SLU

Epsilon Open Archive http://epsilon.slu.se

1   **Impact of temperature and precipitation on yield and plant diseases of winter**

2   **wheat in southern Sweden 1983-2007**

3   Lars Wiik [a, *], Torbjörn Ewaldz [b]

4

5   [a] Swedish University of Agricultural Sciences, Department of Plant Protection Biology, PO
6   Box 102, SE-230 53 Alnarp, * Lars.Wiik@ltj.slu.se
7   [b] Swedish Board of Agriculture, Plant Protection Centre, PO Box 12, SE-230 53 Alnarp

8

9   **Abstract**

10   Weather factors are driving forces in plant disease development and differ between years and

11   locations. Results from long-term fungicide field trials 1983-2007 and disease surveys 1988-

12   2007 in winter wheat in southern Sweden were used to evaluate relationships between yield,

13   the yield increase obtained by fungicide treatment, thousand grain weight (TGW), disease

14   severity and disease incidence, and the independent variables air temperature and

15   precipitation as monthly means. These two weather variables explained more than 50% of the

16   variation between years regarding yield increase, TGW, LBDs (Leaf Blotch Diseases,

17   including Septoria tritici blotch, Stagonospora nodorum blotch and tan spot), brown rust,

18   yellow rust and eyespot, but less than 50% of the variation in yield and powdery mildew.

19   Precipitation in May was the factor most consistently related to LBD disease intensity, and

20   adding another two weather factors further improved the degree of explanation. Weather

21   factors in the preceding growing season influenced growth stage, powdery mildew and brown

22   rust. Mild winters and springs favoured the biotrophics such as powdery mildew, brown rust

23   and yellow rust. Statistically significant correlations between incidence and severity were

24   found for LBDs, brown rust and eyespot, but not for yellow rust and powdery mildew.

25   Regression models with disease incidence as dependent variable generally had a higher

26   degree of explanation and lower P-value than models with disease severity as dependent

1 variable. Our results confirm that weather data can be successfully used in wheat disease

2 prediction models.

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

4

5 **1. Introduction**

6 Plant disease is governed by a number of factors, some of which can be controlled by farmers

7 (Campbell and Madden, 1990). Resistance breeding against fungal diseases of wheat can give

8 significant results (Bockus *et al*., 2001). However, the varieties currently in use are not

9 resistant to all important diseases. Furthermore, fungi normally adapt to new varieties and

10 overcome resistance. The impact of disease can be reduced by agricultural practices such as

11 crop rotation and sowing date, but cannot be fully controlled in epiphytotic situations. Many

12 important diseases of winter wheat are effectively controlled by fungicides and fungicide use

13 has therefore been standard procedure in many countries for decades (Cook and Thomas,

14 1990). Fungicide use needs to take into account the crop protection requirements of the

15 farmer and the environmental aspirations of society at large. Both are met if fungicide use can

16 be restricted to clearly justifiable situations.

17

18 Disease prediction can help in decisions on whether fungicide treatment is worthwhile and, if

19 so, when and how fungicides should be used (Milne *et al*., 2007). As weather factors are

20 driving forces in plant disease development they are essential in plant disease prediction,

21 including the effect of weather on different parts of the disease cycle – dormancy,

22 reproduction, dispersal and pathogenesis (Polley and Clarkson, 1978; De Wolf and Isard,

23 2007). The influence of the weather on diseases of winter wheat has been the subject of a

24 great many studies, but further studies are needed to carefully evaluate relationships and

1   provide information useful to farmers (Coakley *et al*., 1988; Pietravalle *et al*., 2003; Gladders

2   *et al*., 2007; Te Beest *et al*., 2008). Prediction accuracy will probably be improved if disease

3   intensity is included in the models proviso sampling and methods of measurement are

4   appropriate (Polley and Clarkson, 1978). Disease intensity has to be measured in some way,

5   and as incidence is less tedious and faster to measure than severity, incidence would probably

6   be preferable unless severity is a much better predictor (McRoberts *et al*., 2003).

7

8   This study evaluated long-term relationships between yield of winter wheat and

9   temperature/precipitation, and relationships between plant disease attack and

10 temperature/precipitation in southern Sweden, with the aim of providing useful forecasts and

11 warnings on plant diseases of winter wheat and thereby optimising fungicide input. Plant

12 diseases included in the evaluation were Leaf Blotch Diseases [LBDs, including Septoria

13 tritici blotch caused by *Mycosphaerella graminicola* (anamorph *Septoria tritici* – the major

14 leaf blotch disease in Sweden), Stagonospora nodorum blotch caused by *Phaeosphaeria*

15 *nodorum* (anamorph *Stagonospora nodorum*), tan spot caused by *Pyrenophora tritici-repentis*

16 (anamorph *Drechslera tritici-repentis*)], powdery mildew caused by *Blumeria graminis*,

17 brown rust caused by *Puccinia triticina*, yellow rust caused by *Puccinia striiformis* and

18 eyespot caused by *Oculimacula acuformis* and *Oculimacula yallundae*. In addition, the use of

19 disease severity and disease incidence as predictors was compared and the potential use of

20 weather factors in plant disease prediction was evaluated.

21 **2. Materials and methods**

22 ***2.1. Weather***

23 Temperature and precipitation data were obtained from the Swedish Meteorological and

24 Hydrological Institute (SMHI, www.smhi.se). Weather stations in the main agricultural areas

1   in southern Sweden (Scania) were chosen, i.e. the same areas in which the field trials and

2   surveys were carried out. Temperature and precipitation data from the following 36 stations

3   were pooled to produce a mean value for each month and year for southern Sweden during

4   1983-2007: Temperature (position in Scania/SMHI station no): S.W./5223, 5235, 5336;

5   Lund/5343; S.E./5430; N.E./5455, 6402, 6403, 6413; Helsingborg/6203, 6204; N.W./6214,

6   6218, 6219. Precipitation: Landskrona/5252; Trelleborg/5323; S./5326, 5332, 5340; Skurup

7   5328; Malmö/5336; Björnstorp/5338 and Vomb/5341; Lund/5343; Stehag/5354 and

8   Svalöv/5356; S.E./5423, 5429, 5430, 5431; N.W./6202, 6203, 6204, 6205; N.W./6209, 6212,

9   6213, 6214, 6215, 6219; N.E./6401, 6403, 6405, 6408.

10   *2.2. Study site*

11   The county of Scania (55°23'-56°25'N, 12°50'-14°31'E) is the southernmost part of Sweden

12   and comprises 11 035 km^2 in area compared with 410 335 km^2 for the whole country. Scania

13   is a lowland area with more than 40% arable land bordered by coastline to the south, west and

14   east. In general, slightly more than 1/4 of the Swedish winter wheat of about 275 000 ha was

15   grown in Scania during 1983-2007 (www.sjv.se, accessed February 2009). Cultural practices

16   in commercial fields and the varieties used in southern Sweden are presented in an earlier

17   paper (Wiik, 2009).

