Research Article

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Large reductions in pesticides made possible by use of an insect-trapping lamp: a case study in a winter wheat-summer maize rotation system

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Abstract

BACKGROUND: Increasing attention is being paid to physical methods to control pests such as insect trapping. In order to examine how pesticides can reasonably be combined with the use of an insect-trapping lamp and by how much this can reduce the amount of pesticide used, five treatments were applied to a winter wheat–summer maize rotation system in eastern China: a treatment in which only pesticides were used; a treatment with only insect-trapping lamps; insect-trapping lamps plus one application of pesticides; insect-trapping lamps plus two applications of pesticides; insect-trapping lamps plus three applications of pesticides.

RESULTS: The results showed that, when pesticides were reduced by 25–35%, the insect-trapping lamps controlled the insect population well and yields were not decreased but were actually increased, with pesticides being applied only at 2 days before winter wheat planting, at winter wheat flowering and at the big flare stage of summer maize. Reducing pesticides by 35–65% had no adverse effect on crop yields, and thus had the potential to reduce the costs of pest control and produce the greatest economic benefit. When no pesticides were used in the insect-trapping lamp control area, the annual yield was still >15 t hm^{-2}.

CONCLUSION: If pesticides are used in a timely fashion and at the appropriate stage, their use may be greatly reduced with the help of an insect-trapping lamp.

Keywords: pesticide; insect-trapping lamp; pest species; winter wheat; summer maize; economic benefit

1 INTRODUCTION

As a consequence of population growth and the resulting requirement to improve crop yields, agriculture now involves heavy usage of pesticides, plant growth regulators and chemical fertilizers.[1–3] The intensive usage of chemical inputs, notably pesticides, is associated with serious health and environmental risks.[4] At present, over 16 000 pesticide formulations based on 1055 active ingredients are labeled for use globally, while in China alone, over 9700 pesticides based on 502 active ingredients have been registered.[5]

When more and more pesticides are used on crops, they directly affect the health of agriculturists and consumers as well as the environment.[6] Also, pesticide usage results in pests becoming chemically resistant. For instance, more than 500 species of targeted pests have developed resistance to pesticides since 1945.[6,7] Another unwanted consequence is the decimation of ambient populations of natural enemies which could provide biological control services.[8] Therefore, how to reduce or delay pest resistance to pesticides and how to use pesticides responsibly are becoming urgent issues for sustainable agriculture.[7]

In addition to the use of pesticides, there are many pest control techniques, such as mechanical, physical, and biological methods.[6] There is currently pressure from consumers to produce safe, non-chemically polluted foods which need less or no usage of chemical pesticides. As a result, many researchers are now focusing on strategies other than chemical pest control, including the deployment of crop varieties that are resistant to pests, using genetic, cultural and biological approaches.[6,8] The control of pests by natural enemies represents an important ecosystem service

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that suppresses pest population growth and has great potential to mitigate pest control costs and crop yield loss.[8] Biological control can be achieved by manipulation of existing natural enemies and their release into a new environment to increase their effectiveness.[9,10] This can be achieved by mass production and periodic release of natural enemies of the pest. However, cultivation of natural enemies in laboratories is very difficult; some practices are cost-effective but others may be not.[8] Integrated pest management is a long-term management strategy for controlling pests with a combination of biological, cultural, and chemical tactics, which has been proved to be more effective than chemical methods both experimentally[9–11] and theoretically.[12,13] Nevertheless, it still has not been widely used by farmers, because such technology is too complex and difficult to manage.[14] Farmers still prefer to choose pesticides to eliminate pests, not only because of the lower cost and time investments and the ease of application, but also because pesticides can quickly kill a significant proportion of the pest population.[8,15,16]

Although agriculturalists and governments are now paying more attention to pesticide pollution problems, little has been achieved in practice in the field.[4] Faced with this thorny issue, governments in developed and developing countries have merely set objectives to control the use of pesticides. For instance, in France, the objectives of the 2008 *Grenelle del'Environnement* regarding reductions in pesticide usage were reaffirmed in 2015. These objectives are a 25% reduction by 2020 and a 50% reduction by 2025 with respect to the levels of pesticide use observed over the past 10 years.[17] In China, an action plan that the usage of pesticides will not increase in 2020 was issued in 2015.[18] However, the targets are still too unambitious, and more efficient and less harmful methods of pest control must be developed through the use of physical and/or biological measures.

