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PHYTOPATHOLOGY

Development of Soil-Borne Infections in Spring Wheat and Barley as Influenced by Hydrothermal Stress in the Forest-Steppe Conditions of Western Siberia and the Urals

E. Yu. Toropova[a, b], A. P. Glinushkin[a, *], M. P. Selyuk[a, b], O. A. Kazakova[a, b], and A. V. Ovsyankina[a]

[a]*All-Russia Research Institute of Phytopathology, Moscow oblast, 143050 Russia*
[b]*Novosibirsk State Agrarian University, Novosibirsk, 630039 Russia*
**e-mail: a.glinushkin@vniif.ru*

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Abstract—This is a first-time assessment of the direct and indirect effects of hydrothermal conditions on pathogenesis of root infections in cultivated varieties of spring wheat and barley. Long-term field research (2000–2015) was carried out in the area of risk farming combined with laboratory experiments. The effects of the phytosanitary condition of soil, seeds, and underground plant organs were taken into account. It was found that soil pathogenic population and the development of soil-borne infections largely depend on hydrothermal factors. The development of root rot of spring wheat was stimulated by arid conditions during tillering and heading: the disease rate was increased by 33.5% compared to the optimal moisture supply against a background of a high plant pathogen population of the soil. In drought conditions, the number of saprotrophic microorganisms decreased 3.3 times and suppressive soil activity fell 3.0 times provoking root infections. Microorganisms consuming inorganic forms of nitrogen and cellulolytic agents were found to be highly sensitive to hydrothermal factors. Arid conditions increased the plants' susceptibility to the inoculum of soil origin, since the increase in the number of conidia in the inoculum from 5–15 to 150–180 per 1 g of soil increased the frequency of infections by root rots by 7.8 times, especially on the epicotyl and the base of the stem. Damage of root rot was increased by pest flies *Oscinella frit* L., *O. pusilla* Mg., *Phorbia genitalis* Schnb., and *Mayetiola destructor* Say. Their activity increased in warm, arid conditions. Drought-resistant gramineous weeds *Panicum miliaceum* ssp. *ruderales* L. (Kitag.) Tzvei., *Setaria glauca* (L.) Beauv., *Avena fatua* L., *Setaria viridis* (L.) Beauv. competed with the crop and consequently increased the development of root rot by 20% or more in dry years. Seeds of gramineous weeds, multiplied after dry years, contributed to reproduction and survival of many soil-borne phytopathogens. Grain ripening in moistened conditions led to transmission of the root rot agents *Bipolaris sorokiniana* Sacc. Shoem. (syn. *Helminthosporium sativum* Pam., King et Bakke) and *Fusarium* fungi via seeds. This led to proliferation of root rot in the germination phase and significantly (53%) affected the cereals' germ.

Keywords: hydrothermal stress, soil-borne pathogen, root rot, suppressiveness, soil microorganism, spring wheat, barley

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INTRODUCTION

Internationally phytosanitary monitoring of contemporary agrocenoses indicates that agricultural crops are cultivated in fields with an infectious background of soil phytopathogens that exceeds the biological and economic damage threshold by far, causing annual epiphytoty of root and tuber infections [1–10]. In areas of risk agriculture, the situation is exacerbated by soil moisture deficiency during early spring and summer droughts, which are often accompanied by high soil and air temperature [11]. Analyzing the dynamics of climatic factors in the forest-steppe zone of western Siberia over the past 20 years has revealed an increase in the number of dry periods during vegetation [12]. Thus, in May, the average decadal temperature in 18 of 20 years of observations (80–90%) was higher than the average long-term value, while the amount of precipitation turned out to be below the normal rate for 13 years (65%); that is, the hydrothermal conditions of the month changed towards arid, and the plants experienced water deficit in 90% of cases. In 50% of cases, June only exacerbated the May drought, and there was also a water deficit in the first and second decades of July in 70 and 55% cases, respectively.

