

# Thiamethoxam, Clothianidin, and Imidacloprid Seed Treatments Effectively Control Thrips on Corn Under Field Conditions

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Subject Editor: Fangneng Huang

Received 24 July 2018; Editorial decision 20 November 2018

## Abstract

With the widespread adoption of no-tillage technology, outbreaks of thrips have caused serious damage to summer corn fields in China. Therefore, effective control of pest populations is often essential for cost-effective crop production. In this study, experiments were conducted in 2014 and 2015 to determine the control efficacy of seven neonicotinoid insecticide seed treatments against corn thrips and the effects of these treatments on natural enemy population densities and emergence rates, seedling characteristics, and yield of corn. The results showed that among the tested neonicotinoid seed treatments, thiamethoxam (1.0 and 2.0 g active ingredient (AI)/kg of seeds), clothianidin (1.0 and 2.0 g AI/kg of seeds), and imidacloprid (2.0 g AI/kg of seeds) showed the highest control efficacy against corn thrips throughout the corn growing season. Seed treatments with acetamiprid, nitenpyram, dinotefuran, and thiacloprid at rates of 1.0 and 2.0 g AI/kg of seeds were difficult to effectively control thrips on summer corn. Neonicotinoid seed treatments showed no adverse effects on the numbers of spiders and lady beetles. Furthermore, treatments did not negatively influence the seedling growth or development of corn but did prevent yield losses. Therefore, treating corn seeds with thiamethoxam, clothianidin, and imidacloprid can provide effective protection against early-season thrips and reduce yield losses under field conditions.

**Key words:** corn thrip, neonicotinoid seed treatment, natural enemy, seedling characteristics, yield

Corn (*Zea mays* L.), one of the most important cereal and commercial crops in China, is attacked by various diseases and insect pests during the growing season, including corn thrips which threaten the production of corn beginning in the seedling stage. In recent years, because of the widespread adoption of no-tillage technology, corn has been sown directly after the harvesting of wheat, while wheat stubble remains in the area. Therefore, thrips on wheat and weeds may migrate to summer corn after it emerges in China, causing serious damage and resulting in outbreaks. Although thrips exhibit varied food habits, most species are mainly phytophagous. *Frankliniella tenuicornis* (Uzel), *Anaphothrips obscurus* (Müller), and *Haplothrips aculeatus* (Fabricius) are the dominant species of thrips in areas of China where summer corn is grown (Institute of Plant Protection, Chinese Academy of Agricultural Sciences and China Society of Plant Protection 2015). Adult and immature thrips can feed on cell contents, causing damaged leaves to roll up and twist into a 'whip' and making new leaf growth difficult. In addition, feeding may affect the growth point of corn, resulting in retarded growth or even growth cessation and death. The harm characteristics of thrips are typical, and they can spread among different Poaceae host plants, such as

rice, wheat, and sorghum (Reitz et al. 2011). Furthermore, abundant evidence has demonstrated that thrips can carry and spread bacterial, fungal, and viral diseases among plants via their feeding (Jones 2005, Kucharczyk et al. 2011, Knight et al. 2015). Therefore, an effective control measure for thrips is crucial to protect the normal growth and development of corn.

At present, biological control and chemical control are mainly used to achieve thrips suppression in agricultural systems. Habitat management by interplanting flowering plants (such as buckwheat, cowpea, and sunn hemp) within corn fields may be an effective method of thrips suppression because flowers can offer resources (nectar, pollen, prey, and shelter) that attract natural predatory and parasitic enemies (Manandhar and Wrih 2015, 2016). However, predator populations are generally not sufficient in seedling corn to control thrips; thus, conservation-based agricultural and biological control measures are less effective with an increase in pest density. Traditionally, manual foliar sprays with organophosphates, pyrethroids, and neonicotinoid insecticides have been used as chemical controls for thrips in corn fields (Bereš et al. 2016, Nazemi et al. 2016). However, thrips are too small to be easily identified and are

usually not directly exposed to foliar sprays, as they are mostly concentrated on internal leaves. At present, neonicotinoid seed treatments are widely used in integrated pest management systems because they are easy to handle, relatively safe, and cause less pollution. Neonicotinoid seed treatments have shown long-lasting residual activity against aphids (Zhang et al. 2016a,b), and have been shown to be effective against thrips as a seed treatment application in other crops, such as cotton, soybeans, and groundnuts (Reisig et al. 2012, Zidan 2012, Nataraja et al. 2016). Although, imidacloprid and thiamethoxam mixed with other types of insecticides have been used as corn seed treatments to control thrips and other pests in China, little information is available on the control efficacy of these registered insecticides against thrips or their effects on the natural enemies of thrips, and their impacts on corn growth and development. In addition, the differences between registered insecticides and other neonicotinoid insecticides used as seed treatments in terms of their control efficacy against thrips and safety for corn and natural enemies still require systematic study.

The present investigation was undertaken to compare the efficacy of seven neonicotinoid insecticides used as seed treatments in the management of thrips and their impacts on natural enemy populations in corn fields. Additionally, the emergence rates, seedling characteristics, and yield of corn were evaluated. The data acquired from this research can be used to determine which neonicotinoids exhibit the highest efficiency as seed treatments against thrips in corn fields in China.

