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An outlook on wheat health in Europe from a network of field experiments

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ABSTRACT

Wheat disease management in Europe is mainly based on the use of fungicides and the cultivation of resistant cultivars. Improving disease management implies the formal comparison of disease management methods in terms of both crop health and yield levels (attainable yield, actual yield), thus enabling an assessment of yield losses and yield gains. Such an assessment is not available for wheat in Europe. The objective of the analysis reported here is to provide an overview of wheat health and yield performance in field experiments in Europe. Data from field experiments in six European countries (Belgium, France, Germany, Italy, Norway, and Sweden) conducted between 2013 and 2017 were analysed to that aim. Relationships between multiple disease levels, yield, level of cultivar resistance, level of fungicide protection, and weather patterns were assessed. The analyses included 73 field experiments, corresponding to a total of 447 [fungicide protection level x cultivar] combinations. Analyses across the six countries led to ranking the importance of foliar wheat diseases as follows, in decreasing order: leaf blotch (septoria tritici blotch, septoria nodorum blotch, and tan spot), leaf rust, yellow rust, and powdery mildew. Fusarium head blight was observed in France and Italy, and stem rust was sporadically observed in Italy. Disease patterns, crop inputs (fertiliser, fungicides), and yields widely varied within and across countries. Disease levels were affected by the level of fungicide use, by cultivar resistance, as well as by weather patterns. While this analysis enables a better documentation of the status of wheat health in Europe, it also highlights the critical need for policies in Europe enabling a more judicious use of pesticides. First, common standards for field experiments are needed (experimental designs and protocols; disease assessment procedures and scales; references, including reference-susceptible cultivars); second, assessments in farmers' fields – and not in research stations – are necessary; and third, there is a need to use available process-based crop models to estimate attainable yields, and so, yield losses.

Keywords: wheat, host plant resistance, fungicide, fertiliser, disease, weather

1. Introduction

Wheat production in the EU (28 countries) is important at the global scale, contributing about 20% of the world production (151 out of 742 million tons per year, average 2013-2017; FAO, 2019). Wheat production depends on a number of factors, including wheat health. Improving the management of wheat diseases has triggered important research efforts, and has also been targeted by EU directives meant to decrease the use of pesticides for all EU crops, while retaining high production targets (Rossi et al., 2012).

The main wheat diseases occurring in Europe are caused by fungal pathogens (Jørgensen et al., 2014; Figueroa et al., 2018; Singh et al., 2016; Savary et al., 2017; 2019). Septoria tritici blotch, caused by *Zymoseptoria tritici*, is an important disease in most parts of EU (Fones and Gurr, 2015; Savary et al., 2015; 2019). Yellow (stripe) rust, caused by *Puccinia striiformis*, was generally well controlled by cultivar resistance until the beginning of this century, when more aggressive strains emerged, which overcame the resistances that were currently deployed in wheat cultivars (Hovmøller et al., 2008; 2016). Leaf (brown) rust, caused by *Puccinia triticina*, continues to occur in most parts of EU, with varying intensity depending on the weather (e.g., low winter temperatures may restrict survival in Northern Europe), and on the pathogen population and its capacity to overcome the currently deployed resistance (Singh et al., 2016). Powdery mildew, caused by *Blumeria graminis* f. sp. *tritici*, occurs in many parts of Europe, although the disease is generally associated with limited impacts on wheat production (Singh et al., 2016). Septoria nodorum blotch, caused by *Parastagonospora nodorum*, was the dominant leaf blotch disease in Europe until the 1980's, when the pathogen was replaced by *Z. tritici*, and is currently the dominating disease in Norway (Ficke et al., 2018). Tan spot (yellow spot), caused by *Pyrenophora tritici-repentis*, mainly occurs in cool temperate climate (Cotuna et al., 2015). Fusarium head blight, caused by *Fusarium* spp., has re-emerged in Europe in the 1990s, as in other parts of the world (Singh et al., 2016). Stem rust, caused by *Puccinia graminis* f. sp. *tritici*, has caused sporadic epidemics in several EU countries over the last years, has generated important losses after the outbreak in Sicily in 2016 (Bhattacharya, 2017; Saunders et al., 2019), and was the source of widespread epidemics in Northern Italy in 2019 (Salerno et al., 2019). Other wheat diseases with impact on wheat production in parts of Europe include Barley Yellow Dwarf Disease (BYDV), eyespot (*Oculimacula yallundae*), sharp eyespot (*Rhizoctonia cerealis*), and take-all (*Gaeumannomyces graminis*)(CABI, 2018).

Wheat disease management in Europe is mainly based on the use of fungicides and resistant cultivars. In spite of the protection measures currently implemented in farmers' fields, yield losses from wheat diseases in North Western Europe are estimated at about 25% (Savary et al., 2019). Improving disease management with respect to its specific efficiency and its environmental impacts requires information on actual crop health and quantification of yield levels (attainable yield of an un-injured crop, actual yield, yield losses) in relation with disease management methods (Savary et al., 2006). This is because decisions must be based on rational choices where specific costs-benefits, and environmental costs, need to be considered. Because wheat health problems vary over time (from season to season) and space, such an assessment needs to be conducted every year, in a range of geographical locations. Such assessments are not available currently for wheat in EU: only fragmented information of wheat health status is available, at the scale of Europe (e.g., Jørgensen et al., 2014; Figueroa et al., 2018; Singh et al., 2016; Savary et al., 2017; 2019), or at the country scale (e.g., Jahn et al., 2012; Savary et al., 2016a; Djurle et al., 2018; Willocquet et al., 2018). In the same way, information on fungicide use is also incomplete, and the information pertaining, e.g., to the number of fungicide applications on wheat crops in Europe, is seldom available. Information on the level of resistance of wheat cultivars against the main wheat diseases is often available on a country basis only, but no consistent information across countries is available, because a number of different methods are used to classify resistance. Actual yields are in general available on a country basis, and at finer grain for some EU countries (e.g., FAO, 2019). But information on attainable yield and yield losses is not available.

The objective of the work presented here was to provide an overview of wheat health and yield status based on field experiments conducted in Europe. For this, data from field experiments conducted between 2013 and 2017 in six European countries, which were aiming at improving the management of wheat diseases, were mobilised in order to analyse the relationships between disease level, yield, level of resistance, level of fungicide protection, and weather patterns.

2. Materials and methods

2.1 Characteristics of field experiments

This work considers wheat field experiments conducted between 2013 and 2017 in six European countries: Belgium, France, Germany, Italy, Norway, and Sweden (Table 1, Figure 1). The experiments were located in 1, 5, 4, and 3 regions in Belgium, France, Germany, and Italy, respectively. Experiments were located at 4 sites in Norway, grouped into two regions. In the same way, experiments were located at 7 sites in Sweden, grouped into 4 regions (Table 1, Figure 1). These experiments were established with the general aim to improve wheat disease management, with specific objectives varying between countries. For example, while emphasis was on cultivar resistance in Germany, experiments in Belgium compared a large number of fungicide application modalities.

Across the six countries, experiments included one treatment where fungicide use was determined according to the local recommendations (France, Germany), or was close to farmers' practices (Belgium, Italy, Norway, Sweden). This treatment is here referred to as: "reference fungicide protection level", and corresponds to one fungicide application in Norway and Sweden, and to two fungicide applications in Belgium, while the number of applications varied according to local recommendations in the other countries. Other fungicide protection levels were established and varied across countries: these protection levels were based on the number of fungicide applications (Belgium, Norway, Sweden), on local practices (Germany, Italy), or on a chosen level of chemical input intensification (France; Savary et al., 2016a). Several cultivars, with varying levels of resistance to wheat diseases, were included in the experiments conducted in Belgium, France, and Germany. The analyses reported here included 73 field experiments, consisting of a total of 447 [fungicide protection level x cultivar] combinations.

In terms of crop management, all experiments were rainfed, and wheat was grown according to the current local practices. Winter wheat was established in all countries except in Norway where spring wheat was sown. Soft wheat (*Triticum aestivum*) cultivars were used in all countries, except in Italy where durum wheat (*Triticum durum*) was used. Experiments were established according to a randomised complete block design (RCBD) with four blocks, except in Norway (2 – 3 blocks) and France (split-plot with 1 - 4 replicates; crop management as main unit and cultivar as sub-unit). Individual plot size at all locations was at least 10 m^2.

In each plot, 10 plants (main tillers) were sampled in Belgium, Germany, Italy, and Sweden, while 25 plants (main tillers) were assessed in Norway for disease assessments. Disease severity of foliar diseases was assessed on all the leaves (Belgium), or on the top three leaves (Germany, Italy, Norway, Sweden). In France, foliar diseases were assessed as disease incidence or disease severity. Foliar diseases assessed were septoria tritici blotch (STB; in all six countries), tan spot (in Norway and Sweden), septoria nodorum blotch (in Norway and Sweden), leaf rust (LR), yellow rust (YR), powdery mildew (PM), and stem rust (SR; in Italy). Because of uncertainty attached to the differentiation of symptoms of tan spot, septoria tritici blotch, and septoria nodorum blotch in Norway and Sweden, all three diseases were grouped and referred to as leaf blotch (LB). FHB (fusarium head blight) was assessed as the fraction of diseased ears. FHB was not assessed in Belgium, Norway and Sweden.

Diseases were assessed between Zadoks decimal codes for development stages (DVS; Zadoks et al., 1974) 70 and 80 in Belgium and France, and between DVS 70 and 75 in Germany, Norway and Sweden. Disease was assessed at DVS 55 for yellow rust and powdery mildew, and at DVS 85 for all other diseases in Italy. Yield (Y) was measured in all experiments and was expressed as grain weight at 15% water content.

Daily weather data recorded at less than 30 km from the respective field experiments were collected from national weather networks. Weather data included daily minimum and maximum temperature, global radiation, and rainfall.