18   *2.3. Growth stages*

19   In assessment of crop stands, growth stages (GS) according to Tottman and Broad (1987) for

20   a crop stand were used: Stem elongation [ear at 1 cm (pseudostem erect) (GS 30) to flag leaf

21   ligule just visible (GS 39)]; Booting [flag leaf sheath extending (GS 40) to first awns visible

22   (GS 49)]; Inflorescence (ear/panicle) emergence [first spikelet of inflorescence just visible

23   (GS 50) to emergence of inflorescence completed (GS 59)]; Anthesis (flowering) [beginning

1 of anthesis (GS 60) to anthesis completed (GS 69)]; Milk development [caryopsis (kernel)

2 water ripe (GS 70) to late milk (GS 79)].

3 *2.4. Surveys*

4 Disease surveys and forecasts were carried out in southern Sweden (Scania) in about 55

5 winter wheat fields per year during the period 1988-2007. Each field contained an 18-24 m x

6 25 m marked plot in which no treatment with fungicides or insecticides was allowed but the

7 plot was treated similarly to the rest of the field in every other respect. Crop growth stage

8 (GS) and disease incidence of LBDs (assessed collectively), powdery mildew, yellow rust and

9 brown rust were recorded every week from late April to early July (~GS 24 to ~GS 75).

10 Irrespective of leaf level, disease incidence was assessed on the upper three leaves of 17

11 randomly collected straws. Due to this method of assessment, disease incidence very seldom

12 reached 100%. If needed, disease incidence and growth stage were linearly estimated. An

13 eyespot index was calculated from assessments on samples taken in July at ~GS 75 as 0.25 x

14 (% weakly attacked tillers) + 0.5 x (% moderately attacked tillers) + 1.0 x (% severely

15 attacked tillers). Each of these approximately 55 plots represented ~1700 hectares of wheat

16 and the varieties in the plots were representative of regional use. In later years, untreated plots

17 in variety trials and in fungicide trials were included in the disease surveys.

18 *2.5. Field trials*

19 In this study, data from 432 field trials of winter wheat in 1983-2005 as reported in an earlier

20 paper (Wiik, 2009) and supplementary data from 14 field trials performed in 2006-2007 were

21 used. Yields from untreated and fungicide-treated plots (a single treatment at GS 45-61),

22 thousand grain weight (g) and disease severity (proportion of plant tissue affected by disease)

23 were used in the analyses. Disease severity variables included were percentage damage to flag

24 leaf (F), leaf 2 (F-1) and leaf 3 (F-2) for LBDs, powdery mildew, yellow rust, brown rust and,

1 for eyespot, a disease index. The field trials were carried out on farms comprising more than

2 30 varieties. Different yield attributes were measured but in the present study we have chosen

3 to use only yield and thousand grain weight reported at 15% water content (Wiik, 2009).

2.6. Severity and incidence

5 Plant disease severity from field trials was compared with plant disease incidence from

6 surveys. Assessments of severity and incidence were not carried out on the same plants or in

7 the same fields. However, the comparison was considered justified due to the uniformity of

8 the study site and the fact that the field trials and surveys were carried out in the same parts of

9 the region. Weather factors from models established from severity data were tested on

10 incidence data and *vice versa*.

2.7. Statistical methods

12 Following ANOVA, the Student-Newman-Keuls multiple range test (SNK-test) was used to

13 compare means. Correlation, stepwise regression and regression (SPSS ver. 16.0) were used

14 to analyse the results (Hawkins, 2005). Yearly means of yield, thousand grain weight, disease

15 severity (in field trials, N=25) and disease incidence (in survey plots, N=20) were used as

16 dependent variables, respectively, and monthly mean temperature and precipitation as

17 independent variables. The best regression models from a statistical point of view were

18 chosen (highest R^2 and P<0.01 with the exception of the eyespot model (P=0.034)). The

19 models are based on the results of the stepwise regressions, sometimes including one or two

20 additional weather factors. As a rule, monthly mean temperature and precipitation for the

21 entire growing season (usually Sep-Aug) were used. Likewise, mean temperature and

22 precipitation for the month of August in the year of sowing were included in the correlation

23 analyses. Only weather factors that preceded a potential fungicide treatment were used in the

24 models. No more than three weather factors were used in any model. Temperature and

1   precipitation from the same month were not used in the same model due to possible cross-

2   correlations. More than one model is presented for some dependent variables due to the

3   possibility of earlier predictions.

4   *2.8. Designations*

5   Mean temperature (T) and precipitation (P) for a specific month are abbreviated to Jan

6   (January) T, Jan P, Feb T etc., the month of August before sowing to Aug^{-1} and growth stage

7   to GS. Yield increase is defined as fungicide-treated yield minus untreated yield, and

8   thousand grain weight is abbreviated to TGW. Disease incidence (I) and severity (S)

9   relationships are referred to as I-S relationships. In correlation analysis, the Pearson

10   correlation coefficient is denoted r. In stepwise regression the determination coefficient or

11   degree of explanation is designated R^2 and the sign of coefficient is given in the Tables.

12   Probability is abbreviated to P.

13   **3. Results**

14   *3.1. Weather*

15   The lowest mean temperature was recorded in February (0.5 °C) and the highest in July (17.3

16   °C) (Figure 1). Mean annual precipitation was 664 mm per year during the 25-year period.

17   Precipitation for a specific month varied considerably between years. The amount of

18   precipitation and the standard deviations were highest in June, July, August and September

19   with a mean of 66.2 mm per month and lowest in February, March, April and May with a

20   mean of 40.7 mm per month (Figure 1). No statistically significant trend in temperature or

21   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).

1   Jun P was the only weather factor with a significant correlation to yield increase (Table 2). In

2   stepwise regression, Jun P + Dec T + Nov T were the most important weather factors for yield

3   increase (Table 1). The best degree of explanation was found in a regression model with yield

4   increase as the dependent variable and Jun P, Dec T and Feb P as the independent weather

5   factors (Table 3, footnote a). Actual and predicted yield increase (Table 3) were significant

6   correlated (r=0.55, P=0.005).

