trials performed in 2006-2007 were used. Yields from untreated and fungicide-treated plots (a single treatment at GS 45-61), thousand grain weight (g) and disease severity (proportion of plant tissue affected by disease) were used in the analyses. Disease severity variables included were percentage damage to flag leaf (F), leaf 2 (F-1) and leaf 3 (F-2) for LBDs, powdery mildew, yellow rust, brown rust and, for eyespot, a disease index. The field trials were carried out on farms comprising more than 30 varieties. Different yield attributes were measured but in the present study we have chosen to use only yield and thousand grain weight reported at 15% water content (Wiik, 2009).

2.6. Severity and incidence

Plant disease severity from field trials was compared with plant disease incidence from surveys. Assessments of severity and incidence were not carried out on the same plants or in the same fields. However, the comparison was considered justified due to the uniformity of the study site and the fact that the field trials and surveys were carried out in the same parts of the region. Weather factors from models established from severity data were tested on incidence data and *vice versa*.

2.7. Statistical methods

Following ANOVA, the Student-Newman-Keuls multiple range test (SNK-test) was used to compare means. Correlation, stepwise regression and regression (SPSS ver. 16.0) were used to analyse the results (Hawkins, 2005). Yearly means of yield, thousand grain weight, disease severity (in field trials, N=25) and disease incidence (in survey plots, N=20) were used as dependent variables, respectively, and monthly mean temperature and precipitation as independent variables. The best regression models from a statistical point of view were chosen (highest R^2 and $P<0.01$ with the exception of the eyespot model ($P=0.034$)). The models are based on the results of the stepwise regressions, sometimes including one or two additional weather factors. As a rule, monthly mean temperature and precipitation for the entire growing season (usually Sep-Aug) were used. Likewise, mean temperature and precipitation for the month of August in the year of sowing were included in the correlation analyses. Only weather factors that preceded a potential fungicide treatment were used in the models. No more than three weather factors were used in any model. Temperature and precipitation from the same month were not used in the same model due to possible cross-correlations. More than one model is presented for some dependent variables due to the possibility of earlier predictions.

2.8. Designations

Mean temperature (T) and precipitation (P) for a specific month are abbreviated to Jan (January) T, Jan P, Feb T etc., the month of August before sowing to Aug^{-1} and growth stage to GS. Yield increase is defined as fungicide-treated yield minus untreated yield, and thousand grain weight is abbreviated to TGW. Disease incidence (I) and severity (S) relationships are referred to as I-S relationships. In correlation analysis, the Pearson correlation coefficient is denoted r. In stepwise regression the determination coefficient or degree of explanation is designated R^2 and the sign of coefficient is given in the Tables. Probability is abbreviated to P.

3. Results

3.1. Weather

The lowest mean temperature was recorded in February (0.5 °C) and the highest in July (17.3 °C) (Figure 1). Mean annual precipitation was 664 mm per year during the 25-year period. Precipitation for a specific month varied considerably between years. The amount of precipitation and the standard deviations were highest in June, July, August and September with a mean of 66.2 mm per month and lowest in February, March, April and May with a mean of 40.7 mm per month (Figure 1). No statistically significant trend in temperature or precipitation was observed during the 25-year period.

3.2. Growth stages and weather

Mean sowing date for winter wheat in southern Sweden was 18 September (range 11 September - 3 October) and in spring, GS 23-24 was usually reached at the end of April. During the first two to three weeks of May growth stages proceeded slowly and the crop remained in GS 30-32. During approximately two months, from late May to early July, growth was rapid, and GS 80 was eventually reached when dough development started (Figure 2). Development of winter wheat, defined as the day number or Julian day when a specific growth stage was reached, was especially dependent on Aug^{-1} P (month before sowing of winter wheat), Sep T (the month of sowing) and May T. According to correlation analyses, all these factors were significant at $P<0.01$ level (not shown in tables). In stepwise regression, GS development was consistently dependent on temperature (Table 1), being approximately two days earlier for each °C increase in mean temperature in September and more than three days earlier for each °C increase in mean temperature in May.

3.3. Yield, TGW and weather

Mean temperatures in September and April were the only weather factors with a statistically significant correlation to yield (Table 2). In stepwise regression, with untreated yield as the dependent variable, Sep T was the most important weather factor, while with fungicide-treated yield as the dependent variable, Sep T plus Feb P were the most important weather factors (Table 1). The best degree of explanation in regression, with untreated yield and fungicide-treated yield as the dependent variables, was achieved with the weather factors Sep T + Feb P + Mar T (R^2=0.35, P=0.019), and Sep T + Feb P + Mar P (R^2=0.41, P=0.011), respectively (not shown in tables). Adding Jun P as a fourth weather factor to the regression model considerably improved the degree of explanation (R^2=0.67, $P<0.001$).

Jun P was the only weather factor with a significant correlation to yield increase (Table 2). In stepwise regression, Jun P + Dec T + Nov T were the most important weather factors for yield increase (Table 1). The best degree of explanation was found in a regression model with yield increase as the dependent variable and Jun P, Dec T and Feb P as the independent weather factors (Table 3, footnote a). Actual and predicted yield increase (Table 3) were significant correlated (r=0.55, P=0.005).

TGW of the yield from both untreated and fungicide-treated plots was significantly correlated to May T and to May P (Table 2). In stepwise regression, May T was the most important weather factor with TGW from untreated plots as the dependent variable, whereas May T and Jun T were the most important factors with TGW from fungicide-treated plots as the dependent variable (Table 1). More than 50% of the variation in TGW was explained using Dec T, May T and Jun T in regression analysis (R^2=0.51, P<0.001).

3.4. LBDs and weather

Using severity data Wiik (2009) showed LBDs to be the most devastating diseases of winter wheat in southern Sweden, and this was confirmed by incidence data in the present study (Figure 3). Different severity assessments at different growth stages were significantly correlated to May P and May T (Table 2). Incidence of LBDs at GS 45 and 65 was also significantly correlated to May P and May T (not shown in tables). Significant correlations to May P and May T also appeared when incidences in different growth stages or severity of different leaf levels were added [Table 2, LBDs GS 45-75 (I) and LBDs leaf 1-3 (S)]. Furthermore, incidence at GS 55 was significantly correlated to Jan T, Dec T, Dec P and Mar P, incidence at GS 75 to Jan T, and incidence at GS 45-75 to Jan T and Dec T. In stepwise regression, May P was the most important weather factor explaining the intensity of LBDs, followed by Feb P, Apr P, Apr T and Jun P depending on the LBD-dependent variable chosen (Table 1). May P was an important independent weather factor in three models for prediction of LBDs, two with LBD incidence at GS 45 and 55 as the dependent variables and one with LBD severity at GS 55 as the dependent variable. By adding weather data from another two months the degree of explanation was further improved (Table 3, footnotes b, c and d). The correlations between actual and predicted LBDs in the three models in Table 3 were high ($r=0.76$, $P<0.001$; $r=0.69$, $P<0.001$; and $r=0.83$, $P<0.001$, respectively).

