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RESEARCH

Screening of Oat Accessions for Fusarium Head Blight Resistance Using Spawn-Inoculated Field Experiments

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ABSTRACT

Use of resistant cultivars is one of the most important measures to reduce the risk of Fusarium head blight (FHB, caused by various *Fusarium* spp.) and mycotoxins in cereals. Research on resistance to FHB has mainly focused on wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) and is very limited in oat (*Avena sativa* L.). In Norway, routine testing of cultivars and breeding lines has been performed in spawn-inoculated field experiments with *Fusarium graminearum* Schwabe as part of a concerted research and breeding effort to improve FHB resistance in oat. Data on FHB symptom, days to flowering, and plant height have been collected during the field seasons. Together with the field data, deoxynivalenol (DON) content and germination capacity of harvested kernels are used to score resistance levels of genotypes. In this paper, results are presented from a combined analysis of data from 9 yr of field trials from 2008 to 2016. Consistent and highly significant differences in DON content and germination capacity were documented among the current oat cultivars on the Norwegian market. These two negatively correlated parameters are used as selection criteria in breeding since they are relevant for the different end uses of the grains: DON content for use as food and feed, and germination capacity for seed production. In the paper, we discuss the pros and cons of the various screening methods and parameters used in assessing FHB resistance in oat and present the progress made in resistance breeding based on an established field testing methodology.

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Abbreviations: DON, deoxynivalenol; DTF, days to flowering; FHB, Fusarium head blight; NMBU, Norwegian University of Life Sciences; PDA, potato dextrose agar; PH, plant height; QTL, quantitative trait loci.

Frequent and severe Fusarium head blight (FHB, caused by various *Fusarium* spp.) epidemics have occurred in wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.) in Norway during the past two to three decades. Therefore, increased levels of *Fusarium* toxins (Sundheim et al., 2013) and reduced germination capacity in certified seed (Bjørnstad and Skinnes, 2008) became major challenges in Norwegian oat production. Frequent precipitation during flowering and grain-filling stages, reduced tillage practices, and the lack of crop rotation in specialized cereal production regions are some of the factors that led to the frequent epidemics (Sundheim et al., 2013). Although lower FHB incidence and toxin levels were observed in recent years (2014–2016), the expected climate change to warmer and more humid conditions is projected to be favorable for FHB in the Nordic region (Parikka et al., 2012, Uhlig et al., 2013).

Fusarium avenaceum (Fr.) Sacc., *F. poae* (Peck) Wollenw., *F. tricinctum* (Corda) Sacc., and *F. culmorum* (W.G. Sm.) Sacc. were the most prevalent *Fusarium* species in cereals in Norway in the 1990s (Kosiak et al., 2003). Recent records show increase in *F. graminearum* Schwabe prevalence, making this pathogen the major deoxynivalenol (DON) producer in Norwegian grain (Hofgaard et al., 2010; Sundheim et al., 2013). Deoxynivalenol is phytotoxic

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and acts as a virulence factor during infection (McCormick, 2003). *Fusarium* toxins impose major health risks and reduce productivity and performance in farm animals (Conkova et al., 2003; Bergsjø et al., 1992; Rotter et al., 1995). Therefore, DON content is monitored in every Norwegian oat harvest, and price penalties are imposed on grain lots exceeding 1.75 mg kg^{-1}.

Agronomic and physiological traits such as inflorescence structure, flowering time, plant height (PH), flower opening, and anther extrusion play important roles in resistance of oat to FHB (Langevin et al., 2004; Tekle et al., 2012; He et al., 2013). These traits are not directly involved in disease resistance but provide escape or avoidance of infection and are considered as passive resistance mechanisms. Infection from a single spikelet can easily spread through the rachis to adjacent spikelets in compact and short inflorescences of wheat and barley (*Horedum vulgare* L.). In oat, however, infections occur on a single-spikelet basis and infections rarely spread from spikelet to spikelet because of the long rachilla and rachis of the oat panicle (Langevin et al., 2004; Tekle et al., 2012).

Oat is most susceptible to *Fusarium* infection during anthesis, and this susceptibility decreases as plants develop and mature (Tekle et al., 2012). The duration of flowering is longer in oats compared with wheat and barley. In a single oat panicle, flowering can take up to 10 d from the first flowering floret until the last. It can take up to 1 mo until all florets of a single oat plant complete flowering (Misonoo, 1936). This extended period of flowering gives a wide window of susceptibility. Profuse fungal growth was observed on anthers compared with other floret parts during the first few days after spray inoculation both in oat and wheat (Strange and Smith, 1971; Tekle et al., 2012), suggesting that nonextruded anthers are infection foci for *Fusarium*. We have observed a wide variation in anther extrusion and flower opening both in oat mapping populations and in collection of oat varieties (Å. Bjørnstad, personal communication, 2012).