In eastern China, the winter wheat (*Triticum aestivium* L.)–summer maize (*Zea mays* L.) rotation system is the main agricultural system, in which the major pests are aphids and soil insects such as black cutworm, chafers, and the mole cricket.[19] The peasant farmers in this region still prefer to use pesticides to eliminate these pests, and several pesticides are widely used, including phoxime, imidacloprid, avermectin and lambda-cyhalothrin, so the dosages and application frequencies of these pesticides are still increasing. In the last decade, researchers have found that physical methods, in particular use of insect-trapping lamps, can capture most of the pests in open crop systems.[19,20] When insects are trapped in these lamps, the eggs of the captured females cannot develop into larvae, and so use of pesticides can be greatly reduced because there are fewer pests and the ecological balance is restored. However, there is no clear evidence regarding the extent to which the amount of pesticides can be reduced through the use of insect-trapping lamps and how best to combine pesticides with insect-trapping lamps.

In the present study, in a winter wheat–summer maize rotation system in the Yimeng Mountainous Region of eastern China, we installed insect-trapping lamps to control pests and reduced the use times of pesticides in the different treatments. The aim of the study was to determine the effects of insect-trapping lamps on pests and crop yields, and to analyze comprehensively the costs of pest control in the different treatments. We aimed to investigate: (1) how much the amount of pesticide applied could be reduced by using insect-trapping lamps; (2) how pesticides and insect-trapping lamps could best be used to balance yield maintenance and environmental conservation. We hope that the findings of this study will help to provide a theoretical basis and data supporting for the reduction of pesticides and restoration of the ecological balance in the winter wheat–summer maize rotation system.

2 MATERIALS AND METHODS

2.1 Experimental site

The field experiment was conducted at the Eco-farm Research Station of Shandong Agricultural University, based in Pingyi County, Shandong Province, eastern China (35°26′21″ N, 117°50′11″ E). The study area experiences a typical temperate and monsoonal climate, with the mean annual rainfall being 725 mm and average annual temperature 13.6 °C. The soil is Alfisols, according to soil taxonomy.[21] The main cropping system is winter wheat–summer maize rotation. Winter wheat grows from early October to early June of the following year, and summer maize from mid June to early October. Winter wheat seeds were sown at a rate of 225 kg hm^{-2} and a depth of 3–5 cm using a seeding machine, with the distance between rows being 0.24 m. During the growth period, winter wheat was irrigated at the seedling and jointing stages (75–85 mm each time), and weeding was carried out 3–5 days later. Summer maize seeds were sown at a depth of 5–7 cm by hand, with the distance between rows being 0.6 m, and that between plants being 0.27 m. During the growth period, summer maize was irrigated at the seedling stage (75–85 mm), and weeding was carried out 3–5 days later.

2.2 The insect-trapping lamp

The insect-trapping lamp (RJKJ-S-01; Jingzhou Shadong Plastic Technology Co., Ltd., Hubei Province, China) utilized a 365 ± 50 nm wavelength spectrum and purple colored light to attract and trap adult pests. Once trapped, the pests were electrocuted by the high-voltage electricity generated by the device. The lamp had an automatic photosensitive switch which turned the light on at night and off at daybreak. We collected the captured pests every morning from April to October in accordance with the growing periods of the crops.

2.3 Experimental design

The experiment was performed from October 2012 to October 2014. The experimental area was divided into an area with only pesticide control of pests (the 'pesticide control area'; 13.3 hm^2) and an area with insect-trapping lamp control of pests (the 'insect-trapping lamp control area'; 13.3 hm^2), with 22 insect-trapping lamps which were installed on 5 May 2013 (Fig. 1); pesticides were also applied to parts of this area, as described below.