7   TGW of the yield from both untreated and fungicide-treated plots was significantly correlated

8   to May T and to May P (Table 2). In stepwise regression, May T was the most important

9   weather factor with TGW from untreated plots as the dependent variable, whereas May T and

10 Jun T were the most important factors with TGW from fungicide-treated plots as the

11 dependent variable (Table 1). More than 50% of the variation in TGW was explained using

12 Dec T, May T and Jun T in regression analysis (R^2=0.51, P<0.001).

13 ### 3.4. LBDs and weather

14 Using severity data Wiik (2009) showed LBDs to be the most devastating diseases of winter

15 wheat in southern Sweden, and this was confirmed by incidence data in the present study

16 (Figure 3). Different severity assessments at different growth stages were significantly

17 correlated to May P and May T (Table 2). Incidence of LBDs at GS 45 and 65 was also

18 significantly correlated to May P and May T (not shown in tables). Significant correlations to

19 May P and May T also appeared when incidences in different growth stages or severity of

20 different leaf levels were added [Table 2, LBDs GS 45-75 (I) and LBDs leaf 1-3 (S)].

21 Furthermore, incidence at GS 55 was significantly correlated to Jan T, Dec T, Dec P and Mar

22 P, incidence at GS 75 to Jan T, and incidence at GS 45-75 to Jan T and Dec T. In stepwise

23 regression, May P was the most important weather factor explaining the intensity of LBDs,

24 followed by Feb P, Apr P, Apr T and Jun P depending on the LBD-dependent variable chosen

25 (Table 1). May P was an important independent weather factor in three models for prediction

1   of LBDs, two with LBD incidence at GS 45 and 55 as the dependent variables and one with

2   LBD severity at GS 55 as the dependent variable. By adding weather data from another two

3   months the degree of explanation was further improved (Table 3, footnotes b, c and d). The

4   correlations between actual and predicted LBDs in the three models in Table 3 were high

5   (r=0.76, P<0.001; r=0.69, P<0.001; and r=0.83, P<0.001, respectively).

6   ### *3.5. Powdery mildew and weather*

7   Using severity data Wiik (2009) found powdery mildew to be the second most important

8   disease of winter wheat after the LBDs in southern Sweden, and this was confirmed by

9   incidence data in the present study (Figure 3). Incidence of mildew shown at five different

10   growth stages was significantly correlated to the Aug^{-1} T at GS 39, 65 and 75 (Table 4).

11   Furthermore, mildew incidence was significantly correlated to May P at GS 39, to Jan T at GS

12   65, and to Dec T, Jan T, Mar P and May P at GS 75. Severity of mildew at maximum attack

13   was significantly correlated to Sep T. In stepwise regression, with incidence data as the

14   dependent variable, Jan T, May P, and Jan T and Jul T were the most important weather

15   factors, whereas Sep T was the most important for severity data (Table 5). The best degree of

16   explanation was shown for a model based on severity data with autumn weather factors

17   (R^2=0.42, P=0.023). However, the variation explained by this model was quite poor and it is

18   not included in the tables.

19   ### *3.6. Brown rust and weather*

20   Brown rust was usually of minor importance (Figure 3) but in some years (e.g. 1990 and

21   2007) the incidence was high (Table 6). Incidence of brown rust at GS 75 was significantly

22   correlated to Aug^{-1} P as well as Jan T and Jan P (Table 4). Severity of brown rust at maximum

23   attack was also significantly correlated to Aug^{-1} P. In stepwise regression with incidence data

24   as the dependent variable, Apr T or Jan T was found to be the most important factor, whereas

1   Jul P and Dec P were the most important with severity data as the dependent variable (Table

2   5). The model based on incidence data at GS 65 as the dependent variable and the

3   independent weather factors Apr T, Mar P and Feb T accurately predicted three years (1990,

4   1993 and 2007) with high actual incidences of brown rust (Table 6, footnote a). The

5   prediction accuracy of the model based on severity data was quite poor (not shown in tables).

6   The correlation between actual and predicted brown rust (Table 6) was statistically significant

7   (r=0.73, P<0.001). Actual and predicted brown rust intensity diverged in a few years in all

8   models.

9   *3.7. Yellow rust and weather*

10 Yellow rust was usually of minor importance (Figure 3) but in some years (1990, 1999, 2002

11 and 2007) the disease occurred at a high severity and incidence (Table 6). Incidence of yellow

12 rust at GS 75 was significantly correlated to Mar T and Feb T (Table 4). Severity of yellow

13 rust at maximum attack was significantly correlated to Feb P, Jan P and Jun T. In stepwise

14 regression Feb T and Mar T were found to be the most important factors with incidence data

15 as the dependent variables, and Feb P with severity data as the dependent variable (Table 5).

16 The model in Table 6 (footnote b) with incidence data as the dependent variable and Mar T,

17 Nov P and Oct T as the independent weather factors correctly predicted four years (1989,

18 1990, 1999 and 2007) with high actual incidence of yellow rust. The model in Table 6

19 (footnote c) with severity data as the dependent variable and Feb P, Jan P and May T as the

20 independent weather factors quite accurately predicted four years (1988, 1989, 2002 and

21 2007) with high actual severity of yellow rust, but the predicted values were higher than the

22 actual levels in some years. Actual and predicted yellow rust intensity (Table 6) were

23 significantly correlated, both with incidence (r=0.47, P=0.037) and with severity data (r=0.68,

24 P<0.001). Actual and predicted yellow rust intensity diverged in a few years in all models.

1 ***3.8. Eyespot and weather***

2 Actual mean eyespot index in the disease survey plots 1988-2007 was quite low in most years

3 and high only in a few years (1990, 1991 and 2001) (Table 6). Eyespot index in the disease

4 survey plots was significantly correlated to Jun T and Nov P, and in the field trials to May P

5 (Table 4). In stepwise regression, with eyespot index in the survey plots as the dependent

6 variables, Jun T plus Nov P or Nov P and Jan T were found to be the most important weather

7 factors, while with eyespot index in the field trials as the dependent variable Nov P was found

8 to be the most important weather factor (Table 5). The models tested were not very accurate,

9 with the exception of the model '% straws with Eyespot index >25', which correctly

10 identified several years with low eyespot attacks, i.e. a negative prognosis (Table 6, footnote

11 d). However, the correlations between the predicted eyespot index of the models and actual

12 eyespot index (Table 6) were not statistically significant.

13 ***3.9. Severity and incidence***

14 The correlation between incidence and severity of brown rust was statistically significant

15 (r=0.79, P<0.001). Furthermore, the correlation between incidence and severity of LBDs at

16 GS 55 was statistically significant (r=0.55, P=0.012). However, no statistically significant

17 correlation was found between incidence and severity of yellow rust and between incidence

18 and severity of powdery mildew. The weather factor May P was particularly important in two

19 three-factor models of LBDs based on incidence as the dependent variable (Table 3, footnotes

20 b and c) and in one three-factor model with severity as the dependent variable (Table 3,

21 footnote d). In the two models based on incidence, Oct P and Feb T, and Jan T and Dec P

22 were the second and third weather factors, respectively, whereas Feb P and Apr P were the

23 second and third factors in the model based on severity. The two models based on incidence

24 (Table 3, footnotes b and c) gave higher degrees of explanation than the model based on

25 severity (Table 3, footnote d). The most important weather factors for the yellow rust model

1 based on incidence were in autumn (Nov P and Oct T) and early spring (Mar T) (Table 6,

2 footnote b), whereas the model based on severity was coupled to winter factors (Feb P and

3 Jan P) and spring factors (Apr T and May T) (Table 6, footnote c). The I-S relationship for

4 LBDs was reciprocal, i.e. weather factors in models for LBDs based on severity could be

5 successfully used to explain the actual incidence of LBDs at GS 45 and GS 55, but in the

6 corresponding comparisons for mildew, brown rust, yellow rust and eyespot no reciprocal

7 relationships were found.