2.2 Data analyses

2.2.1 Overview of variation in disease levels, yield, and crop inputs

Disease severity on the three top leaves was computed from Belgian data and used in further analyses. Foliar disease data from France were standardized as disease severity on leaves. The average of disease intensity and yield measurement over replicates was used for all analyses. Variation in disease levels, fertiliser and fungicide use, and yield levels between and within countries, was visualized using box plots (SYSTAT Software Inc.; Wilkinson, 2009) for the reference fungicide protection level, and for plots with no (or limited, in France) fungicide protection.

2.2.2 Categorisation of variables

Because experiments conducted in the different countries had been designed with specific objectives country-wise, experimental designs and protocols for data collection differed among countries. It was therefore decided to conduct an analysis over all countries using categorical, ordinal, rather than quantitative variables. While reducing the precision of results, the use of categorised variables increases the robustness of the results produced (Savary et al., 1995; 2016a).

Categorical variables were designed for multiple disease and yield variables according to their frequency distribution, as follows:

- Powdery mildew: 2 categories: PM_Abs: =0; PM: >0;
- Yellow rust: 2 categories: YR_Abs: =0; YR: >0;
- Leaf rust: 3 categories: LR_Low: <0.1%; LR_Mod: <5%; LR_High: ≥ 5%;
- Fusarium head blight: 3 categories: FHB_Abs: =0 or missing data (Norway, Sweden); FHB_Low: <5%; FHB_High: ≥ 5%;
- Leaf blotch: three categories: LB_Low: <1%; LB_Mod: <10%; LB_High: ≥ 10%;

- Crop yield: four categories: LowY: <6000 kg/ha; MedY: <8000 kg/ha; HighY: <10000 kg/ha; VHighY: ≥ 10000 kg/ha.

Two fungicide protection levels were considered, low and high. Low fungicide protection level (LowP) included plots with no protection, or with protection below the reference fungicide protection level, while other plots were grouped as plots under high protection level (HighP). Cultivar characteristics with respect to levels of resistance to the five diseases (1-9 scale) were retrieved from national institutions country-wise. Wheat cultivars were categorised as resistant (R; 1-3), moderately resistant (MR; 4-6), and susceptible (S; 7-9; Zadoks and Schein, 1979). The levels of resistance of wheat cultivars for leaf rust were not available for Norway, nor was it for FHB in Sweden. In both cases, these levels were assumed intermediate, and were set as MR. Cultivar characteristics in the network of experiments are displayed in Supplementary Table 1.

Weather variables were aggregated over three cropping season periods: winter, vegetative/growth phase, and reproductive phase. The winter period started at sowing and ended when the sum of temperature above 0°C from January 1 had reached 200 °C.day, which is when wheat growth resumes after winter (Willocquet et al., 2008). In Norway, where spring wheat was grown, experimental plots were harvested on September 29 at the latest. Therefore, the beginning of the winter period was set to October 1, so that the winter period starts after the end of the reproductive period. In Norway, the end of the winter period was set at the time of wheat sowing in spring. In all countries, the end of the vegetative phase corresponded to the beginning of the reproductive phase, and was set so that the temperature sum of the reproductive phase reaches 1000°C.day (Willocquet et al., 2008). The reproductive phase ended at harvest.

For each of the three periods considered, the averages of daily minimum temperature, maximum temperature, and global radiation were computed, as well as the fraction of days when rainfall was above 1 mm ("rainy day"). A total of 12 variables were thus generated for each experiment, synthesizing the weather conditions associated to these field experiments. Field experiments were then grouped according to these 12 variables, using a hierarchical cluster analysis with the Ward criterion and the Mahalanobis distance (Wilkinson et al., 2007). This allowed representing the daily weather variables as one categorical variable, defined on the basis of the cluster analysis.

2.2.3 Relationships between categorised disease levels, yield levels, disease management modalities and weather groups across countries

In a first step, relationships between categorised disease levels, yields, fungicide protection levels, countries, and cultivar resistance levels to diseases, were analysed with a chi-square test on pairwise categorical variables. Weather groups could not be included in the analyses because more than five cells had less than five expected individuals (Benzécri, 1973) in most contingency tables involving weather groups.

In a second step, relationships between categorised disease levels, categorised yield, fungicide protection levels, cultivar resistance levels to diseases, and weather groups were analysed with a multiple correspondence analysis (Benzécri, 1973; Greenacre, 1984; Lê et al., 2008; Savary et al. 1995). Categorised disease levels and yield categories were used as active variables, while fungicide protection levels, cultivar resistance levels and weather groups were considered as supplementary variables.

In a third step, logistic regressions were conducted in order to identify factors which affect disease levels. Binary logistic regressions were conducted for yellow rust and powdery mildew (categorised as binary variables), while multinomial logistic regressions were conducted for leaf blotch, leaf rust, and FHB (categorised with three categories; Harrell, 2001). The predictors considered for each individual disease analysis were the categorised variables for weather (weather groups), cultivar resistance (three levels: R, MR, S), and fungicide use (two fungicide protection levels). In all logistic regressions, the likelihood ratio and its associated probability provided an overall criterion of model suitability (Harrel, 2001). Predictors were described according to their estimate, the standard error of the estimates, and their attached probability.

Finally, a heat map (Wilkinson and Friendly, 2009) was generated to provide a synthetic visualisation of disease levels variation according to three factors: weather, cultivar resistance, and fungicide use. The heat map of disease levels displays the proportion (as percentage) of occurrence of high disease level in each category of these three factors using observed frequencies and a colour scale from green (low percentage) to red (high percentage).

2.2.4 Effects of fungicide protection levels and cultivar on disease and yield country-wise

The effects of fungicide protection on multiple disease intensities and on yield were assessed with mixed model analyses of variance (Schabenberger & Pierce, 2002; Garrett et al., 2004). Because the levels of fungicide use varied across countries, their effects on diseases and yield were analysed on a country basis. Several cultivars were involved in experiments in three countries (Belgium, France, Germany). The effect of cultivars was therefore also analysed in these countries. Fungicide protection levels, cultivars, and their interactions, were considered as fixed effects, while year and region were considered as random effects. The significance of random effects (pure and interaction effects) was tested with a likelihood ratio test based on the difference of fit statistics between the initial model and the model where the considered random effect had been removed (Schabenberger & Pierce, 2002). Analyses were performed using Proc MIXED with SAS v. 9.3 (SAS Institute Inc.). The effects of fungicide protection levels and of cultivars on multiple disease intensities were illustrated by box plots for selected countries and diseases.

3. Results

3.1 Variation in multiple disease intensities, inputs, and yield in two levels of fungicide protection

Wheat diseases assessed were septoria tritici blotch, septoria nodorum blotch, tan spot, yellow rust, leaf rust, stem rust, powdery mildew, and fusarium head blight. In this study, leaf blotch refers to septoria tritici blotch in Belgium, France, Germany, and Italy, while leaf blotch refers to a complex of septoria tritici blotch, septoria nodorum blotch, and tan spot in Norway and Sweden. Disease intensity (severity on leaves for foliar diseases; percent of diseased ears for FHB) varied greatly from one disease to another, in both fungicide protection levels (Figure 2). Leaf blotch reached the highest level of severity across the six countries. Other leaf diseases had lower severity on leaves, and did not occur in all countries. Stem rust was assessed in two instances in Southern Italy, in unprotected plots. Fusarium head blight was recorded in France and Italy.

Large differences in disease intensities were observed between countries, in both fungicide protection levels (Figure 2). The overall levels of disease were in general highest in Italy, and lowest in Germany. Yellow rust had the highest level in Germany, in unprotected plots (Figure 2b). No powdery mildew was observed in the Belgian trials, while low levels were generally recorded in France, Germany, and Norway, and moderate levels were recorded in the Italian unprotected plots (Figure 2b). Fusarium head blight was observed in France and Italy, and did not occur to detectable levels in Germany. There was a large variation in disease intensity within country and level of protection, which corresponds to variation over years and regions. Multiple disease intensities were in general lower when the reference fungicide protection level was implemented (Figure 2a) than at the no or limited protection level (Figure 2b).

Fertiliser inputs in the reference fungicide protection level were the highest in Belgium, in France, and in Sweden, and were the lowest in Italy (Figure 2a). The largest variation in fertiliser inputs occurred in Germany and Italy. Fungicide use (number of applications and total dose) was greater in Belgium, France, and Germany, than in Italy, Norway, and Sweden. There was a large variation in fungicide use in France and Germany, while variation was low in the other countries.

There were important yield differences between and within countries (Figure 2). The highest yields were obtained in Belgium and Sweden, while the lowest yields were recorded in the Norwegian spring wheat. Yield variation was the highest in Germany. Yields were higher in the reference fungicide protection level than in the no (or low) fungicide protection level (compare Figure 2a and Figure 2b).

3.2 Multivariate analyses of categorised diseases intensities, yields, fungicide protection, and weather groups

Seven weather groups were defined from cluster analysis, and were strongly associated to the geographical location of the experiments (Figure 3). Clusters W1, W2, and W3 included experiments from Norway and Sweden, while cluster W4 included experiments from Norway, Sweden, and the bulk of experiments in Germany. Cluster W5 included the bulk of experiments from France, and all experiments from Belgium. Cluster W6 included mainly experiments in Foggia (South Italy) and cluster W7 was constituted of experiments in Ravenna and Ancona (North and Centre Italy, respectively).

Figure 4 displays the weather characteristics associated with each cluster. Clusters W1 to W7 displayed increasing levels of minimum temperature in winter (Fig. 4). W1 was characterized by low temperature during the reproductive phase, and high temperature and rainfall during the vegetative phase; W2 displayed high radiation during the vegetative phase; field experiments in W3 were exposed to low temperature and radiation during the reproductive phase; W4 presented intermediate values of most weather variables in the three periods; W5 presented in general intermediate values, except for low maximum temperature in the vegetative stage and high fraction of rainy days in winter; W6 had the highest maximum temperature and radiation in winter; and W7 had the highest minimum temperature in all three periods and the lowest fraction of rainy days in winter and during the reproductive phase.

