Pathotype, Resistance Classification, and Seed-Coating Control of *Heterodera avenae* and *H. filipjevi* in the North China Plain

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Abstract

Heterodera avenae and *H. filipjevi* are cereal cyst nematodes (CCNs) that infect cereals in 16 provinces of China. CCN populations from Xuchang, Tangyin, Qihe, and Juye were tested using 23 barley, oat, and wheat entries of the International Test Assortment for Defining Cereal Cyst Nematode Pathotypes. *H. avenae* populations from Tangyin, Qihe, and Juye were classified as pathotype Ha91, and *H. filipjevi* from Xuchang was classified as a new pathotype similar to pathotype West. Among 42 other winter wheat cultivars, 29 and 30 were differentially susceptible, 13 and 12 were differentially resistant to *H. avenae* and *H. filipjevi*, respectively. Three entries were resistant to both species, and three other entries were resistant to *H. avenae* and moderately

resistant to *H. filipjevi*. Coating wheat seed with abamectin + isopropynic imidacloprid or methylene (bis) thiocyanate + thiamethoxam reduced the number of *H. avenae* and *H. filipjevi* cysts by 46 to 56%, increased wheat yield by 9 to 27%, and improved net income by 660 to 2,640 Chinese Yuan ha⁻¹, respectively. Resistant wheat cultivars are scarce in China, and seed coating is considered the most suitable method for controlling CCNs in the North China Plain, where crop rotation cannot be practiced.

Keywords: cereal cyst nematode, pathotype West, pathotype Ha91, seed coating, wheat resistance

As the staple food for 35% of the global population, wheat (*Triticum aestivum* L.) is one of the most important crops worldwide (Singh et al. 2011). The most globally recognized and economically important wheat-damaging nematodes are the cereal cyst nematodes (CCNs) *Heterodera avenae*, *H. filipjevi*, and *H. latipons* (Nicol et al. 2011). In Australia, grain loss caused by *H. avenae* was estimated to be 20 to 50% for barley and wheat, with an annual economic loss of \$58 million (Murray and Brennan 2009). In Turkey, *H. filipjevi* is economically important, causing an average yield loss of 42% in rain-fed winter wheat (Nicol et al. 2006). In the Pacific Northwest region of the United States, the annual impact on wheat production by the CCN was estimated to be approximately 21,000 tons, valued at \$3.4 million (Smiley 2009). In China, an area of more than 4 million ha in major wheat-producing regions is infested by the CCNs, resulting in 10 to 40% reductions in wheat grain yield (Cui et al. 2015). Where the density of CCNs is greater than 10 eggs g soil⁻¹, yield losses can range from 16 to 55% (Hou et al. 2012). *H. avenae* (Wollenweber 1924) was first identified in Hubei Province of China in 1989 (Chen et al. 1992) and has subsequently been reported in Henan, Hebei, Beijing, Inner Mongolia, Qinghai, and Anhui Provinces. *H. avenae*

has been detected in a total of 16 wheat-producing provinces in China (Cui et al. 2015). *H. filipjevi* (Madzhidov 1981) Stelter 1984 was first reported in Henan Province in 2010 (Peng et al. 2010) and subsequently detected in Anhui Province, the Xinjiang Uygur Autonomous Region, and Shandong Province (Peng et al. 2016, 2018; Zhen et al. 2018). The infestation of wheat by CCNs is increasing in China, resulting in losses of 1.9 billion Chinese Yuan (CNY) year⁻¹ (Peng et al. 2009).

The relative ability of a nematode to damage a particular plant is defined as “pathogenicity” (Nicol et al. 2011). The first pathotype of *H. avenae* was defined by Andersen (1959), after which Andersen and Andersen (1982) reviewed the pathotype variations in *H. avenae* and established the “International Cereal Test Assortment for Defining Cereal Cyst Nematode Pathotypes”. The four cultivars Ortolan (*Rha1+*), KVL 191 (*Rha2+*), Siri (*Rha2+*), and Morocco (*Rha3+*) could distinguish CCN pathotypes; group 1 is avirulent to cultivars with the resistance gene *Ha1*, group 2 is virulent to those cultivars with the resistance gene *Ha1* but not to cultivars with the resistance gene *Ha2*, and group 3 is virulent to cultivars with both the resistance genes *Ha1* and *Ha2* but not to cultivars with the resistance gene *Ha3* (Andersen and Andersen 1982; Cook and Rivoal 1998). Andersen and Andersen (1982) reported that the “*H. avenae*” populations that were initially designated as pathotypes Ha23 and Ha33 were actually pathotypes of the closely related species *H. filipjevi*. Ireholm (1994) distinguished *H. filipjevi* pathotypes G (West) and G (East), known as the *H. avenae* Gotland race in Sweden. To date, 15 *H. avenae* pathotypes have been described and named worldwide (Cui et al. 2015). At least three pathotypes of *H. filipjevi* can be differentiated using the International Cereal Test Assortment (Holgado et al. 2004; Subbotin et al. 2010; Toktay et al. 2013). However, there are no reports of *H. filipjevi* pathotypes being distinguished in China.

Multiple studies and control measures have been performed to overcome the CCN problem globally. The use of resistant and tolerant wheat varieties has been the most effective, economically beneficial, and environmentally friendly option for controlling these nematodes (Nicol et al. 2011; Smiley et al. 2012, 2017). After

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Funding: This research was supported by the National Natural Science Foundation of China (31801717), the Key Scientific Research Projects Plan of Henan Higher Education Institutions (19A210017), the Open Research Fund of the State Key Laboratory for Biology of Plant Diseases and Insect Pests (SKLOF201910), and the Special Fund for Young Talents in Henan Agricultural University (30500663).

The author(s) declare no conflict of interest.

Accepted for publication 1 June 2020.

suitable resistance sources from barley and wild wheat relatives were identified and confirmed, the resistance genes were transferred to different cultivars (Ogbonnaya et al. 2001). However, Smiley et al. (2017) indicated that the effect of designated *Cre* genes depends on both the CCN species and pathotypes. Currently, applications of chemical nematicides are among the primary means for controlling plant-parasitic nematodes. Fosthiazate is effective for reducing and suppressing *Globodera pallida* hatching (Woods et al. 1999). The application of abamectin (Aba) + carbendazim + thiram as a seed coating treatment effectively decreased the number of soybean cyst nematodes with a control efficiency of 48% (Chen et al. 2008). Soil applications of Aba at a rate of 45 kg ha⁻¹ in greenhouse and field trials significantly decreased the number of CCN white females by 66 to 77% and 47 to 65%, respectively, and increased the wheat grain yield by 19% (Zhang et al. 2017). Coating seed with methylene (bis) thiocyanate (MT) and MT + thiamethoxam (MTT) reduced the number of *H. avenae* cysts by 53 and 56% and increased wheat yield by 38 and 19%, respectively (Hao et al. 2014). Cui et al. (2017c) demonstrated that the application of seed treatments with 1.0% MT + 10% MTT (flowable concentration for seed coating [FSC]) and 3% fipronil + 15% chlorpyrifos (FSC) effectively decreased the number of cysts, inhibited the reproduction of *Heterodera* spp., and increased the wheat yield under field conditions.