## Materials and Methods

### Insecticides and Plant Material

Seven neonicotinoid insecticides were used in the experiments: thiamethoxam (Cruiser 30% FS, Syngenta Crop Protection (Suzhou) Co., Ltd., Suzhou, China), imidacloprid (Gaucho 600 g/liter FS, Bayer CropScience (China) Co., Ltd., Hangzhou, China), clothianidin (Poncho 600 g/liter FS, Bayer CropScience (China) Co., Ltd., Hangzhou, China), nitenpyram (50% SG, Jiangshan Agrochemical & Chemical Co., Ltd., Nantong, China), dinotefuran (20% SG, Mitsui Chemicals, Inc., Guangdong, China), thiacloprid (48% SC, Noposion Agrochemicals Co., Ltd., Shenzhen, China), and acetamiprid (20% SG, Shandong United Pesticide Industry Co., Ltd., Tai'an, China). These insecticide formulations were diluted to two concentrations (1.0 and 2.0 g of active ingredient (AI)/kg of seeds) with water before the seed treatment. Corn seeds (Zhengdan-958) were purchased from Shandong Wuyue Taishan Seeds Co., Ltd. (Tai'an, China).

### Field Experiments

Experiments were conducted in 2014 and 2015 at the experimental base of Shandong Agricultural University in the city of Tai'an (site: 36.1°N, 117.9°E). The soil type was Shajiang black soil, which was composed of 56% sand, 40% silt, and 4% clay, with 1.45% organic matter. The plots were all located in fields with at least a 10-yr history of corn cultivation in rotation with wheat.

Summer corn was sown at this site on 22 May in 2014 and 2015 after the winter wheat had been harvested. Corn seeds were sown 4.0 cm deep in 0.30 m rows at a density of 25.0 kg seeds per ha, with plots measuring 1.2 m by 20.0 m, separated by 1.5 m of bare cultivated ground. All experiments were arranged in a randomized complete block design with 15 treatments (four replicates each). The treatments consisted of one untreated control and seven neonicotinoid treatments (thiamethoxam, clothianidin, imidacloprid, acetamiprid, nitenpyram, thiacloprid, and dinotefuran) applied at a rate of

1.0 or 2.0 g AI/kg of seeds. Before sowing, corn seeds were treated with diluted insecticides at a rate of 1:50 ( $m_{\text{insecticide}}:m_{\text{seed}}$ ) and then air dried. All plots were sown using a ration sowing machine, and the interval between seeds was 0.2 m. One hundred seeds were manually sown between the same plots to investigate the emergence date and rate under all the treatments. Glyphosate (Zhejiang Xin'an Chemical Group Co., Ltd., Zhejiang, China) was applied after sowing at a rate of 600 g of AI/ha. No additional pesticides were applied throughout the growing season of corn.

The emergence date was recorded as the date on which more than 50% seed emergence was observed. When the treated plants in all plots were no longer emerging, the emergence rate was assessed. Twenty randomly selected plants were sampled from each plot at 29 days after sowing (DAS) to determine the plant height, root length, and fresh weight of seedlings both aboveground and underground. The average values of all the seedling characteristic indexes were recorded.

Thrips counts on the corn were determined at 22, 29, and 36 DAS by randomly selecting 100 corn plants across each plot (five locations per plot, 20 plants per location). Adult and immature thrips collected from each plot were counted without classification. The control efficacy of each insecticide treatment against thrips was calculated using equation 1.

$$\text{Control efficacy for killing insect (\%)} = (NS_0 - NS_1) / NS_0 \times 100 \quad (1)$$

$NS_1$  and  $NS_0$  represent the number of surviving thrips in the treatment groups and the untreated group, respectively.

Natural enemy species including adult and larval lady beetles and spiders were monitored in each treatment when corn thrips were sampled at 36 DAS at the same time that thrips were sampled. The natural enemies in each plot were surveyed on 100 randomly selected corn plants and calculated as the total number.

Corn was harvested on 20 September in 2014 and 22 September in 2015. Two hundred corn plants were randomly selected in each plot, and the kernels of each plant were collected, dried outdoors, and weighed to assess the corn yield per plot. Data were subsequently converted to corn yield per ha.

### Statistical Analysis

All statistical analyses were carried out using the SPSS statistical software (version 18.0, SPSS Inc., Chicago, IL). Statistically significant mean values were compared using one-way ANOVA tests followed by Tukey's HSD method ( $P < 0.05$ ). Arcsine square-root-transformed percentages were compared using separate ANOVAs with treatment as the main factor. Significant differences in the number of thrips, the number of natural enemies, and the emergence rates and yields of corn in the various neonicotinoid-treated field plots versus untreated control plots were determined using a multivariate ANOVA (MANOVA).

## Results

### Effect of Neonicotinoid Seed Treatments on Control Efficacy Against Thrips

Thrips infested corn plants at the corn seedling stage in 2014 and 2015, and the highest population densities occurred in the untreated control plots. In 2015, the number of thrips on corn plants in the untreated plots reached an average of 3,504.00 per 100 plants on 20 June (29 DAS). This value was much higher than that observed

in 2014 (3,125.00 per 100 plants). In 2014, the thrips population increased remarkably between the untreated and insecticide-treated groups at 29 DAS and decreased at 36 DAS (Fig. 1). Similar population dynamics of thrips between the untreated and insecticide-treated plots were also observed in 2015 (Fig. 1).