3.5. Powdery mildew and weather

Using severity data Wiik (2009) found powdery mildew to be the second most important disease of winter wheat after the LBDs in southern Sweden, and this was confirmed by incidence data in the present study (Figure 3). Incidence of mildew shown at five different growth stages was significantly correlated to the Aug^{-1} T at GS 39, 65 and 75 (Table 4). Furthermore, mildew incidence was significantly correlated to May P at GS 39, to Jan T at GS 65, and to Dec T, Jan T, Mar P and May P at GS 75. Severity of mildew at maximum attack was significantly correlated to Sep T. In stepwise regression, with incidence data as the dependent variable, Jan T, May P, and Jan T and Jul T were the most important weather factors, whereas Sep T was the most important for severity data (Table 5). The best degree of explanation was shown for a model based on severity data with autumn weather factors ($R^2=0.42$, $P=0.023$). However, the variation explained by this model was quite poor and it is not included in the tables.

3.6. Brown rust and weather

Brown rust was usually of minor importance (Figure 3) but in some years (e.g. 1990 and 2007) the incidence was high (Table 6). Incidence of brown rust at GS 75 was significantly correlated to Aug^{-1} P as well as Jan T and Jan P (Table 4). Severity of brown rust at maximum attack was also significantly correlated to Aug^{-1} P. In stepwise regression with incidence data as the dependent variable, Apr T or Jan T was found to be the most important factor, whereas

Jul P and Dec P were the most important with severity data as the dependent variable (Table 5). The model based on incidence data at GS 65 as the dependent variable and the independent weather factors Apr T, Mar P and Feb T accurately predicted three years (1990, 1993 and 2007) with high actual incidences of brown rust (Table 6, footnote a). The prediction accuracy of the model based on severity data was quite poor (not shown in tables). The correlation between actual and predicted brown rust (Table 6) was statistically significant (r=0.73, P<0.001). Actual and predicted brown rust intensity diverged in a few years in all models.

3.7. Yellow rust and weather

Yellow rust was usually of minor importance (Figure 3) but in some years (1990, 1999, 2002 and 2007) the disease occurred at a high severity and incidence (Table 6). Incidence of yellow rust at GS 75 was significantly correlated to Mar T and Feb T (Table 4). Severity of yellow rust at maximum attack was significantly correlated to Feb P, Jan P and Jun T. In stepwise regression Feb T and Mar T were found to be the most important factors with incidence data as the dependent variables, and Feb P with severity data as the dependent variable (Table 5). The model in Table 6 (footnote b) with incidence data as the dependent variable and Mar T, Nov P and Oct T as the independent weather factors correctly predicted four years (1989, 1990, 1999 and 2007) with high actual incidence of yellow rust. The model in Table 6 (footnote c) with severity data as the dependent variable and Feb P, Jan P and May T as the independent weather factors quite accurately predicted four years (1988, 1989, 2002 and 2007) with high actual severity of yellow rust, but the predicted values were higher than the actual levels in some years. Actual and predicted yellow rust intensity (Table 6) were significantly correlated, both with incidence (r=0.47, P=0.037) and with severity data (r=0.68, P<0.001). Actual and predicted yellow rust intensity diverged in a few years in all models.

3.8. Eyespot and weather

Actual mean eyespot index in the disease survey plots 1988-2007 was quite low in most years and high only in a few years (1990, 1991 and 2001) (Table 6). Eyespot index in the disease survey plots was significantly correlated to Jun T and Nov P, and in the field trials to May P (Table 4). In stepwise regression, with eyespot index in the survey plots as the dependent variables, Jun T plus Nov P or Nov P and Jan T were found to be the most important weather factors, while with eyespot index in the field trials as the dependent variable Nov P was found to be the most important weather factor (Table 5). The models tested were not very accurate, with the exception of the model '% straws with Eyespot index >25', which correctly identified several years with low eyespot attacks, i.e. a negative prognosis (Table 6, footnote d). However, the correlations between the predicted eyespot index of the models and actual eyespot index (Table 6) were not statistically significant.

3.9. Severity and incidence

The correlation between incidence and severity of brown rust was statistically significant (r=0.79, P<0.001). Furthermore, the correlation between incidence and severity of LBDs at GS 55 was statistically significant (r=0.55, P=0.012). However, no statistically significant correlation was found between incidence and severity of yellow rust and between incidence and severity of powdery mildew. The weather factor May P was particularly important in two three-factor models of LBDs based on incidence as the dependent variable (Table 3, footnotes b and c) and in one three-factor model with severity as the dependent variable (Table 3, footnote d). In the two models based on incidence, Oct P and Feb T, and Jan T and Dec P were the second and third weather factors, respectively, whereas Feb P and Apr P were the second and third factors in the model based on severity. The two models based on incidence (Table 3, footnotes b and c) gave higher degrees of explanation than the model based on severity (Table 3, footnote d). The most important weather factors for the yellow rust model based on incidence were in autumn (Nov P and Oct T) and early spring (Mar T) (Table 6, footnote b), whereas the model based on severity was coupled to winter factors (Feb P and Jan P) and spring factors (Apr T and May T) (Table 6, footnote c). The I-S relationship for LBDs was reciprocal, i.e. weather factors in models for LBDs based on severity could be successfully used to explain the actual incidence of LBDs at GS 45 and GS 55, but in the corresponding comparisons for mildew, brown rust, yellow rust and eyespot no reciprocal relationships were found.

Discussion

Our best three-factor regression model for yield after fungicide treatment, which used the independent weather factors Sep T, Feb P and Mar P, predicted yields fairly accurately. Thus, high yield was promoted by a warm September that gave the crop a good start and good water saturation in February in good time for tillering to support growth. Furthermore, the degree of explanation was considerably improved when Jun P was included in the model, demonstrating the importance of precipitation during booting, inflorescence emergence and anthesis. Weather conditions including the critical meteorological variables precipitation, air temperature and solar radiation have been said to explain up to 80% of the variation in agricultural production, but grain yield also depends on edaphic, hydrological and agronomic factors (Hoogenboom, 2000). In our correlation analyses, we showed Apr T to be an important weather factor for grain yield, in agreement with Chmielewski and Potts (1995) in their evaluation of the Broadbalk long-term experiment at Rothamsted, i.e. a high T_{max} in April appeared to favour plant development after winter. In our correlation analysis Sep T was also a strong factor, probably due to the fact that a high Sep T results in a high soil temperature, which promotes germination and seedling growth as described by Hoogenboom (2000). The lower yields in 2006 and 2007 compared with yields during the latter part of the period 1983-2005 (Wiik, 2009) might be due to a very high intensity of LBDs in 2006 and an extremely high precipitation the month before sowing in 2006.