In 2013, the treatments were as follows. (1) A treatment in which only pesticides were used to control pests (CK), in the pesticide control area. Pesticides were applied five times: 2 days before winter wheat planting (to control soil pests), 2–3 days before the winter wheat flowering stage (to control wheat aphids), 5–7 days after the winter wheat flowering stage (to control wheat aphids), at the summer maize seedling stage (to control maize pests) and at the big flare stage (to control maize pests). (2) A treatment using only insect-trapping lamps to control pests (LM), within the insect-trapping lamp control area. (3) A treatment using insect-trapping lamps plus two applications of pesticides (LM2), within the insect-trapping lamp control area. Here, pesticides were applied two times: 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage. (4) A treatment

Figure 1. The insect-trapping lamps *in situ* in the field. A rotation of winter wheat–summer maize was treated using this method together with pesticide applications at different times.

with insect-trapping lamps plus three applications of pesticides (LM3), within the insect-trapping lamp control area. Pesticides were applied three times: 2 days before winter wheat planting, 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage. In the insect-trapping lamp control area, there were 2.4 m separations between different plots (plot size 2.4 m × 16 m).

In 2014, another treatment [insect-trapping lamps plus one application of pesticides (LM1), within the insect-trapping lamp control area; pesticides were applied only at 2–3 days before the winter wheat flowering stage] was added to the treatments used in the 2013 experiment.

The type of applied pesticides, application stages, application doses and active ingredients of pesticides are listed in Table 1.

2.4 Sampling and data collection

2.4.1 Pests captured by the insect-trapping lamp

During periods in which the insect-trapping lamps were operational, the pests trapped were collected in the morning at 6–7 am every day except on rainy days. The captured pests were placed in polyethylene bags, carried to the laboratory and frozen in a refrigerator. The pests were categorized as moths, chafers, oriental mole crickets, and other small insects and then weighed separately.

2.4.2 Wheat aphids and their natural enemy: ladybirds

After winter wheat heading, four replications of a square area (1 m × 1 m) of winter wheat were selected randomly for investigation of ladybirds in each plot every 3–5 days. In each of the same square areas, 30 consecutive plants were randomly selected for investigation of wheat aphids.

2.4.3 Maize pests

Three days after pesticide application at the seedling stage and the big flare stage of summer maize, 30 consecutive plants were selected to investigate the pest population, with three replications.

2.4.4 Crop yields

At wheat maturity, three replications of all plants in a quadrate area (2.4 m × 1 m) were selected randomly for measurement of wheat grain yield in each plot. When maize was harvested, three replications of 15 consecutive plants in the same row were selected randomly for estimation of maize grain yield.

2.4.5 Costs of pest control

The costs of pest control included the costs of installing the insect-trapping lamp facilities, the costs of pesticides and the costs of labor to apply the pesticides. The costs of the insect-trapping lamps consisted of those of purchasing the insect-trapping lamps, buying wire, installing the lamps, labor for collecting pests and utilization of electricity.

2.5 Statistical analysis

Statistical analysis was performed using the software SPSS 17.0 (SPSS Inc., Chicago, IL, USA). All data were analyzed using one-way analysis of variance (ANOVA) and the least significance difference (LSD) test was used to establish if the differences in the treatments were significant at the $P \leq 0.05$ level. Figures were generated using Sigmaplot 10.0 (Systat Software Inc., San Jose, CA, USA).

3 RESULTS

3.1 The pests captured by the insect-trapping lamps

In this experiment, 21 species of pests belonging to 16 families and four orders were identified, with the species being listed in Table 2. The main species included moths (e.g. *Ostrinia furnacalis* and *Agrotis ypsilon*), chafers (e.g. *Holotrichia oblita* and *Anomala corpulenta*) and mole crickets (e.g. *Gryllotalpa orientalis*). Natural enemies of the pests were not found among the captured insects.

According to the daily change of pests, we found that there were massive bursts of pest emergence in late May to middle July and from September to October, with chafers emerging from late May to early July. Huge numbers of moths were captured from late August to September; mole crickets were captured from late September to early October (Fig. 2).

From the monitoring results of the two consecutive years (2013 and 2014), we found that the numbers of annually captured moths and mole crickets decreased by 62% and 88%, respectively, from 2013 to 2014, and their weights decreased by 58% and 87%, respectively ($P \leq 0.05$). Although the number of annually captured chafers increased in 2014, there was no significant difference in weight. The annual weight of other pests was significantly reduced by 57% ($P \leq 0.05$) (Fig. 2).