In plots treated with neonicotinoid insecticides, the control efficacy of the insecticides against thrips increased as insecticide concentrations increased. However, the acetamiprid seed treatment exhibited an inverse effect, in that the application rate of 2.0 g AI/kg of seeds showed reduced efficacy against thrips. In 2014, the thiamethoxam (1.0 and 2.0 g AI/kg of seeds), clothianidin (1.0 and 2.0 g AI/kg of seeds), and imidacloprid (2.0 g AI/kg of seeds) seed treatments exhibited excellent efficacy against thrips, achieving significantly greater control than was observed in the untreated and other insecticide-treated groups (Table 1). The results in 2015 were similar to those from 2014.

The year, neonicotinoid seed treatment, and sampling date had significant effects on the numbers of thrips (year:  $F_{1,359} = 114.06$ ,  $P < 0.0001$ ; neonicotinoid seed treatment:  $F_{14,359} = 295.06$ ,  $P < 0.0001$ ; sampling date:  $F_{2,359} = 347.99$ ,  $P < 0.0001$ ), and an interaction was observed between the neonicotinoid seed treatment and the sampling date ( $F_{28,359} = 13.98$ ,  $P < 0.0001$ ). No differences in thrips abundance were observed in relation to the interactions between year and neonicotinoid seed treatment ( $F_{14,359} = 0.52$ ,  $P = 0.9857$ ), year and sampling date ( $F_{2,359} = 0.05$ ,  $P = 0.9551$ ), year, neonicotinoid seed treatment, and sampling date ( $F_{28,359} = 0.56$ ,  $P = 0.9677$ ) (Supp Table S1 [online only]).

### Effect of Neonicotinoid Seed Treatments on Spider and Lady Beetle Population Densities

The population densities of natural enemies in corn plots treated with neonicotinoids in 2014–2015 are shown in Fig. 2. The spider species *Hylyphantes graminicola* (Sundevall, 1829) and *Pardosa T-insignita* (Boes. et Str.) and the lady beetle species *Harmonia axyridis* (Pallas), *Propylaea japonica* (Thunberg, 1781), and *Coccinella septempunctata* L. were found on corn plants when counts were performed. The species abundance of lady beetles was much higher than that of spiders in 2014 and 2015. However, no significant differences in the number of spiders (2014:  $F_{14,59} = 0.81$ ,  $P = 0.6515$ ; 2015:  $F_{14,59} = 0.87$ ,  $P = 0.5934$ ) or lady beetles (2014:  $F_{14,59} = 1.59$ ,  $P = 0.1188$ ; 2015:  $F_{14,59} = 0.45$ ,  $P = 0.9465$ ) were observed among the neonicotinoid seed treatment groups and the untreated control (Fig. 2). Similarly, no significant interactions were found between year and neonicotinoid seed treatments (Supp Table S2 [online only]).

### Effect of Neonicotinoid Seed Treatments on Corn Plant Growth

With the exception of plots treated with acetamiprid applied at a rate of 2.0 g AI/kg of seeds, the emergence date of all neonicotinoid treatments was approximately at 5 DAS, and the corresponding emergence rates were all above 90% (2014:  $F_{14,59} = 3.64$ ,  $P = 0.0005$ ; 2015:  $F_{14,59} = 4.92$ ,  $P < 0.0001$ ) (Fig. 4). When treatments from the 2 yr were examined together, a significant difference was observed between treatments for the emergence rate (year:  $F_{1,119} = 35.51$ ,