Very little is known about variation in active resistance mechanisms to *Fusarium* in oat. Resistance to initial infection (Type 1) is not reported. Resistance to spreading of infection (Type 2) is strong because of the long rachis of the oat panicle (Langevin et al., 2004; Tekle et al., 2012). Resistance to kernel infection (Type 3) is difficult to score in oat because of the presence of hulls. Tolerance (Type 4) is indirectly accounted for in yield trials (Mesterházy, 1995, 2003). Production of *Fusarium* toxins (Type 5) (Miller et al., 1985; Mesterházy, 1995) is scored by analyzing the level of selected toxins in the harvested grain.

Genetic studies for FHB resistance in oat are very limited. This may be attributed to the smaller cultivation area of this crop, the underestimated effect of FHB in this crop (Langevin et al., 2004), or the limited knowledge available in oat genomics. The few available studies show that resistance to FHB in oat, as in wheat and barley, is a quantitative trait and is controlled by many genes with low to medium effect (He et al., 2013). In the same study, quantitative trait loci (QTL) for low DON content and FHB were colocated with QTL for days to heading, days to maturity, and PH (He et al., 2013). Taller and late-maturing lines displayed less disease than shorter and earlier lines (He et al., 2013).

Breeding for resistance to FHB is one of the main objectives of the cereal breeding program of the Norwegian plant breeding company Graminor AS. The results presented in this paper are collaborative work between Graminor AS and the Norwegian University of Life Sciences (NMBU) to screen oat cultivars and breeding lines over several years. The objectives of this paper are (i) to document the progress in reducing DON levels and improving germination capacity in the Norwegian oat breeding program, (ii) to report lessons learned during years of evaluating oat for FHB resistance in our nurseries, and (iii) to name cultivars that can serve as better alternatives to growers and as sources of resistance for oat breeders.

MATERIALS AND METHODS

General Description

Since 2010, hundreds of advanced oat breeding lines and cultivars are screened for FHB resistance every year at the Vollebekk research farm in Ås, Norway, by NMBU and at Staur research farm in Stange, Norway, by Graminor AS. Between 2007 and 2009, fewer accessions were tested in Ås. These accessions and breeding lines were mainly from Graminor AS, and a few were from their collaborating breeding companies in the Nordic countries. Only promising lines with good agronomic and resistance traits, major cultivars and checks covering the resistance range for FHB are subjected to multiple year tests, while new breeding lines are added every year. Therefore, the results presented in this paper are based on selected breeding lines and cultivars that were tested at least in four of the experimental years from 2008 to 2016.

Experimental Field Setup

The oat materials were sown in the field-testing nurseries during the second or third week of May. Fifty grams of seed were seeded in 0.75-m by 3-m plots. Four rows were planted per plot. Space between plots and space between rows within a plot were 0.30 and 0.15 m, respectively. Plot length was subsequently reduced from 3 to 2 m to remove border effects and make space for alleys between blocks. Planting dates varied depending on soil and weather conditions, but early plantings were avoided to match the flowering period with the warmer weeks of July. Fields were fertilized with a compound fertilizer (YaraMila, NPK 23–3–10, Yara Norge AS) just before planting at a rate of 600 kg ha^{-1}. In cases of heavy precipitation, extra N fertilizer was applied around heading at a rate of 300 kg ha^{-1} (Yara, N 15.5).

Grain spawn inoculum was spread in the field during the second or third week of June, at the Zadoks 31 or 32 growth

stage (Zadoks et al., 1974) at a rate of 10 g m^{-2}. One week before inoculation, plots were sprayed with a combination of propiconazole and fenpropidin (Zenith575EC, Syngenta Crop Protection AS) at a rate of 1 L ha^{-1} against leaf diseases. The herbicides Ariane S. (Dow AgroSciences A/B) or Granstar Power (Du Pont, Norge AS) were sprayed against weeds at a rate of 2.5 L ha^{-1} and 1 kg ha^{-1}, respectively. The insecticide Perfekthion (BASF AS) was used at a rate of 0.8 L ha^{-1} against thrips and aphids when necessary.

Mist irrigation (PowerNet, medium-size sprinklers) was applied to create wet conditions for ascospore release and germination. Three 10-min cycles of mist irrigation were applied every hour from 1900 to 2200 h after inoculation until the earliest date of flowering. Irrigation was then raised to four cycles, from 1900 to 2300 h, from the start of flowering until 10 d after the last flowering date.