The results of chi-square tests of pairwise categorical variables between multiple disease intensities, yield, countries, cultivar resistance, and level of protection are displayed in Table 2. There was an overall positive association between levels of rusts (leaf and yellow) and powdery mildew. Leaf blotch was positively associated with leaf rust and FHB. FHB was the disease which was least associated with other diseases. Yield levels were negatively associated with all diseases, except leaf rust. Associations between disease levels, yield levels, and countries varied depending on the country. Protection level was negatively associated with all diseases except FHB, and was positively associated with yield. There was a negative association between resistance level and disease level in all diseases except powdery mildew. All these results were in line with patterns observed in Figure 2.

Multiple correspondence analysis captures associations amongst levels of diseases, yield, disease management levels (cultivar resistance and fungicide protection), and weather (Figure 5). The first and second axes account for 14.2% and 13.5% of total inertia, respectively, providing a sufficient insight in the association patterns. Figure 5 reports a single analysis, in different steps: Figures 5a and 5b show the patterns of linkage between (categorized) multiple disease levels (Fig. 5a) and yield (active variables; Fig. 5b); Figure 5b also outlines the pattern of yield variation within these associations as a path of successive levels; Figure 5c displays the positions of level of fungicide protection and host plant resistance (supplementary variables) in the same graphical output; and Figure 5d displays the position of weather groups (supplementary variables). Figure 5a positions diseases levels on the two first dimensions generated by multiple correspondence analysis. Low levels of disease are clustered in the low-left corner of the graph (small negative or positive values on the x-axis, small negative or positive values on the y-axis), while higher disease levels are positioned with small negative values on the x-axis, and high positive values on the y-axis for leaf rust, yellow rust, and powdery mildew. Large disease levels are displayed on the far right of x-axis for FHB, leaf rust and leaf blotch. With respect to multiple disease, three patterns are thus suggested in Fig. 5a: (1) occurrence of yellow rust (YR) and powdery mildew (PM), together with moderate levels of leaf rust (LR_Mod); (2) high leaf rust (LR_High), high leaf blotch (LB_High) and some FHB (FHB_Low); and (3) high FHB (FHB_High). Increasing yield levels follow a path, from positive to negative co-ordinates, on both the x- and the y-axis, as shown in Figure 5b. This path coincides with change in multiple disease levels, away from high to low disease levels shown in figure 5a. The path from low fungicide protection to high fungicide protection corresponds to increasing co-ordinates on the y-axis, and cultivars susceptible to diseases are all located on the domain with positive x and y co-ordinates on the axes (Figure 5c). Weather groups positioning (Figure 5d) shows that groups W3 and W5 are close to the centre of the graph, while W6 and W7 appear on the upper right quadrant (associated to high disease levels), W1 and W3 on the lower right quadrant, and W2 on the lower left quadrant (associated to low disease levels).

Logistic regressions were conducted for leaf blotch, leaf rust, yellow rust and powdery mildew. Regressions could not however be achieved for FHB, owing to the imbalanced data among disease, weather, and cultivar resistance levels. Logistic regressions were significant ($P < 0.001$) for all four foliar diseases (Table 3). In all cases, higher fungicide protection level significantly and negatively affected disease level. Cultivar resistance against leaf blotch and yellow rust significantly and negatively affected the respective disease levels. Weather group W4 was negatively associated with high level of leaf blotch and leaf rust, and positively associated with powdery mildew. Weather group W7 was positively associated with leaf rust and powdery mildew, while weather group W6 was positively associated with leaf rust.

Figure 6 displays the occurrence of high disease levels in the different categories of weather, fungicide protection, and cultivar resistance variables. This figure highlights (1) the dominance of leaf blotch over other diseases, (2) the interaction between weather and disease patterns, (3) the vulnerability of susceptible cultivars to diseases, especially in the case of yellow rust and powdery mildew, but also in the case of the multi-pathogen leaf blotch, and (4) the effect of fungicide protection on disease level, especially for leaf blotch, yellow rust, and powdery mildew.

3.3 Effects of fungicide protection and cultivars on disease levels and yield

Leaf blotch severity was affected ($P < 0.1$) by fungicide protection level in all countries except Norway (Table 4). Cultivar (as pure effect or in interaction) affected leaf blotch only in France. Year and region affected leaf blotch in Belgium, France, and Germany, in general in interaction with another factor. Leaf rust was affected by different factors depending on the country: no significant ($P > 0.1$) effect of fungicides, cultivars, year or region was detected in France; one significant effect (fungicide protection) was detected in Italy; but significant fungicide and cultivar effects (pure or in interaction) were detected in Belgium and Germany. Main effects of fungicide protection and cultivar were not significant on FHB incidence, but some effects of interactions involving year or region were significant. Yellow rust in Germany was affected by fungicide, cultivar, and year as interaction effects (Table 4, footnote). Powdery mildew in Germany was affected by fungicide, fungicide x region, and year x region (Table 4, footnote).

Yield was in general significantly affected by more factors than diseases were (Table 4). Protection level significantly affected yield in four out of the six considered countries. Cultivar affected yield as a pure effect or in interaction with another factor in all three countries where several cultivars had been considered in the experiments. Year and region affected yield in all countries as pure or as interaction effects, except in Norway.

The effects of fungicide use, cultivar, and their interaction on multiple diseases is illustrated in the case of septoria tritici blotch, leaf rust and yellow rust (Figure 7). In the case of septoria tritici blotch, disease severity was reduced when the level of fungicide protection was increased, while differences between cultivars could be observed in Belgium, France, and Germany. Differences in disease severity between two levels of fungicide protection varied with cultivar: there were higher in Avatar than in Edgar in Belgium, higher in Pakito than in Attlass in France, and higher in Apertus than in Dichter in Germany. Similarly, differences between cultivars were larger when the level of fungicide protection was lower. Similar patterns were observed for leaf rust and yellow rust, but with larger differences displayed between cultivars, as illustrated in the case of yellow rust in Germany.

4. Discussion

4.1 General patterns generated from the European field experiments

This work provides some insight in the wheat health status in European countries over recent years, according to field experiments conducted in order to improve disease management. First, wheat health in Europe appears dominated by leaf blotch diseases. “Leaf blotch” collectively refers to septoria tritici blotch and septoria nodorum blotch, as well as tan spot in Norway and Sweden (weather groups W1-W3), and to septoria tritici blotch in the other countries. The dominant role of septoria tritici blotch in Europe has been documented in several recent studies (Fones and Gurr, 2015; Savary et al., 2015; 2019), while septoria nodorum blotch, alone or within the leaf blotch complex, has been recognised as an important disease in several parts of the world (Ficke et al., 2018). The other foliar diseases, ranked according to decreasing disease severity in non- or low protected conditions, were: leaf rust, yellow rust, and powdery mildew. FHB was observed in experiments in France and Italy. This general pattern, and the ranking of diseases in Europe, conforms to recent analyses and reviews on wheat health (Jørgensen et al., 2014; Figueroa et al., 2018; Singh et al., 2016; Savary et al., 2017; 2019). Some diseases were not observed in the analysed field experiments, despite their reported occurrence (CABI, 2018). This is the case of yellow rust in Sweden; yellow rust and powdery mildew in Belgium; and FHB in Germany. FHB was not assessed in Belgium, Sweden and Norway, but the disease is also present in these countries (CABI, 2018). Stem rust was found in two experiments in Italy, indicating that the disease is established in this country, after the epidemic which affected Sicily in 2016 (Bhattacharya, 2017). This evolution is further confirmed by the recent epidemics observed in Tuscany in 2019 (Salerno et al., 2019).

Nitrogen fertilisation varied across countries, with highest quantities applied in France, Belgium and Sweden, whereas the lowest level of fertilisation was applied in Italy. The ranking of countries according to levels of nitrogen fertilisation was strongly associated with the ranking observed for yield levels. The positive association between nitrogen fertilisation and yield is indeed well documented (e.g., Sinclair, 1990). The ranking among countries according to yield is in agreement with the ranking according to national yields estimates from the FAO (http://www.fao.org/faostat/), although yields from the experiments were in general larger than the national estimates. The lowest yields obtained in Norway may be partly explained by the fact that the experiments were conducted with spring wheat, which has a much lower potential yield than winter wheat, which was grown in experiments in all other countries. Because the experiments used in this study did not include nitrogen as a factor (as they did for protection level, and in some countries, for cultivars with different levels of resistance), it was not possible to analyse the effect of nitrogen on disease in this study. The effect of nitrogen on plant diseases depends on the ecological attributes of the causal agent, and has been addressed in many articles on plant diseases (e.g., Veresoglou et al., 2013), and on wheat diseases (e.g. Savary et al., 2017).

The weather groups generated from the cluster analysis are in line with recent analyses of climate typology (Metzger et al., 2005; 2013). These groups capture climatic variations from Nemoral, Continental, Oceanic, to Mediterranean environments.

Multivariate analyses indicated that high disease levels were associated with lower fungicide use, susceptible cultivars, weather groups with higher winter temperature, and lower yields. These multivariate associations may be interpreted according to causational relationships. On the one hand, disease levels are affected by weather and disease management levels (fungicide use and host plant resistance). Such relationships have been documented for wheat in France (Savary et al., 2016a; 2016b). On the other hand, yields are affected by the combined effects of weather, crop management, disease management, and disease levels. Such relationships were quantitatively estimated for wheat in France using a process-based modelling approach (Willocquet et al., 2018), and in Sweden using logistic regression models (Djurle et al., 2018).

4.2 Effects of disease management tools on wheat health and yield

The effects of fungicide use and cultivars on disease and yield, tested country-wise (Table 4), indicated that both fungicide use and cultivars had significant effects ($P < 0.05$) on diseases and yield. Fungicides have an indirect effect on yield by protecting the crop from the yield-reducing effects of diseases. Fungicides can moreover have a direct, positive effect on yield (e.g., Hampton and Hebblethwaite, 1984). The detected cultivar effect on crop yield may be associated with traits such as competitiveness or tolerance to abiotic stress, but may also be due to cultivar resistance against diseases. While resistance has also an indirect positive effect on yield through the reduction of disease, it may also have a direct yield penalty effect (Brown and Rant, 2013).