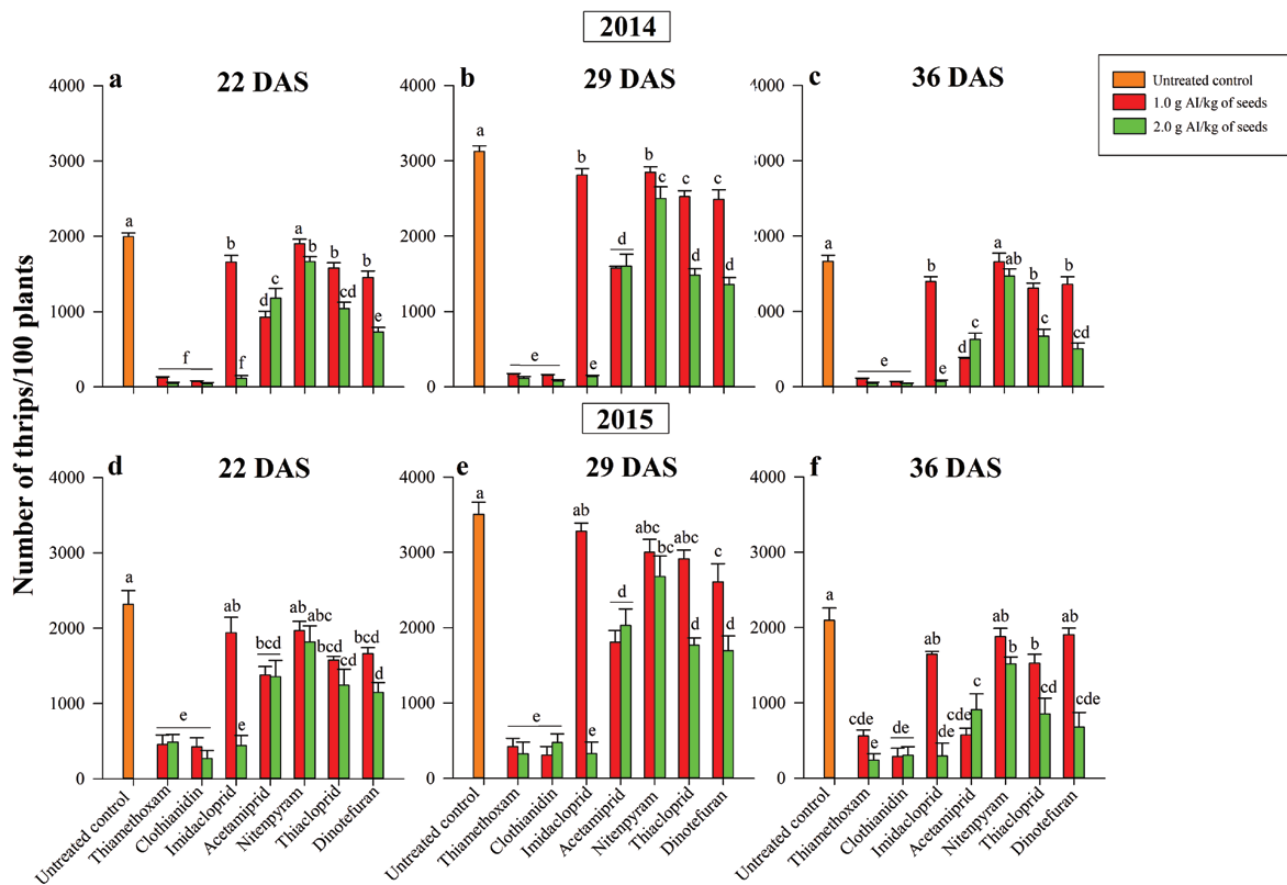


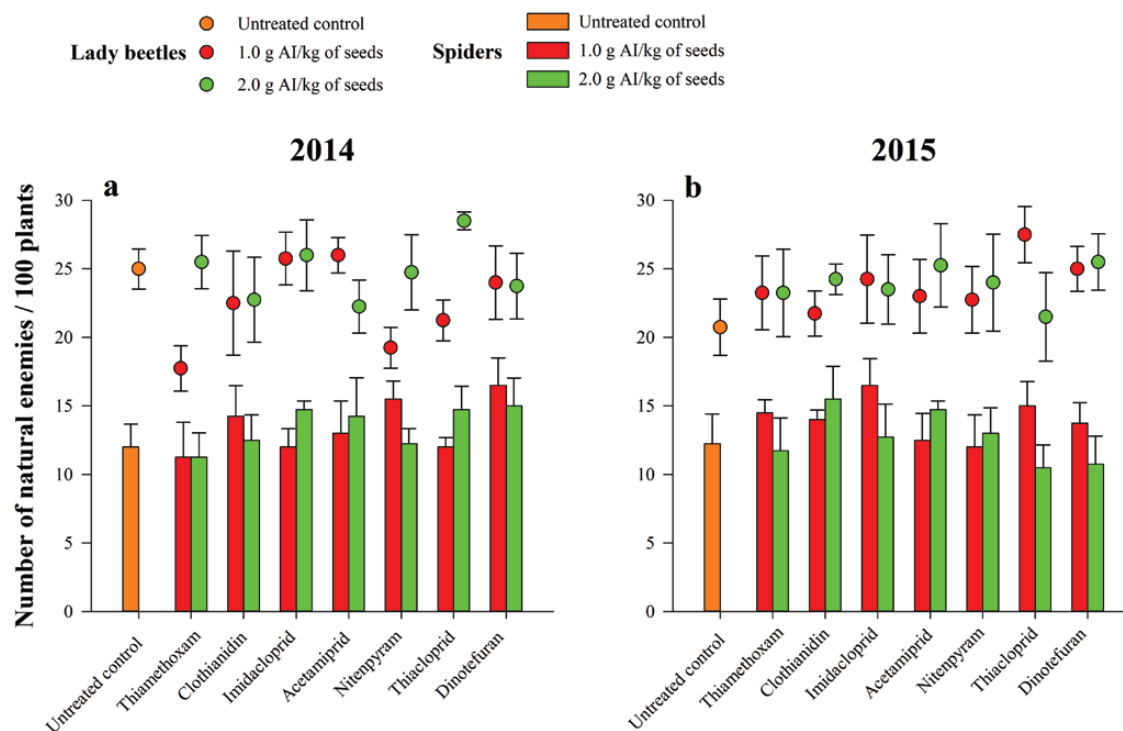
Fig. 1. Mean ± SE numbers of corn thrips per 100 plants in the corn field treated with neonicotinoid insecticides in 2014 (a: 22 DAS, b: 29 DAS, c: 36 DAS) and 2015 (d: 22 DAS, e: 29 DAS, f: 36 DAS). Different letters indicate significant differences among treatments (Tukey's HSD test,  $P < 0.05$ ). DAS, days after sowing.