The objectives of this study were to (i) characterize the pathotypes of three populations of *H. avenae* and one population of *H. filipjevi* collected from a major wheat-producing region, (namely, the North China Plain), (ii) screen international and Chinese winter wheat sources that might carry resistance genes that could be transferred to locally adapted cultivars via introgression and subsequently deployed to control CCNs, and (iii) test and evaluate the pathogenicity of different pathotypes of CCNs in China.

Materials and Methods

Nematode collection. CCNs were collected from the soil of severely infested wheat fields in Xuchang (34°02'019" N, 113°44'023" E) and Tangyin (35°53'057" N, 114°26'011" E) in Henan Province and in Qihe (36°57'065" N, 116°57'023" E) and Juye (35°17'012" N, 115°55'028" E) in Shandong Province, China, at the end of the wheat growing season. These locations, which are separated by 250 to 350 km, represent four counties with heavy infestations of *H. avenae* and *H. filipjevi* that have caused significant damage to wheat. Cysts were extracted from the soil via Cobb's sieving gravity method (Persmark et al. 1992). Using molecular methods previously described by Qi et al. (2012) and Peng et al. (2013), the nematodes collected in Xuchang were identified as *H. filipjevi* and those collected from Tangyin, Qihe, and Juye were identified as *H. avenae*. The cysts were incubated at 4°C for 60 days and then at 16°C to stimulate the hatching of preparasitic second-stage juveniles (J2s).

Experimental design. *Pathotype tests.* Four CCN pathotype tests were conducted to distinguish the *H. avenae* populations from Tangyin, Qihe, and Juye and *H. filipjevi* populations from Xuchang. Seed of standard hosts, including 13 barley species, 6 oat species, and 7 wheat species (Table 1), were germinated in Petri dishes and then transplanted into polyvinyl chloride (PVC) tubes (3 cm in diameter and 25 cm in length) that contained 150 cm³ of a sterile soil mixture (loamy soil/compost/sand = 3:2:5). Approximately 300 J2s were placed into each tube immediately after seed planting, and two additional batches of 250 J2s were added at 3-day intervals to obtain a final inoculum density of approximately 800 juveniles per tube (Cui et al. 2015). The susceptible (S) wheat cultivars Wenmai 19 and Aikang 58 were used as local controls. Each cultivar underwent five replicates four times. Plants were grown in a glasshouse for 1 week at 14 and 18°C, 2 weeks at 16 and 20°C, 5 weeks at 18 and 25°C, and 2 weeks at 22 and 30°C, under 8 h of darkness and 16 h of light and

Table 1. Reactions of international standard hosts to populations of cereal cyst nematodes from four locations in the North China Plain^a

Entry (resistance gene)	Xuchang		Tangyin		Qihe		Juye	
	Mean	PR	Mean	PR	Mean	PR	Mean	PR
Barley								
Varde	26.7 ± 4.9	+	33.9 ± 4.7	+	27.8 ± 2.8	+	38.3 ± 3.7	+
Emir (<i>RhaE</i>)	0	—	2.3 ± 0.7	(—)	Nt	Nt	Nt	Nt
Ortolan (<i>Rha1+</i>)	1.3 ± 1.5	—	0.3 ± 0.4	—	0	—	0	—
KVL 191 (<i>Rha2+</i>)	4.5 ± 1.8	(+)	1.5 ± 0.7	(—)	4.0 ± 1.3	(+)	5.1 ± 1.8	(+)
Siri (<i>Rha2+</i>)	1.5 ± 0.9	—	0	—	0	—	0	—
Morocco (<i>Rha3+</i>)	2.7 ± 1.6	(—)	0.7 ± 0.6	—	0.3 ± 0.5	—	0.3 ± 0.4	—
Marocaine C.I.8341	0.7 ± 0.9	—	0	—	2.9 ± 1.8	(+)	4.5 ± 1.3	(+)
Bajo Aragon 1-1 (<i>Rha2</i>)	1.3 ± 1.2	—	0	—	0	—	0	—
Herta	3.8 ± 1.7	(+)	0.7 ± 1.1	—	0	—	0	—
Martin 403-2 (<i>Rha2+</i>)	1.1 ± 0.7	—	0	—	1.2 ± 1.1	—	0.4 ± 0.6	—
Dalmatische	13.2 ± 3.0	+	20.3 ± 4.6	+	13.1 ± 2.6	+	20.5 ± 4.1	+
La Estanzuela	0	—	7.5 ± 1.7	+	6.5 ± 2.1	+	12.5 ± 2.7	+
Harlan 43	27.3 ± 6.5	+	4.8 ± 1.1	(+)	0.9 ± 0.6	—	1.3 ± 0.7	—
Oat								
ANSI	0	—	0	—	0	—	0	—
Sun II	0.4 ± 0.6	—	0	—	0	—	0	—
IGV.H72-646	29.2 ± 9.4	+	26.6 ± 5.0	+	0.1 ± 0.3	—	2.3 ± 2.0	(—)
Silva (>1 gene)	0.7 ± 0.6	—	0	—	0	—	0	—
I.376	0	—	0	—	0	—	0	—
Pusa hybrid BS1 (<i>RI</i>)	0.7 ± 0.6	—	0	—	0	—	0	—
Wheat								
Capa	55.6 ± 8.3	+	41.6 ± 5.9	+	31.3 ± 4.7	+	34.6 ± 5.2	+
LorosxKoga (<i>CreI</i>)	33.4 ± 6.2	+	27.3 ± 4.2	+	20.8 ± 3.3	+	25.2 ± 4.1	+
Iskamisch-K-2-light	43.9 ± 16.9	+	20.1 ± 3.9	+	1.5 ± 1.0	(—)	2.8 ± 1.9	(+)
AUS 10894 (<i>CreI</i>)	48.2 ± 6.5	+	34.3 ± 7.8	+	29.2 ± 6.2	+	31.3 ± 5.9	+
Psathias	14.1 ± 3.9	+	11.9 ± 2.4	+	3.7 ± 1.1	(+)	4.5 ± 1.3	(+)
Aikang 58	49.0 ± 5.8	+	32.6 ± 4.4	+	31.1 ± 8.2	+	33.7 ± 11.5	+
Wenmai 19	61.0 ± 8.3	+	48.3 ± 2.7	+	44.6 ± 6.9	+	52.2 ± 12.3	+

^a Data are presented as the means ± standard deviation of 20 replicates. Phenotypic reactions (PR) are classified as follows: — indicates resistant (<3% of the white females present on the local cultivar Wenmai 19), (—) indicates moderately resistant (3 to 5%), (+) indicates moderately susceptible (5 to 10%), + indicates susceptible (>10%), and Nt indicates not tested.

normal culturing practices (irrigation, fertilization, and disease and insect control). Ten weeks after the last inoculation, the wheat roots and soil were washed with a gentle stream of tap water over a 250- μ m sieve. White female nematodes attached to the roots and soil were collected and counted under a stereoscope, and the mean numbers of white females per plant were calculated. The cultivars were categorized by resistance responses on the basis of a rating system (Smiley et al. 2011). The degree of resistance was classified as resistant (R), moderately resistant (MR), moderately susceptible (MS), and S if the plants contained less than 3, 3 to 5, 5 to 10, and more than 10%, respectively, of the number of white females present on the most S wheat cultivar (Wenmai 19).

