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Comparative soil distribution and dissipation of phoxim and thiamethoxam and their efficacy in controlling *Bradysia odoriphaga* Yang and Zhang in Chinese chive ecosystems

Peng Zhang [a, b], Min He [c], Yan Wei [a], Yunhe Zhao [a], Wei Mu [a], Feng Liu [a, *]

[a] College of Plant Protection, Shandong Provincial Key Laboratory for Biology of Vegetable Diseases and Insect Pests, Key Laboratory of Pesticide Toxicology & Application Technique, Shandong Agricultural University, Tai'an, Shandong 271018, PR China

[b] College of Environmental Science and Engineering, Nankai University, Tianjin 300071, PR China

[c] Institute of Plant Protection and Environment Protection, Beijing Academy of Agricultural and Forestry Science, Beijing 100097, PR China

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ABSTRACT

Bradysia odoriphaga Yang and Zhang (the chive gnat) is the major insect pest affecting Chinese chives (*Allium tuberosum* Rottl. ex Spreng.) in Northern China. Only three insecticide products are registered for its control. In the present study, we compared the persistence and distribution of thiamethoxam and phoxim in soil and determined their long-acting control effects against *B. odoriphaga* and two other secondary pests, *Thrips alliorum* Priesner and the Asiatic onion leaf miner *Acrolepia alliella* Semenov and Kuznetsov (Lepidoptera: Acrolepiidae), after a single soil application using the directional spray-washing method during the early Chinese chive root-rearing period. Under the same applied dosage, the rhizosphere soil at a depth of 4.0–10.0 cm had concentrations of thiamethoxam and phoxim ranging from 2.21 to 7.44 mg/kg and 0.09–0.44 mg/kg, respectively, at the 7th day after application. The half-lives of thiamethoxam and phoxim in the soil were 27.5 and 6.7 days, respectively. Thiamethoxam persisted for 210 days, whereas phoxim only persisted for 45 days in the soil and plants. In addition, thiamethoxam applied at 6.0 kg a.i./ha maintained a low population density of *B. odoriphaga, T. alliorum* and *A. alliella* for nine months longer than phoxim. In conclusion, thiamethoxam may help farmers more effectively manage *B. odoriphaga* and other secondary pests on Chinese chive and reduce the costs of insecticide use while sustaining protection.

1. Introduction

The chive gnat *Bradysia odoriphaga* Yang and Zhang (Diptera: Sciaridae) is a major insect pest of Chinese chives (*Allium tuberosum* Rottl. ex Spreng.) in Northern China (Li et al., 2007), with the larvae feeding on the plants of seven families and more than thirty species, including Chinese chives, garlic (*Allium sativum* L.), onion (*Allium cepa* L.), and cucumber (*Cucumis sativus* L.) (Yang and Zhang, 1985; Feng and Zheng, 1987; Zhang et al., 2015a). The larvae often live in the roots and stems of Chinese chives under the ground (at depths of approximately 5–10 cm), which increases the difficulty of controlling the pest via extensive chemical irrigation (Zhang et al., 2015c). In China, outbreaks of the chive gnat (*B. odoriphaga*) have occurred frequently in recent years (Li et al., 2015a). This insect attacks 20–30% of Chinese chives and causes 30–80% losses of production, with replanting required in severe cases (Feng and Zheng, 1987). *B. odoriphaga* has 4 to 6 overlapping generations each year in the chive fields of northern China, with peak damage occurring in the spring and autumn (Mei et al., 2004). Perennial Chinese chive plants usually store nutrients in the bulbs for approximately one year after sowing, and the harvest of leaves and re-growth is repeated for a period of 4–5 years in the open or in low plastic tunnels (Misawa and Takeuchi, 2015). However, the development of a counter season for these vegetables in China has led to an increasing number of farmers to produce Chinese chives in winter using low plastic tunnels to improve their economic returns (Wang et al., 2014). This type of successive planting pattern increased the damage caused by *B. odoriphaga* and two other secondary pests, *Thrips alliorum* and the Asiatic onion leafminer *Acrolepia alliella* (Lepidoptera: Acrolepiidae) (Chen et al., 2012).