**Table 1.** Control efficacy of seed treatment with seven neonicotinoid insecticides against thrips in 2014 and 2015<sup>a</sup>

Insecticides	Dosage <sup>b</sup>	% Control efficacy (2014)			% Control efficacy (2015)		
		22 DAS	29 DAS	36 DAS	22 DAS	29 DAS	36 DAS
Thiamethoxam	1	93.87 ± 0.82a	94.75 ± 0.38a	93.71 ± 0.73a	79.68 ± 6.37ab	87.87 ± 3.07a	73.71 ± 1.91a
	2	97.67 ± 0.67a	96.22 ± 0.78a	97.48 ± 1.04a	77.49 ± 6.57ab	90.29 ± 4.73a	88.61 ± 3.70a
Clothianidin	1	96.30 ± 0.46a	95.03 ± 0.29a	96.08 ± 0.68a	80.32 ± 6.32ab	91.30 ± 2.99a	85.14 ± 6.14a
	2	97.89 ± 0.90a	97.43 ± 0.62a	97.54 ± 0.54a	87.01 ± 6.03a	86.43 ± 3.12a	85.77 ± 4.67a
Imidacloprid	1	16.54 ± 5.87ef	7.37 ± 3.70c	16.10 ± 2.03cd	14.65 ± 10.57c	5.73 ± 5.66e	20.15 ± 6.06cd
	2	94.26 ± 1.86a	95.51 ± 0.52a	95.93 ± 1.01a	80.13 ± 6.52ab	91.12 ± 4.06a	86.69 ± 7.31a
Acetamiprid	1	53.73 ± 3.24bc	48.16 ± 0.71b	77.47 ± 0.37ab	39.35 ± 6.77bc	47.59 ± 6.65bc	73.13 ± 2.34a
	2	40.86 ± 6.36cd	47.40 ± 4.92b	61.60 ± 6.03b	38.45 ± 14.98bc	41.42 ± 7.29bcd	54.50 ± 11.22abc
Nitenpyram	1	4.62 ± 2.96f	6.16 ± 2.74c	0.66 ± 3.58d	12.75 ± 10.68c	13.59 ± 7.18e	8.33 ± 9.55d
	2	16.55 ± 2.29ef	17.59 ± 5.22c	10.52 ± 9.82cd	20.12 ± 11.14c	24.17 ± 4.54cde	26.18 ± 7.43bcd
Thiacloprid	1	20.62 ± 5.26ef	16.77 ± 3.31c	21.52 ± 1.72c	30.29 ± 7.14c	16.60 ± 3.25de	26.86 ± 4.45bcd
	2	48.04 ± 3.37bc	51.11 ± 3.27b	59.53 ± 5.68b	46.12 ± 8.74abc	49.16 ± 3.85bc	58.25 ± 11.44ab
Dinotefuran	1	27.31 ± 2.98de	18.22 ± 3.11c	18.56 ± 3.60cd	26.36 ± 9.32c	25.54 ± 5.93cde	8.35 ± 3.22d
	2	63.29 ± 3.44b	55.37 ± 2.91b	69.11 ± 5.95b	50.86 ± 2.16abc	51.77 ± 4.78b	65.46 ± 11.26a

<sup>a</sup>Values shown are the means and standard errors (±SEs) of four replicates. Different lowercase letters refer to significant differences (Tukey's HSD test,  $P < 0.05$ ).

<sup>b</sup>The unit is g AI/kg of seeds.



**Fig. 2.** Mean ± SE numbers of spiders and lady beetles per 100 plants in corn field treated with neonicotinoid insecticides in 2014 (a) and 2015 (b). Different letters indicate significant difference among treatments (Tukey's HSD test,  $P < 0.05$ ).

$P < 0.0001$ ; neonicotinoid seed treatment:  $F_{14,119} = 5.76$ ,  $P < 0.0001$ ). However, the interaction between year and neonicotinoid seed treatments was not associated with any difference in emergence rates ( $F_{14,119} = 0.46$ ,  $P = 0.9481$ ) (Supp Table S2 [online only]).

Neonicotinoid seed treatments did not negatively impact seedling growth or development (Fig. 3 and Supp Fig. S1 [online only]). The plant height, root length, and fresh weight of the seedlings (both aboveground and underground) in plots treated with neonicotinoids were much greater than those of the untreated control (except for the nitenpyram applied at 1.0 g AI/kg of seeds). Furthermore, thiamethoxam and clothianidin applied at 1.0 and 2.0 g AI/kg of seeds and imidacloprid applied at 2.0 g AI/kg of seeds accelerated the

growth indexes of corn compared to other treatments in both 2014 (Fig. 3) and 2015 (Supp Fig. S1 [online only]).