The strong correlation between LBDs and May P in the present study is in agreement with several other studies. Precipitation promotes disease spread and development (Shaner and Finney, 1976; Coakley *et al*., 1985; Emmerman *et al*., 1988; Daamen and Stol, 1992; Verreet *et al*., 2000; Gladders *et al*., 2001; Pietravalle *et al*., 2003; Henze *et al*., 2007; Shaw *et al*., 2008). A well-timed fungicide treatment on emerging top leaves (F, F-1 and F-2) usually gives good protection against LBDs and promotes high yields (Shaw and Royle, 1993; Cook *et al*., 1999; Paveley *et al*., 2000). May P seemed to be an essential weather factor in our LBD models although, as proposed by Pietravalle *et al*. (2003), an early indication of *Septoria tritici* at GS 31 seems difficult to achieve. We also found a strong correlation between LBDs and May T, probably mainly due to the relationship between May T and May P ($r = -0.629$, $P<0.001$). Nonetheless, temperature has been shown to be an important variable for the progress of Septoria tritici blotch. Low temperatures during autumn and winter might delay the development of Septoria tritici blotch, e.g. by increased latent periods and reduced ascospore production (Royle *et al*., 1993; Parker *et al*., 1999; Verreet *et al*., 2000; Gladders *et al*., 2001; Henze *et al*., 2007). In the present study we found a negative correlation between the incidence of LBDs and Dec T and Jan T, and a negative coefficient on Jan T in the regression model with the highest degree of explanation. A negative relationship between annual intensity of *Septoria* spp. and sunshine duration in Aug^{-1} has been reported in the Netherlands (Daamen and Stol, 1992), indicating an effect on ascospore production. Furthermore, Shaw *et al*. (2008) found a positive relationship between *S. tritici* abundance and Jul^{-1} T and Aug^{-1} T. In our investigation we found no statistically significant correlations for such an out-of-season weather relationship with LBDs. On the other hand, we found out-of-season relationships between weather and other diseases (see below). These conflicting results call for more research on the weather dependence of LBDs. Yield increase, achieved by a fungicide treatment just before/during heading (principally directed against LBDs) was positively correlated to Jun P. This was expected, as precipitation is decisive for the disease progress of LBDs during a period of four weeks after heading (Wiik, 1993). TGW, known to be directly affected by LBDs, was found to be significantly positively correlated to May T, demonstrating the unfavourable impact of inaccurate temperatures during GS 25-40, a time for initiation and abortion of grains in the spike.

The positive correlation between powdery mildew and temperatures in Aug^{-1} and Sept might be explained by the importance of a suitable temperature for the establishment and formation of inoculum on volunteer plants, enabling the green-bridge phenomenon (Eversmeyer and Kramer, 1998). The importance of winter temperature but also precipitation during spring is supported by the results of both Daamen *et al*. (1992) and Te Beest *et al*. (2008). Brown rust correlated well to Aug^{-1} P, similar to findings by Eversmeyer and Kramer (1998), and in the present study also to Jul P and Jan T. Our findings are in agreement with Daamen *et al*. (1992) who indicated that a high Mar T probably facilitated sporulation and infection on young leaves. In our regression model based on yellow rust incidence, temperature – in the beginning of the epidemic and overwintering temperature – was important, in agreement with results from other countries (Daamen *et al*., 1992; Gladders *et al*., 2007; van den Berg and van den Bosch, 2007; Te Beest *et al*., 2008). However, in our model based on severity, winter precipitation and temperature during late spring and early summer were key factors. Besides winter temperature, precipitation was included in the model by Coakley *et al*. (1988) but they used spring precipitation, as opposed to our winter precipitation.

The negative correlations observed in the present study between eyespot index and Nov P, and eyespot index and Jun T perhaps indicate that eyespot establishment was suppressed by excessive precipitation during November, and that penetration of successive leaf sheaths was suppressed by excessive temperatures in June (Fitt *et al*., 1988). In a HGCA-funded project in the UK, Burnett and Hughes (2004) developed a risk algorithm with rainfall during spring (March, April and May) included as the only weather factor. In the present study the only statistically significant weather factor in the field trials was May P, but not Mar P and Apr P. Our models were not accurate and our results differ from those found in many other countries, e.g. Daamen and Stol (1990), and the weather factors included in our model (Nov P, Sep T and Feb T) were rejected by Burnett and Hughes (2004) in their risk algorithm. Nonetheless, we were able to predict years with low eyespot attacks. A negative forecast might be useful for other diseases too, probably as one of several models for a specific disease. Diverging data in the literature call for more research on eyespot weather dependence.

The incidence measurements from more than 50 untreated field plots per year in this study are almost certainly more representative of southern Sweden than the severity measurements from a few field trials each year. Subsequently, our models with disease incidence as dependent variable usually had a higher degree of explanation and a lower P-value than models with disease severity as a dependent variable. Incidence measurements are preferable as they are faster to perform, probably more accurate and less variable, especially if several observers are involved. I-S relationships (Seem, 1984; McRoberts *et al*., 2003) have been found in wheat diseases such as powdery mildew (James and Shih, 1973; Hughes *et al*., 2004), brown rust (James and Shih, 1973), LBDs (Shaw and Royle, 1987) and eyespot (Fitt *et al*., 1988). Our evaluation showed a statistically significant correlation between incidence and severity for LBDs, brown rust and eyespot, but not for yellow rust and powdery mildew. This was probably an effect of differences in the proportion of host resistance between varieties used in the field trials and in the survey plots, with resistance being more pronounced for powdery mildew and yellow rust than for LBDs, brown rust and eyespot. We only evaluated linear relationships, which most likely restricted possible resulting I-S relationships (McRoberts *et al*., 2003).

In this study temperature and precipitation data from weather stations in the national meteorological network were used. Coakley (1988) recommended the use of weather stations in the national meteorological network and Bourke (1970) preferred them to in-field weather stations on account of the supervision by professional personnel and the cheaper and more accurate values. The spatial distribution in monthly precipitation in southern Sweden is high (Finnander Linderson, 2002) and hence it would be more accurate to use in-field weather stations. Such stations are in use but unfortunately not during all years of the present study and not during the entire growing season, with significantly more missing values than the regular (SMHI) network. Temperature and precipitation are important meteorological variables but variables such as humidity, leaf wetness, dew period, evaporation, wind and radiation would probably increase the degree of explanation in the models. Monthly mean values, as chosen in the present study, have limitations – a biological time-scale would probably improve the models. In a previous study Wiik (1993) evaluated accumulated precipitation before heading, and found four weeks preceding GS 55 to be a better predictor of the yield increase achieved by a fungicide application than one, two or three weeks. This result guided us in choosing month as a suitable period for the analyses. In Window Pane and similar software, points in time and periods of time are identified for each meteorological variable best correlated to yield or disease intensity. Such software has been used for winter wheat diseases such as stripe rust (Coakley *et al*., 1982: Coakley *et al*. 1988; Te Beest *et al*., 2008), Septoria tritici blotch (Coakley *et al*. 1985; Royle *et al*., 1993; Pietravalle *et al*., 2003), powdery mildew (Te Beest *et al*., 2008) and common bunt (Johnsson, 1992). Pietravalle *et al*. (2003) and Te Beest *et al*. (2008) used a qualitative model to determine whether a threshold value of disease was exceeded, followed by a quantitative model predicting the severity of the epidemic. This two-step analysis seemed to work and might be a good but complicated method for future evaluations of this type of data, although concerns about spurious relationships, due to iterative searches with thousands of comparisons, have to be considered (Te Beest *et al*., 2008).