The effects of fungicide use and cultivar on disease and yield appear to depend on both the country and the considered disease, allowing a characterisation of ecological features of disease and crop performance according to countries. Some diseases were significantly only affected by fungicide use (leaf blotch in Sweden and Italy, leaf rust in Italy). This may suggest that in these cases, the disease is chronic, i.e., occurs every year and in all regions (Savary et al., 2011), that cultivars are not expressing a strong level of host plant resistance (see supplementary Table 1), and that fungicide use is important for the management of these diseases in these countries. Some diseases were not affected by any factor (leaf blotch in Norway, leaf rust in France), which may suggest that under these environments the disease level was low, was marginally affected by weather, or by disease management. Some diseases were affected by interactions involving year or region (leaf rust in Belgium; FHB in France and Italy). In that case, it can be assumed that the disease is acute, i.e., its level varies over time (year) or space (region; Savary et al., 2011). In other cases (septoria tritici blotch in Belgium, France, and Germany; leaf rust and powdery mildew in Germany), the disease level was affected both by pure and interaction effects. This could represent diseases which are significantly affected both by weather and by disease management tools.

Leaf blotch (or septoria tritici blotch alone) is in most countries affected by fungicide use, reflecting the importance of fungicide use for the management of that disease (Fones and Gurr, 2015). Cultivar resistance however significantly affects septoria tritici blotch, as shown in France. The role of quantitative resistance to reduce septoria tritici blotch has been documented (Fones and Gurr, 2015; Lynch et al., 2017). Our results indicate that septoria tritici blotch can be chronic in some parts of Europe (Italy, Sweden), but acute in others (Belgium, France, Germany). Leaf rust is chronic in Italy because the weather conditions are in general favourable to the disease and the cultivars are not expressing a high level of resistance, whereas the disease displays acute patterns in Belgium, where the weather conditions may be more or less favourable to the disease, depending on the year, and where the pathogen population may have adapted to the resistance of cultivars established in the experiments. Leaf rust level can be significantly affected by cultivar resistance (Duveiller et al., 2007; Singh et al., 2016), as shown in Belgium. The low levels of yellow rust was strongly associated with the use of resistant cultivars, as illustrated in Belgium, where no disease was observed on the resistant cultivars used in all experiments (Fig. 2). Furthermore, in Germany, the contrast between susceptible (JB Asano) and resistant cultivars was very well expressed according to the levels of yellow rust observed in the non- protected plots (Fig. 7). Because of its strong ecological requirements (warm and moist conditions during a relatively short period of time, around flowering; e.g., Xu, 2003), FHB is expected to display acute patterns, which are found in this analysis. FHB can be affected by fungicide use (Mesterhazy et al., 2003), as observed in France and Italy, and by cultivar resistance (Bai and Shaner, 2004), as displayed in France.

Yield was in general affected by all factors (fungicide use, cultivar, year, region), as pure effects or as effects in interaction. This reflects the fact that yield is a proxy of crop performance, involving a range of physiological processes affected by the biophysical environment reflected by the factors tested in the analysis of variance.

The variation in levels of multiple-disease intensity according to cultivar and fungicide use (Figure 7) reveals that the effect of cultivar resistance can be masked by fungicide use: differences between cultivars are reduced as the level of fungicide protection increases. This was already documented in other studies (e.g., Willocquet et al., 2018). This echoes a common situation in farmers' practices (Jørgensen et al., 2014), whereby the decision to use fungicides does not take into account the level of host plant resistance of the cultivar used. Taking into account the level of cultivar resistance is a critical component to incorporate in the improvement of the use of fungicides for disease management (i.e., IPM: Teng and Savary, 1992). This has been particularly well documented in the case of wheat (e.g., Rijsdijk et al., 1989; Zadoks, 1989; Lynch et al., 2017). Figure 7 further shows that the effect of cultivar (i.e., of host plant resistance) in suppressing disease depends on the disease considered, and reflects the difference in common types of resistance deployed in wheat cultivars: quantitative for STB, qualitative for rusts (Duveiller et al., 2007; Singh et al., 2016).

4.3 Avenues and requirements for networked crop health research

This analysis documents the status of wheat health in Europe. This work also highlights avenues and needs for networked crop health research, which would allow a deeper description, and a better understanding of wheat health, with its drivers at a continental or global scale. We identify three critical areas for necessary progress along this avenue.

First comes the acute need for standardization of field experiments so that they can be analysed as a network. Two key elements of standardisation are: (1) disease assessment procedures (sampling; scale; protocol; number of assessments at pre-set crop development stages), and (2) experimental design (involving the effects of cultivar and fungicide protection). Standardised disease assessment is critical, and should reach the same level of standardization as used, for example, to measure yield. Standardisation of disease assessment should rely on the available literature (e.g., Large, 1966; Chiarappa, 1971; James 1971, 1974; Savary et al., 2006; Bock et al., 2010). Experimental designs may differ amongst sites and countries, but should allow a combined analysis. Experimental designs should in particular include the required control treatments. While this is generally implemented for fungicide evaluation, it is not the case for cultivar effects. Yet, measuring the effect of host plant resistance on disease suppression is an important goal; including reference (“control”) cultivars with no (documented) disease resistance in the experimental design would allow to truly assessing the effect of cultivar resistance as a pure effect. This would also allow comparing the cultivar effect with the effect of fungicide protection, and assessing their interaction.

Such networked field experiments may be conducted on a country basis, or over countries. Experimental information and data at the country scale is difficult to access, and is in general not standardised over countries, as illustrated by the current work. Aggregated information over countries may exist in the private sector, but is not made publicly available. Networked experiments over countries, in which experimental information (assessments, measurements, crop management, and weather) would be made available for public research, would be a critical step to improve disease management.

A second point refers to the concept of yield gaps in the literature (Herdt and Mandac, 1981; Van Ittersum et al., 2013). While this work is based to a large extent on experimental station studies (and also in well-supervised and well-managed farmers’ field experiments), economists (e.g., Herdt and Mandac, 1981) and agronomists (e.g., Van Ittersum et al., 2013) have long been distinguishing crop performances measured in research station or in farmer's fields. Experimental stations, or localised experiments, often do not provide accurate information on the actual state of wheat health in farmers' (commercial) fields. Beyond networked field experiments, there is a need to quantitatively assess wheat health, crop yield, and cropping practices in farmers' fields to guide research and policy. We are not aware of the availability of such information in the EU. This is however the starting point necessary to improve wheat health management strategies (Large, 1966; James, 1974; Zadoks and Schein, 1979; Savary et al., 2006).

Third, there is a need to implement complementary approaches that would enable yield loss estimation under current conditions as well as under scenarios of future conditions, because yield loss is the yardstick of any work focusing on disease management (Zadoks, 1985; Savary et al., 2006). Yield loss is the difference between the attainable (un-injured) and the actual yield. The measurement of actual yield is relatively easy, while measurement or estimation of the attainable yield is difficult. Process-based models for yield loss modelling, combined with observed, past, and current data (wheat health and yield from farmers' fields and from field experiments; weather data) would enable to quantify the impacts of policies on wheat health under future scenarios and explore a range of disease management strategies.

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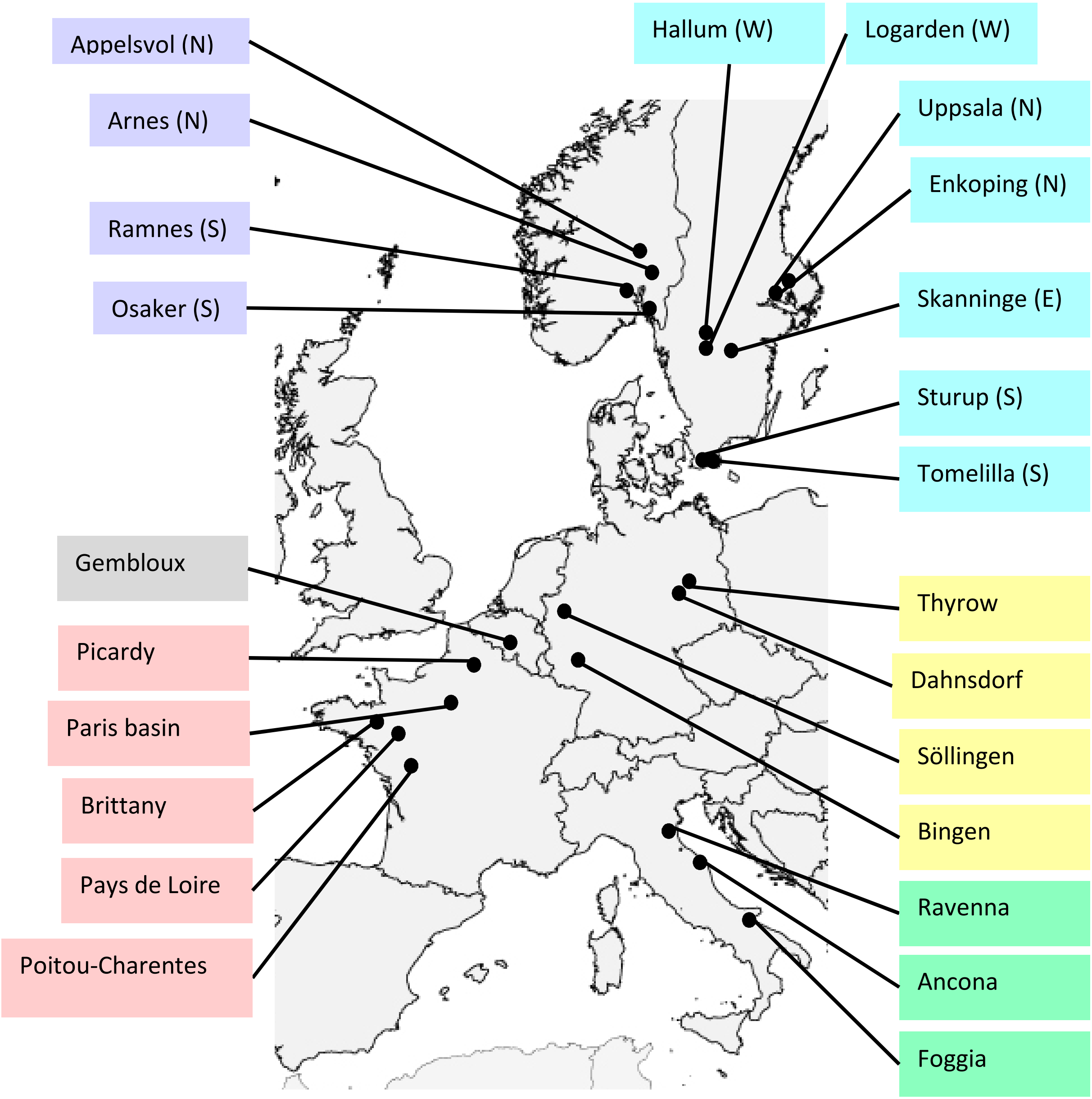


Figure 1. Map of the regions were wheat field experiments were conducted.