#### Effect of Neonicotinoid Seed Treatments on Corn Yield

Thiamethoxam and clothianidin seed treatments applied at a rate of 1.0 and 2.0 g AI/kg of seeds and imidacloprid applied at a rate of 2.0 g AI/kg of seeds were associated with the highest corn yields among all treatments, which were approximately 10 t/ha in both years (Fig. 4). In contrast, the yield of the plots treated with imidacloprid (1.0 g AI/kg of seeds), nitenpyram (1.0 and 2.0 g AI/kg of seeds), acetamiprid (2.0 g AI/kg of seeds), and thiacloprid (1.0 g AI/kg of seeds) were significantly lower than the other treatments.

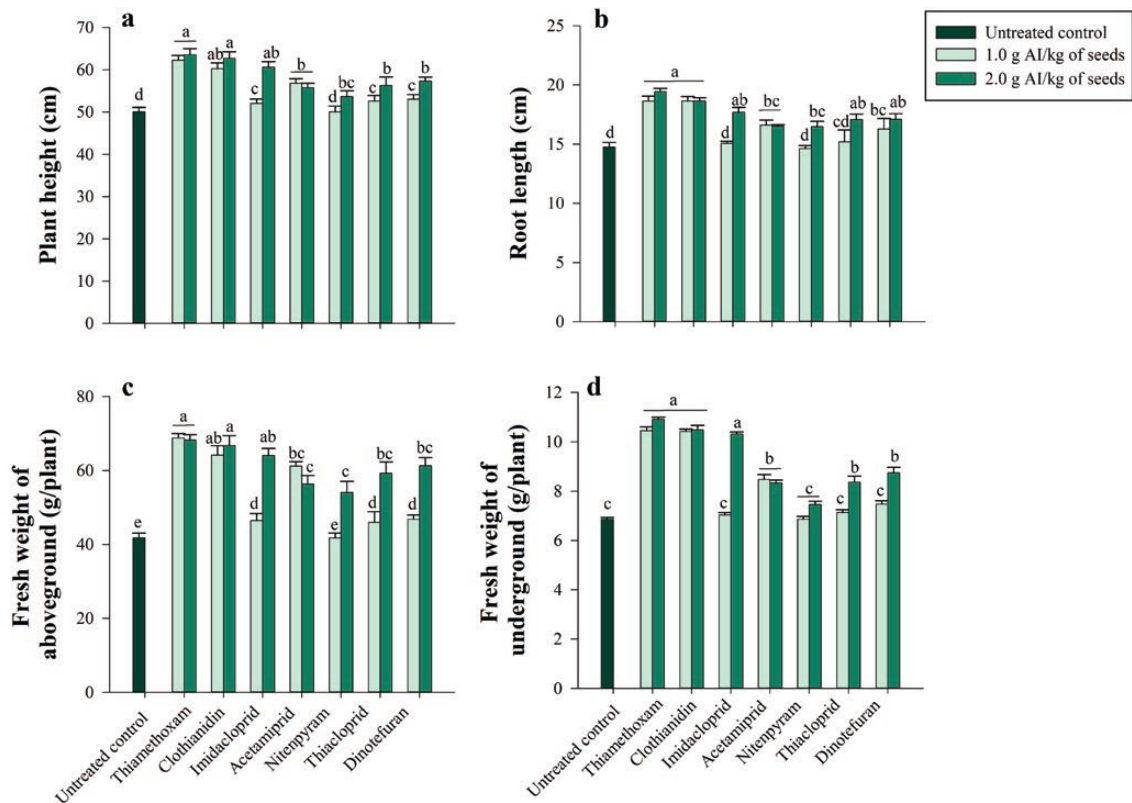


Fig. 3. Mean ± SE the plant height (a); root length (b); fresh weight of aboveground (c); and fresh weight of underground (d) of corn seedlings in corn field treated with neonicotinoid insecticides in 2014. Different letters indicate significant difference among treatments (Tukey's HSD test,  $P < 0.05$ ).