Flowering began during the first week of July and was usually completed by the third week of July. We observed flowering dates when ~50% of the panicles of the main tillers in a plot had flowered. Fusarium head blight scores were taken ~2 wk after the first flowering date, either as the percentage of spikelets with visible symptoms, or with the use of a simplified 0 to 5 scale. Field FHB scores were subjective and may have introduced considerable errors. Scores were taken two to three times (4 to 5 d apart) to minimize such errors and biases that may have arisen from differences in flowering dates. For the statistical analyses presented in this paper, the 0 to 5 scores were converted to percentages using the following scale of conversion: 0 = 0%, 1 = 5%, 2 = 15%, 3 = 30%, 4 = 50% and 5 = 70%. Plant height was measured around physiological maturity, at the Zadoks 88 to 90 growth stage, (Zadoks et al., 1974) from the soil to the base of the main panicles of the average plants. Plots were harvested at full maturity (15–20% seed moisture) during the first or second week of September. Samples were dried and cleaned mechanically with low air speed in order to not blow away the small and poorly filled kernels.

Inoculum Preparation

Spawn inoculum (*F. graminearum*-inoculated oat kernels) was used in our experiments. Inoculum was prepared following a protocol adapted from Dr. Bernd Rodemann (Julius Kühn-Institut, Germany). Two isolates with medium aggressiveness (isolates 101118 and 101018) and two other isolates with low aggressiveness (isolates 101177 and 101023) provided by the Norwegian Veterinary Institute were used in the years 2008 to 2010. From 2011, the first two isolates were replaced by isolates 200726 (low aggressiveness) and 200838 (medium aggressiveness), provided by the Norwegian Institute of Bioeconomy Research. All the isolates were collected either from wheat or oat fields in Norway.

Isolates were grown on potato dextrose agar (PDA) for 7 d at ambient temperature and light (Fig. 1A). At the end of the incubation period, three to five pieces of PDA containing mycelia of each isolate were transferred to flasks containing sterile mixtures of 100 mL deionized water and 1 g of oat flour. These mixtures were placed on a laboratory shaker set at 90 rpm for 7 d at ambient temperature and light to make liquid *F. graminearum* cultures (Fig. 1B). Two kilograms of cooked and sterile oat kernels (soaked in water overnight, autoclaved at 121°C for 3 h in heat-stable polyethylene bags) were then inoculated by the liquid culture. These preparations were left in an upright position for 3 wk at ambient temperature and light to colonize the kernels (Fig. 1C). At the end of this period, the colonized oat kernels were spread on trolleys to dry (Fig. 1D). The kernels were misted occasionally with sterile distilled water to stimulate prethecial development. After 3 wk, the inoculum was collected and stored at cool temperature (15–20°C) until the date of inoculation.

Determination of Germination Capacity and Mycotoxin Content

Germination tests were performed at the Kimen Seed Testing Laboratory AS, Ås. Two parallel samples of 100 kernels each were tested from each field plot. Kernels were placed in sand in darkness at 10°C for 7 d and then under 8 h of fluorescent light at 20°C for 3 d. At the end of the incubation period, seedlings and kernels were categorized as normal seedlings, abnormal seedlings, dormant (healthy, ungerminated) kernels, and dead kernels according to International Seed Testing Association standards (ISTA, 2009). Normal seedlings and dormant kernels were summed up and considered as the final germination capacity of the seed lot.

For mycotoxin analysis, representative samples from each plot were taken using a Rationel Sample Divider Vario and sent to the University of Minnesota, Department of Plant Pathology. During 2008 and 2009, 15-g samples were sent for analysis. However, sample size was increased to 70 g to reduce sampling errors that may have arisen due to heterogeneity in kernel infection rates. Samples were ground with a Stein Laboratories mill, and mycotoxin content (DON, 3A-DON, 15A-DON, and NIV) was determined from a 4-g subsample by gas chromatography coupled with mass spectroscopy following a protocol originally described in Mirocha et al. (1998) and modified in Fuentes et al. (2005). Only DON results are reported in this paper.

Statistical Analysis

To calculate averages for cultivars and lines across years and analyzing trait relationships, a total of nine field trials for the period 2008 to 2016 exhibiting good differentiation in FHB resistance were selected for analysis in this paper. A summary of the available data is given in Supplemental Table S1.

The data was analyzed in two steps. First, each field trial was analyzed individually using mixed linear modeling in SAS 9.4 (SAS Institute, 2013). PROC MIXED was used to calculate LSMEANS of each trait by treating lines (i.e., genotypes) as fixed effects and trial design factors like replication and block within replication as random effects. Gradients in the field trials were corrected for by including row and column factors when necessary. In the second step, the calculated means of all lines that were included in at least four field trials were combined in a new dataset, and LSMEANS across trials were calculated in PROC MIXED by treating lines as fixed effects and trials (i.e., environments) as random effects. Visualization of trait relationships was done by principal component analysis (PCA) in Unscrambler X version 10.3 (CAMO Software, 2010). Other diagrams were created in Microsoft Excel 2013.