8 **Discussion**

9 Our best three-factor regression model for yield after fungicide treatment, which used the

10 independent weather factors Sep T, Feb P and Mar P, predicted yields fairly accurately. Thus,

11 high yield was promoted by a warm September that gave the crop a good start and good water

12 saturation in February in good time for tillering to support growth. Furthermore, the degree of

13 explanation was considerably improved when Jun P was included in the model, demonstrating

14 the importance of precipitation during booting, inflorescence emergence and anthesis.

15 Weather conditions including the critical meteorological variables precipitation, air

16 temperature and solar radiation have been said to explain up to 80% of the variation in

17 agricultural production, but grain yield also depends on edaphic, hydrological and agronomic

18 factors (Hoogenboom, 2000). In our correlation analyses, we showed Apr T to be an

19 important weather factor for grain yield, in agreement with Chmielewski and Potts (1995) in

20 their evaluation of the Broadbalk long-term experiment at Rothamsted, i.e. a high T_{max} in

21 April appeared to favour plant development after winter. In our correlation analysis Sep T

22 was also a strong factor, probably due to the fact that a high Sep T results in a high soil

23 temperature, which promotes germination and seedling growth as described by Hoogenboom

24 (2000). The lower yields in 2006 and 2007 compared with yields during the latter part of the

1   period 1983-2005 (Wiik, 2009) might be due to a very high intensity of LBDs in 2006 and an

2   extremely high precipitation the month before sowing in 2006.

3

4   The strong correlation between LBDs and May P in the present study is in agreement with

5   several other studies. Precipitation promotes disease spread and development (Shaner and

6   Finney, 1976; Coakley *et al*., 1985; Emmerman *et al*., 1988; Daamen and Stol, 1992; Verreet

7   *et al*., 2000; Gladders *et al*., 2001; Pietravalle *et al*., 2003; Henze *et al*., 2007; Shaw *et al*.,

8   2008). A well-timed fungicide treatment on emerging top leaves (F, F-1 and F-2) usually

9   gives good protection against LBDs and promotes high yields (Shaw and Royle, 1993; Cook

10 *et al*., 1999; Paveley *et al*., 2000). May P seemed to be an essential weather factor in our LBD

11 models although, as proposed by Pietravalle *et al*. (2003), an early indication of *Septoria*

12 *tritici* at GS 31 seems difficult to achieve. We also found a strong correlation between LBDs

13 and May T, probably mainly due to the relationship between May T and May P (r = -0.629,

14 P<0.001). Nonetheless, temperature has been shown to be an important variable for the

15 progress of Septoria tritici blotch. Low temperatures during autumn and winter might delay

16 the development of Septoria tritici blotch, e.g. by increased latent periods and reduced

17 ascospore production (Royle *et al*., 1993; Parker *et al*., 1999; Verreet *et al*., 2000; Gladders *et*

18 *al*., 2001; Henze *et al*., 2007). In the present study we found a negative correlation between

19 the incidence of LBDs and Dec T and Jan T, and a negative coefficient on Jan T in the

20 regression model with the highest degree of explanation. A negative relationship between

21 annual intensity of *Septoria* spp. and sunshine duration in Aug[-1] has been reported in the

22 Netherlands (Daamen and Stol, 1992), indicating an effect on ascospore production.

23 Furthermore, Shaw *et al*. (2008) found a positive relationship between *S. tritici* abundance

24 and Jul[-1] T and Aug[-1] T. In our investigation we found no statistically significant correlations

25 for such an out-of-season weather relationship with LBDs. On the other hand, we found out-

1   of-season relationships between weather and other diseases (see below). These conflicting

2   results call for more research on the weather dependence of LBDs. Yield increase, achieved

3   by a fungicide treatment just before/during heading (principally directed against LBDs) was

4   positively correlated to Jun P. This was expected, as precipitation is decisive for the disease

5   progress of LBDs during a period of four weeks after heading (Wiik, 1993). TGW, known to

6   be directly affected by LBDs, was found to be significantly positively correlated to May T,

7   demonstrating the unfavourable impact of inaccurate temperatures during GS 25-40, a time

8   for initiation and abortion of grains in the spike.

9

10   The positive correlation between powdery mildew and temperatures in Aug[-1] and Sept might

11   be explained by the importance of a suitable temperature for the establishment and formation

12   of inoculum on volunteer plants, enabling the green-bridge phenomenon (Eversmeyer and

13   Kramer, 1998). The importance of winter temperature but also precipitation during spring is

14   supported by the results of both Daamen *et al*. (1992) and Te Beest *et al*. (2008). Brown rust

15   correlated well to Aug[-1] P, similar to findings by Eversmeyer and Kramer (1998), and in the

16   present study also to Jul P and Jan T. Our findings are in agreement with Daamen *et al*.

17   (1992) who indicated that a high Mar T probably facilitated sporulation and infection on

18   young leaves. In our regression model based on yellow rust incidence, temperature – in the

19   beginning of the epidemic and overwintering temperature – was important, in agreement with

20   results from other countries (Daamen *et al*., 1992; Gladders *et al*., 2007; van den Berg and

21   van den Bosch, 2007; Te Beest *et al*., 2008). However, in our model based on severity, winter

22   precipitation and temperature during late spring and early summer were key factors. Besides

23   winter temperature, precipitation was included in the model by Coakley *et al*. (1988) but they

24   used spring precipitation, as opposed to our winter precipitation.

25

1   The negative correlations observed in the present study between eyespot index and Nov P,

2   and eyespot index and Jun T perhaps indicate that eyespot establishment was suppressed by

3   excessive precipitation during November, and that penetration of successive leaf sheaths was

4   suppressed by excessive temperatures in June (Fitt *et al.*, 1988). In a HGCA-funded project in

5   the UK, Burnett and Hughes (2004) developed a risk algorithm with rainfall during spring

6   (March, April and May) included as the only weather factor. In the present study the only

7   statistically significant weather factor in the field trials was May P, but not Mar P and Apr P.