In this straightforward evaluation of data from 25 years, we demonstrated the potential for using weather factors in plant disease prediction. We found a significant impact of air temperature and precipitation on yield and on important diseases of winter wheat. Temperature during germination and seedling growth in September, and temperature during tillering in April were important for yield formation. Precipitation during tillering, stem elongation and booting was a powerful predictor for the LBDs, while temperature and precipitation in the month prior to sowing were important for growth stage development, powdery mildew and brown rust. Temperature during tillering, stem elongation and booting was important for TGW, and temperature during booting, inflorescence emergence and anthesis for yield increase in response to fungicide treatment. In most of our regression models we found incidence assessments to be better than severity assessments. Meteorological variables other than precipitation and temperature, site factors and agricultural practices are of course very important in decision support systems and forecasting models, but that were beyond the scope of this paper.

Acknowledgements

The Swedish Farmers' Foundation for Agricultural Research (SLF), the Swedish Board of Agriculture and the Swedish University of Agricultural Sciences funded this research. Field trials were carried out by the Agricultural Societies in southern Sweden. Our sincere thanks for creative discussions and critical reviews of this paper go to: Eva Johansson, Erland Liljeroth, Arnulf Merker, and Jan-Eric Englund, Gareth Hughes, Lennart Johnsson, Hans Larsson, Mary McAfee and Christer Nilsson.

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Table 1. Impact of monthly temperature (T) and precipitation (P) on dependent variables Julian year day of growth stages (GS) 31, 45, 55 and 75, Yield, Thousand grain weight (TGW), Straw strength, Severity and Incidence of leaf blotch diseases (LBDs). Stepwise regression on data from southern Sweden 1983-2007

Dependent variables	Constant	Weather factor(s)	Coefficient(s)	R^2	P-value
In surveys					
Julian day at GS 31	+180	Apr T	-3.2		
		Sep T	-1.9		
		Feb T	-0.9	0.79	0.001
Julian day at GS 45	+228	May T	-3.6		
		Sep T	-2.2	0.82	0.001
Julian day at GS 55	+233	May T	-3.5		
		Sep T	-2.1	0.84	0.001
Julian day at GS 75	+250	May T	-3.4		
		Mar T	-1.0		
		Jun T	-1.3	0.87	0.001
In field trials					
Yield, untreated	+227	Sep T	+570	0.24	0.014
Yield, fungicide-treated	+213	Sep T	+540		
		Feb P	+30	0.35	0.009
Yield increase	+130	Jun P	+8		
		Dec T	-189		
		Nov T	+114	0.61	0.001
TGW, untreated	+15.0	May T	+2.3	0.33	0.003
TGW, fungicide-treated	+34.3	May T	+3.0		
		Jun T	-1.6	0.47	0.001
Incidence (surveys)					
LBDs leaf 1-3 GS 45	+1.5	May P	+0.2	0.56	0.001
LBDs leaf 1-3 GS 55	+2.2	May P	+0.3	0.62	0.001
LBDs leaf 1-3 GS 65	-4.8	May P	+0.4		
		Apr P	+0.3	0.73	0.001
LBDs leaf 1-3 GS 75	+29.1	May P	+0.6	0.39	0.004
LBDs leaf 1-3 GS 45-75	+30.6	May P	+0.3		
		Apr T	-3.2	0.73	0.001
Severity (field trials)					
LBDs leaf 3 GS 55	+2.3	May P	+0.1		
		Feb P	-0.1	0.49	0.001
LBDs leaf 2 GS 75	+5.8	May P	+0.2	0.23	0.016
LBDs leaf 1-3 GS 70-80	+19.2	May P	+0.3		
		Jun P	+0.2		
		Apr T	-3.6	0.60	0.001

Table 5. Impact of monthly temperature (T) and precipitation (P) on the dependent variables Severity and Incidence of Powdery mildew, Brown rust, Yellow rust and Eyespot index. Stepwise regression on data from southern Sweden 1983-2007.

Dependent variable	Constant	Weather factor(s)	Coefficient(s)	R^2	P-value
Incidence (surveys)					
Mildew leaf 1-3 GS 65	+17.2	Jan T	-1.7	0.24	0.028
Mildew leaf 1-3 GS 75	+11.3	May P	+0.2	0.23	0.033
Mildew leaf 1-3 GS 31-75	+37.3	Jan T	-1.4		
		Jul T	-1.4	0.39	0.014
Severity (field trials)					
Mildew at max attack	-12.1	Sep T	+1.0	0.24	0.012
Incidence (surveys)					
Brown rust leaf 1-3 GS 65	-28.9	Apr T	+4.9	0.20	0.046
Brown rust leaf 1-3 GS 75	+6.3	Jan T	+4.1	0.26	0.022
Severity (field trials))					
Brown rust max attack	-3.55	Jul P	+0.04		
		Dec P	+0.05	0.40	0.004
Incidence (surveys)					
Yellow rust leaf 1-3 GS 45	+0.1	Feb T	+0.5	0.20	0.047
Yellow rust leaf 1-3 GS 55	+0.3	Feb T	+1.2	0.26	0.022
Yellow rust leaf 1-3 GS 65	-3.8	Mar T	+2.3	0.29	0.013
Yellow rust leaf 1-3 GS 75	-3.2	Mar T	+2.5	0.30	0.012
Yellow rust leaf 1-3 GS 31-75	-2.0	Mar T	+1.3	0.27	0.018
Severity (field trials)					
Yellow rust at max attack	-0.71	Feb P	+0.03	0.33	0.003
In survey plots					
Eyespot index	+84.1	Jun T	-3.7		
		Nov P	-0.2	0.63	0.001
% Eyespot index ≥ 25	+221.6	Jun T	-11.0		
		Nov P	-0.4		
		Jan T	+3.1	0.72	0.001
% Eyespot index ≥ 35	+78.8	Nov P	-0.2		
		Jun T	-3.8	0.43	0.008
In field trials					
Eyespot index	+33.6	Nov P	-0.2	0.21	0.023