Resistance tests. The resistance tests involved a subset of the 42 most promising wheat cultivars screened against CCN populations from the International Wheat and Maize Improvement Center (CIMMYT) and from the North China Plain, the major wheat-growing

area in China (Table 2). The seed were germinated in Petri dishes, and five replicates of each cultivar were transplanted into PVC tubes, as previously described. Cysts from a population of *H. avenae* Ha91 from Daxing County in Beijing Province (Cui et al. 2015) and from the Xuchang population of *H. filipjevi* were hatched at 14 to 16°C. Freshly hatched J2s were used to infect the roots of wheat plants, as previously described. Ten weeks after the last inoculation, the wheat roots and soil were washed, and white females were collected and counted, as described previously. The degree of resistance of the cultivars was classified as follows on the basis of the number of cysts per root system: immune (M) (0 females), R (0.1 to 5.0 females), MR (5.1 to 10.0 females), MS (10.1 to 15.0 females), S (15.1 to 25.0 females), and highly susceptible (HS) (>25.0 females) (Nicol et al. 2009).

Field trials of chemical treatments. Four seed-coating compounds were tested against CCN populations of *H. avenae* from Tangyin

Table 2. Results of the most promising wheat cultivars from China and International Maize and Wheat Improvement Centre (CIMMYT) screened against the *Heterodera avenae* Ha91 (Daxing population) and *H. filipjevi* (Xuchang population) from China

Entry (cross name)	Origin	Season	Cereal cyst nematode RR ^z			
			<i>H. avenae</i>		<i>H. filipjevi</i>	
			Mean	RR	Mean	RR
Aizao8-15	Henan	Semiwinter	0.4 $\pm$ 0.51	R	1.1 $\pm$ 0.88	R
GA951079-3-5/Neuse	CIMMYT	Winter	1.6 $\pm$ 0.89	R	9.4 $\pm$ 2.70	MR
MV17/3/Azd/Vee"s"/Seri82/Rsh/4/Fln/ Acc//Ana/3/Pew"s"/5/Rsk/CA8055// Cham6	CIMMYT	Winter	1.8 $\pm$ 1.09	R	4.0 $\pm$ 1.00	R
Wo0608	Anhui	Semiwinter	2.8 $\pm$ 0.79	R	6.6 $\pm$ 2.59	MR
Mirzabey2000	CIMMYT	Winter	3.2 $\pm$ 1.30	R	2.0 $\pm$ 1.58	R
Xinong509	Shaanxi	Semiwinter	3.4 $\pm$ 1.34	R	9.4 $\pm$ 2.63	MR
Zhong155	Beijing	Semiwinter	5.2 $\pm$ 1.39	MR	7.5 $\pm$ 2.95	MR
Wanke06290	Anhui	Weak spring	5.8 $\pm$ 1.55	MR	9.1 $\pm$ 3.14	MR
Xin25	Henan	Semiwinter	6.1 $\pm$ 1.73	MR	18.5 $\pm$ 3.84	S
Zheng7698	Henan	Semiwinter	6.5 $\pm$ 1.35	MR	19.9 $\pm$ 4.31	S
Wennong14	Shandong	Semiwinter	6.9 $\pm$ 1.45	MR	16.7 $\pm$ 2.11	S
Pingan8	Henan	Semiwinter	7.4 $\pm$ 1.58	MR	18.8 $\pm$ 4.47	S
Patwin	CIMMYT	Winter	13.0 $\pm$ 2.12	MS	1.2 $\pm$ 0.83	R
Fengdecun1	Henan	Semiwinter	14.0 $\pm$ 2.71	MS	31.9 $\pm$ 8.74	HS
Pfau/Milan//Fung Mai 24	CIMMYT	Winter	14.2 $\pm$ 3.11	MS	7.8 $\pm$ 3.76	MR
Tosunbey	CIMMYT	Winter	16.0 $\pm$ 2.23	S	29.4 $\pm$ 7.53	HS
Zhengyu9989	Henan	Semiwinter	16.7 $\pm$ 2.11	S	28.8 $\pm$ 7.22	HS
Jinhe9123	Hebei	Semiwinter	17.8 $\pm$ 3.15	S	14.5 $\pm$ 2.41	MS
Aizao4110	Henan	Weak spring	20.1 $\pm$ 3.38	S	35.1 $\pm$ 5.84	HS
Clear White	CIMMYT	Winter	21.0 $\pm$ 4.89	S	23.0 $\pm$ 5.24	S
P8-6	CIMMYT	Winter	27.0 $\pm$ 9.35	HS	6.6 $\pm$ 2.70	MR
Taishan22	Shandong	Semiwinter	28.8 $\pm$ 7.22	HS	21.4 $\pm$ 4.38	S
Huai29	Anhui	Semiwinter	29.7 $\pm$ 3.06	HS	36.9 $\pm$ 5.04	HS
Taikong6	Henan	Weak spring	29.8 $\pm$ 6.37	HS	15.4 $\pm$ 3.86	S
Zhongyu6	Henan	Semiwinter	30.9 $\pm$ 3.35	HS	14.9 $\pm$ 2.60	MS
Tarm (Ankara-98)	CIMMYT	Winter	31.2 $\pm$ 6.14	HS	6.6 $\pm$ 0.54	MR
Shixin733	Hebei	Semiwinter	31.6 $\pm$ 4.88	HS	28.6 $\pm$ 4.48	HS
Bainong207	Henan	Semiwinter	32.5 $\pm$ 7.12	HS	39.9 $\pm$ 3.21	HS
Liangxing66	Hebei	Semiwinter	34.1 $\pm$ 4.93	HS	40.7 $\pm$ 5.10	HS
Anara	CIMMYT	Winter	35.6 $\pm$ 7.73	HS	32.4 $\pm$ 5.77	HS
Bainong196	Henan	Semiwinter	36.2 $\pm$ 5.98	HS	48.5 $\pm$ 5.58	HS
Huai1	Jiangsu	Semiwinter	37.0 $\pm$ 6.41	HS	44.2 $\pm$ 5.31	HS
Ak702	CIMMYT	Winter	38.4 $\pm$ 7.92	HS	13.6 $\pm$ 3.21	MS
Aikang58	Henan	Semiwinter	39.3 $\pm$ 5.10	HS	56.0 $\pm$ 6.65	HS
Yujiao5	Henan	Semiwinter	41.9 $\pm$ 7.43	HS	43.9 $\pm$ 6.51	HS
Huai18	Anhui	Semiwinter	43.0 $\pm$ 5.09	HS	33.0 $\pm$ 4.13	HS
Zhou27	Henan	Semiwinter	43.5 $\pm$ 4.30	HS	38.8 $\pm$ 5.12	HS
Taishan24	Shandong	Semiwinter	44.1 $\pm$ 6.01	HS	28.0 $\pm$ 3.89	HS
Ji22	Shandong	Semiwinter	44.7 $\pm$ 4.39	HS	25.2 $\pm$ 5.37	HS
Kern (YR15; GPC; 2NS)	CIMMYT	Winter	45.0 $\pm$ 9.47	HS	9.6 $\pm$ 4.72	MR
Zhou18	Henan	Semiwinter	51.2 $\pm$ 7.98	HS	30.7 $\pm$ 4.06	HS
Shannong820	Shandong	Semiwinter	66.1 $\pm$ 8.21	HS	51.3 $\pm$ 5.52	HS