8   Our models were not accurate and our results differ from those found in many other countries,

9   e.g. Daamen and Stol (1990), and the weather factors included in our model (Nov P, Sep T

10   and Feb T) were rejected by Burnett and Hughes (2004) in their risk algorithm. Nonetheless,

11   we were able to predict years with low eyespot attacks. A negative forecast might be useful

12   for other diseases too, probably as one of several models for a specific disease. Diverging data

13   in the literature call for more research on eyespot weather dependence.

14

15   The incidence measurements from more than 50 untreated field plots per year in this study are

16   almost certainly more representative of southern Sweden than the severity measurements

17   from a few field trials each year. Subsequently, our models with disease incidence as

18   dependent variable usually had a higher degree of explanation and a lower P-value than

19   models with disease severity as a dependent variable. Incidence measurements are preferable

20   as they are faster to perform, probably more accurate and less variable, especially if several

21   observers are involved. I-S relationships (Seem, 1984; McRoberts *et al.*, 2003) have been

22   found in wheat diseases such as powdery mildew (James and Shih, 1973; Hughes *et al.*,

23   2004), brown rust (James and Shih, 1973), LBDs (Shaw and Royle, 1987) and eyespot (Fitt *et*

24   *al.*, 1988). Our evaluation showed a statistically significant correlation between incidence and

25   severity for LBDs, brown rust and eyespot, but not for yellow rust and powdery mildew. This

1 was probably an effect of differences in the proportion of host resistance between varieties

2 used in the field trials and in the survey plots, with resistance being more pronounced for

3 powdery mildew and yellow rust than for LBDs, brown rust and eyespot. We only evaluated

4 linear relationships, which most likely restricted possible resulting I-S relationships

5 (McRoberts *et al*., 2003).

6

7 In this study temperature and precipitation data from weather stations in the national

8 meteorological network were used. Coakley (1988) recommended the use of weather stations

9 in the national meteorological network and Bourke (1970) preferred them to in-field weather

10 stations on account of the supervision by professional personnel and the cheaper and more

11 accurate values. The spatial distribution in monthly precipitation in southern Sweden is high

12 (Finnander Linderson, 2002) and hence it would be more accurate to use in-field weather

13 stations. Such stations are in use but unfortunately not during all years of the present study

14 and not during the entire growing season, with significantly more missing values than the

15 regular (SMHI) network. Temperature and precipitation are important meteorological

16 variables but variables such as humidity, leaf wetness, dew period, evaporation, wind and

17 radiation would probably increase the degree of explanation in the models. Monthly mean

18 values, as chosen in the present study, have limitations – a biological time-scale would

19 probably improve the models. In a previous study Wiik (1993) evaluated accumulated

20 precipitation before heading, and found four weeks preceding GS 55 to be a better predictor

21 of the yield increase achieved by a fungicide application than one, two or three weeks. This

22 result guided us in choosing month as a suitable period for the analyses. In Window Pane and

23 similar software, points in time and periods of time are identified for each meteorological

24 variable best correlated to yield or disease intensity. Such software has been used for winter

25 wheat diseases such as stripe rust (Coakley *et al*., 1982: Coakley *et al*. 1988; Te Beest *et al*.,

1   2008), Septoria tritici blotch (Coakley *et al.* 1985; Royle *et al.*, 1993; Pietravalle *et al.*, 2003),

2   powdery mildew (Te Beest *et al.*, 2008) and common bunt (Johnsson, 1992). Pietravalle *et al.*

3   (2003) and Te Beest *et al.* (2008) used a qualitative model to determine whether a threshold

4   value of disease was exceeded, followed by a quantitative model predicting the severity of the

5   epidemic. This two-step analysis seemed to work and might be a good but complicated

6   method for future evaluations of this type of data, although concerns about spurious

7   relationships, due to iterative searches with thousands of comparisons, have to be considered

8   (Te Beest *et al.*, 2008).

9

10   In this straightforward evaluation of data from 25 years, we demonstrated the potential for

11   using weather factors in plant disease prediction. We found a significant impact of air

12   temperature and precipitation on yield and on important diseases of winter wheat.

13   Temperature during germination and seedling growth in September, and temperature during

14   tillering in April were important for yield formation. Precipitation during tillering, stem

15   elongation and booting was a powerful predictor for the LBDs, while temperature and

16   precipitation in the month prior to sowing were important for growth stage development,

17   powdery mildew and brown rust. Temperature during tillering, stem elongation and booting

18   was important for TGW, and temperature during booting, inflorescence emergence and

19   anthesis for yield increase in response to fungicide treatment. In most of our regression

20   models we found incidence assessments to be better than severity assessments.

21   Meteorological variables other than precipitation and temperature, site factors and agricultural

22   practices are of course very important in decision support systems and forecasting models, but

23   that were beyond the scope of this paper.

8   **References**

9   Bockus, W.W., Appel, J.A., Bowden, R.L., Fritz, A.K., Gill, B.S., Martin, T.J., Sears, R.,

10   Seifers, D.L., Brown-Guedira, G.L., Eversmeyer, M.G., 2001. Success stories: Breeding for

11   wheat disease resistance in Kansas. Plant Dis. 85, 453-461.

12

13   Bourke, P.M.A., 1970. Use of weather information in the prediction of plant disease

14   epiphytotics. Annu. Rev. Phytopathol. 8, 345-369.

15

16   Burnett, F.J., Hughes, G., 2004. The development of a risk assessment method to identify

17   wheat crops at risk from eyespot. HGCA (The Home-Grown Cereals Authority, UK) project

18   report No. 347, pp. 67.

19

20   Campbell, C.L., Madden, L.V., 1990. Introduction to plant disease epidemiology, pp. 532.

21   John Wiley and Sons, Inc., USA.

22

23   Chmielewski, F.M., Potts, J.M., 1995. The relationship between crop yields from an

24   experiment in southern England and long-term climate variations. Agric. For. Meteorol. 73,

25   43-66.

1

2 Coakley, S.M., 1988. Historical weather data: Its use in epidemiology. In Plant Disease

3 Epidemiology, ed. K Leonard and W Fry, Vol. II, 54-83. New York: MacMillan Publ. Co.

4

5 Coakley, S.M., Boyd, W.S., Line, R.F., 1982. Statistical models for predicting stripe rust on

6 winter wheat in the Pacific Northwest. Phytopathol. 72, 1539-1542.

7

8 Coakley, S.M., Line, R.F., McDaniel, L.R., 1988. Predicting stripe rust severity on winter

9 wheat using an improved method for analysing meteorological and rust data. Phytopathol. 78,

10 543-550.

11

12 Coakley, S.M., McDaniel, L.R., Shaner, G., 1985. Model for predicting severity of Septoria

13 tritici blotch on winter wheat. Phytopathol. 75, 11, 1245-1251.

14

15 Cook, R.J., Thomas, M.R., 1990. Influence of site factors in responses of winter wheat to

16 fungicide programmes in England and Wales, 1979-1987. Plant Pathol. 39, 548-557.