* Corresponding author. College of Plant Protection, Shandong Agricultural University, 61 Daizong Street, Tai'an, Shandong 271018, PR China.
E-mail address: fliu@sdau.edu.cn (F. Liu).

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The application of synthetic insecticides, such as organophosphates, carbamates and neonicotinoids, is one of the most widespread management practices for controlling *B. odoriphaga* in China (Ma et al., 2013). Chemical control remains a major strategy in integrated pest management (IPM) systems because it is a rapid, efficient, easy to use, cost-effective, and reliable method of controlling targeted insects (Zhao, 2000; Endo and Tsurumachi, 2001). Laboratory toxicity and field efficacy studies of synthetic insecticides, such as phoxim, diazinon, chlorpyrifos, malathion and imidacloprid, have been reported (Mu et al., 2005, 2004, 2002; Li and Yang, 2012; Wang et al., 2011b). However, only three active ingredients of insecticides, which are used singly or in mixtures, are registered for use on *B. odoriphaga* in China. These active ingredients include phoxim, imidacloprid, imidacloprid + phoxim and malathion + phoxim, respectively (China Pesticide Information Network, 2015). Phoxim (CAS: 14816-18-3) has been the most common organophosphorous insecticide used on chives in China to control *B. odoriphaga* since the 1980s (Feng and Zheng, 1987). Chemigation is a method of transferring insecticides to underground biological targets on roots via water as a carrier. Research into the use of insecticides to control this pest is focused on maximizing the toxic effect by ensuring efficient contact between the pest and the insecticide (Tu, 1986), which is particularly important for soil applications to control *B. odoriphaga*. However, phoxim has low water solubility (1.5 mg/L, 20 °C) and high soil adsorption (log K_{OC} = 1753–2292); thus, it presents low mobility in soil, which results in most of the insecticide being adsorbed by the surface soil and little to no available insecticide entering deep into the soil to contact the underground pests (Jiang et al., 2004). Rotich et al. (2004) also found that degradation of phoxim followed first-order kinetics, and its half-life was only 2.02–2.26 days at 25 °C, which indicated its relatively low persistence in humid soil after chemigation. In China, farmers frequently apply excessive amounts of phoxim (15–18 kg a.i./ha in some places) to control *B. odoriphaga* (Jiang et al., 2004), although such applications have provided unsatisfactory control during the Chinese chive root-rearing period, which extends over eight months. Therefore, alternative insecticides to phoxim that have a long-lasting effect are required during the Chinese chive root-rearing period. In addition, imidacloprid is registered for use on *B. odoriphaga* in China, although our previous study found that this chemical had a high toxicity to *Eisenia foetida* Savigny (Opisthopora: Lumbricidae); imidacloprid: medium toxicity level; thiamethoxam: low toxicity level) and a low selective toxicity to *E. foetida* and *B. odoriphaga* relative to thiamethoxam in soil (Zhang et al., 2014a).

Organophosphorus and neonicotinoid insecticides are broad-spectrum insecticides that are frequently applied to soil and foliage and used as a seed dressing to control unwanted insects and underground pests worldwide (Ni et al., 2007; Elbert et al., 2008; Jin et al., 2010). However, neonicotinoid insecticides are considered potential alternative products for carbamate and organophosphorus insecticides, and their usage in global insecticide markets is expected to increase (Jeschke and Nauen, 2008) because of their superior insecticidal activity against a wide spectrum of insects, low rates of application, long-term controls, systemic activity, variety of application methods and high crop safety (Uneme, 2011). Thiamethoxam (CAS: 153719-23-4) is a second generation neonicotinoid possessing stomach and contact activity, and it operates by interfering with the nicotinic acetylcholine receptors in the insect nervous system (Armstrong et al., 1993; Sallam et al., 2009). Thiamethoxam has the ability to control sucking insects, leafminers, weevils and various species of beetles (Tomlin, 2009; Jeschke et al., 2001), and it has been reported to control *B. odoriphaga* (Zhang et al., 2015c) and possess high acute lethal toxicity and adverse sublethal effects to this pest, such as prolonged development time and reduced pupation rate, adult emergence rate, fecundity and egg hatchability (Zhang et al., 2014c).