3.2 Pests in the winter wheat–summer maize system and their natural enemies

In this experiment, pesticide was applied to eliminate wheat aphids in all treatments except that without pesticides (LM) on 24 April 2014. Before pesticide application, we determined the numbers of aphids and their natural enemy, ladybirds, and found that the numbers of aphids and ladybirds were about the same among the treatments. After pesticide application, both aphids and ladybirds disappeared. In the LM plots, both aphid and ladybird numbers increased at first and and then decreased; nevertheless, the number of aphids reached a peak earlier than that of ladybirds (Fig. 3).

At the summer maize seedling stage, pesticides were applied only in the pesticide control area (CK). It was noted that the numbers of pests in this area were lowest among the treatments, and those in the LM treatment were highest, and there were no significant differences among the other treatments. At the summer

Table 1. The types, application stages, application doses and active ingredients of pesticides applied in 2013 and 2014

Year	Pesticide application stage	Pesticides	Application dose (g hm^{-2})	Active ingredients (g hm^{-2})
2013	2 days before winter wheat planting	Phoxime	7500	225
	2–3 days before winter wheat flowering	Avermectin and imidacloprid	450	45
	5–7 days after winter wheat flowering	Avermectin and imidacloprid	450	45
	Summer maize seedling stage	Phoxime	7500	225
	Summer maize big flare stage	Phoxime and imidacloprid	12000	480
2014	2 days before winter wheat planting	Phoxime	7500	225
	2–3 days before winter wheat flowering	Imidacloprid and lambda-cyhalothrin	900	56.3
	5–7 days after winter wheat flowering	Imidacloprid and lambda-cyhalothrin	900	56.3
	Summer maize seedling stage	Phoxime	7500	225
	Summer maize big flare stage	Phoxime	7500	225

Table 2. The main pests captured by the insect-trapping lamps

Order	Family	Species
Lepidoptera	Pyralididae	*Ostrinia furnacalis*
		Conogethes punctiferalis
		Helicoverpa armigera
		Chilo sacchariphagus
	Noctuidae	*Agrotis ypsilon*
		Mythimna separata
		Anomis flava Fabricius
	Plutellidae	*Plutella xyllostella*
	Pieridae	*Pierisrapae linne*
	Olethreutidae	*Leguminivora glycinivorella*
Coleoptera	Melolonthidae	*Holotrichia oblita*
	Scarabaeidae	*Holotrichia parallela*
	Rutelidae	*Anomala corpulenta*
	Cetoniidae	*Protaetia brevitarsis*
	Elateridae	*Pleonomus canaliculatus*
	Cerambycidae	Unidentified
Orthoptera	Gryllotalpidae	*Gryllotalpa orientalis*
	Gryllidae	*Gryllulus*
	Tettigoniidae	Longhorned grasshoppers
	Acrididae	*Acrida cinerea*
Hemiptera	Delphacidae	*Laodelphax striatellus*

maize big flare stage, pesticides were applied in the CK, LM2 and LM3 treatments. No differences were found in numbers of pests among these treatments; however, numbers in all these treatments were significantly lower than in the LM and LM1 treatments (Fig. 3).

3.3 Pesticide application and crop yields

In eastern China, the winter wheat–summer maize rotation system is the main agricultural system. Pesticides are often applied at five different times: before winter wheat planting (to control soil pests), before the winter wheat flowering stage (to control wheat aphids), after the winter wheat flowering stage (to control wheat aphids), at the summer maize seedling stage (to control maize pests) and at the big flare stage (to control maize pests). When this application scheme was used in this experiment, the total dose of pesticides was 24.3–27.9 kg hm^{-2} with a content of 0.79–1.02 kg of active ingredients. We found that this application of pesticides resulted in no natural enemies of pests appearing in the agricultural system. However, with lower or no pesticide usage, more and more natural enemies appeared, such as ladybirds (Fig. 3).

In 2013, the yield of wheat in the plots without pesticide application was significantly lower than that in plots with pesticide application ($P \leq 0.05$); the yield of maize was also lower than that in other plots; however, there was no significant difference ($P > 0.05$), with the annual yields being >15 t hm^{-2} (Table 3). In 2014, we found that the yields in all the treatments were not significantly different. Nevertheless, it was noted that pesticides applied before winter wheat planting, before the winter wheat flowering stage and at the summer maize big flare stage combined with the use of insect-trapping lamps to control pests produced the highest yields, with pesticides being reduced by 25–35%. Pesticides applied only before the winter wheat flowering stage and at the summer maize big flare stage, together with the use of insect-trapping lamps, had no adverse effect on crop yields, but could reduce the cost of pest control and yield the highest economic benefit, with a reduction of pesticides of 35–65% (Table 3).