17

18 Cook, R.J., Hims, M.J., Vaughan, T.B., 1999. Effects of fungicide spray timing on winter

19 wheat disease control. Plant Pathol. 48, 33-50.

20

21 Daamen, R.A., Stol, W., 1990. Surveys of cereal diseases and pests in the Netherlands. 2.

22 Stem-base diseases of winter wheat. Neth. J. Plant Pathol. 96, 251-260.

23

24 Daamen, R.A., Stol, W., 1992. Surveys of cereal diseases and pests in the Netherlands. 5.

25 Occurrence of *Septoria* spp. in winter wheat. Neth. J. Plant Pathol. 98, 369-376.

1

2 Daamen, R.A., Stubbs, R.W., Stol, W., 1992. Surveys of cereal diseases and pests in the

3 Netherlands. 4. Occurrence of powdery mildew and rusts in winter wheat. Neth. J. Plant

4 Pathol. 98, 301-312.

5

6 De Wolf, E.D., Isard, S.A., 2007. Disease cycle approach to plant disease prediction. Annu.

7 Rev. Phytopathol. 45, 203-220.

8

9 Emmerman, A., Gustafsson, G., Hedene, K-A., Sigvald, R., Wiik, L. 1988. Prediction of leaf

10 and glume blotch diseases in winter wheat and spring barley. Växtskyddsnotiser 52:5, 112-

11 116.

12

13 Eversmeyer, M.G., Kramer, C.L., 1998. Models of early spring survival of wheat leaf rust in

14 the central Great Plains. Plant Dis. 82, 987-991.

15

16 Finnander Linderson M-L., 2002. The spatial distribution of precipitation in Scania, southern

17 Sweden. Observations, model simulations and statistical downscaling. Thesis 145.

18 Department of Physical Geography and Ecosystem Analysis, Lund University, Sweden.

19

20 Fitt, B.D.L., Goulds, A., Polley, R.W., 1988. Eyespot (*Pseudocercosporella herpotrichoides*)

21 epidemiology in relation to prediction of disease severity and yield loss in winter wheat – a

22 review. Plant Pathol. 37, 311-328.

23

24 Gladders, P., Paveley, N.D., Barrie, I.A., Hardwick, N.V., Hims, M.J., Langton, S, Taylor,

25 M.C., 2001. Agronomic and meteorological variables affecting the severity of leaf blotch

1 caused by *Mycosphaerella graminicola* in commercial wheat crops in England. Ann. Appl.

2 Biol. 138, 301-311.

3

4 Gladders, P., Langton, S., Barrie, I.A., Hardwick, N.V., Taylor, M.C., Paveley, N.D., 2007.

5 The importance of weather and agronomic variables for the overwinter survival of yellow rust

6 (*Puccinia striiformis*) and subsequent disease risk in commercial wheat crops in England.

7 Ann. Appl. Biol. 150, 371-382.

8

9 Hawkins, D., 2005. Biomeasurement. Understanding, Analysing, and Communicating Data in

10 the Biosciences. 284 p. Oxford University Press, UK.

11

12 Henze, M., Beyer, M., Klink, H., Verreet, J-A., 2007. Characterizing meteorological scenarios

13 favorable for *Septoria tritici* infections in wheat and estimation of latent periods. Plant Dis.

14 91, 1445-1449.

15

16 Hoogenboom, G., 2000. Contribution of agrometeorology to the simulation of crop

17 production and its applications. Agric. Forest Meteorol. 103, 137-157.

18

19 Hughes, G., McRoberts, N., Madden, L.V., 2004. Daamen's incidence-severity relationship

20 revisited. Eur. J. Plant Pathol. 110, 759-761.

21

22 James, W.C., Shih, C.S., 1973. Relationship between incidence and severity of powdery

23 mildew and leaf rust on winter wheat. Phytopathol. 63, 183-187.

24

1 Johnsson, L., 1992. Climate factors influencing attack of common bunt (*Tilletia caries* (DC)

2 Tul.) in winter wheat in 1940-1988 in Sweden. Z. PflKrankh. PflSchutz 99, 21-28.

3

4 McRoberts, N., Hughes, G., Madden, L.V., 2003. The theoretical basis and practical

5 application of relationships between different disease intensity measurements in plants. Ann.

6 appl. Biol. 142, 191-211.

7

8 Milne, A., Paveley, N., Audsley, E., Parsons, D., 2007. A model of the effect of fungicides on

9 disease-induced yield loss, for use in wheat disease management decision support systems.

10 Ann. appl. Biol. 151, 113-125.

11

12 Parker, S.R., Lovell, D.J., Royle, D.J., Paveley, N.D., 1999. Analysing epidemics of *Septoria*

13 *tritici* for improved estimates of disease risk. In: Lucas JA, Bowyer P, Anderson HM (eds),

14 Septoria on cereals. A Study of Pathosystems. CABI Publishing ISBN 0 85199 269 2, pp. 96-

15 107.

16

17 Paveley, N.D., Lockley, D., Vaughan, T.B., Thomas, J., Schmidt, K., 2000. Predicting

18 effective fungicide doses through observation of leaf emergence. Plant Pathol. 49, 748-766.

19

20 Pietravalle, S., Shaw, M.W., Parker, S.R., van den Bosch, F., 2003. Modeling of relationships

21 between weather and *Septoria tritici* epidemics on winter wheat: A critical approach.

22 Phytopathol. 93, 1329-1339.

23

24 Polley, R.W., Clarkson J.D.S., 1978. Forecasting cereal disease epidemics. In: Scott, P.R. &

25 Bainbridge, A. (eds.), Plant Disease Epidemiology, Blackwell Sci. Publ., pp. 141-150.

1

2   Royle, D.J., Lovell, D.J., Coakley, S.M., Shaner, G., 1993. Predicting the effects of climate

3   change on *Septoria tritici* in winter wheat. Abstracts of the 6th International Congress of Plant

4   Pathology, Montreal, p. 97.

5

6   Seem, R.C., 1984. Disease incidence and severity relationships. Annu. Rev. Phytopathol. 22,

7   133-150.

8

9   Shaner, G., Finney, R.E., 1976. Weather and epidemics of Septoria leaf blotch of wheat.

10 Phytopathol. 66, 781-785.

11

12 Shaw, M.W., Royle, D.J., 1987. Spatial distributions of *Septoria nodorum* and *S. tritici* within

13 crops of winter wheat. Plant Pathol. 36, 84-94.

14

15 Shaw, M.W., Royle, D.J., 1993. Factors determining the severity of *Mycosphaerella*

16 *graminicola* (*Septoria tritici*) on winter wheat in the UK. Plant Pathol. 42, 882-899.