Fig. 1. Spawn inoculum preparation. Isolates of *Fusarium graminearum* are grown on potato dextrose agar (A), which are then transferred into a sterile mixture of deionized water and oat flour to prepare a liquid culture (B). The liquid culture is then used to inoculate autoclaved oat kernels to produce abundant mycelia (C). Colonized kernels are then spread on trolleys to dry (D) and are misted occasionally to facilitate development of perithecia.

RESULTS

During the period 2008 to 2016, a total of 543 cultivars and breeding lines were tested in the nine field trials that were considered for the present study. Most lines were tested only once or twice, and only 46 lines were included in at least four trials and analyzed further for calculating averages across years and studying trait relationships. Deoxynivalenol content and germination capacity were measured in all trials, whereas data on PH, days to flowering (DTF), and FHB were available from seven, six, and five field trials, respectively. The average DON contamination in the trials varied from 5.6 mg kg^{-1} in Staur 2014 to 27.7 mg kg^{-1} in Vollebekk 2016 (Table 1), whereas the mean germination capacity after *Fusarium* infection ranged from 53.7% in Vollebekk 2009 to 78.9% in Vollebekk 2013 and Staur 2011.

Trait Correlations

The correlation coefficients among the measured traits is shown in Table 2 and visualized in the form of a principal component biplot in Fig. 2. Deoxynivalenol content showed a highly significant negative correlation with germination capacity after *Fusarium* infection. The variation in these two traits falls along the first principal component (Fig. 2), indicating that the biggest proportion of the variation in the dataset can be explained by these two traits. Deoxynivalenol content was also negatively correlated with PH, indicating that taller plants in general had less mycotoxin contamination. A smaller but still significant positive correlation with DON was also present for DTF, indicating a tendency for the later-flowering lines to get higher mycotoxin contamination. It is also worth noticing

Table 1. Summary of data used for statistical analysis of Fusarium head blight (FHB) resistance in oat for the period 2008 to 2016. The mean scores (with the range in parentheses) are listed from each nursery that the respective trait was obtained. The summary statistics are based on the lines that were included in at least 4 yr and used for calculating averages across years. Empty cells mean that the trait was not measured in that nursery.

Nursery	Deoxynivalenol	Germination	FHB	Days to flowering	Plant height
	ppm	%			cm
Vollebekk 2008	6.8 (4.0–12.8)	78.8 (69.9–86.9)	12.5 (0.9–30.9)		90.5 (80.6–109.6)
Vollebekk 2009	16.5 (10.3–25.5)	53.7 (39.5–71.0)	11.9 (1.3–33.1)	48.0 (47.4–49.3)	74.2 (67.7–81.6)
Vollebekk 2010	12.8 (6.4–20.1)	68.8 (56.6–85.6)		54.6 (50.5–56.5)	78.2 (72.8–84.0)
Staur 2011	6.7 (3.2–14.3)	78.9 (59.9–87.2)	7.1 (3.0–17.0)	51.2 (47.0–54.0)	97.8 (87.0–107.0)
Vollebekk 2012	6.9 (2.7–12.9)	67.9 (55.2–78.1)	10.3 (3.5–33.3)	62.7 (60.0–65.5)	85.5 (76.0–97.3)
Vollebekk 2013	6.0 (2.2–12.3)	78.9 (69.0–87.1)		57.9 (52.9–60.9)	78.1 (68.2–86.3)
Staur 2014	5.6 (3.0–11.9)	69.8 (54.9–80.5)		48.1 (44.3–51.3)	87.1 (79.3–95.1)
Vollebekk 2015	11.5 (6.5–23.9)	65.0 (48.2–79.4)	35.8 (17.6–58.5)	53.5 (49.9–55.6)	86.6 (77.5–95.0)
Vollebekk 2016	27.7 (15.2–48.8)	56.9 (40.8–70.4)	30.9 (20.7–41.0)	54.2 (50.8–57.4)	78.1 (68.7–84.8)

Table 2. Pearson correlation coefficients among the traits measured in the field trials. The data are based on the line averages across field trials (listed in Supplemental Table S1) for the 46 cultivars and breeding lines that were included at least in four of the field trials.