^z RR = resistance reaction; mean $\pm$ standard error. The degree of resistance of the cultivars was classified based on the number of cysts per root system as follows: immune (M, 0 females), resistant (R, 0.1 to 5.0 females), moderately resistant (MR, 5.1 to 10.0 females), moderately susceptible (MS, 10.1 to 15.0 females), susceptible (S, 15.1 to 25.0 females), and highly susceptible (HS, >25.0 females).

(pathotype Ha91) and *H. filipjevi* from Xuchang (new pathotype) in Henan Province during the 2017 and 2018 wheat seasons. The plots were 10 m long and 3.5 m wide (18 plant rows), and the wheat cultivar Aikang 58 was used. Three replicates were arranged as randomized complete blocks. Compound fertilizer (N + P₂O₅ + K₂O, 18-18-18; Shandong Stanley Fertilizer Co., Ltd., Linyi, Shandong Province, China) was applied at a rate of 450 kg ha⁻¹, and urea was applied at 150 kg ha⁻¹ at the tillering stage (Feekees 3.0 wheat growth stage) (Large 1954). The wheat seed were coated with Aba (10% active ingredient [a.i.], suspension concentration; Zhongda Agricultural Technology Co., Ltd., Qingdao, Shandong Province, China) and isopropyl imidacloprid (Imi; 60% a.i., FSC, Bayer Crop Science, Hangzhou City, China), MTT (1.0% MT and 10% thiamethoxam FSC; Gansu Agricultural University, China), fosthiazate (10% a.i., granular; Ishihara Industries Corp., Japan), or tap water. Aba + Imi, MTT, or water were mixed with seed (25 ml kg⁻¹) using a Huaxing 100 seed dresser (Huaxing Machinery Co., Ltd., Guangzhou, Guangdong Province, China). Granular fosthiazate (30 kg ha⁻¹) was applied to the fields, which were plowed with a 3wg-11 garden tiller (Keshida Agricultural Machinery Group Co., Ltd., Weifang, Shandong Province, China) 1 day before planting. The seed were planted using a 2BXF-9 drill (Nonghaha Machinery Group Co., Ltd., Shijiazhuang, Hebei Province, China) equipped with a disk coulters and nine openers spaced 18 cm apart. The seed were sown at a rate of 150 kg ha⁻¹ into moist soil at a depth of 3 to 5 cm when the seed-zone temperature was 15 to 17°C. Normal cultural practices such as irrigation; fertilization; and weed, disease, and insect control were performed by field workers.

The initial population (*P*_i) densities of nematodes in the experimental area were determined by collecting five samples in a zigzag pattern from each of the 12 plots. Similarly, the final population (*P*_f) densities of mature brown cysts in the field were determined after wheat harvest. Each sample comprised a composite of 15 soil cores 2.5 cm in diameter and 35 cm deep. The collected soil cores were thoroughly mixed, and three 100-cm³ subsamples were removed for counting (Cui et al. 2017c). The cysts were extracted from the soil by wet sieving and sucrose flotation centrifugation (Zheng et al. 1995), then counted using a stereomicroscope. The agronomic characteristics of the treated wheat plants (spike number per square meter, thousand-seed weight, and grain yield per square meter) were compared with those of the untreated control plants after three random 1-m² areas of each plot were harvested with a KTY-100 seed sheller (Xinchang Machinery Group Co., Ltd., Weihui, Henan Province, China).

Statistical analysis. The wheat growth indices, grain yield, number of white female cysts in the greenhouse pot trials, and number of mature brown cysts in the field trials were subjected to statistical analyses. Analysis of variance was performed individually for each experiment. Significant differences (*P* ≤ 0.05) among treatments were determined in conjunction with the least significant difference test via SPSS 12.0 software (SPSS Inc.).

The reproductive factor (RF) and reduction in population over the control (ROC) metrics were calculated to reflect the protective efficacy of the chemicals against CCNs (Jagdale and Grewal 2002). The following equations were used in the statistical analyses:

$$RF = P_f / P_i$$

$$ROC = (\text{cyst number of the control} - \text{cyst number of treatment}) \times 100\% / \text{cyst number of the control}$$

$$\text{Yield increase}(\%) = (\text{yield of treatment} - \text{yield of the control}) \times 100\% / \text{yield of the control}$$

Results

Pathotype tests. The number of white females on the roots of each plant was counted at 70 days after inoculation with 800 *H. filipjevi* from a population from Xuchang and *H. avenae* populations from Tangyin, Qihe, and Juye. The four repeat tests showed similar results,

and the responses of each cultivar and the mean number of white females per plant are shown in Table 1. The local wheat cultivar Wenmai 19 produced the largest number of white females among all of the populations.