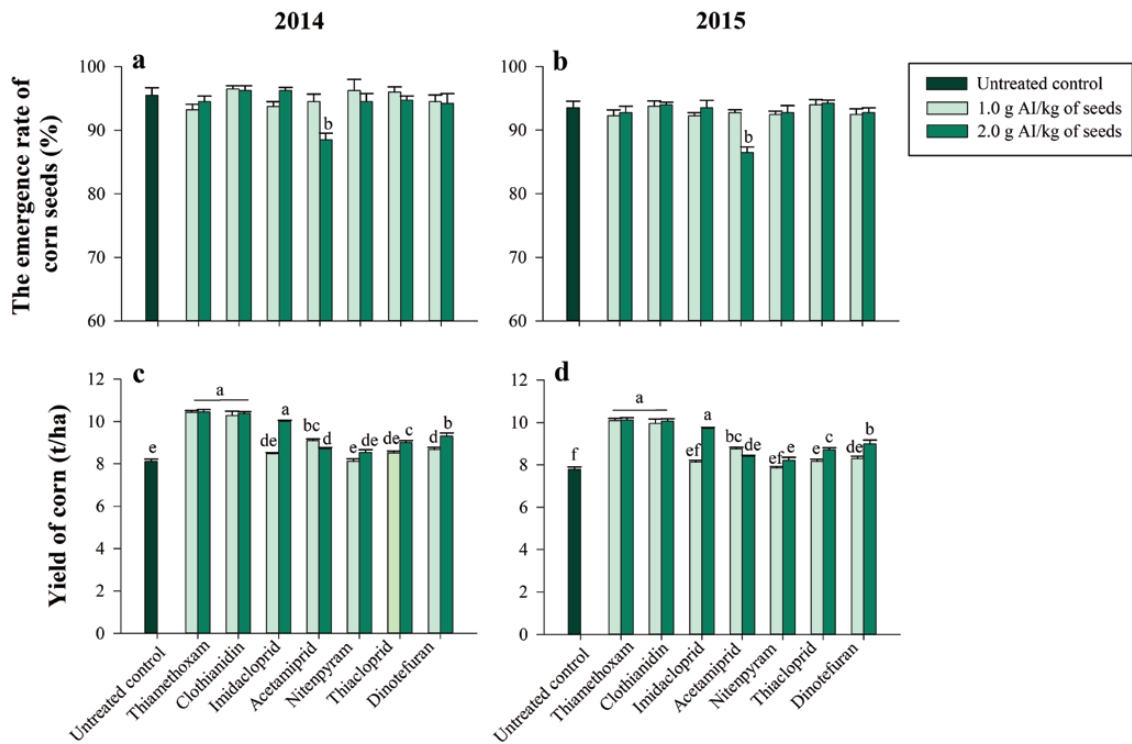


Fig. 4. Mean ± SE the emergence rate and yield of each plot in corn field treated with neonicotinoid insecticides in 2014 (a, c) and 2015 (b, d). Different letters indicate significant difference among treatments (Tukey's HSD test,  $P < 0.05$ ).

kg of seeds) was approximately 8 t/ha, which was similar to the yield in the untreated control plots either year. When treatments for both years were examined together, a significant difference was observed

among treatments for corn yields (year:  $F_{1,119} = 62.27, P < 0.0001$ ; neonicotinoid seed treatment:  $F_{14,119} = 120.56, P < 0.0001$ ); however, the interaction between year and neonicotinoid seed treatment

showed no difference in corn yield ( $F_{14,119} = 0.03$ ,  $P = 0.9999$ ) (Supp Table S2 [online only]).

## Discussion

Corn thrips are major pests of corn sown in the summer in China, and the identification of effective control measures against thrips will help reduce economic losses. This study, which was conducted in 2014 and 2015, demonstrated that treating corn seeds with thiamethoxam (1.0 and 2.0 g AI/kg of seeds), clothianidin (1.0 and 2.0 g AI/kg of seeds), and imidacloprid (2.0 g AI/kg of seeds) reduced thrips infestations and prevented yield losses throughout the corn growing season. None of the neonicotinoid seed treatments showed adverse effects on the population densities of spiders and lady beetles. Furthermore, the neonicotinoid insecticide seed treatments had no negative influence on the emergence rate and seedling characteristics of the corn.

In late May, corn thrips move from their early-season host plants to corn fields. Thus, intense corn thrips outbreaks occur at the beginning of the crop cycle and continue until mid- to late June. During this time, the climate in North China presents suitable temperatures for the development of thrips. Meteorological data obtained from the Shandong Meteorological Bureau suggested that the rainfall at the test site in June of 2014 and 2015 was less than 70 mm, which is consistent with findings reported by Kucharczyk et al. (2011), who demonstrated that higher temperatures and lower rainfalls promote the occurrence of corn thrips. Additionally, thrips breed rapidly at high temperatures and continually migrate to newly emerged corn leaves. However, it is difficult to transfer pesticides from old leaves to tender leaves via the foliar spray application method (Buchholz and Nauen 2002). Therefore, frequent insecticide applications are needed to protect new leaves, resulting in an increase in control costs. Compared with foliar sprays, seed treatments provide a good solution to this problem because the strong upward conduction of neonicotinoids allows insecticides on seeds to be continuously absorbed and transferred to new leaves (Elbert et al. 2008, Alford and Krupke 2017). Thus, a single application of insecticide to seeds can prevent thrips throughout the seedling stage.

Our results indicated that the control efficacy differed among plots treated with different neonicotinoids. More satisfactory levels of thrips control and yield protection were achieved using thiamethoxam and clothianidin than imidacloprid at the same dose (1.0 g AI/kg of seeds). However, compared with other tested neonicotinoids and untreated control, imidacloprid (2.0 g AI/kg of seeds) had a better control effect. The differences in efficacy were probably related to the toxicity of the different neonicotinoid insecticides to thrips. Byrne et al. (2007) reported that thiamethoxam, clothianidin, and imidacloprid provide good control of avocado thrips in bioassays, whereas Shan et al. (2012) found that the toxicities of thiamethoxam and acetamiprid to larvae and adult females of western flower thrips (*Frankliniella occidentalis* Pergande) were higher than those of other tested neonicotinoids (nitenpyram, imidacloprid, and thiacloprid). Another reason for these results may be that neonicotinoid insecticides demonstrate different water solubilities, degradation rates, and insecticide–soil interactions (Wu et al. 2012, Huseth and Groves 2014, Schaafsma et al. 2015, He et al. 2016, Schaafsma et al. 2016). Thiamethoxam exhibits good systematicity in plants (via the roots) and breaks down into clothianidin, which may contribute to its continued or extended activity in plants and insects (Nauen et al. 2003). This continuous activity may explain the better efficacy of thiamethoxam and clothianidin against thrips and other pests in corn fields.