In Norway and Sweden, regions (N = North; S = South; E = East; W = West) regroup 1 or 2 sites.

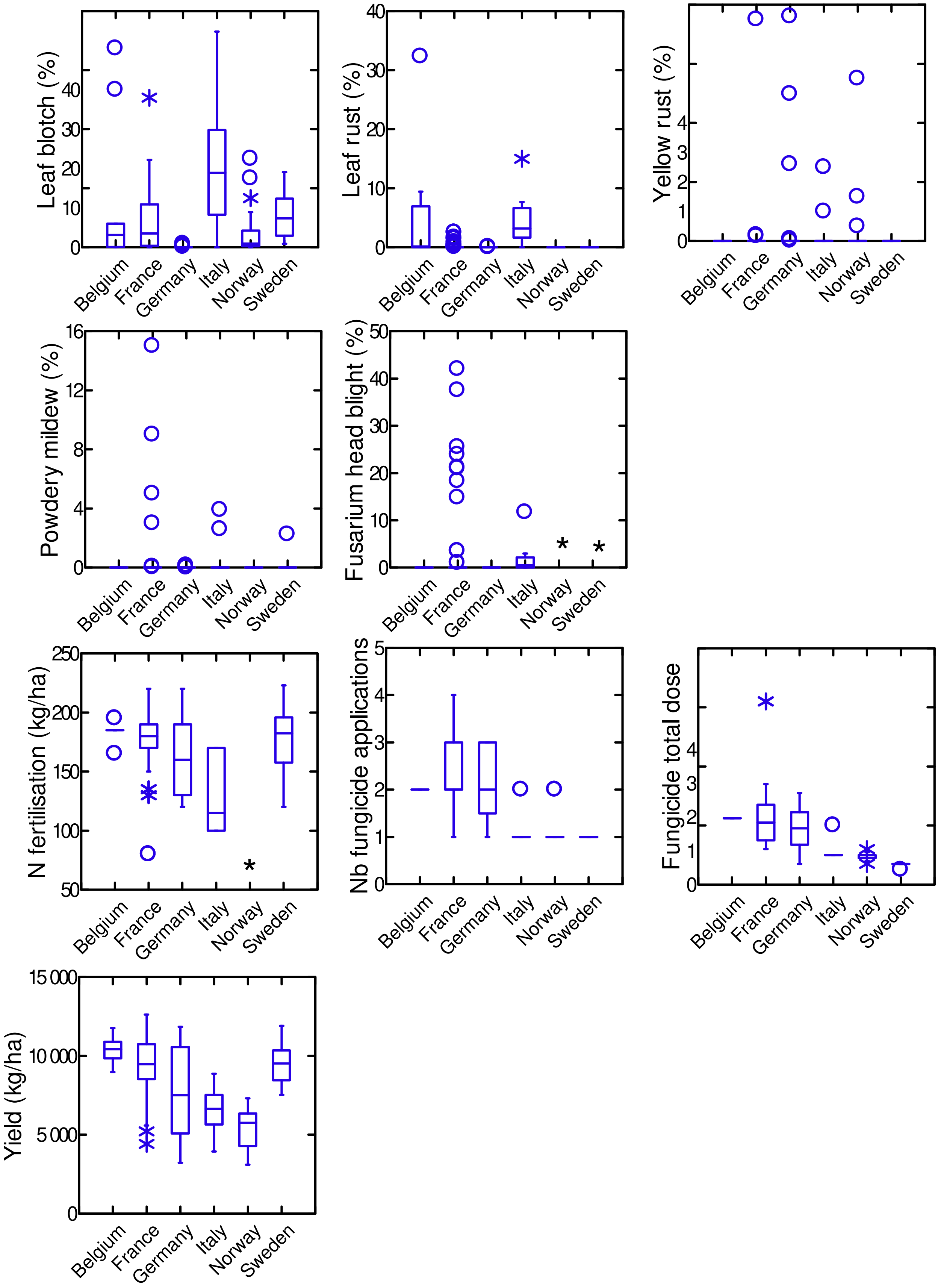


Figure 2a. Box plots of disease levels, fertilizer (N) input, fungicide use and yield across countries for plots with the reference fungicide protection level.

Note that the y-axes of plots displaying disease levels have different ranges depending on the disease.

Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries.

5-branched stars symbols represent missing data.

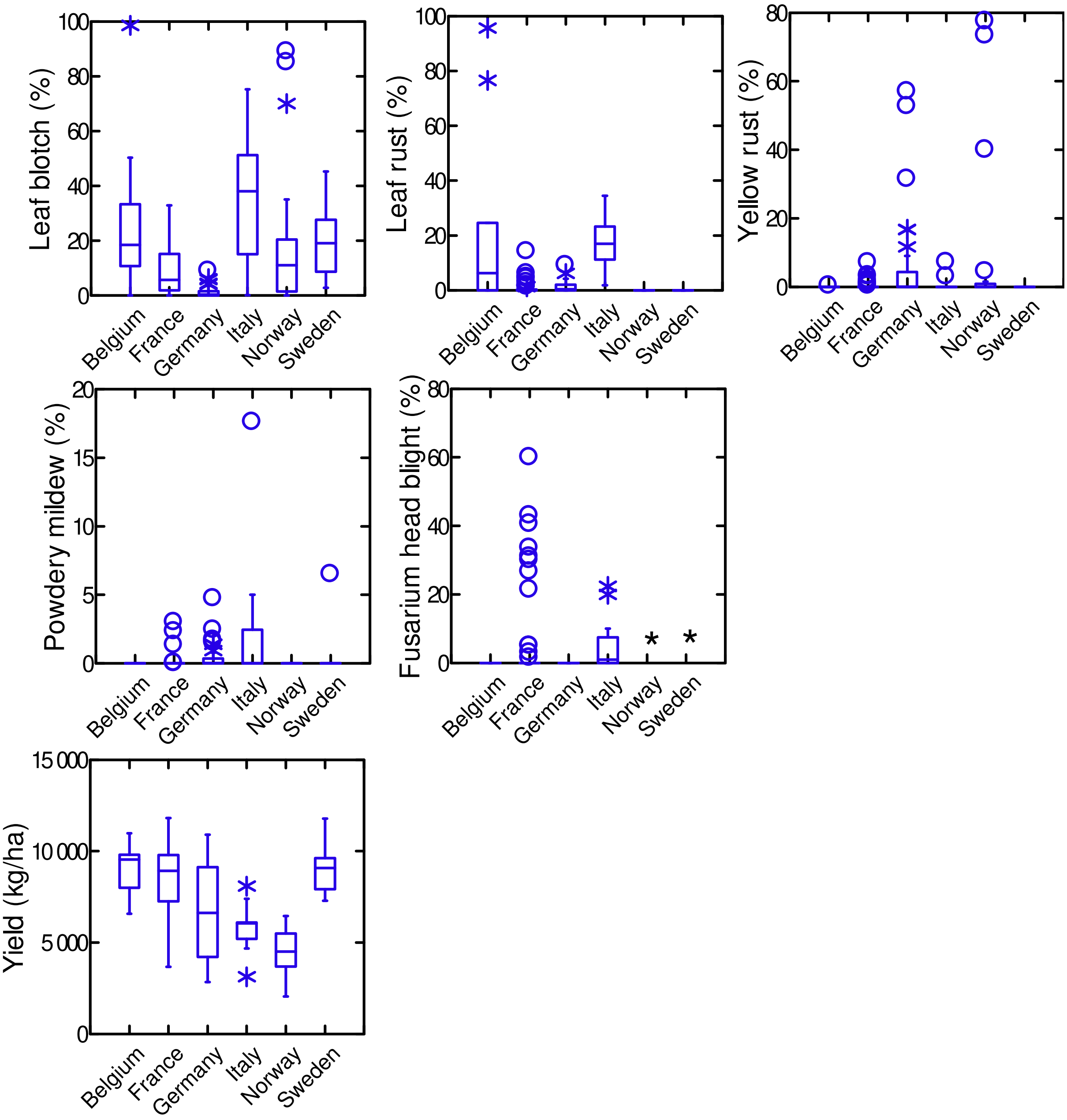


Figure 2b. Box plots of disease levels and yield across countries for plots with no or limited (France) fungicide protection.

Note that the y-axes of plots displaying disease levels have different ranges depending on the disease.

Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries.

5-branched stars symbols represent missing data.

Stem rust occurred in two instances, in Ravenna and Foggia, Italy (data not shown).