In arid conditions, root rot activity and harmfulness can increase, strengthening the stressful effect of

Table 1. Microbial count (MC) and soil suppressiveness (S) in wheat rhizosphere throughout plant development stages in high and low moisture conditions (pot trial), 2011–2014

Development stage	70% Field moisture capacity		40% Field moisture capacity	
	S, %	MC, mln per 1 g of soil	S, %	MC, mln per 1 g of soil
Sprouting	37.2	29	12.4	11
Tillering	49.3	56	20.1	17

drought, which adversely affects yield formation in cereal crops. Probably, this can explain the increased harmfulness of root rot in the zones of risk agriculture [1, 4, 11, 12].

The purpose of this research was to assess the direct and indirect effects of hydrothermal conditions on the pathogenesis of root infections in spring wheat and barley.

EXPERIMENTAL

In 2000–2015, the subject of research were the spring wheat and barley varieties as well as soil samples from the plants' rhizosphere. Soil colonization with conidia of *Bipolaris sorokiniana* Sacc. Shoem. (syn. *Helminthosporium sativum* Pam., King et Bakke) was detected with the flotation method in 1991–2013 [13]. The abundance of microbial saprotrophic groups in soil samples was analyzed through the dilution method: fungi were counted on Czapek agar (CA) diluted 10^{-3}, oligonitrophilic microorganisms on soil agar medium (SA); the group of bacteria, consuming organic nitrogen, was counted on meat-and-peptone agar medium (MPA); bacteria and actinomycetes consuming inorganic nitrogen were counted on starch-and-ammonia agar (SAA), while cellulolytic microorganisms on Hutchinson agar medium (HA) (all diluted 10^{-5}).

To estimate the damage caused by root rot on different plant organs, 100 plants were excavated at six random points of the field. The underground organs of plants were carefully extracted from the soil and thoroughly washed in running water, then the state of primary and secondary roots was evaluated along with coleoptile, epicotyl, and plant basal part. The 6-grade scale corresponded to 0–100% of the surface being damaged. The stage of disease and its extent was recorded both separately for each organ and for the whole plant on average.

In the mycological analysis of field samples, micromycetes were isolated in a pure culture and the species were identified according to the classical guides on the 7th and 14th days of cultivation, revealing the proportion of fragments (or seeds) populated by fungi of each taxon [14, 15].

Statistical data processing included calculating the means (M) and their standard errors (± SEM). The influence of factors was determined by the variance analysis using software packages SNEDEC-OR (20) and Statistica 6.0 (StatSoft, Inc., United States). Statistical significance was evaluated at the level of $P \leq 0.01$ and $P \leq 0.05$.

RESULTS AND DISCUSSION

Under controlled change of the hydrothermal factors, a significant effect of moisture deficiency on the activity of soil pathogenic fungus *B. sorokiniana* was revealed. When the soil moisture content decreased 2.7 times, the aggressiveness of *B. sorokiniana* increased 3.0 times, which, in our opinion, is associated with a decrease in the viability of plants and the physiological stability of their tissues caused by the drought.

The increased phytopathogen aggressiveness can also be caused by a decrease in microbiological activity and soil suppressivity during the drought. Indeed, we found a negative impact of low soil moisture on these indicators (Table 1). Under the influence of drought in the seedling and tillering phase, the number of oligotrophic microorganisms on soil agar decreased 2.6 and 3.3 times, respectively. Monitoring of soil microbiota in open agrocenoses in the southern forest-steppe of western Siberia (2011–2014) showed that, during direct sowing of the crops, the influence of weather conditions on the number of the five groups of microorganisms participating in the metabolism of nitrogen and carbon reached 87.8%, which is significantly higher than the share of the influence of the cultivated crop in most cases (Table 2). The decrease in the number of microorganisms under the influence of drought may be 27-fold and a sustainable trend throughout the growing season. On a moderately infectious background, the difference in plant damage between the optimal moistening and the arid variant was 13.7%, with a high (33.5%) content of conidia in the soil.

Thus, drought in critical phases (tillering to shooting) is a stressor that enhances the development of root rot. The total susceptibility of spring wheat to root rots increased by 13.7% after water stress. The damage of the epicotyl and the stem base worsened by 17.9 and 45.8%, respectively.