3.4 Cost analysis

In this experiment, the cost of pest control with pesticides was US$251.1–259.0 hm^{-2}, which included the costs of buying and applying pesticides. However, peasant farmers pay only US$50.3–51.3 hm^{-2} for pesticides without considering their labor. By contrast, the cost of pest control with only insect-trapping lamps was about US$46.9 hm^{-2}, including the costs of buying the insect-trapping lamps, buying wire, installing the insect-trapping lamps, collecting pests and utilizing electricity (Table 3). Combining insect-trapping lamps with pesticides cost US$53.7–78.7 hm^{-2}, which is a little higher for peasant farmers than only applying pesticides.

4 DISCUSSION

The use of insect-trapping lamps to control pests has been suggested to be an effective physical control method.[22] In this study,

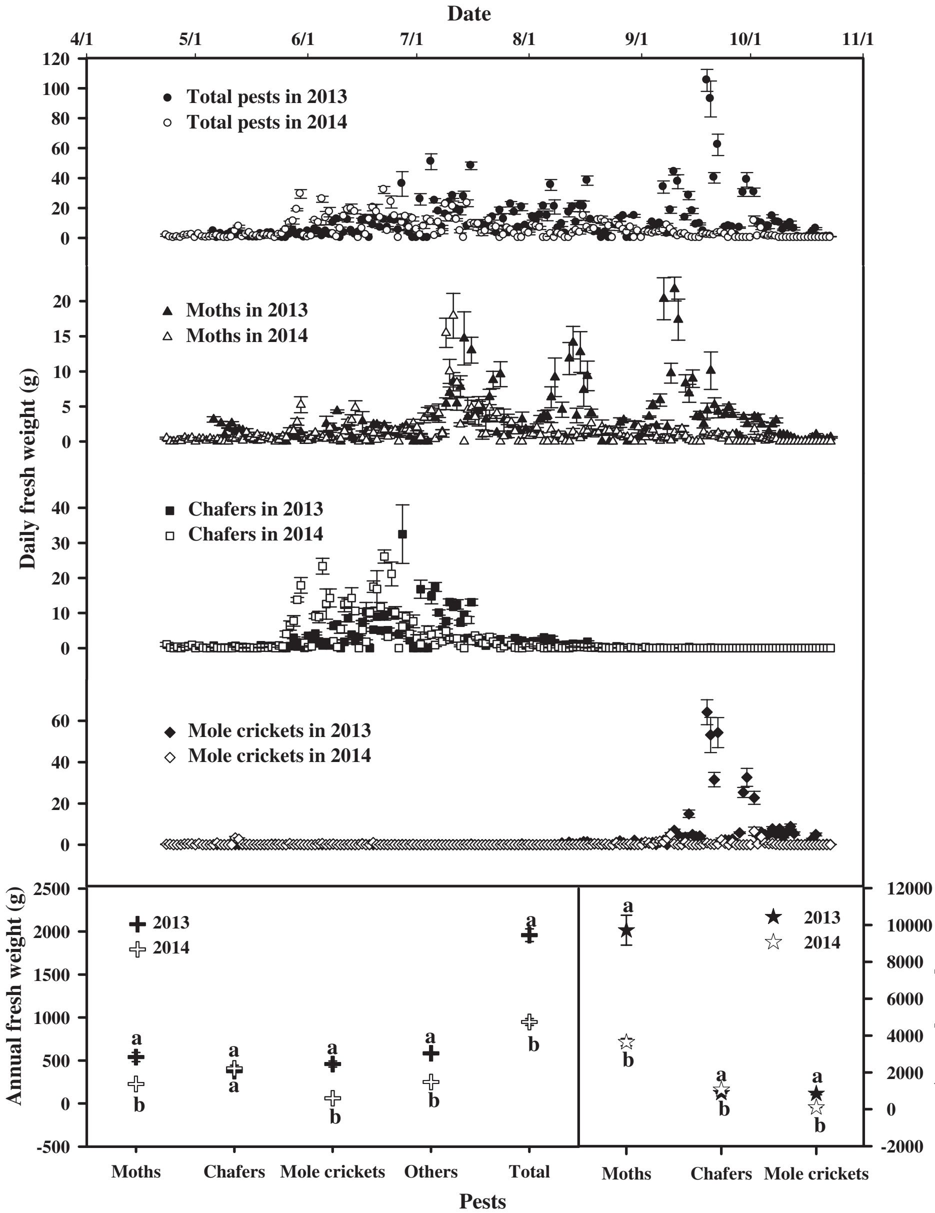

Figure 2. Daily fresh weight, annual fresh weight and number of pests, including moths, chafers and mole crickets, captured by the insect-trapping lamps in the winter wheat–summer maize rotation system from 2013 to 2014. Values are mean ± standard error ($n \geq 3$). Different lowercase letters in the same graph for the same pest indicate significant differences at $P \leq 0.05$.

we found that most of the pests captured by the insect-trapping lamps were the Lepidoptera, Coleoptera and Orthoptera species that are the main pests in the winter wheat–summer maize rotation system (Table 2). From the monitoring results for the two consecutive years, we found that both the daily fresh weight and the annual fresh weight of all captured pests combined displayed a generally declining tendency, as did those of moths and mole crickets (Fig. 2). Some other studies also demonstrated that effective pest control can be achieved using insect-trapping lamps.[19,20,22,23] A consecutive 6-year study showed that both daily and annual average fresh weights of trapped pests decreased substantially with each passing year, with the average daily fresh weight of trapped pests declining from 0.45 kg day^{-1} in 2009 to 0.012 kg day^{-1} in 2014, and the annual total fresh weight of trapped pests decreasing by 93.8%.[19] The reason for the huge decrease in pest numbers may be that our method controlled populations of adults to reduce egg production in the early stages of outbreaks, thus decreasing the numbers of offspring. So, over years, the number of pests could be controlled effectively by the insect-trapping lamps. Also, by monitoring daily changes in the patterns of pest captures, it may be possible to forecast when massive outbreaks of pest emergence will occur. The results could help peasant farmers to use appropriate amounts of pesticides to deal with the target pests.

Although using insect-trapping lamps is an environmentally friendly approach to pest control, peasant farmers still prefer to use pesticides to eliminate pests, because they can quickly kill a significant proportion of the pest population.[8,15,16] In recent years, however, the excessive use of pesticides has begun to pose a serious threat to the health of farmers.[3,4] Moreover, it causes pollution affecting the biological community, soil, water, air and even the global ecosystem. In addition, pesticide residues