Trait	Germination	Fusarium head blight	Days to flowering	Plant height
Deoxynivalenol	−0.612**	−0.052	0.450*	−0.478**
Plant height	0.142	−0.087	−0.337*	
Days to flowering	−0.304*	−0.216		
Fusarium head blight	−0.008			

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

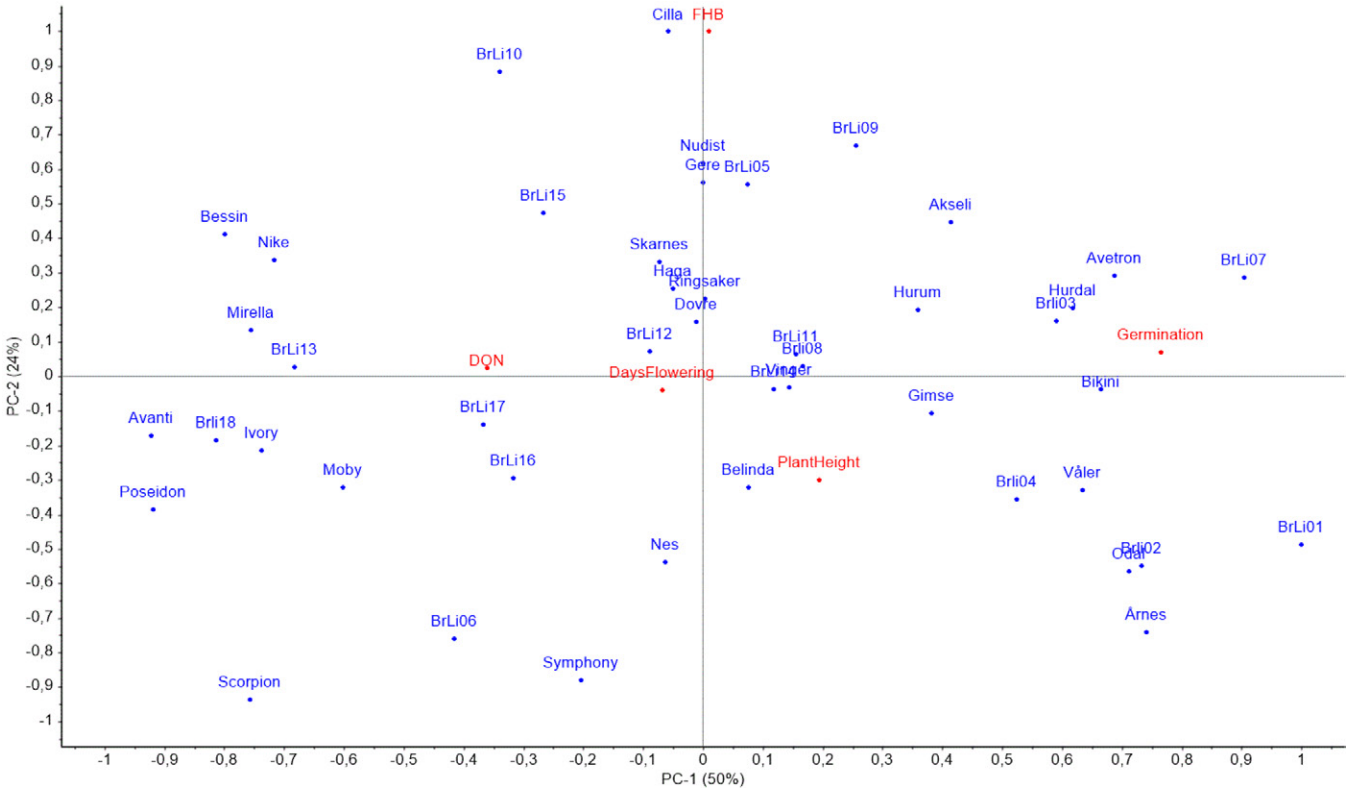

Fig. 2. Biplot from principal component (PC) analysis of trait averages of the 46 oat cultivars and breeding lines tested in at least four spawn-inoculated field trials of the field seasons from 2008 to 2016. BrLi, breeding lines; DON, deoxynivalenol; FHB, field Fusarium head blight symptoms.

that the visual scoring of FHB did not show any correlation at all with DON content or germination capacity. However, it showed a weak but not significant negative correlation with DTF (Table 2).

Cultivar Differences in Deoxynivalenol Content and Germination Capacity

The mean data for DON content and germination capacity for the selected cultivars and breeding lines are shown in Fig. 3. The mean DON level among the selected cultivars and breeding lines ranged from 5.7 to 19.8 mg kg^{-1}. The two naked cultivars, Bikini and Nudist, showed the overall lowest mycotoxin levels of the registered cultivars. Among the conventional hulled oat, Årnes, Odal, Gimse, Vinger, Ringsaker, Hurum, and Hurdal all had significantly lower DON content than the market leader Belinda, which has been the dominating cultivar on the Norwegian market for the last 15 yr. At the other end of the scale, we find the cultivars Nike, Ivory, Symphony, Avanti, Bessin, and Poseidon. The cultivars Bessin and Poseidon have significantly higher DON content than the market leader Belinda and are used as susceptible checks in our field trials.