For the *H. filipjevi* population, no white females were observed on the barley cultivars Emir (*RhaE*) and La Estanzuela. Ortolan (*Rha1+*), Siri (*Rha2+*), Marocaine C.I.8341, Bajo Aragon 1-1 (*Rha2*), and Martin 403-2 (*Rha2+*) were also classified as R, with a mean number of white females less than 1.8 (<3% of white females present on cultivar Wenmai 19). However, KVL 191 (*Rha2+*) was MS and Morocco (*Rha3+*) was MR to the tested *H. filipjevi* population, with mean white female numbers of 4.5 and 2.7, respectively. Varde and Harlan 43 were the most S cultivars in barley group, with mean white female numbers of 26.7 and 27.3, respectively. All of the oat cultivars were strongly R, with the exception of IG.V.H72-646, which was S, with a mean of 29.2 white females. All of the wheat cultivars were S to the *H. filipjevi* population, and Capa was the most S wheat cultivar, with a mean of 55.6 white females. In summary, the results observed for the *H. filipjevi* population from Xuchang were inconsistent with the reaction of pathotype East, particularly for the cultivars carrying resistance genes; namely, Ortolan (*Rha1+*), Siri (*Rha2+*), Martin 403-2 (*Rha2+*), and Morocco (*Rha3+*) that can distinguish CCN pathotypes (Table 3). Although the responses of Ortolan (*Rha1+*), KVL 191 (*Rha2+*), Siri (*Rha2+*), Bajo Aragon 1-1 (*Rha2*), and Morocco (*Rha3+*) were identical to those obtained with pathotype West when challenged with the *H. filipjevi* population from Xuchang, the responses obtained for barley with Martin 403-2 (*Rha2+*) and Herta, oat with Sun II (minor genes), and wheat with Psathias were inconsistent with those obtained for pathotype West (Table 3). Furthermore, the reaction data regarding Marocaine

Table 3. Resistance reactions of 23 standard reference cereals to *Heterodera filipjevi* populations from China in this study and as reported by Ireholm (1994)^z

Cereal cultivar	Present study	Ireholm West		Ireholm East	
	XC	NH	Mol	Et	Ha
Barley					
Varde	S	S	S	S	S
Ortolan (<i>Rha1+</i>)	R	R	R	S	S
KVL 191 (<i>Rha2+</i>)	S	(R)	(S)	*	S
Siri (<i>Rha2+</i>)	R	R	R	S	S
Morocco (<i>Rha3+</i>)	(R)	R	(S)	S	S
Marocaine C.I.8341	R	*	*	*	*
Bajo Aragon 1-1 (<i>Rha2</i>)	R	R	R	R	R
Herta	(S)	R	R	*	*
Martin 403-2 (<i>Rha2+</i>)	R	S	S	S	S
Dalmatische	S	*	*	*	*
La Estanzuela	R	R	R	R	R
Harlan 43	S	(R)	(S)	(S)	(S)
Oat					
ANSI	R	*	*	*	*
Sun II (minor genes)	R	S	S	(S)	S
IGV.H72-646	S	*	*	*	*
Silva (>1 gene)	R	*	*	*	*
I.376 (1-3 dominant genes)	R	R	R	R	(S)
Pusa Hybrid BS1 (<i>R1</i>)	R	*	*	*	*
Wheat					
Capa	S	S	S	S	S
LorosxKoga (<i>Cre1</i>)	S	S	S	S	S
Iskamish-K-2-light	S	*	*	*	*
AUS 10894 (<i>Cre1</i>)	S	S	S	S	S
Psathias	S	R	R	R	(S)

^z Populations in the present study (XC = Xuchang County in Henan Province, China) and in a previous report by Ireholm (1994) (NH = Norra Harene population in Sweden, pathotype West; Mol = Molltorp population in Sweden, pathotype West; Et = Etelhem population in Sweden, pathotype East; and Ha = Havor population in Sweden, pathotype East). R = resistant, S = susceptible, (S) or (R) = intermediate reaction, and * = not tested.

C.I.8341, Dalmatische, ANSI, IGV.H72-646, Silva, Pusa Hybrid BS1 (*R1*), and Iskamish-K-2-light for pathotype West were lacking (Ireholm 1994). Our results indicated that the *H. filipjevi* population from Xuchang was a new pathotype.

The *H. avenae* populations from Tangyin, Qihe, and Juye exhibited similar resistance responses. Ortolan (*Rha1+*), Siri (*Rha2+*), Martin 403-2 (*Rha2+*), Bajo Aragon 1-1 (*Rha2*), Morocco (*Rha3+*), and Herta showed high resistance to the three populations. Marocaine C.I.8341 was R to the Tangyin population and MS to the Qihe and Juye populations. Harlan 43 was MR to the Tangyin population and R to the Qihe and Juye populations. The most S barley cultivar was Varde, followed by Dalmatische and La Estanzuela, with 33.9, 27.8, and 38.3 mean white females, respectively. IGV.H72-646 was S to the Tangyin population, and all of the other tested oat cultivars were nearly R. Most of the tested wheat cultivars were S to the three *H. avenae* populations, except Iskamish K-2-light, which was MR to the Qihe population. In conclusion, the resistance responses of six cultivars carrying resistance genes distinguished CCN pathotypes: the responses of Ortolan (*Rha1+*), KVL 191 (*Rha2+*), Siri (*Rha2+*), Bajo Aragon 1-1 (*Rha2*), Martin 403R2 (*Rha2+*), and Morocco (*Rha3+*) were completely consistent with pathotype Ha91 (Table 4). The responses of the other cultivars, with the exception of Marocaine C.I.834, were all consistent with pathotype Ha91 (Table 4). Our data supported the conclusion that the *H. avenae* populations from Tangyin, Qihe, and Juye were pathotype Ha91.

Resistance tests. Resistance screening of the 42 target cultivars of winter wheat from China and CIMMYT (Table 2) revealed that 22

were HS, 5 were S, 3 were MS, 6 were MR, and 6 were R to the Daxing population of *H. avenae* pathotype Ha91 and 19 were HS, 7 were S, 3 were MS, 9 were MR, and 4 were R to the Xuchang population classified as the new *H. filipjevi* pathotype. GA951079-3-5/Neuse, Wo0608, and Xinong509 were R to *H. avenae* and MR to *H. filipjevi*. Patwin was R to *H. filipjevi* but MS to *H. avenae*, and Zhong 155 and Wanke 06290 were MR to the *H. avenae* and *H. filipjevi* populations. Xin25, Zheng7698, Wennong 14, and Pingan 8 were MR to the *H. avenae* population but S to the *H. filipjevi* population. Pfau/Milan//Fung Mai 24, P8-6, Tarm (Ankara-98), and Kern (YR15; GPC; 2NS) were differentially S to the *H. avenae* population but MR to the *H. filipjevi* population. The other tested wheat cultivars were S to the two CCN populations. The local S wheat cultivar Aikang 58 and the tolerant wheat cultivar Taikong 6 were HS and S to the *H. avenae* and *H. filipjevi* populations, respectively (Table 2).