17

18 Shaw, M.W., Bearchell, S.J., Fitt, B.D.L., Fraaije, B.A., 2008. Long-term relationships

19 between environment and abundance in wheat of *Phaeosphaeria nodorum* and

20 *Mycosphaerella graminicola*. New Phytol. 177, 229-238.

21

22 Te Beest, D.E., Paveley, N.D., Shaw, M.W., van den Bosch, F., 2008. Disease-weather

23 relationships for powdery mildew and yellow rust on winter wheat. Phytopathol. 98, 609-617.

24

1   Tottman, D.R., Broad, H., 1987. The decimal code for the growth stages of cereals, with

2   illustrations. Ann. appl. Biol. 110, 441-454.

3

4   van den Berg, F., van den Bosch, F., 2007. The elasticity of the epidemic growth rate to

5   observed weather patterns with an application to yellow rust. Phytopathol. 97, 1512-1518.

6

7   Verreet, J.A., Klink, H., Hoffmann, G.M., 2000. Regional monitoring for disease prediction

8   and optimization of plant protection measures: The IPM wheat model. Plant Dis. 84, 816-826.

9

10   Wiik, L., 1993. Väderleken och *Septoria* spp.: Sambandet mellan några klimatparametrar och

11   skördeförlusten orsakad av *Septoria* spp. Engl. summary. 34:e svenska

12   växtskyddskonferensen. Skadedjur och växtsjukdomar, 85-90. SLU, Uppsala, Sweden.

13

14   Wiik, L., 2009. Yield and disease control in winter wheat in southern Sweden during 1977-

15   2005. Crop Protection 28, 82-89.

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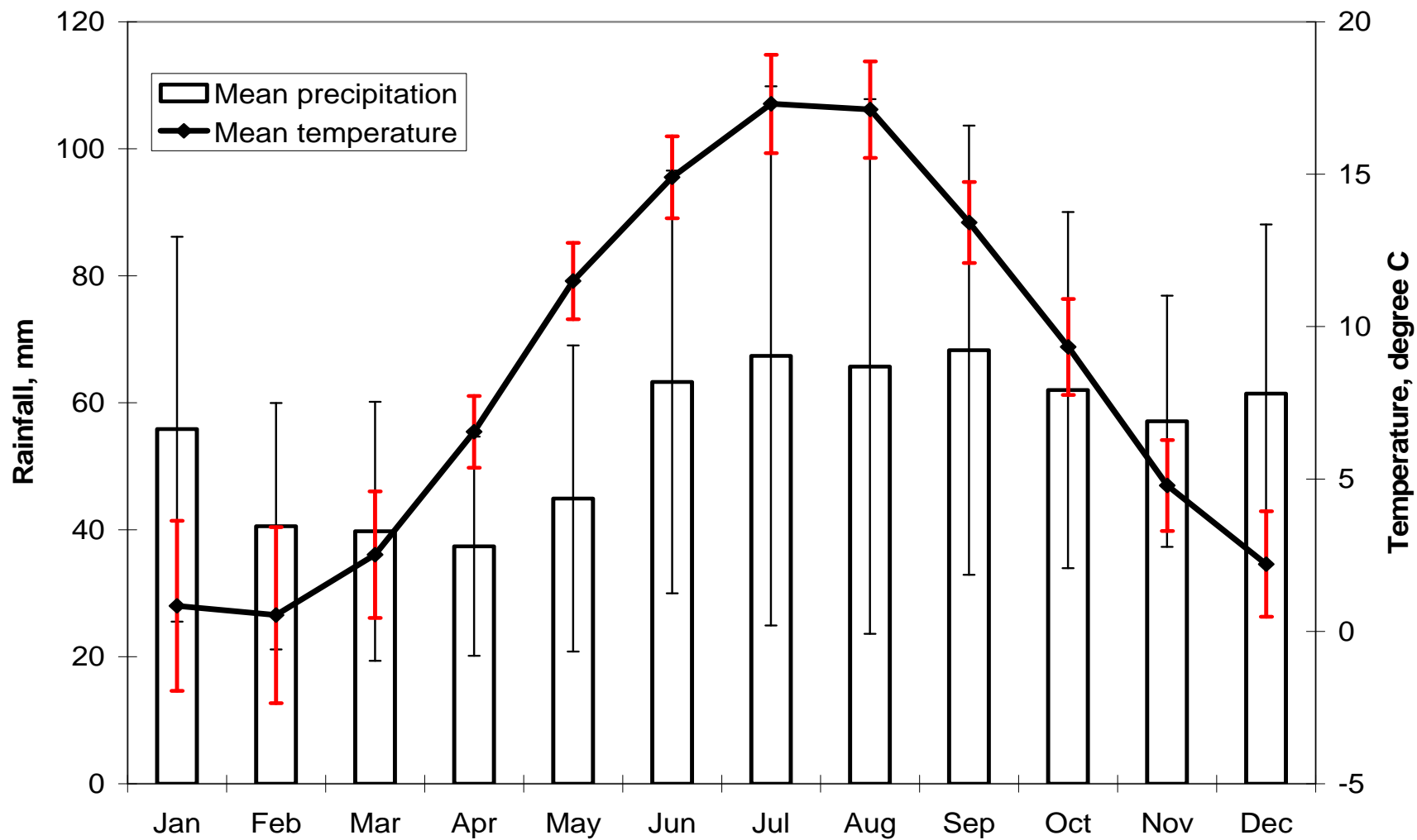
Figure 1. Mean monthly temperature, °C (solid line) and precipitation, mm (bars) in southern Sweden during 1983-2007, with standard
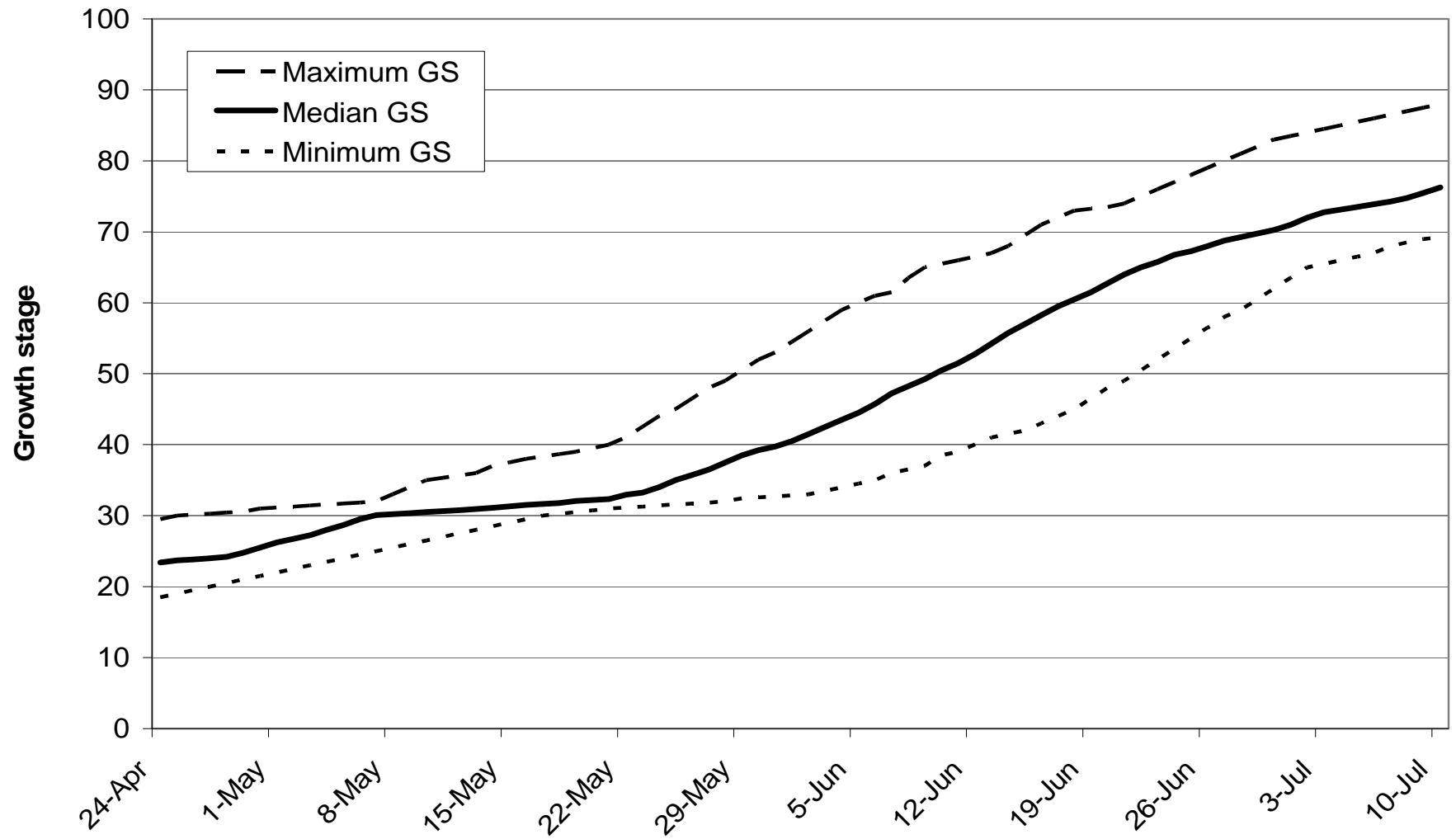
deviations.