According to our data, the seasonal dynamics of root rot development is caused not only by the amount but also by the regime of moisture income. Modeling various types of drought in a series of pot experiments has shown that plants' development and their damage by root rot largely depend on the period of vegetation when the plants were exposed to water stress. The total yield decreased by 54.0% after the June–July drought, so, in terms of biotic and abiotic stressors, the period from tillering to the beginning of grain-filling should be considered critical for yield formation of spring wheat.

Monitoring of more than 50 open agrocenoses in the forest-steppe zone of western Siberia showed that weather conditions of the vegetation period significantly affect the phytosanitary state of the soil, as well as root rot development and etiology (Table 3). The total number of *B. sorokiniana* conidia in the soil was largely determined by the hydrothermal conditions of the vegetation period. The maximum development of root rot was recorded (SCC = 0.69) in the arid conditions of 2012 in comparison with the relatively humid 2011 (SCC = 0.99). *B. sorokiniana* was the most weather-dependent fungus; the influence of the hydrothermal factor on successful occupation of the pathogen's ecological niche in the underground plant organs was 78.3%, which exceeds the same index for *Fusarium spp.* by 3.4 times.

The intra-stalk pests, such as *Oscinella frit* L., *O. pusilla* Mg., *Phorbia genitalis* Schnb., and *Mayetiola destructor* Say, stimulate the root rot pathogenesis significantly, especially increasing its effect in warm arid conditions. A close correlation was found between the damage of wheat stalks by corn flies and the development of root rot ($r = 0.98 \pm 0.09$), especially on stems' basis and coleoptile [1].

Weed plants (gramineous species like *Setaria glauca* (L.), Beauv., *Avena fatua* L., *Setaria viridis* (L.) Beauv.) often dominate in phytocenoses; their number exceeds the density of wheat plants up to 6.2 times. The influence of weather conditions on the biological diversity and the quantity of weed seeds in the soil was 36.2 and 69.8%, respectively. The following pathogenic micromycetes were isolated from the seeds of gramineous weeds: *Bipolaris sorokiniana* (Sacc.) Shoemaker, several representatives of the genera *Alternaria* Nees, *Fusarium* Link, *Penicillium* Link, *Epicoccum* Link, etc. *Fusarium* fungi were the dominant taxon, both on seeds and on underground organs of the weeds. Jaccard index for the *Fusarium* fungi for the underground organs of cereal weeds and spring wheat was 0.55.

In the humid years, the causative agents of the cereal root rot expanded their ecological niche, infecting the spikes via airborne droplets, and the development of root rot intensified in the next season due to transmission of the pathogenic micromycetes through the seeds. Studies on the pathogenic mycotogenesis of barley seeds were carried out in the forest-steppe of western Siberia and the eastern Trans-Urals in 2006–2012. In western Siberia, three years (2006, 2007, 2009) of seven during the period of research were wet (SCC > 1) and the years 2008, 2010, 2011, 2012 were arid (SCC < 1). For the same period of research in the eastern Trans-Urals, the seasons of 2006, 2007, 2008, 2009, 2011 were wet, and 2010 and 2012 were arid. In wet years (SCC > 1.0) in western Siberia, barley grain was mainly affected by *Fusarium* fungi (55.4%), *B. sorokiniana* prevailed in the eastern Urals (84.3%) (Fig. 1). The character of the seasonal dynamics of abundance of *B. sorokiniana* on the seeds was determined by the amount of precipitation in August and was definitely moisture-dependent ($r = 0.731 \pm 0.210$). Seasonal dynamics of *Fusarium* fungi was also determined by the amount of precipitation in August ($r = 0.864 \pm 0.159$) but it can also be considered as temperature-dependent due to earlier colonization of grain in warm years.