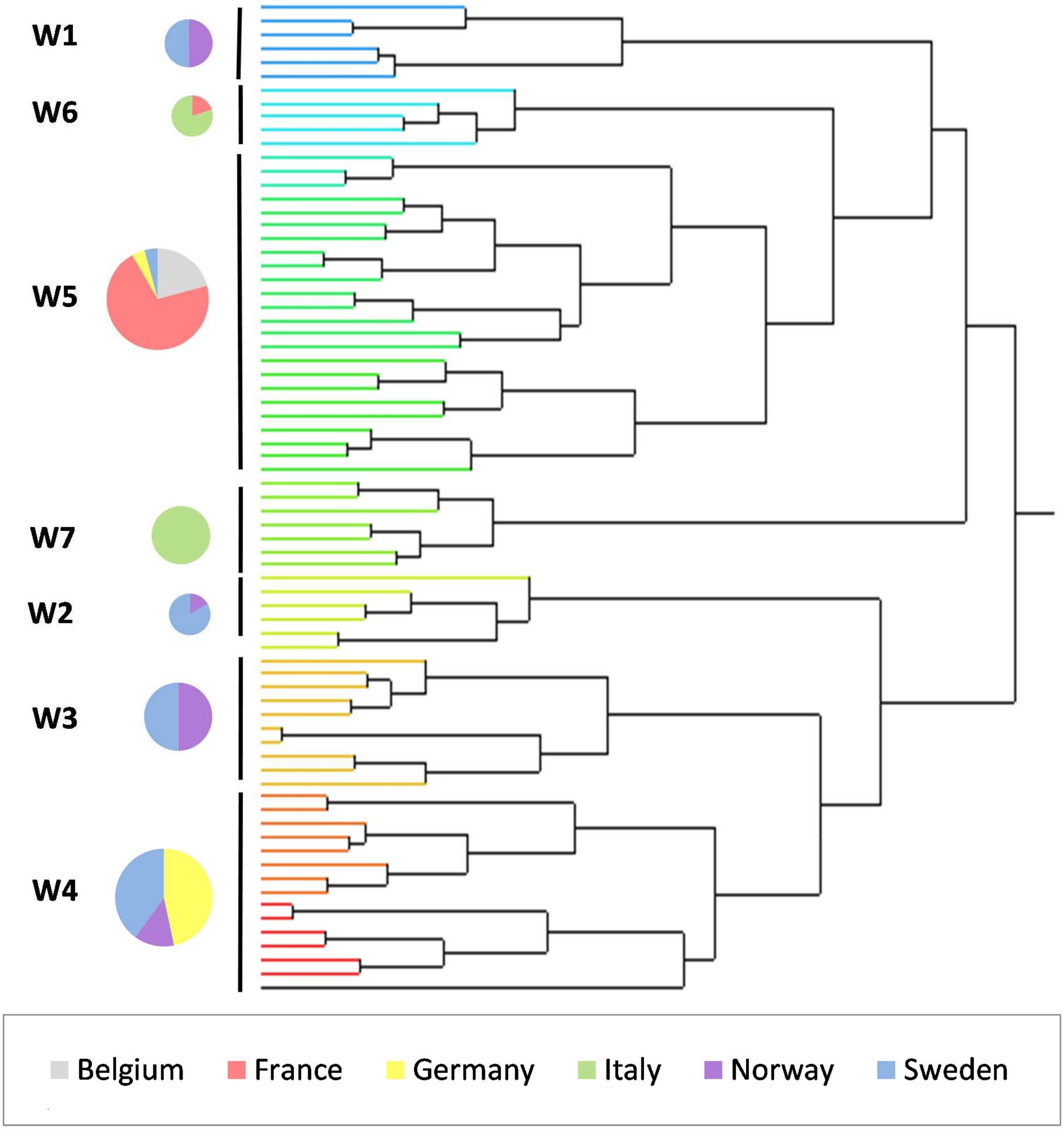


Figure 3. Cluster tree of experiments according to weather and proportion of experiments according to countries for the seven groups identified.

Weather groups W1 to W7 were identified from a hierarchical cluster analysis (Ward criterion, Mahalanobis distance) which grouped field experiments according to daily minimum temperature, maximum temperature, rainfall, and radiation over winter, vegetative/growth, and reproductive periods. W1 to W7 are characterised in Figure 4.
See text for details.

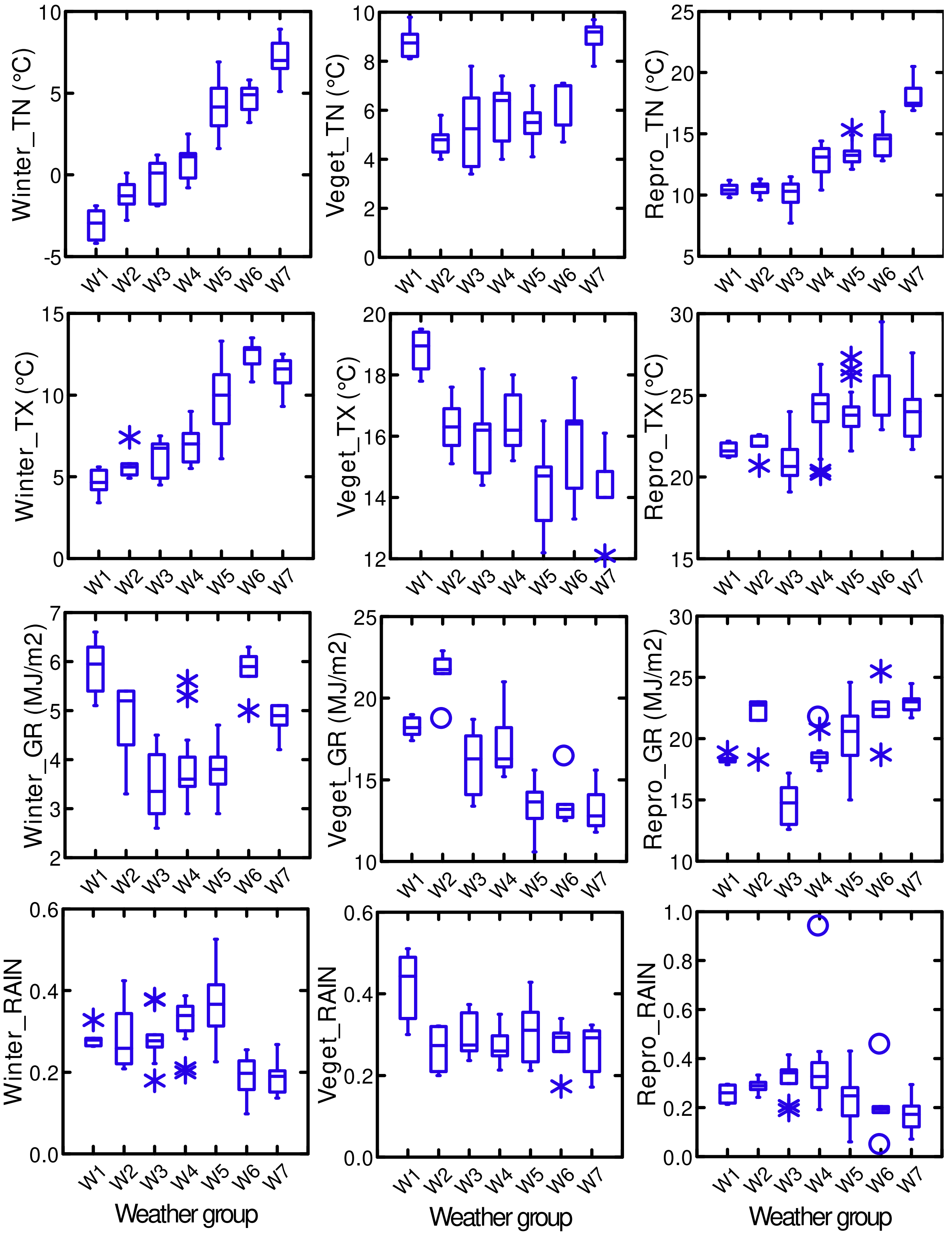


Figure 4. Box plots of weather groups generated from the cluster analysis (Ward criterion which grouped field experiments according to daily minimum temperature, maximum temperature, rainfall, and radiation over winter, vegetative/growth, and reproductive periods.

TN: minimum daily temperature; TX: maximum daily temperature; GR: global radiation; RAIN: fraction of days with rainfall larger than 1 mm. Left column: winter period; central column: vegetative/growth period; right column: reproductive period.