Table 2. Pearson coefficients for correlations between monthly temperature (T, °C) and precipitation (P, mm), and yield, thousand grain weight, straw strength, disease incidence (I) and disease severity (S) of LBDs. Significance marked with * or **, in addition see footnotes [a, b]

Monthly T and P	Yield untreated	Yield fungicide-treated	Yield increase	TGW untreated	TGW fungicide-treated	LBDs GS 55 (I) [a]	LBDs GS 55 (S) [b]	LBDs GS 75 (I) [a]	LBDs GS 75 (S) [b]	LBDs GS 45-75 (I) [a]	LBDs leaf 1-3 (S) [b]
Temperature											
Aug^{-1} T [c]	0.30	0.34	0.14	-0.01	0.01	0.36	0.15	0.27	-0.22	0.35	-0.07
Sep T	0.49*	0.46*	-0.08	0.23	0.18	-0.01	-0.07	-0.07	-0.21	-0.10	-0.17
Oct T	-0.07	-0.02	0.18	-0.14	-0.12	0.30	0.13	0.43	0.47*	0.41	0.46*
Nov T	-0.03	-0.01	0.10	-0.11	-0.08	-0.16	0.07	0.05	0.31	-0.05	0.23
Dec T	0.03	-0.09	-0.39	0.20	0.06	-0.59**	-0.24	-0.38	-0.02	-0.54*	-0.16
Jan T	0.19	0.11	-0.26	0.18	0.11	-0.69**	-0.07	-0.45*	-0.10	-0.65**	-0.20
Feb T	0.17	0.22	0.17	0.04	0.16	-0.38	-0.36	-0.24	-0.03	-0.34	-0.16
Mar T	0.06	0.06	-0.01	0.09	0.11	-0.39	-0.16	-0.34	-0.15	-0.43	-0.23
Apr T	0.37	0.40*	0.12	0.08	0.17	-0.32	-0.21	-0.28	-0.17	-0.38	-0.18
May T	0.24	0.18	-0.20	0.57**	0.56**	-0.54*	-0.40*	-0.50*	-0.36	-0.60**	-0.52**
Jun T	0.18	0.14	-0.15	0.12	-0.01	n.a.[d]	n.a.[d]	-0.23	-0.09	-0.14	-0.32
Jul T	0.20	0.10	-0.33	-0.08	-0.28	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]
Aug T	0.22	0.28	0.20	-0.27	-0.28	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]
Precipitation											
Aug^{-1} P [c]	0.15	0.16	0.02	0.16	0.16	-0.31	-0.05	-0.21	0.26	-0.30	0.10
Sep P	-0.08	-0.09	-0.06	0.06	0.03	0.01	-0.14	0.12	-0.05	0.20	0.01
Oct P	0.01	0.06	0.16	-0.22	-0.17	-0.08	0.27	0.03	0.02	-0.09	0.12
Nov P	-0.07	-0.12	-0.16	0.10	0.03	-0.34	-0.13	-0.32	-0.03	-0.38	-0.19
Dec P	-0.07	-0.13	-0.24	0.18	0.09	-0.50*	0.09	-0.37	0.05	-0.42	0.06
Jan P	0.02	0.03	0.02	0.10	0.09	-0.40	-0.14	-0.05	0.12	-0.23	-0.01
Feb P	0.26	0.37	0.39	-0.11	0.02	0.05	-0.33	0.36	0.36	0.29	0.17
Mar P	-0.11	-0.19	-0.28	0.09	0.01	-0.47*	0.08	-0.33	-0.03	-0.44	-0.07
Apr P	-0.25	-0.22	0.09	-0.27	-0.27	-0.07	0.36	0.28	0.13	0.17	0.22
May P	-0.02	0.08	0.34	-0.53**	-0.49*	0.79**	0.58**	0.62**	0.48*	0.80**	0.63**
Jun P	0.03	0.18	0.52**	-0.23	-0.02	n.a.[d]	n.a.[d]	0.42	0.32	0.18	0.37
Jul P	0.03	0.09	0.19	0.10	0.19	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]
Aug P	0.16	0.08	-0.25	0.03	-0.12	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]	n.a.[d]

[a] If $r>0.444$ then $P<0.05$, if $r>0.562$ then $P<0.01$. [b] If $r>0.396$ then $P<0.05$, if $r>0.506$ then $P<0.01$. [c] The month before sowing of winter wheat. [d] n.a. = not applicable.

Table 3. Comparison between actual and predicted (by weather factors) yield increase, severity and incidence of LBDs in southern Sweden 1983-2007

Year	Actual yield increase kg/ha field trials	Predicted yield increase kg/ha field trials [a]	Actual LBDs leaf 1-3 GS 45 incidence	Predicted LBDs leaf 1-3 GS 45 incidence [b]	Actual LBDs leaf 1-3 GS 55 incidence	Predicted LBDs leaf 1-3 GS 55 incidence [c]	Actual LBDs leaf 3 GS 55 severity	Predicted LBDs leaf 3 GS 55 severity [d]
1983	630	630	-	-	-	-	19.4	12.0
1984	760	1100	-	-	-	-	3.9	3.2
1985	420	520	-	-	-	-	1.4	4.1
1986	430	290	-	-	-	-	5.5	6.2
1987	1850	850	-	-	-	-	9.7	5.3
1988	840	730	3.8	5.0	7.1	7.8	0.2	-1.6
1989	140	540	7.4	3.4	9.9	4.6	2.2	0.1
1990	1230	720	10.6	10.3	14.3	11.6	0.9	1.0
1991	900	1180	11.2	10.8	17.8	14.3	8.4	6.1
1992	130	200	8.6	3.8	8.1	8.4	0.2	1.0
1993	320	450	3.8	3.3	3.3	5.3	0.2	0.1
1994	260	550	2.2	6.9	4.9	7.6	1.0	2.4
1995	480	1450	9.3	12.4	11.9	18.3	0.9	4.2
1996	1000	930	24.3	22.4	31.4	32.4	6.6	10.3
1997	1180	820	15.0	15.8	21.3	24.5	0.8	4.7
1998	1360	1260	6.8	4.8	10.9	10.4	1.9	2.8
1999	1210	1020	6.6	10.9	11.6	10.0	1.7	4.6
2000	770	730	4.0	8.9	3.9	12.0	2.9	2.9
2001	640	1050	1.9	6.3	4.1	10.9	1.0	3.3
2002	1790	1790	19.6	11.6	20.3	18.4	4.9	0.0
2003	1100	330	5.7	10.4	19.6	18.3	9.6	8.3
2004	910	730	10.5	4.6	17.9	13.5	1.1	1.2
2005	270	820	13.2	8.8	14.8	12.1	2.6	0.5
2006	480	0	16.4	12.0	30.9	19.9	3.1	6.5
2007	970	1260	6.4	13.7	9.9	13.2	1.6	2.1

[a] Model: Yield increase in field trials = 332 + 7.7 x Jun P - 136 x Dec T + 6.8 x Feb P (R^2=0.59, P<0.001).