Thus, the influence of climatic factors on the development of soil infections in cereal plants can be both direct (propagation, survival of phytopathogens, and plant susceptibility) and indirect—mediated by other biotic factors (antagonistic microorganisms, intra-stem phytophages, gramineous weeds). In all cases, the emerging climatic trend (the increase in the frequency of droughts, the amplitudes of temperature and humidity, especially in the first half of the growing season) contributes to the intensification of soil and

Table 2. Share (%) of crops and weather effect on soil saprotrophic microorganisms (by Snedecor) in the open agrocenoses of the southern steppe of western Siberia, 2011–2014

Group of microorganisms	Weather conditions of the year	Crop
Fungi on CA	43.2*	40.8*
Microorganisms on HA	64.3*	18.2*
Bacteria on SAA	87.8**	7.6*
Actinomycetes on SAA	84.7**	6.1*
Bacteria on MPA	12.2*	30.6*

*,** Values are statistically significant at $P \leq 0.05$ and $P \leq 0.01$.

Table 3. Share (%) of weather effect on phytosanitary condition of the soil, plants, and root rot etiology (by Snedecor) in the open agrocenoses of the southern steppe of western Siberia, 2011–2014

Index	Share of effect	
	max	min
Number of *Bipolaris sorokiniana* conidia in the soil:		
Total	43.4	17.9
Share of degradation (survival rate)	27.1	0
Development of the root rot	63.0	16.2
Root infection rate:		
Bipolaris sorokiniana	78.3	25.8
Fusarium fungi	23.2	7.7

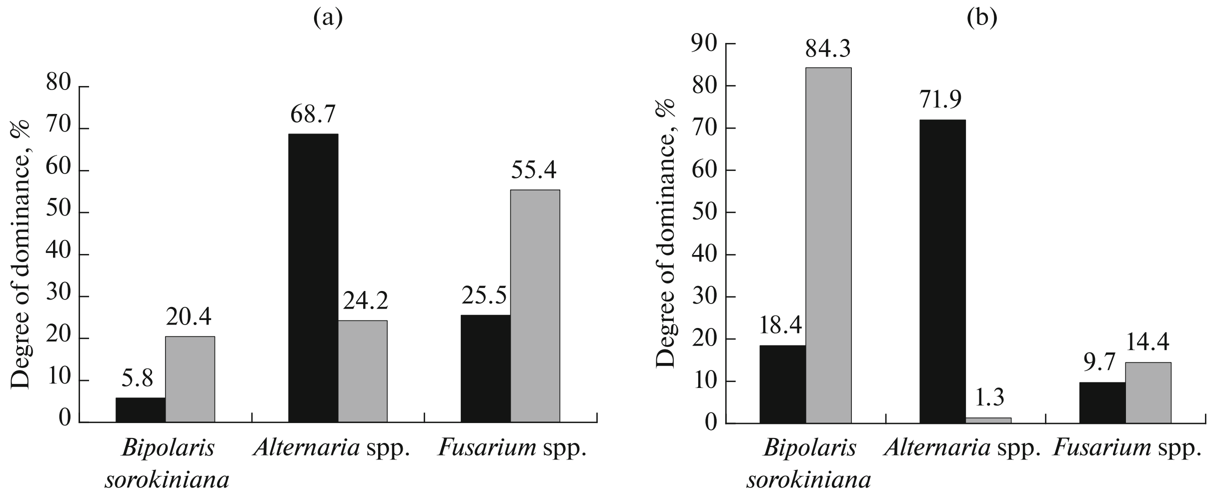

Fig. 1. Percentage of pathogenic microorganisms on barley seeds in (a) western Siberia and (b) the eastern Trans-Urals in the years varying in moisture conditions: (a) hydrothermal index < 1.0, (b) hydrothermal index > 1.0; (a) 11.1 LSD_{05} for *B. sorokiniana*, 21.3 for *Alternaria* spp., 21.6 for *Fusarium* spp.; (b) 8.9 LSD_{05} for *B. sorokiniana*, 23.3 for *Alternaria* spp., 3.9 for *Fusarium* spp.

root infections, which requires commodity producers to take urgent adequate measures to improve the soil and increase the stress resistance of the plants. Wet conditions during grain ripening contributed to its infection with root rot pathogens, so special attention should be paid to phytosanitary diagnostics of seeds and their sanitation.

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