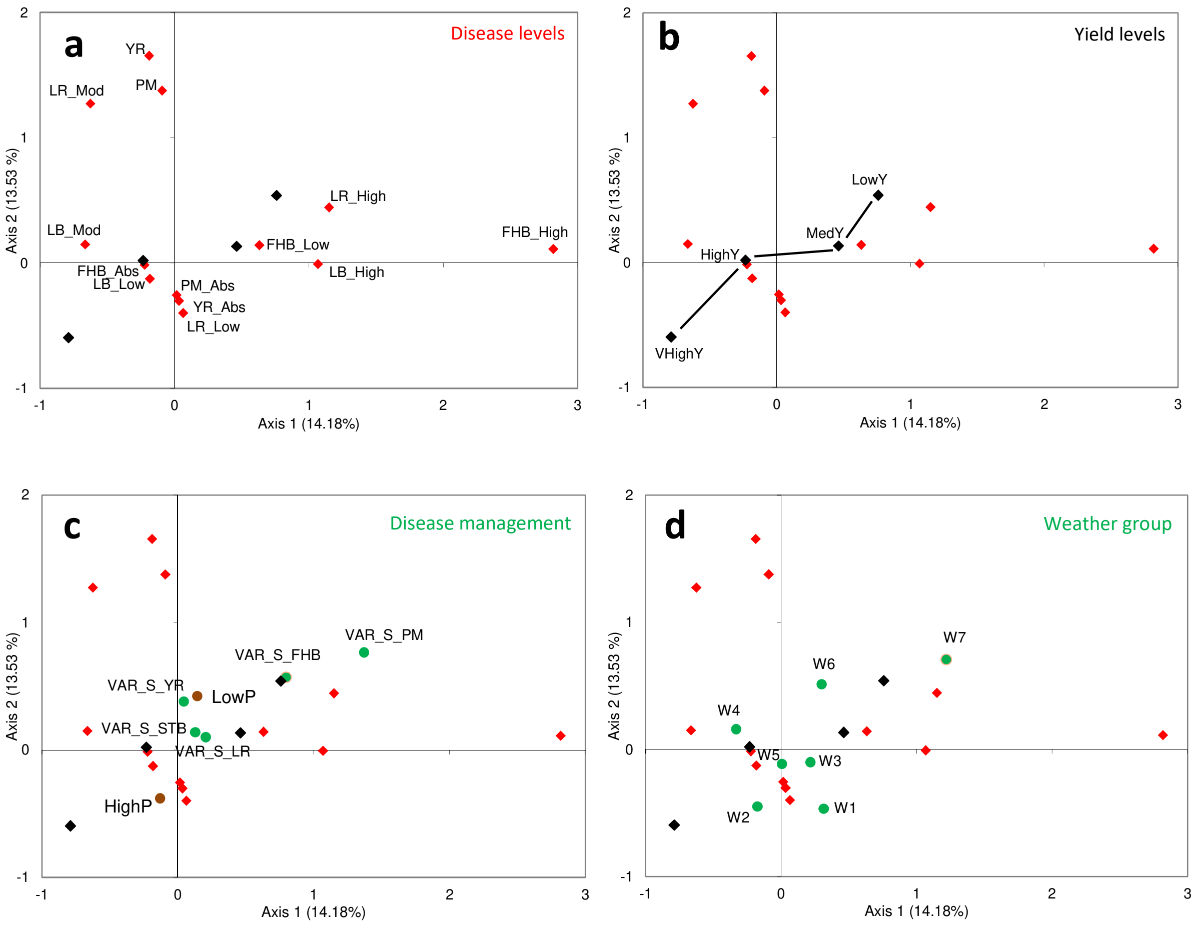


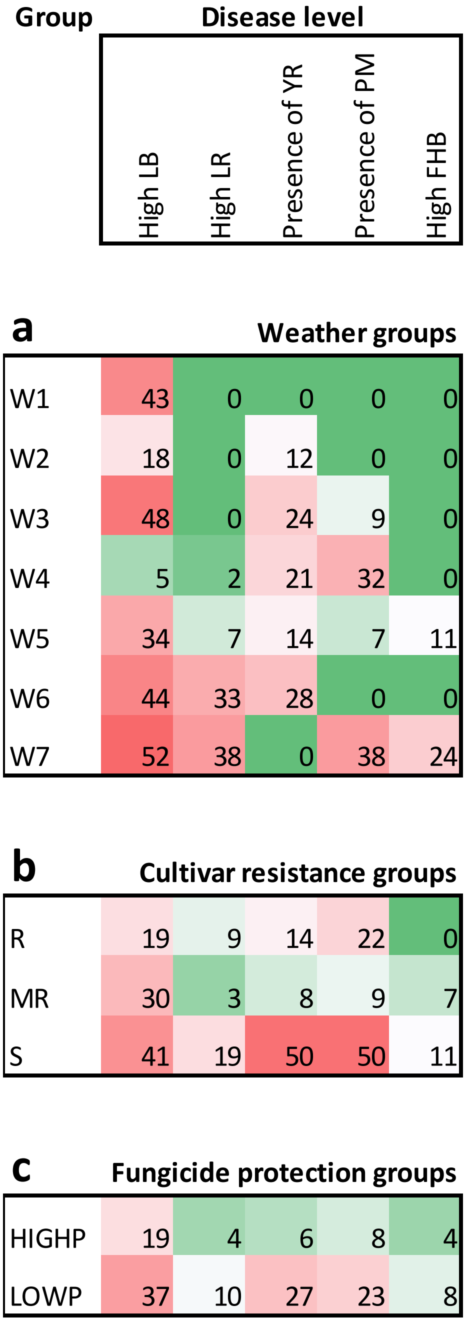
Figure 5. Multiple correspondence analysis among diseases, yield, disease management levels, and weather groups.

Diseases (red symbols) and yield (black symbols) are active variables, while disease management and weather groups (green and brown symbols) are additional variables.
a: display of disease categories; b: display of yield categories; c: display of disease management categories; d: display of weather groups.

LB: leaf blotch; LR: leaf rust; YR: yellow rust; PM: powdery mildew; FHB: fusarium head blight.
Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries.

Disease categories: PM_Abs: =0; PM: >0; YR_Abs: =0; YR: >0; BR_Low:<0.1%. LR_Mod: <5%; LR_High: >=5%; FHB_Abs:=0 or missing data -Norway, Sweden); FHB_Low:<5%; FHB_High: >=5%; LB_Low:<1%; LB_Mod: <10%; LB_High: >=10%.
Yield categories: LowY: <6000 kg/ha; MedY: <8000 kg/ha; HighY: <10000 kg/ha; VHighY: >=10000 kg/ha.
Fungicide use categories: LowP: fungicide protection below the reference fungicide protection level; HighP: fungicide protection level at, or larger than, the reference fungicide protection level.
Cultivar categories: VAR_S_FHB, VAR_S_LR, VAR_S_PM, VAR_S_STB, VAR_S_YR: cultivars susceptible to FHB, leaf rust, powdery mildew, Septoria tritici blotch, and yellow rust, respectively.

Weather groups: W1 to W7 were identified from a hierarchical cluster analysis which grouped field experiments according to daily minimum temperature, maximum temperature, rainfall, and radiation over winter, vegetative/growth, and reproductive periods. W1 to W7 are characterised in Figure 4.



Group	High LB	High LR	Presence of YR	Presence of PM	High FHB
a **Weather groups**					
W1	43	0	0	0	0
W2	18	0	12	0	0
W3	48	0	24	9	0
W4	5	2	21	32	0
W5	34	7	14	7	11
W6	44	33	28	0	0
W7	52	38	0	38	24
b **Cultivar resistance groups**					
R	19	9	14	22	0
MR	30	3	8	9	7
S	41	19	50	50	11
c **Fungicide protection groups**					
HIGHP	19	4	6	8	4
LOWP	37	10	27	23	8

Figure 6. Percent of occurrence of high level of disease in weather (a), cultivar resistance (b), and fungicide protection level groups (c).

LB: leaf blotch; LR: leaf rust; YR: yellow rust; PM: powdery mildew; FHB: fusarium head blight.

Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries.

The percent of occurrence was computes as the percent of high disease level (LB, LR, FHB) or as the percent of disease presence (YR, PM) over the 447 [fungicide protection level x cultivar] combinations in the 73 field experiments.
Disease categories: High LB: leaf blotch >=10%; High LR: leaf rust >=5%; Presence of YR: yellow rust >0; Presence of PM: powdery mildew >0; High FHB: FHB >=5%.
Weather groups: W1 to W7 were identified from a hierarchical cluster analysis which grouped field experiments according to daily minimum temperature, maximum temperature, rainfall, and radiation over winter, vegetative/growth, and reproductive periods. W1 to W7 are characterised in Figure 4.

Cultivar categories: R: Resistant, MR: moderately resistant; S: susceptible to the corresponding disease in each column.

Fungicide use categories: HighP: fungicide protection level at, or larger than, the reference fungicide protection level; LowP: fungicide protection below the reference fungicide protection level.

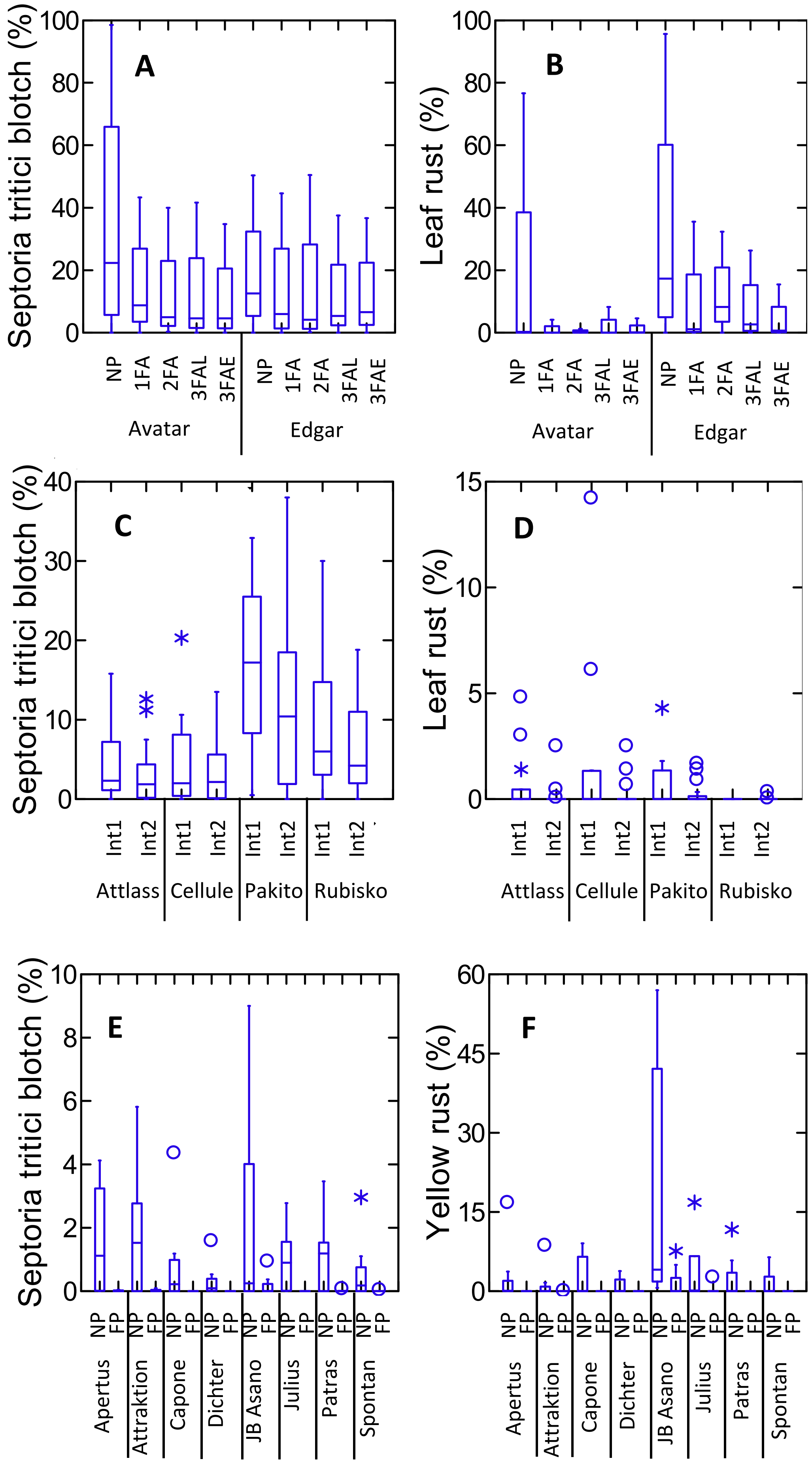


Figure 7. Box plots of disease severity according to cultivar and fungicide level in Belgium (A-B; except 2013), France (C-D), and Germany (E-F). X axes labels: top: fungicide treatment; bottom: cultivar name. NP = no fungicide protection; yFA = y fungicide applications; FAL: late application; FAE: early application; Int1 = low level of chemical intensification; Int2 = high level of chemical intensification; FP = fungicide protection according to local recommendation.