All of the main wheat cultivars in China such as Aikang 58, Zhou18, Ji22, Shixin 733, Liangxing 66, Huai29 and Hua1 were S or HS to both *H. filipjevi* and *H. avenae* pathotype Ha91 (Table 2). Some cultivars from CIMMYT displayed good resistance to *H. avenae* pathotype Ha91 but not to the *H. filipjevi* population from Xuchang. Only 3 of the 42 most promising wheat cultivars tested (Aizao8-15, Mirzabey2000, and MV17/3/Azd/Vee's"/Seri82/Rsh/4/Fln/Acc//Ana/3/Pew's"/5/Rsk/CA8055//Cham6) were R to both *H. filipjevi* and *H. avenae* pathotype Ha91 (Table 2). The resistance reactions for the *H. avenae* pathotype Ha91 populations from Daxing and Tangyin were similar to each other but were significantly different from that to the *H. filipjevi* population from Xuchang (Table 5). The virulence of the *H. filipjevi* and *H. avenae* populations differed strongly according to the pathogenic spectrum results. Out of 16 wheat lines or cultivars, 4, 9, and 3 were classified as R, MR, and MS, respectively, to the *H. filipjevi* population from Xuchang; 6, 2, 2, 1, and 5 were classified as R, MR, MS, S, and HS, respectively, to the *H. avenae* population from Daxing; and 5, 2, 2, 4, and 3 were classified as R, MR, MS, S, and HS, respectively, to the *H. avenae* population from Tangyin (Table 5). The results showed that not only the species and the pathotypes but also different populations from the same pathotypes could impact the effectiveness of the specified R cultivars.

Table 4. Resistance reactions of 23 cultivars in the International Test Assortment for Defining Cereal Cyst Nematode Pathotypes to the populations of *Heterodera avenae* in the North China Plain, compared with *H. avenae* Ha91 described by Cui et al. (2015)^z

Cereal cultivar	Present study			Cui et al. (2015)	
	TY	QH	JY	HY	DX
Barley					
Varde	S	S	S	S	S
Ortolan (<i>Rha1+</i>)	R	R	R	R	R
KVL 191 (<i>Rha2+</i>)	(S)	(S)	(S)	S	(S)
Siri (<i>Rha2+</i>)	R	R	(S)	R	R
Morocco (<i>Rha3+</i>)	R	R	R	R	R
Marocaine C.I.8341	R	(S)	(S)	(S)	S
Bajo Aragon 1-1 (<i>Rha2</i>)	R	R	R	R	R
Herta	R	R	R	(S)	R
Martin 403R2 (<i>Rha2+</i>)	R	R	R	R	R
Dalmatische	S	S	S	S	S
La Estanzuela	S	S	S	S	S
Harlan 43	(R)	R	R	S	R
Oat					
ANSI	R	R	R	(R)	R
Sun II	R	R	R	(R)	R
IGV.H72R646	S	R	(S)	R	S
Silva (>1 gene)	R	R	R	R	R
I.376 <i>A. sterilis</i>	R	R	R	R	R
Pusa Hybrid BS1 (<i>R1</i>)	R	R	R	R	R
Wheat					
Capa	S	S	S	S	S
LorosxKoga (<i>Cre1</i>)	S	S	S	S	S
Iskamish-K-2-light	S	(R)	(R)	(S)	R
AUS 10894 (<i>Cre1</i>)	S	S	S	S	S
Psathias	S	(S)	(S)	(S)	(S)

^z Populations in the present study (TY = Tangyin County in Henan Province, QH = Qihe County in Shandong Province, and JY = Juye County in Shandong Province) and in a previous report by Cui et al. (2015) (HY = Huangyuan County in Qinghai Province and DX = Daxing County in Beijing Province). Pathotype groups are those of Andersen and Andersen (1982), which were based on virulence to the *Ha1*, *Ha2*, and *Ha3* resistance genes. R = resistant, S = susceptible, (S) or (R) = intermediate reaction, and * = not tested.

Table 5. Resistance reactions of the most promising lines or cultivars of winter wheat screened against *Heterodera filipjevi* populations from China in this and previous studies

Entry	Reaction ^y		
	<i>H. avenae</i>		<i>H. filipjevi</i>
	Daxing	Tangyin	Xuchang
Aizao8-15	R	R	R
MV17/3/Azd/Vee's"/Seri82/Rsh/4/Fln/Acc//Ana/3/Pew's"/5/Rsk/CA8055//Cham6 ^z	R	R	R
Mirzabey2000 ^z	R	R	R
Patwin ^z	MS	MS	R
Xinong509	R	R	MR
GA951079-3-5/Neuse ^z	R	R	MR
Wo0608	R	MR	MR
Zhong155	MR	MR	MR
Wanke06290	MR	MS	MR
P8-6 ^z	HS	S	MR
Pfau/Milan//Fung Mai 24 ^z	MS	HS	MR
Kern (YR15; GPC; 2NS) ^z	HS	HS	MR
Tram (Ankara-98) ^z	HS	HS	MR
Ak702 ^z	HS	S	MS
Jinhe9123	S	S	MS
Zhongyu6	HS	S	MS

^y R = resistant, MR = moderately resistant, MS = moderately susceptible, S = susceptible, and HS = highly susceptible.

^z Most-promising lines or cultivars of winter wheat screened against *H. filipjevi* populations reported by Dababat et al. (2015).

Field trials of chemical treatments. *Effects of chemicals on CCN cysts.* All of the chemicals tested in the 2017 and 2018 trials were effective at controlling *H. avenae* and *H. filipjevi*. For each population, the postharvest cyst densities did not differ among the chemical treatments but were significantly lower than those of controls. For *H. avenae*, the Aba + Imi combination was the most effective, with an ROC of 56% and an RF of 0.80 (Table 6). Compared with the initial density, the postharvest cyst density in the control treatment group increased by 77% for *H. avenae* and 129% for *H. filipjevi*. The RFs in the *H. filipjevi* plots treated with fosthiazate, Aba + Imi, and MTT were 1.45, 1.28, and 1.19, respectively. MTT was the most effective chemical treatment for *H. filipjevi* cyst control, with a mean ROC of 47% (Table 6).

Effects of chemicals on wheat yields and economic benefits. Compared with the control treatment, the fosthiazate, Aba + Imi, and MTT treatments increased tillering, thousand-kernel weight, and grain yield (Table 7). However, no differences among nematocidal treatments were found for either *H. avenae* or *H. filipjevi*. The largest numerical percent increase in grain yield was obtained with the application of fosthiazate for the control of *H. avenae* (28%) and Aba + Imi for the control of *H. filipjevi* (19%). Significant increases in the thousand-kernel weight and grain yield were obtained from seed-coating treatment with Aba + Imi for the control of both nematode populations (Table 7).

According to the average market purchase prices for wheat in Xinxiang City in Henan Province in June 2018, the net return was calculated based on the increase in wheat yield minus the costs of the chemical products and application. For the field infested with *H. avenae*, Aba + Imi resulted in the highest additional net income, at 176 CNY 667 m⁻² (= 2,640 CNY ha⁻¹), followed by MTT, at 136 CNY

667 m⁻² (= 2,040 CNY ha⁻¹). For the field infested with *H. filipjevi*, Aba + Imi again resulted in the greatest additional net income, at 100 CNY 667 m⁻² (= 1,500 CNY ha⁻¹), followed by MTT, at 40 CNY 667 m⁻² (= 660 CNY ha⁻¹) (Table 7). For both species, the rate of increase with fosthiazate was positive but the additional net income was negative because the market price of fosthiazate was very high in China.