[b] Model: LBDs incidence leaf 1-3 GS 45 = 2.654 + 0.207 x May P - 0.048 x Oct P + 0.568 x Feb T (R^2=0.67, P<0.001).

[c] Model: LBDs incidence leaf 1-3 GS 55 = 12.385 + 0.182 x May P - 1.178 x Jan T - 0.085 x Dec P (R^2=0.75, P<0.001).

[d] Model: LBDs severity leaf 3 GS 55 = - 0.634 + 0.109 x May P - 0.083 x Feb P + 0.074 x Apr P (R^2=0.57, P<0.001).

Table 4. Pearson coefficients for correlations between monthly temperature (T, °C) and precipitation (P, mm), and disease incidence (I) and disease severity (S) of mildew, brown rust (B rust), yellow rust (Y rust) and eyespot. Significance marked with * or **, see footnotes [a, b]

Monthly T and P	Mildew GS 39 (I) [a]	Mildew GS 45 (I) [a]	Mildew GS 55 (I) [a]	Mildew GS 65 (I) [a]	Mildew GS 75 (I) [a]	Mildew at max. (S) [b]	B rust GS 75 (I) [a]	B rust at max. (S) [b]	Y rust GS 75 (I) [a]	Y rust at max. (S) [b]	Eyespot [c]	Eyespot [d]
<u>Temperature</u>												
Aug T [e]	0.50*	0.38	0.36	0.48*	0.54*	0.10	-0.36	-0.34	-0.28	-0.37	0.08	0.32
Sep T	0.28	0.11	0.08	0.14	0.14	0.49*	0.09	0.02	0.08	-0.07	-0.05	0.30
Oct T	-0.04	-0.05	-0.06	-0.17	0.02	-0.01	0.17	0.27	0.31	0.24	0.16	0.19
Nov T	0.10	0.03	0.10	0.13	0.02	0.07	0.16	0.15	-0.11	0.00	-0.21	-0.10
Dec T	-0.18	-0.15	-0.13	-0.19	-0.45*	-0.17	0.25	0.36	-0.05	-0.03	-0.08	-0.13
Jan T	-0.43	-0.36	-0.38	-0.49*	-0.45*	0.01	0.51*	0.16	0.44	0.31	0.06	0.30
Feb T	-0.17	-0.19	-0.17	-0.21	-0.30	0.16	0.37	-0.01	0.54*	0.31	-0.01	0.13
Mar T	-0.21	-0.31	-0.37	-0.39	-0.38	-0.02	0.40	0.20	0.55*	0.14	0.15	0.20
Apr T	0.15	0.06	0.01	-0.01	-0.05	0.30	0.35	0.14	0.33	0.03	0.20	0.17
May T	-0.17	-0.23	-0.20	-0.14	-0.10	0.34	0.43	0.13	0.32	0.29	-0.42	-0.25
Jun T	n.a.[f]	n.a.[f]	n.a.[f]	-0.25	-0.12	0.08	0.34	0.13	0.27	0.43*	-0.63**	-0.22
Jul T	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	-0.03	-0.16
<u>Precipitation</u>												
Aug P [e]	0.03	-0.04	-0.08	-0.13	-0.16	0.29	0.54*	0.61**	0.28	0.19	-0.16	-0.06
Sep P	0.11	0.20	0.19	0.03	0.02	-0.09	-0.24	-0.33	-0.06	0.13	0.15	0.28
Oct P	0.04	0.02	0.03	0.17	0.12	-0.10	0.06	0.11	0.17	-0.20	0.32	0.06
Nov P	-0.15	-0.12	-0.08	-0.04	-0.09	-0.21	0.20	0.15	-0.37	0.05	-0.57**	-0.37
Dec P	-0.01	-0.02	-0.02	-0.07	-0.27	0.22	0.01	0.37	-0.06	-0.15	-0.01	-0.02
Jan P	0.06	0.16	0.15	0.09	-0.10	0.01	0.45*	0.32	0.07	0.48*	-0.35	-0.01
Feb P	-0.11	-0.02	0.03	-0.03	-0.12	0.06	0.21	-0.02	0.33	0.58**	-0.09	-0.04
Mar P	-0.37	-0.33	-0.29	-0.33	-0.46*	0.04	-0.12	0.03	-0.04	0.06	-0.06	-0.24
Apr P	-0.09	-0.02	0.07	0.12	-0.04	0.04	-0.39	-0.19	-0.18	-0.17	0.26	0.03
May P	0.46*	0.43	0.37	0.34	0.48*	0.02	-0.18	0.03	-0.08	-0.12	0.20	0.42*
Jun P	n.a.[f]	n.a.[f]	n.a.[f]	0.01	-0.10	0.17	0.03	0.11	0.08	0.03	0.44	0.27
Jul P	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	n.a.[f]	-0.35	-0.24

[a] If r>0.444 then P<0.05, if r>0.562 then P<0.01. [b] If r>0.396 then P<0.05, if r>0.506 then P<0.01. [c] Eyespot index in the surveys. [d] Eyespot index in the field trials. [e] The month before sowing of winter wheat. [f] n.a. = not applicable.

Table 6. Comparison between actual and predicted (by weather factors) severity and incidence of yellow rust, brown rust and % of straws with eyespot index >25 in southern Sweden during1983-2007

Year	Actual brown rust incidence on leaf 1-3 GS 65	Predicted brown rust [a] incidence on leaf 1-3 GS 65	Actual yellow rust incidence on leaf 1-3 GS 75	Predicted yellow rust [b] incidence on leaf 1-3 GS 75	Actual yellow rust severity at max. attack	Predicted yellow rust [c] severity at max. attack	Actual eyespot index % straws with index >25	Predicted eyespot index [d] % straws with index >25
1983	-	-	-	-	0.1	0.0	-	-
1984	-	-	-	-	0.0	0.5	-	-
1985	-	-	-	-	0.0	-0.1	-	-
1986	-	-	-	-	0.0	-0.1	-	-
1987	-	-	-	-	0.0	-0.3	-	-
1988	1.5	-4.7	2.0	1.7	4.0	1.5	0	33
1989	2.5	5.5	12.1	15.6	0.2	-0.2	36	44
1990	45.3	23.5	35.1	12.6	1.0	0.7	53	31
1991	0.1	2.5	2.7	4.9	0.0	-0.1	69	20
1992	0.0	-1.9	0.0	-4.1	0.2	0.2	0	-1
1993	17.6	14.4	0.1	1.2	0.0	0.5	2	50
1994	2.2	-7.1	0.1	4.6	0.0	0.8	36	33
1995	2.7	8.5	0.1	11.4	0.0	0.9	26	40
1996	0.3	0.5	0.0	-3.9	0.0	-0.5	36	38
1997	0.5	2.4	0.6	4.4	0.0	0.2	32	24
1998	0.1	4.3	0.0	5.3	0.0	0.6	49	34
1999	1.3	4.3	5.4	8.6	0.9	0.6	39	27
2000	1.8	8.9	1.2	7.8	0.0	0.4	36	30
2001	0.8	-0.2	1.6	3.4	0.1	0.3	53	37
2002	1.2	12.1	18.7	3.3	2.3	2.2	5	-2
2003	1.2	1.6	0.1	-0.8	0.1	-0.3	10	32
2004	0.6	5.7	0.1	5.1	0.0	0.4	15	29
2005	0.0	2.2	0.0	1.0	0.0	0.5	40	28
2006	0.0	-7.0	0.1	-6.8	0.0	0.2	4	-3
2007	11.0	16.1	4.8	13.3	0.6	1.4	7	39

[a] Model: Brown rust incidence leaf 1-3 GS 65 = -29.568 + 6.184 x Apr T - 0.296 x Mar P + 2.283 x Feb T (R^2=0.54, P=0.005).