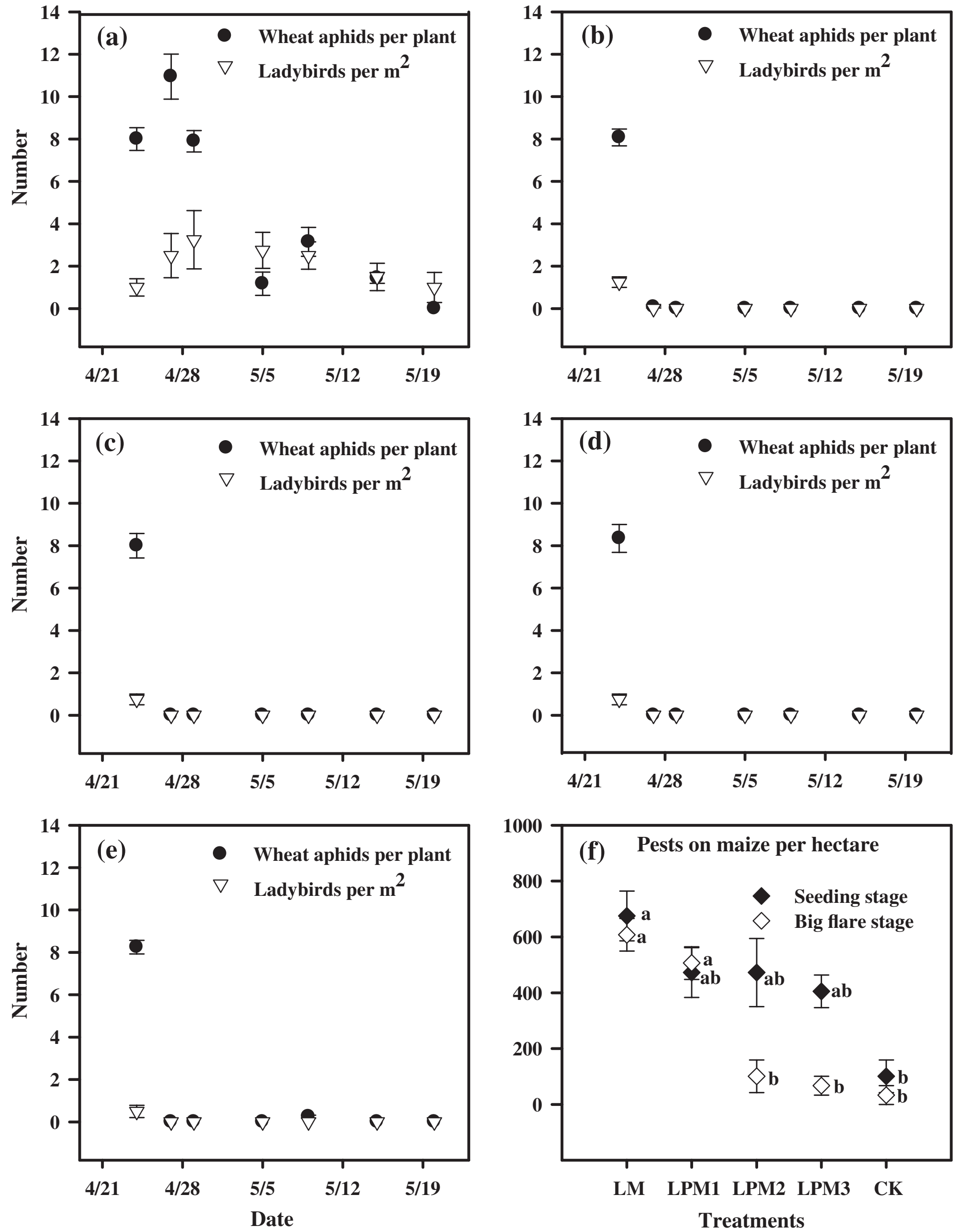

Figure 3. Effects of reducing pesticides and using insect-trapping lamps to control pests on (a–e) wheat aphids and ladybirds and (f) maize pests. Values are mean ± standard error ($n \geq 3$). Different lowercase letters for the same stage indicate significant differences at $P \leq 0.05$. (a) Use of insect-trapping lamps only (LM). (b) Use of insect-trapping lamps plus one application of pesticides (2–3 days before the winter wheat flowering stage) (LM1). (c) Use of insect-trapping lamps plus two applications of pesticides (2–3 days before the winter wheat flowering stage and at the summer maize big flare stage) (LM2). (d) Use of insect-trapping lamps plus three applications of pesticides (2 days before winter wheat planting, 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage, respectively) (LM3). (e) Use of only pesticides. The pesticides were applied five times: 2 days before winter wheat planting, 2–3 days before the winter wheat flowering stage, 5–7 days after the winter wheat flowering stage, at the summer maize seedling stage and at the big flare stage, respectively (CK). (f) Pests at the seedling stage and the big flare stage of summer maize.

cause frequent food safety incidents and restrict the export of agricultural products.[24]

Pesticide application not only eliminates pests, but also kills their natural enemies. In the treatment CK, the total dose of pesticides was 24.3–27.9 kg hm^{-2} with a content of 0.79–1.02 kg of active ingredients (Table 3), which resulted in both aphids and ladybirds disappearing. Most of the natural enemies of pests are diurnal and seldom appear at night, and few have phototaxic characteristics. Therefore, using insect-trapping lamps is an environmentally friendly approach to pest control that does not harm diurnal helpful insects and natural enemies such as ladybirds and birds.[22] We found that, without pesticide application, both aphids and ladybirds increased at first and then decreased (Fig. 3). This conforms to the ecological predator–prey relationship. Initially, the high numbers of aphids provide plentiful food for ladybirds. As the number of ladybirds consequently increases, the number of aphids preyed upon also increases, which leads to a reduction in the number of aphids. However, without enough food, the population of ladybirds also decreases. Thus, the numbers of aphids and ladybirds achieve a reasonable balance without outside interference. More and more studies have discovered that a complex natural enemy community is better than a single enemy