Note that the y-axes of plots have different ranges.

Table 1. Characteristics of the wheat field experiments

Country	Years	Wheat type	Regions	Number of cultivars per experiment*	Number of fungicide protection levels per experiment	Number of experiments	Number of combinations of factor levels
Belgium	2013-17	Winter soft wheat	1 (Gembloux)	2	5 (0, 1, 2, 3-early, 3-late fungicide applications)	5	46
France	2013-16	Winter soft wheat	5 (Brittany, Loire, Paris basin, Picardy, Poitou)	4	3 (no protection with low N input; protection and N input below recommendation; protection and N input according to local recommendation)	18	144
Germany	2016-17	Winter soft wheat	4 (Bingen, Dahnsdorf, Söllingen, Thyrow)	8	2 (no protection; protection according to farmers practices)	8	126
Italy	2014-17	Winter durum wheat	3 (Ancona, Foggia, Ravenna)	1	3 (no protection; protection according to farmers practices; full protection)	11	33
Norway	2013-16	Spring soft wheat	2 (North = Appelsvol, Arnes; South = Osaker, Ramnes)	1	2 (no protection; 1 fungicide application)	11	38
Sweden	2013-17	Winter soft wheat	4 (East = Skanninge; North = Enkoping, Uppsala; South = Sturup, Tomelilla; West = Hallum, Logarden)	1	3 (no protection; 1 fungicide application; 2 fungicide applications)	20	60

* Cultivars within a country are varying across sites and years in Italy, Norway and Sweden.

Table 2. Results of chi-square tests on pairwise categorical variables of disease, yield, country, protection level, and cultivar resistance.

	LB		LR		YR		PM		FHB		Yield	
	pattern	Proba.	pattern	Proba.	pattern	Proba.	pattern	Proba.	pattern	Proba.	pattern	Proba.
LB												
LR	positive association	0.001										
YR	not significant	0.20	positive association	<0.001								
PM	positive association	0.085	positive association	<0.001	positive association	0.008						
FHB	positive association	<0.001	no clear pattern	0.015	Not significant	0.10	not significant	0.99				
Yield	negative association	<0.001	not significant	0.75	negative association	<0.001	negative association	0.043	negative association	<0.001		
Country	positive association: France, Italy; negative association: Germany	<0.001	positive association: Italy, Belgium; negative association: Norway, Sweden	<0.001	positive association: Germany	<0.001	positive association: Germany	<0.001	positive association: France, Italy	<0.001	positive association: Belgium, France, Sweden; negative association: Italy, Norway	<0.001
BINPROT	negative association	<0.001	negative association	<0.001	negative association	<0.001	negative association	<0.001	no clear pattern	0.04	positive association	<0.001
VAR-RES-GRP	negative association	<0.001	negative association	<0.001	negative association	<0.001	no clear pattern	<0.001	negative association	<0.001		

LB: leaf blotch (Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries); LR: leaf rust; YR: yellow rust; PM: powdery mildew; FHB: fusarium head blight; BINPROT: binary variable with BINPROT = 0 when fungicide application is below the reference disease management practices, and 1 otherwise. VAR-RES-GRP: resistance group of the cultivar against the corresponding disease.

Green: significant ($P < 0.05$) positive association; red: significant ($P < 0.05$) negative association between variables; yellow: significant ($P < 0.05$) bidirectional association between variables.

Table 3. Results from logistic regressions of categorised disease levels on level of fungicide protection, level of cultivar resistance, and weather group.

Disease	Regression statistics		Disease level	Predictor	Predictor statistics		
	Likelihood ratio	Probability			Estimate	Standard error	Probability
Leaf Blotch Reference = Low disease level	169	< 0.001	High	HIGHP	-1.704	0.302	< 0.001
				STB_MR	-0.987	0.493	0.045
				STB_R	-1.996	0.548	< 0.001
				W4	-3.486	0.509	< 0.001
			Moderate	HIGHP	-0.836	0.258	0.001
				W4	-1.602	0.293	< 0.001
Leaf Rust Reference = Low disease level	142	< 0.001	High	HIGHP	-1.949	0.505	< 0.001
				W4	-1.542	0.780	0.048
				W6	3.235	0.802	< 0.001
				W7	3.955	0.799	< 0.001
			Moderate	HIGHP	-1.212	0.271	< 0.001
				W7	1.720	0.627	0.006
Yellow rust Reference = disease absence	102	< 0.001	Presence	HIGHP	-2.339	0.397	< 0.001
				YR_MR	-3.161	0.632	< 0.001
				YR_R	-2.644	0.529	< 0.001
Powdery mildew Reference = disease absence	94	<0.001	Presence	HIGHP	-1.632	0.332	< 0.001
				W4	1.922	0.373	< 0.001
				W7	1.939	0.809	0.017

Only predictors with significant ($P < 0.05$) estimates are displayed.

Leaf blotch stands for the complex of septoria tritici blotch, septoria nodorum blotch, and tan spot diseases in Norway and Sweden, and stands for septoria tritici blotch in other countries.

Low disease level (leaf blotch, leaf rust, FHB), or absence of disease level (yellow rust, powdery mildew) were used as the reference (control) categories in the regressions.

In all regressions, weather group W5 was used as the reference weather category, LowP was used as the reference category for the fungicide protection variable, and susceptible cultivar group was used as the reference group in the cultivar resistance variable.

HighP: fungicide protection level at, or larger than, the reference fungicide protection level.

STB_MR: cultivar with moderate resistance to STB; STB_R: cultivar resistant to STB; YR_MR: cultivar with moderate resistance to YR; YR_R: cultivar resistant to YR;

W4, W6, W7: weather groups (see text for details)

LR high and moderate level: no estimates derived for W1, W2, W3 (no occurrence of high and moderate BR in these weather groups)

YR occurrence level: no estimates derived for W1, W7 (no occurrence of YR in these weather groups)

PM occurrence level: no estimates derived for W1, W2, W6 (no occurrence of YR in these weather groups).

Regression on FHB levels could not be achieved because of the imbalanced occurrences among weather, resistance, and disease levels.

Table 4. Results from mixed model analyses of variance of the effects of fungicide protection level, cultivar, year, and region, on diseases and yield country-wise.

Source of variation	Yield	STB/LB[a]	LR[a]	FHB[a]
Belgium		STB		
Fungicide (F)	0.001	0.04	NS	
Cultivar (C)	NS[b]	NS	NS	
F x C	0.08	NS	NS	
Year (Y)	<0.001	<0.01	NS	
F x Y	<0.05	NS	<0.001	
C x Y	<0.05	NS	<0.01	
France		STB		
Fungicide (F)	0.02	0.08	NS	NS
Cultivar (C)	0.02	0.008	NS	NS
F x C	NS	0.07	NS	NS
Year (Y)	NS	NS	NS	NS
Region (R)	<0.001	NS	NS	NS
F x Y	NS	NS	NS	<0.001
F x R	<0.001	<0.05	NS	NS
C x Y	NS	NS	NS	<0.001
C x R	<0.001	<0.001	NS	NS
Y x R	<0.001	<0.001	NS	<0.001
Germany		STB		
Fungicide (F)	NS	0.06	0.07	
Cultivar (C)	NS	NS	NS	
F x C	0.002	NS	0.02	
Year (Y)	NS	NS	NS	
Region (R)	<0.001	NS	NS	
F x Y	<0.05	NS	NS	
F x R	<0.01	<0.001	<0.001	
C x Y	<0.001	NS	NS	
C x R	NS	NS	NS	
Y x R	<0.001	<0.05	NS	
Italy		STB		
Fungicide (F)	0.002	0.02	<0.0001	NS
Year (Y)	NS	NS	NS	NS
Region (R)	<0.001	NS	NS	NS
F x Y	NS	NS	NS	NS
F x R	NS	NS	NS	<0.01
Y x R	<0.001	NS	NS	NS
Norway		LB		
Fungicide (F)	NS	NS		
Year (Y)	NS	NS		
Region (R)	NS	NS		
F x Y	NS	NS		
F x R	NS	NS		
Y x R	NS	NS		
Sweden		LB		
Fungicide (F)	0.005	<0.0001		
Year (Y)	NS	NS		
Region (R)	NS	NS		
F x Y	NS	NS		
F x R	NS	NS		
Y x R	<0.01	NS		

Random effects, i.e., pure or interaction effects involving Year and Region, were tested by a chi-square test (df = 1) on the difference in AIC between models with and without the effect.

In Germany, significant effects for yellow rust were found for FxC (*P* = 0.0004), FxY (*P* < 0.001), and CxY (*P* < 0.01);

In Germany, significant effects for powdery mildew were found for F (*P* = 0.09), FxR (*P* < 0.1), and YxR (*P* < 0.001); and no significant effects were found for.

[a] STB: septoria tritici blotch; LB: leaf blotch; LR: leaf rust; FHB: fusarium head blight.

[b] NS: *P* > 0.1