However, thiamethoxam has not been registered for use on *B. odoriphaga* in China. Furthermore, there is limited information on the persistence and distribution of thiamethoxam in the soil, its long-acting control effects to *B. odoriphaga* and other secondary pests (*T. alliorum* and *A. alliella*) after one single soil application during the early Chinese chive root-rearing period. Therefore, our goal in this current study was to determine the comparative spatial soil distribution and temporal dissipation of insecticides (thiamethoxam and phoxim), their dissipation in plants after soil application, and their control efficacy for *B. odoriphaga* in the Chinese chives root-rearing period as well as for *T. alliorum* and *A. alliella*. The relationships between control efficacy and soil distribution and insecticide dissipation were then analyzed with regard to their use in the effective management of *B. odoriphaga*.

2. Materials and methods

2.1. Chemicals

Technical-grade thiamethoxam (98%) and 25% thiamethoxam water dispersible granules (WGs) were provided by Shandong United Pesticide Industry Co., Ltd. (Jinan, China) without further purification. Technical-grade phoxim (91%) was provided by Nanjing Red Sun Co., Ltd. (Jiangsu, China), and 40% phoxim Emulsifiable Concentrate (EC) was provided by Shandong Luba Chemical Co., Ltd. (Jinan, China) without further purification. All of the solvents used in this study were laboratory grade. Acetonitrile was high-performance liquid chromatography (HPLC) grade and purchased from the Tianjin Yongda Chemical Reagent Co., Ltd. (Tianjin, China). Magnesium sulfate and sodium chloride were purchased from the Tianjin Kaitong Chemical Reagent Co., Ltd. (Tianjin, China). Solid phase extraction (SPE) cartridges and primary secondary amine (PSA) centrifuge tubes were purchased from Agela Technologies Inc. (Tianjin, China).

2.2. Plant material

Chinese chives seeds (Pingjiu No. 1) were purchased from Pingdingshan Pinglong Co., Ltd. (Henan, China), sown in 2012, grown to the seedling stage, then transplanted to fields at Liaocheng (site: 36°2′52″N, 115°29′3″E) and Tai'an (site: 35°54′11″N, 117°10′56″) in Shandong, China, in 0.20 m rows at a rate of approximately 4,500,000 plants per ha in 2013.

2.3. Experimental design and sampling procedures

The studies are described in the Supporting Information S1 from Mar 2014–Mar 2015 at Liaocheng (Silt loam: 35.6% sand, 45.2% silt and 19.2% clay, with 1.68% organic matter (OM)) and Mar 2015–Mar 2016 at Tai'an (Silt loam: 33.5% sand, 47.6% silt and 18.9% clay, with 1.52% OM) in Shandong, China. The plots were located in Chinese chives fields with a 20-year history of Chinese chive cultivation, and preliminary sampling indicated that high populations of *B. odoriphaga* were present. During the previous season, insecticides, including chlorpyrifos, malathion and phoxim, were applied for *B. odoriphaga* control at a frequency of 4–6 times per year, and the weeds were controlled by spraying pendimethalin each year in June. None of the farms in this area had been treated with thiamethoxam.

Chinese chives plants were raised according to recommended agronomic practices using a randomized complete block design with three treatments (three replicates each). Each Plot was 4.0 m by 24.0 m and separated by 1.0 m of bare cultivated ground.