Corn is attacked by various sucking insect pests and chewing species during the growing season. When used as seed treatments, imidacloprid, thiamethoxam, and clothianidin also exhibit high insecticidal activities in the control of early-season pests, such as viruliferous insects, i.e., aphids, and small brown planthoppers; foliage-feeding insects, i.e., corn borers, chinch bugs, and flea beetles; and underground pests, i.e., wireworms, white grubs, and black cutworms. In addition, these insecticides do not cause production losses in corn (Pons and Albajes 2002, Kuhar et al. 2002, Wilde et al. 2004, Wilde et al. 2007). Neonicotinoid insecticide seed treatments represent a useful tool in integrated pest management systems because seed-applied insecticides can control multiple pests simultaneously. Therefore, this method is widely promoted by most farmers in China. The effectiveness of neonicotinoid insecticide seed treatments on other corn pests under field conditions needs to be studied further.

Neonicotinoid seed treatments showed no adverse effects on the population densities of spiders and lady beetles, consistent with the observations of Seagraves and Lundgren (2012), who found no differences in the abundance of spiders or larval and adult coccinellids on soybeans when seeds were treated with imidacloprid and thiamethoxam compared to untreated soybeans in the field. Compared with foliar applications of insecticides, seed treatment can prevent direct contact between insecticides and natural enemies. In addition, lady beetles and spiders are well-known beneficial natural enemies that are used in biological control programs worldwide; their high feeding capacity made it possible for them to change their diet and consume prey containing fewer insecticides (Obrycki and Kring 1998, Chatterjee et al. 2009). Other studies have suggested that neonicotinoid seed treatments could reduce the abundance of natural enemies in crops (Moser and Obrycki 2009, Cloyd and Bethke 2011, Zhang et al. 2016a,b). These different results may be due to variations in insecticide application rates, survey times, and predator species between these studies. Further research is needed to explore the effects of neonicotinoids on other natural enemies and herbivores in corn fields, as well as the environmental risks they pose to honey bees and wild bees, which should be fully monitored in the future (Tapparo et al. 2012, Tsvetkov et al. 2017, Woodcock et al. 2017).

Neonicotinoid insecticides applied in field trials had no negative effect on seedling growth and development of corn. Previous studies have also shown that neonicotinoid seed treatments cause no differences in crop seedling growth indicators including seed germination, and the primary root length, weight, and height of corn seedlings (Wilde et al. 2007). Furthermore, some reports have suggested that neonicotinoid seed treatments can stimulate the germination and seedling growth of crop plants (Horii et al. 2007, Duan et al. 2012, Zhang et al. 2015). Stimulatory effects of neonicotinoids on seedling growth were found under treatment with thiamethoxam (1.0 and 2.0 g AI/kg of seeds), clothianidin (1.0 and 2.0 g AI/kg of seeds), and imidacloprid (2.0 g AI/kg of seeds) in our study (Fig. 4). These effects may be explained by a study finding that neonicotinoid insecticides increase molecular seed components and their activities, including the activities of G6PDH (glucose-6-phosphate dehydrogenase) and GPX (guaiacol peroxidase), phenolic contents, and antioxidant activity. The activities of these components seem to mirror increased corn plant growth (height and weight) and strengthen the ability of plants to protect themselves against exogenous disturbances (Duan et al. 2012, Tang et al. 2017). A strong corn seedling is essential for resisting thrips infestations, and a powerful self-compensation ability can enable corn to recover quickly after thrips infestation. The present study suggested that only the acetamiprid seed treatment at a rate of 2.0 g AI/kg of seeds delayed the emergence date and decreased the emergence rate of corn. In another study, when applied

as a seed treatment, acetamiprid (4.9 g AI/kg of seeds) significantly reduced the number of nodules and nodule dry weight and inhibited the shoot and root dry weights of faba bean plants (Abdu-Allah et al. 2017). The inhibitory effects of acetamiprid on seedling growth probably contributed to the suppression of growth-promoting microorganisms in the rhizosphere, which may adversely affect seed sprouting, resulting in a longer seed germination period, delaying the emergence date and reducing the emergence rate (Huang et al. 2015, Abdu-Allah et al. 2017).

Currently, fludioxonil, tebuconazole, and other fungicides are widely used in China as seed treatments for controlling corn diseases such as stalk rot (*Pythium* sp., *Fusarium graminearum*) and head smut (*Sporisorium reilianum*) (Xu et al. 2006). Therefore, using neonicotinoid insecticides in combination with fungicides as seed treatments should be a suitable control measure for pest management in corn seeding. However, the application of neonicotinoids as seed treatments should be carefully considered because some studies have indicated that pests can quickly develop resistance to neonicotinoid insecticides. Thus, careful selection and rotation of alternating insecticides should be undertaken (Tang et al. 2006, Bass et al. 2015).

## Supplementary Data

Supplementary data are available at *Journal of Insect Science* online.

## Acknowledgments

This research was supported by the National Key Research Development Program of China (2017YFD0201600).

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