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.

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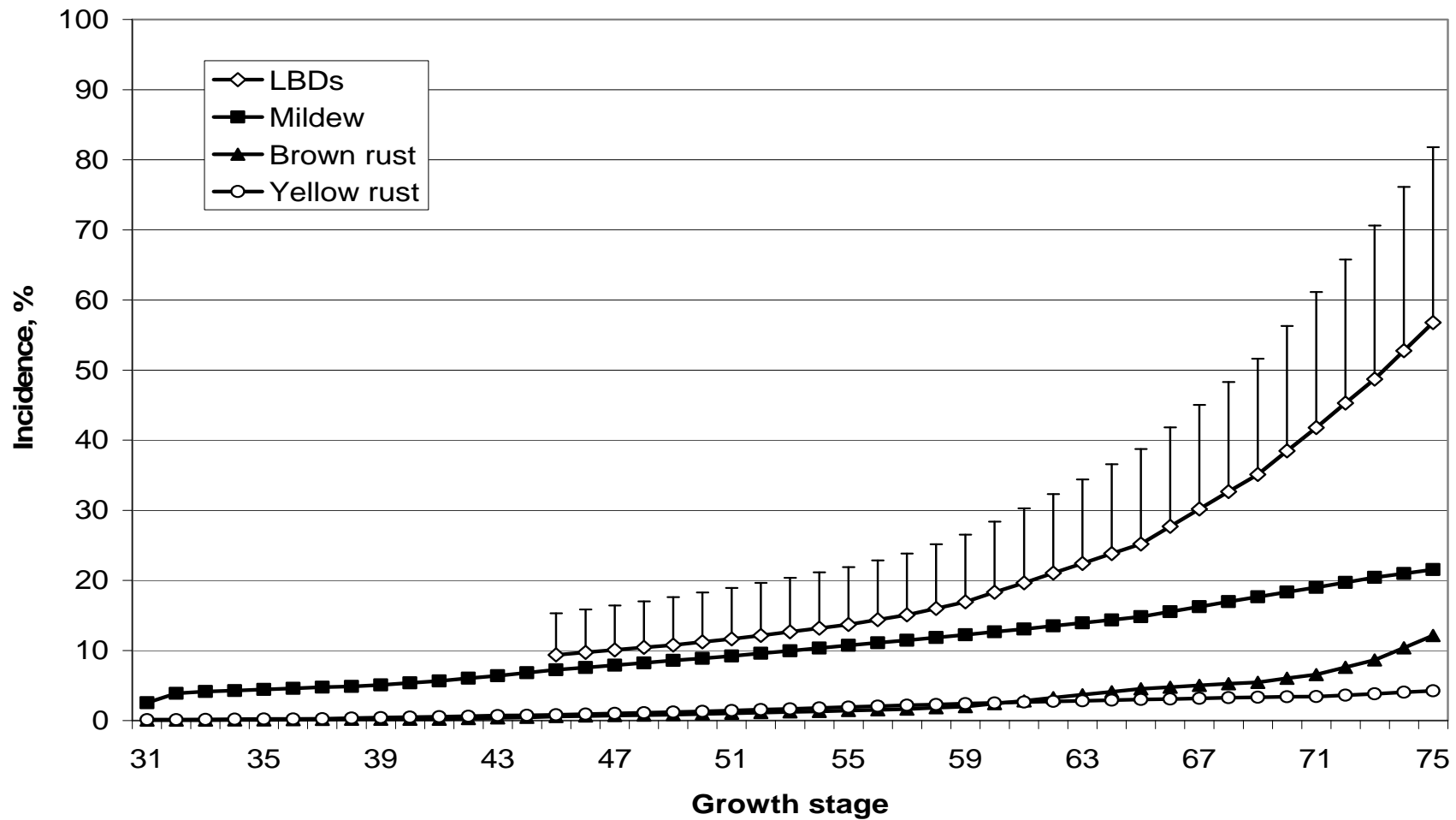
Figure 3. Disease incidence at different growth stages for LBDs, powdery mildew, brown rust and yellow rust of winter wheat in southern Sweden during 1988-2007. Error plus bars show standard deviation for LBDs only, but the trend and magnitude were about the same for mildew, brown rust and yellow rust.