Overall, the ROCs for Aba + Imi and MTT on *H. avenae* cysts were 56 and 54%, respectively, and, under these treatments, the wheat yield increased by 27 and 20%, resulting in net income valued of 176 and 136 CNY 667 m⁻², respectively. The ROCs for Aba + Imi and MTT on *H. filipjevi* cysts were 46 and 47%, respectively, and wheat yield was increased by 19 and 9%, resulting in additional net incomes of 100 and 40 CNY 667 m⁻², respectively.

Discussion

Identifications of novel pathotypes of *H. avenae* and *H. filipjevi* have been much performed. Peng and Cook (1996) first reported that the pathotypes of *H. avenae* populations in China might differ from those in other regions but they did not indicate the identity of those pathotypes. Zheng et al. (1997) demonstrated that the *H. avenae* populations in Taigu and Guzhen were distinctive new pathotypes, and Yuan et al. (2010) reported a new pathotype (Ha43) from Xushui and Xingyang, China. Cui et al. (2015) classified *H. avenae* from the Daxing and Huangyuan populations as the new pathotype Ha91. In the present study, all of the tested barley, oat, and wheat cultivars exhibited the same responses to the three CCN populations from Tangyin, Qihe, and Juye that were clustered into group 1 (Andersen and Andersen 1982) as those to pathotype Ha91 (Table 4); therefore, the virulence phenotype of these three

Table 6. Effects of seed treatment chemicals on the number of cysts in fields naturally infested with *Heterodera avenae* in Tangyin and *H. filipjevi* in Xuchang

Population, chemicals ^x	Dosage	Number of cysts in 100 ml of soil		RF ^y	ROC (%) ^z
		Seeding	Harvesting		
<i>H. avenae</i>					
Fosthiazate (GR) (g/ha)	30,000	8.6 ± 2.07 a	7.4 ± 2.07 b	0.86	52.56
Aba (SC) + Imi (FSC) (ml/kg)	10	8.4 ± 1.34 a	6.8 ± 1.30 b	0.80	56.41
MTT (FSC) (ml/kg)	25	8.0 ± 1.58 a	7.2 ± 1.78 b	0.90	53.84
Tap water	...	8.8 ± 2.39 a	15.6 ± 3.36 a	1.77	
<i>H. filipjevi</i>					
Fosthiazate (GR) (g/ha)	30,000	13.0 ± 2.23 a	18.8 ± 2.86 b	1.45	37.75
Aba (SC) + Imi (FSC) (ml/kg)	10	12.8 ± 3.27 a	16.4 ± 2.41 b	1.28	45.69
MTT (FSC) (ml/kg)	25	13.4 ± 2.30 a	15.0 ± 3.16 b	1.19	47.02
Tap water	...	13.2 ± 3.49 a	30.2 ± 5.80 a	2.29	

^x Aba = abamectin, Imi = isopropyl imidacloprid, MTT = methylene (bis) thiocyanate + thiamethoxam, GR = granular, SC = suspension concentrate, FSC = flowable concentrate for seed coating.

^y Reproduction factor.

^z Reduction in population over the control.

Table 7. Effects of seed treatment chemicals on the agronomic characteristics and net income of wheat^w

Population, treatments ^x	Spike number/m ²	TKW ^y	Yield per m ² (g/m ²)	Yield increase (%)	Net income (CNY) ^z
<i>H. avenae</i>					
Fosthiazate	464.2 ± 11.90 b	45.9 ± 1.06 b	646.8 ± 48.99 b	28.2	-92
Aba + Imi	472.8 ± 10.28 b	45.2 ± 1.32 b	638.6 ± 65.39 b	26.6	176
MTT	466.0 ± 15.38 b	45.4 ± 1.48 b	606.2 ± 21.53 b	20.2	136
Tap water	431.8 ± 12.85 a	41.2 ± 1.42 a	504.4 ± 54.81 a	...	...
<i>H. filipjevi</i>					
Fosthiazate	442.3 ± 19.01 b	43.6 ± 0.35 ab	481.0 ± 31.19 ab	8.8	-257
Aba + Imi	454.3 ± 12.09 b	50.0 ± 2.08 b	527.0 ± 44.31 b	19.2	100
MTT	439.7 ± 31.07 b	47.3 ± 8.15 ab	483.7 ± 45.08 ab	9.4	40
Tap water	403.3 ± 12.58 a	37.8 ± 6.41 a	442.0 ± 34.04 a	...	...

^w Data are shown as the means plus standard deviation. The same letters within a column indicate no significant differences at *P* ≤ 0.05.

^x Aba = abamectin, Imi = isopropyl imidacloprid, and MTT = methylene (bis) thiocyanate + thiamethoxam.

^y Thousand-kernel weight.

^z Net income = additional wheat yields in a 667-m² field after treatment minus the cost of the chemical treatments and application. CNY = Chinese Yuan.

populations could be classified as pathotype Ha91 (Cui et al. 2015). Regarding *H. filipjevi*, the Gotland population was able to reproduce on barley line KVL 191, which is R to pathotypes Ha11 and Ha12 (Ireholm 1994). Martin 403-2 and KVL 191 were S to the typical pathotype G West populations from Norra Harene and Molltorp, while Herta, Siri, Emir, Ortolan, and Bajo Aragon 1-1 were highly resistant (HR) to this pathotype (Ireholm 1994). The results of the barley cultivars from Varde, Emir, Ortolan, and Morocco showed that the studied *H. filipjevi* pathotypes were similar to *H. filipjevi* pathotype West (Table 3). Moreover, all of the wheat cultivars displayed a high degree of susceptibility to the *H. filipjevi* population from Xuchang; nevertheless, AUS 10894 was MS to the Norra Harene population, and Psathias was R to the Norra Harene and Molltorp populations (Ireholm 1994). The responses of the tested cultivars to the *H. filipjevi* population from Xuchang were consistent with the results of previous reports on the *H. filipjevi* population in Norway but only five entries in the test assortment were tested by Holgado et al. (2004). Furthermore, the responses differed from the response to the *H. filipjevi* population pathotype from Huaiyang, Henan Province, because the virulence of the Huaiyang population was broader and more intense (Yuan et al. 2011a).

There have been 18 population pathotypes identified in China (Cui et al. 2015; Peng and Cook 1996; Yuan et al. 2010, 2011a; Zheng et al. 1997). The initial resistance responses of the pathotypes in these studies were classified on the basis of the number of cysts per root system: R (<10.0 females) and S (>10.0 females). Gradients of resistance to one plant disease are usually observed among different environments, populations, and testing methods; thus, this is not the most appropriate criterion for evaluating resistance (Smiley et al. 2011; Toumi 2017). Here, we complied with the most widely used resistance evaluation criterion: R = resistant (<3% of white females present on the most susceptible control cultivar), MR = moderately resistant (3 to 5%), MS = moderately susceptible (5 to 10%), and S = susceptible (>10%) (Smiley et al. 2011). Clearly, the resistance evaluation criteria in those tests were not identical. The lack of a common and standard screening method, including a common scale for resistance, makes global comparisons of pathotype results difficult (Toumi 2017).