[b] Model: Yellow rust incidence leaf 1-3 GS 75 = -9.036 + 2.624 x Mar T - 0.127 x Nov P + 1.382 x Oct T (R^2=0.51, P=0.008).

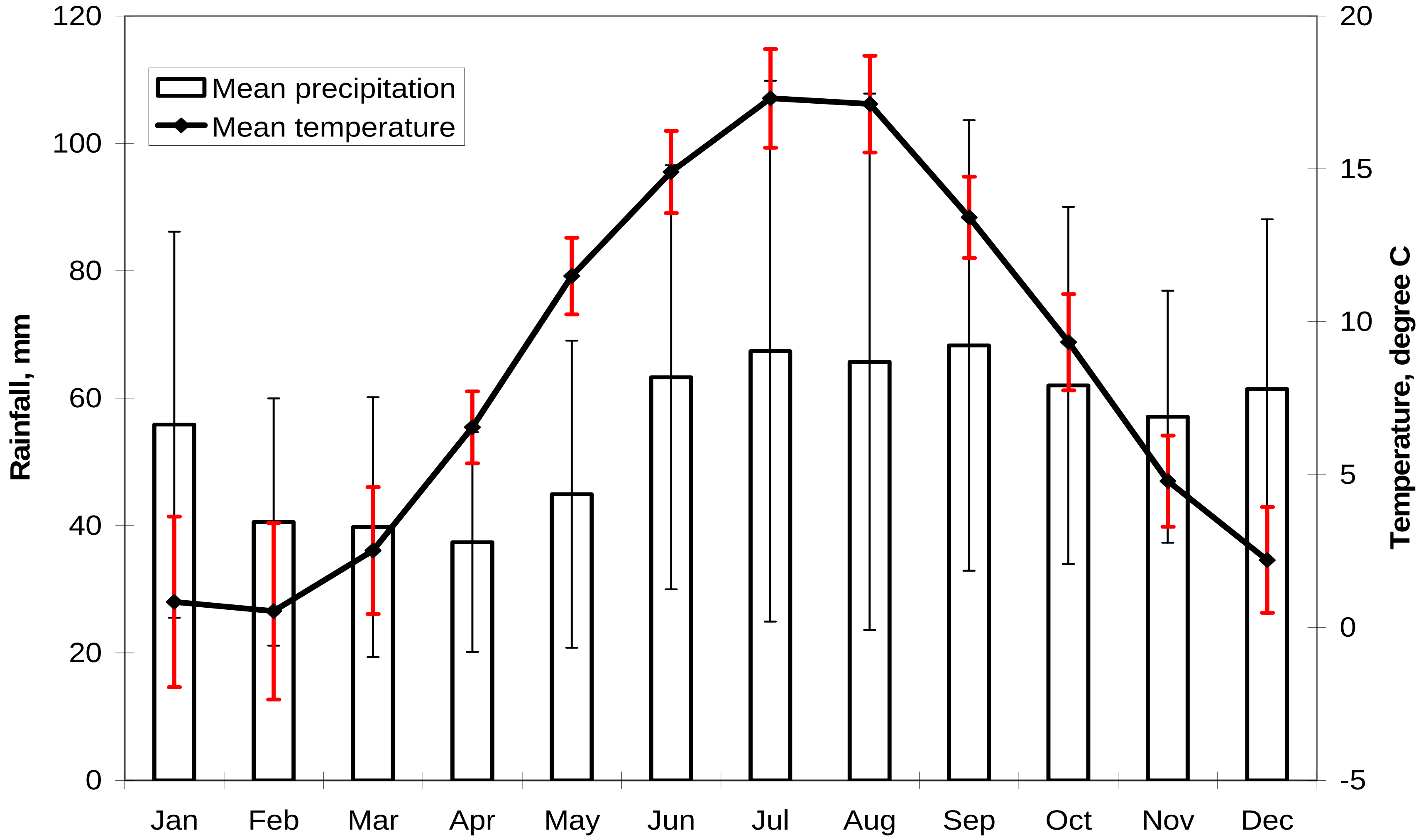
[c] Model: Yellow rust severity at max. attack = - 2.304 + 0.022 x Feb P + 0.009 x Jan P + 0.114 x May T (R^2=0.46, P=0.005).

[d] Model: % Eyespot index >25% in surveys = 159.172 - 0.574 x Nov P - 6.124 x Sep T - 0.334 x Feb T (R^2=0.41, P=0.034).

Figure 1. Mean monthly temperature, °C (solid line) and precipitation, mm (bars) in southern Sweden during 1983-2007, with standard deviations.

Figure 2. Development of winter wheat, maximum, median and minimum growth stages (GS) in southern Sweden during 1988-2007.

Figure 3. Disease incidence at different growth stages for LBDs, powdery mildew, brown rust and yellow rust of winter wheat in southern Sweden during 1988-2007. Error plus bars show standard deviation for LBDs only, but the trend and magnitude were about the same for mildew, brown rust and yellow rust.