The mean germination capacity of the selected cultivars and breeding lines after *Fusarium* infection ranged from 58.1 to 80.1%. Among the registered cultivars, Hurdal, Akseli, Årnes, Odal, Våler, and Avetron had significantly better germination capacity than the cultivars Scorpion, Poseidon, Mirella, Ivory, Avanti, and Bessin. Germination capacity had a significant negative correlation with DON content. The ideal cultivars with good resistance characteristics should have low average DON content and good germination capacity. This characteristic is achieved in the cultivar Odal and the newly

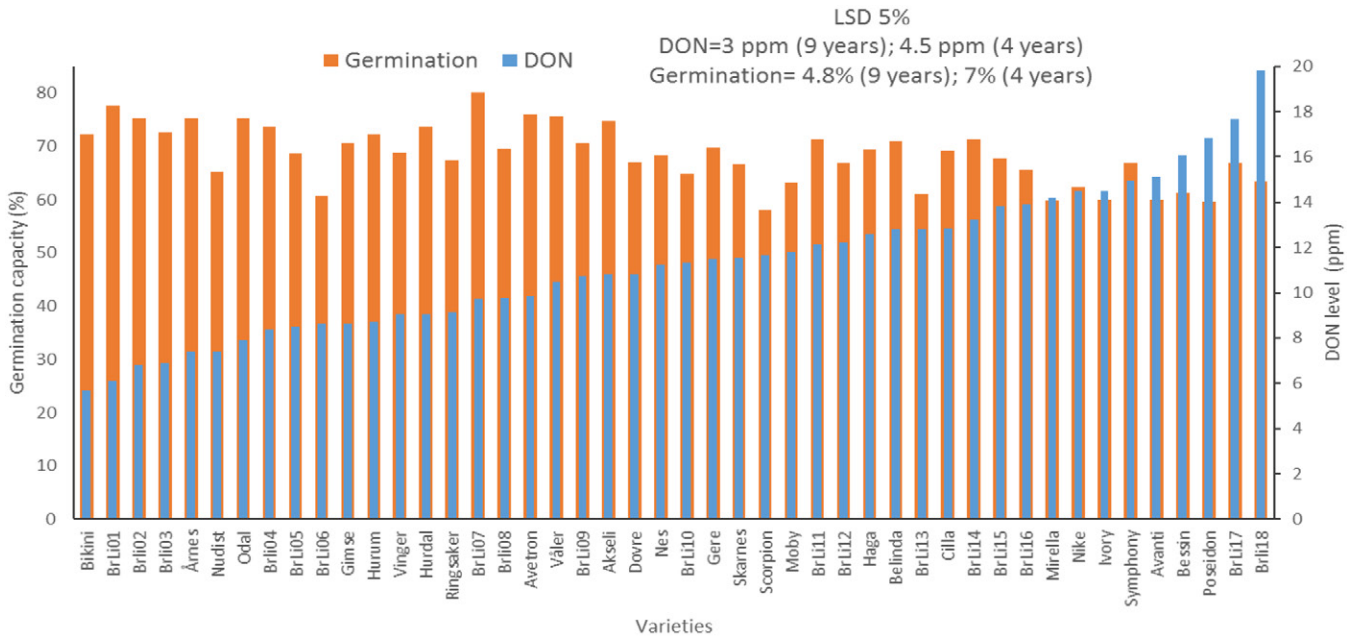

Fig. 3. Germination and deoxynivalenol (DON) data of the 46 oat cultivars and breeding lines tested in at least four spawn-inoculated field trials of the field seasons from 2008 to 2016. BrLi, breeding lines.

registered cultivar Årnes. At the other end of the scale, we find the cultivar Bessin with high DON content and low germination capacity. A positive deviation from the general relationship between the two traits is shown by Belinda, which despite relatively high DON contamination shows good germination capacity.

DISCUSSION

Field testing for *Fusarium* resistance with spawn inoculation and mist irrigation, as described in this paper, has been a useful tool in screening oat genotypes and in providing reliable data across years. Relying on natural infection leads to very low disease levels, in which differentiating resistance levels of accessions is almost impossible. Mist irrigation in the evening creates an environment conducive for ascospore release and disease establishment in the field. Our results show that artificial inoculation and conditions conducive for disease establishment (misting) are crucial for successful screening of accessions, especially using germination capacity. With accurate phenotyping in the field and the laboratory, it is possible to evaluate and rank oat cultivars and breeding lines for FHB resistance (Fig. 4).