R resources are very scarce in China. Zheng et al. (1999) tested 22 main wheat cultivars from eight provinces in the North China Plain; among them, only Yangzhou 5 and Zhengzhou 831 showed resistance while the others were S or MS to the *H. avenae* population from Taigu in Shanxi Province (Zheng et al. 1999). No R lines were found and most of the local wheat cultivars were HS to the *H. avenae* population in Shandong Province of China (J. Liu et al. 2012; Zhao et al. 2012). In all, 40 cultivars from five provinces were tested in a greenhouse experiment, and 3 cultivars—namely, Huamai 1, Wenliang 58, and Yumai 66-18—were R; whereas, in field trials, only Huamai 1 showed resistance to the *H. avenae* population from Peixian County in Jiangsu Province (B. Liu et al. 2012). Hou et al. (2018) obtained four spring wheat lines—MY00653, MY001302, MY001307, and MY001592—from 209 foreign spring wheat germplasm sources, which showed resistance to the *H. avenae* Ha91 population from Qinghai Province, China. According to a 3-year field and greenhouse experiment, Gao et al. (2012) found that two *T. durum* cultivars from Canada (Waskana and Waskowa) were HR to both *H. filipjevi* and *H. avenae* populations in Henan Province, China; nevertheless, the results also demonstrated that small numbers of *H. filipjevi* and *H. avenae* juveniles could easily penetrate Waskana and Waskowa roots. Yuan et al. (2011b) tested 75 wheat cultivars or lines from CIMMYT, and found that 1 spring and 2 winter wheat cultivars showed resistance and moderate resistance, respectively, to the *H. filipjevi* population from Xuchang in Henan Province. Similar resistance results were also obtained in previous studies (Li et al. 2013; Xing et al. 2014). Though most of the main wheat cultivars in China were S, we found that three cultivars or lines in the present study displayed good resistance to the *H. avenae* pathotype Ha91 and *H. filipjevi* population from Xuchang.

Few resistance genes against CCNs have been documented in hexaploid bread wheat (*T. aestivum*) (Cui et al. 2017a; Smiley

2014; Smiley et al. 2012). However, most of these resistance genes provide resistance to limited or specific pathotypes of CCNs (Nicol et al. 2009). Ogbonnaya et al. (2001) reported the inhibition of Ha 13 nematode reproduction in the order $Cre6 > Cre1 > Cre8 \geq Cre5$. Nicol et al. (2009) reported that both *CreR* and *Cre1* were effective sources of resistance against *H. avenae* populations in Henan Province, China but the *Cre1* genes were compatible with *H. filipjevi* and *H. avenae* pathotype Ha91 (Cui et al. 2015, 2017a; Yuan et al. 2011b). In the present study, Wo0608, Xinong509, Zhong 155, and Wanke 06290 from China were found to be R or MR to both *H. avenae* pathotype Ha91 and *H. filipjevi* (Table 2). The genes of these cultivars provide total or partial resistance to different CCN pathotypes; however, the genes conferring resistance to these cultivars remain unclear. We found that some of the cultivars with effective resistance to *H. filipjevi* populations from Turkey (Dababat et al. 2015) such as Ak702 were not R to the *H. filipjevi* population from China (Table 5). Zheng et al. (1999) revealed that wheat cultivars R to the Australian *H. avenae* population were S to the *H. avenae* population from Taigu in Shanxi Province, China. We inferred that the main reasons for the differences in resistance were related to pathotype differences, highly variable virulence (i.e., the capability to reproduce on R plants), and highly variable reproductive capacity (Dababat et al. 2014; Rivoal et al. 2001; Toktay et al. 2013).

In China, the practices recommended for managing CCNs are currently limited and generally not profitable for farmers, and the most acceptable method is seed coating (Cui et al. 2017b; Hao et al. 2014). Fosthiazate is effective against *Meloidogyne* spp. and *Pratylenchus* spp. (Pullen and Fortnum 1999). Recently, fosthiazate was used against *Heterodera glycines*, showing increased J2 mortality and decreased egg hatching and reproductive rates (Wu et al. 2019). Fosthiazate treatment resulted in significantly smaller populations of *G. pallida* and *G. rostochiensis* juveniles at 49 and 63 days after planting, respectively, and significantly higher yields than those obtained from the untreated controls (Tobin et al. 2008). Cui et al. (2017c) demonstrated that Imi strongly increased wheat production, with 48 and 54% reductions in soil cyst populations of *H. avenae* and *H. filipjevi*, respectively. Biological pesticides have been considered to replace chemical pesticides for the control of CCNs but the field stability and efficacies of biological pesticides need improvement (Zhang et al. 2017). Developing effective and simple chemical agents is the main strategy for CCN control. We found that Aba + Imi and MTT were very efficient against *H. avenae* and *H. filipjevi* cysts and, with these treatments, the wheat yield increased significantly.

CCNs can cause significant yield losses in semiarid and temperate regions, particularly under monoculture systems (Rivoal and Cook 1993). The success and usefulness of resistance to CCNs depend on the effectiveness and durability of the sources of resistance (Marshall and Smiley 2016; Toumi 2017). China is the world's largest producer of wheat, with a production value greater than 1.31×10^8 tons and an average yield of more than 54,166 hg/ha in 2018 (<http://www.fao.org/faostat/en/#data/QC>), and the main wheat-producing areas are almost all irrigated fields. The economic importance of *H. filipjevi* and *H. avenae* for winter wheat under rain-fed conditions is reflected by the 42 and 50% reductions, respectively, in wheat yields in heavily infested irrigated fields (Nicol et al. 2006; Smiley et al. 1994). CCNs are easily transferred to noninfested areas by many avenues, resulting in increased species and pathotype complexity. Although coating wheat seed with chemicals and planting combinations of S and R plants can effectively control nematode populations, damage is likely when nematodes are numerous (Cook and Starr 2006).

In conclusion, we provide the first classification of the pathotype of the *H. avenae* population from the main wheat-producing region—the North China Plain. Our results also confirm that the *H. filipjevi* population from China corresponds to a new pathotype. Thus, we systematically demonstrated the potential benefits of developing and deploying cultivars with resistance plus seed-coating chemicals to control CCNs in the North China Plain.

Acknowledgments

We thank the CIMMYT (Mexico) and F. Chen (Henan Agricultural University) for providing the materials; and R. W. Smiley (Oregon State University, United States), who did much work on providing scientific advice on the experiments and revising the manuscript.

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