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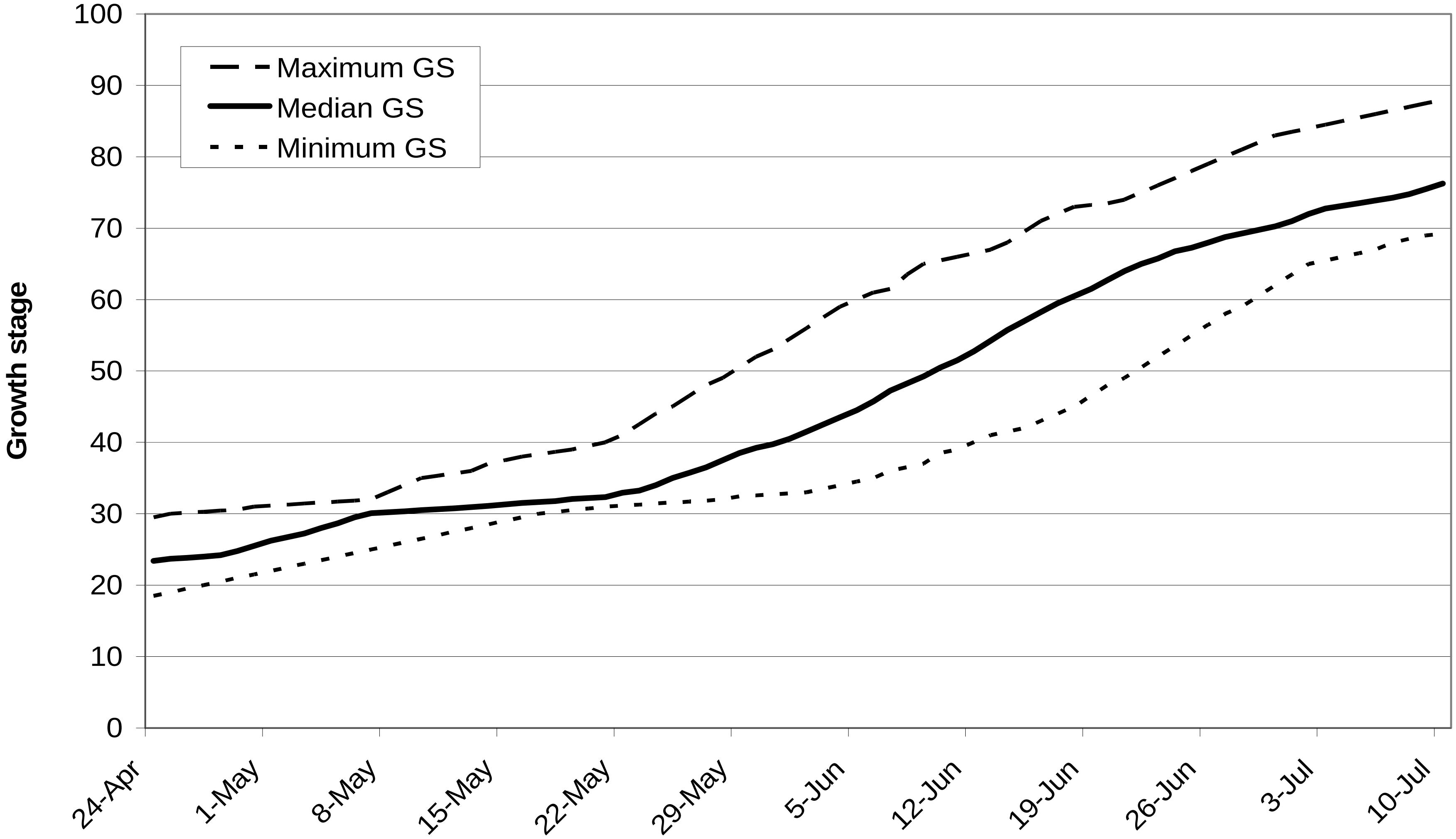

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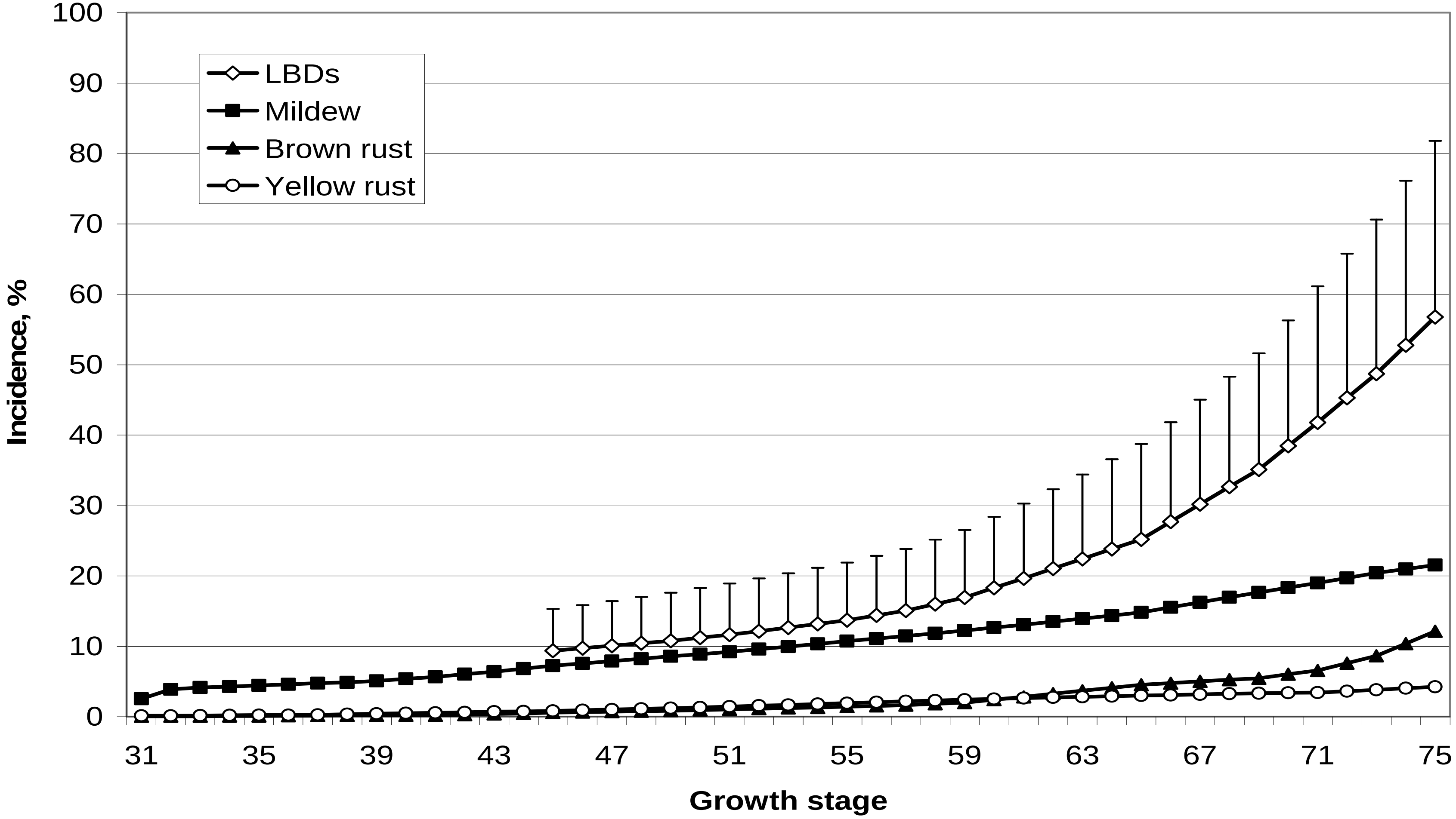

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