Spawn Inoculation for Screening Resistance to Fusarium in Oat

The infection process after spawn inoculation resembles the natural infection process of FHB. Ascospores are released from perithecia on plant debris or the spawn inoculum and are deposited on panicles. Therefore, spawn inoculation technique accounts for both active and passive resistance mechanisms. Spawn inoculum contains populations of perithecia at different developmental stages, maturing and releasing ascospores over an extended period (Paulitz, 1996). Paulitz (1996) was able to sample ascospores over a 3-wk period from a spawn-inoculated field. The extended release of ascospores from spawn inoculum is an important feature that makes spawn inoculation a good inoculation technique for screening oat, as the flowering period in oat is longer (Misonoo, 1936) compared with other small-grained cereals. The extended flowering period entails repeated spray inoculations to catch later-flowering spikelets. Spawn inoculation, therefore, considerably reduces workload, especially in screening nurseries where large numbers of genotypes need to be tested.

Environmental cues such as temperature and relative humidity affect the rate and distance of ascospore discharge. Combining spawn inoculation with mist irrigation in evenings ensured successful disease establishment in our nurseries by creating conducive conditions for higher infection levels by *F. graminearum* (Rossi et al., 2001). Sutton (1982) and Paulitz (1996) found that wet conditions during evening and night are optimal for ascospore release and dispersal. Persistent wetness is associated with a higher number of perithecia on host tissues and plant debris under natural conditions (Sutton, 1982; David et al., 2016; Manstretta and Rossi, 2016).

Resistance Parameters

Ranking of cultivars according to DON data was consistent over years despite variations that had led to different disease levels in the different experimental years. Information from these experiments was used to select foreign and local varieties with low DON levels. These cultivars and breeding lines can serve as parents in breeding programs

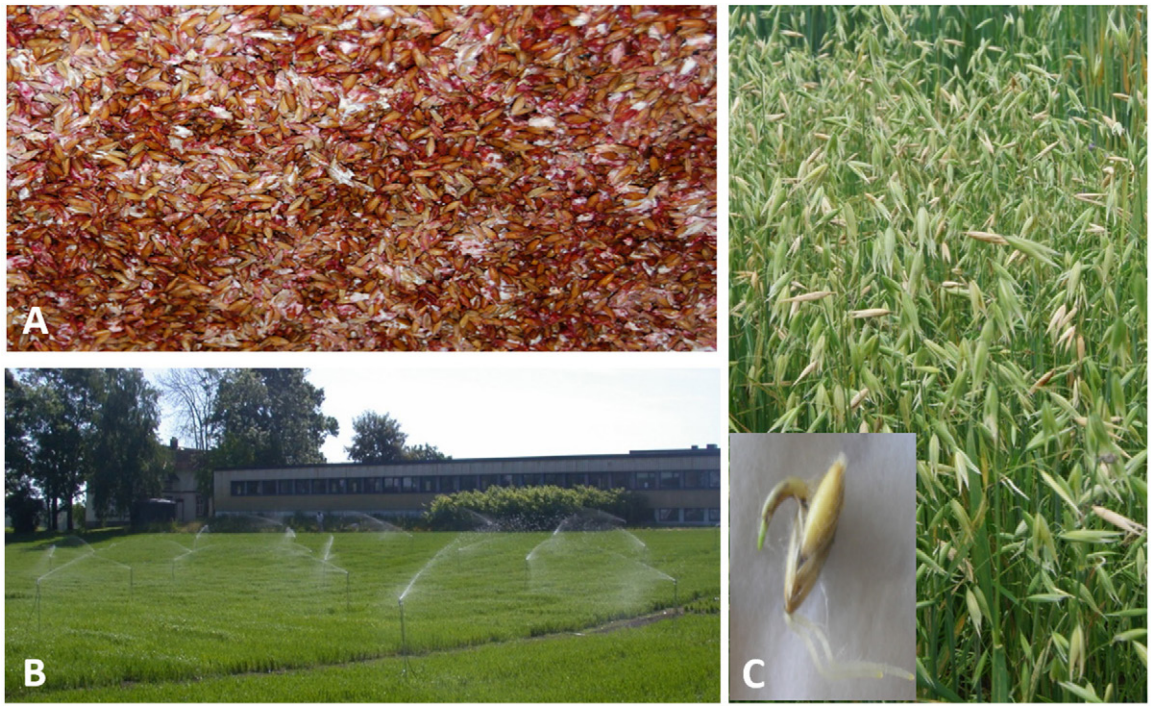

Fig. 4. Field testing of oat cultivars and breeding lines to Fusarium head blight resistance: (A) artificial (spawn) inoculation, (B) conducive environment (mist irrigation), (C) appropriate field (symptoms) and laboratory evaluations gave consistent and reliable data over the years.

and as better alternatives to growers, whereas the poor ones can be used as susceptible checks in experiments.

Our naked varieties had consistently low DON levels. Removal of the hulls is probably the main factor for the low DON levels in the naked oat varieties. Naked varieties have also shown lower levels of T2 and HT2, toxins produced mainly by *F. langsethiae* Torp & Nirenberg and *F. sporotrichioides* Sherb., than hulled varieties in the United Kingdom (Edwards, 2006). Dehulling of husked oat during processing is proven to reduce mycotoxin levels significantly (Scudamore et al., 2007; Yan et al., 2010), hence true genetic resistance in naked oat may not be high.

In years with high disease levels (with mean DON levels from 5 to 35 mg kg^{-1} or more), medium to high negative correlations between germination capacity and DON level were scored. In such years, germination capacity can serve as a quick selection criterion when toxin data are not available. The correlation between these two traits of the selected cultivars and breeding lines over the experimental years was −0.612 ($p < 0.001$). Despite the strong negative correlation between germination capacity and DON content, ranking of accessions according to germination capacity does not necessarily match the ranking according to DON data. Belinda, for example, had higher germination capacity despite having higher DON values, whereas Ringsaker was among the cultivars with relatively low DON levels despite poor germination capacity. Germination tests reflected both seed infection and infestation and toxin levels (Tekle et al., 2013). *Fusarium* infection kills the germ or results in *Fusarium*-damaged kernels that produce less vigorous seedlings due to seedling blight or mycotoxins in the kernels (Tekle et al., 2013). In years with low disease levels (with mean DON levels ranging between 0 and 5 mg kg^{-1}), we saw very low or nonsignificant correlations between DON and germination capacity (data not shown). In such years, germination results were usually >80% and germination problems were probably caused by reasons other than FHB. In such years, germination capacity was not informative and grading of genotypes was based on mycotoxin data only. When data on both toxin content and germination capacity are available, germination capacity is a more relevant trait for certified seed producers, whereas mycotoxin data are more important to food and feed producers that need to meet food safety requirements.

Association of Agronomic Traits with Fusarium Head Blight Parameters

In the present study, we found significant correlations between DON content and PH and between DON content and DTF. Late-flowering and shorter varieties had higher DON contamination, whereas early-flowering and taller varieties had lower DON contamination. However, there was no effect of PH and DTF on germination capacity. Plant height and DTF are reported to affect FHB in oat and other small-grained cereals in one way or the other (Gavrilova et al., 2008; Parikka et al., 2008; Lu et al., 2011, 2013; He et al., 2013). For example, Parikka et al. (2008) and Gavrilova et al. (2008) found that late-maturing lines were more susceptible to FHB than early-maturing lines. On the other hand, He et al. (2013) found early lines to be more susceptible than late lines. In the same study, He et al. (2013) found short

plants to be more susceptible than tall plants, whereas Gavrilova et al. (2008) found no effect of PH on disease level. The effect of DTF and PH on DON level is due to escape or avoidance of infection, rather than true genetic resistance. This effect is dependent on inoculum pressure and environmental conditions that determine disease development on plants, partially explaining the inconsistent effect of PH and DTF on FHB parameters.

In the experiments reported here, we found no correlation of field FHB data with DON or germination capacity, suggesting the unreliability of field FHB scoring in oat. This can be due to the long flowering period and structure of the oat panicle. Early disease scoring in oat fields may underestimate disease, as the disease can potentially develop during the extended flowering period. At later developmental stages, it becomes difficult to differentiate between natural senescence and FHB symptoms. Due to the long rachis and rachilla of the oat panicle, single spikelet infections in oat do not usually spread to neighboring spikelets (Langevin et al., 2004; Tekle et al., 2012) and lead to senescence of whole heads like in wheat and barley. Therefore, repeated and careful disease scorings adjusted to the respective flowering dates of the different accessions are recommended over one-time readings in oat. Resistance screening in oat should rely more on laboratory tests than field FHB data.

Severe *Fusarium* infections can cause significant floret sterility, which can reach up to 50% in very susceptible genotypes (data not shown) or lead to very lightweight kernels that are blown away during harvesting and cleaning. Therefore, it is possible that postharvest resistance parameters can potentially underestimate the real damage caused by FHB. Integrating yield loss or tolerance as part of resistance screening trials, as described by Mesterházy (1995), should be considered.

Conflict of Interest

The authors declare that there is no conflict of interest.

Supplemental Material Available

Supplemental material for this article is available online.

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