Table 3. The yields of wheat and maize, pesticide application doses (active ingredients) and costs of pest control for different treatments in 2013 and 2014

Year	Treatment	Yield of wheat (kg hm^{-2})	Yield of maize (kg hm^{-2})	Annual yield (kg hm^{-2})	Pesticide application dose (g hm^{-2})	Cost of pesticides (US$ hm^{-2})	Costs of pest control (US$ hm^{-2})	Pesticide reduction percentage (%)
2013	LM	7218.9 ± 14.3b	7851.8 ± 51.7a	15070.7 ± 65.7b	0	0	46.9	100
	LM2	7472.2 ± 15.1a	8336.2 ± 188.7a	15808.4 ± 200.5a	525	19.5	176.4	48.5
	LM3	7527.7 ± 84.0a	8341.7 ± 183.4a	15869.4 ± 254.8a	750	31.8	213.0	26.5
	CK	7477.1 ± 17.9a	8202.1 ± 287.2a	15679.2 ± 273.2ab	1020	51.3	259.0	0
2014	LM	9413.0 ± 20.0a	9415.0 ± 137.8a	18828.0 ± 144.6a	0	0	46.9	100
	LM1	9541.0 ± 256.0a	9503.5 ± 147.6a	19044.5 ± 134.1a	56.3	6.84	102.6	92.9
	LM2	9538.0 ± 184.8a	9739.0 ± 136.1a	19277.0 ± 311.8a	281.3	19.1	175.9	64.3
	LM3	9625.5 ± 110.3a	9741.5 ± 187.3a	19367.0 ± 197.2a	506.3	31.3	212.5	35.7
	CK	9719.0 ± 199.0a	9645.5 ± 190.7a	19364.5 ± 202.5a	787.5	50.3	251.1	0

The costs of pest control included the costs of buying pesticides and the insect-trapping lamps, and the cost of labor to apply pesticides.
Values are mean ± standard error ($n = 3$). Different letters in the same column indicate significant differences at $P \leq 0.05$.
LM, use of insect-trapping lamps only; LM1, insect-trapping lamps plus one application of pesticides (2–3 days before the winter wheat flowering stage); LM2, insect-trapping lamps plus two applications of pesticides (2–3 days before the winter wheat flowering stage and at the summer maize big flare stage); LM3, insect-trapping lamps plus three applications of pesticides (2 days before winter wheat planting, 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage, respectively); CK, use of only pesticides (the pesticides were applied five times: 2 days before winter wheat planting, 2–3 days before the winter wheat flowering stage, 5–7 days after the winter wheat flowering stage, at the summer maize seedling stage and at the big flare stage, respectively).

community in regulating phytophagous pest populations.[25–27] In China, more than 1000 kinds of natural enemies have been found in rice fields, 960 species of natural enemies in maize fields, and 840 species of natural enemies in cotton fields.[28] So, reducing pesticides and using insect-trapping lamps could protect natural enemies and re-establish the ecological balance.

In 2013, the yield of wheat in plots without pesticide applications was significantly lower than that in plots with pesticide applications ($P \leq 0.05$); the yield of maize was also lower than that in other plots; however, there was no significant difference ($P > 0.05$), with the annual yields being >15 t hm^{-2} (Table 3). These results indicated that the use of insect-trapping lamps controlled underground and maize pests effectively. It seemed that applying pesticides only to control wheat aphids might be sufficient. In order to test this hypothesis, we added another treatment in which pesticide was applied only before the winter wheat flowering stage in the insect-trapping lamp control area (LM1) in 2014. We found that the yields in all the treatments were not significantly different. So, reducing pesticides and using insect-trapping lamps could maintain yields of winter wheat and summer maize.

In this experiment, the cost of pest control with pesticides was US$251.1–259.0 hm^{-2}, but peasant farmers paid only US$50.3–51.3 hm^{-2} for pesticides, without considering their field labor. By contrast, the cost for pest control with only insect-trapping lamps was about US$46.9 hm^{-2} (Table 3). Unfortunately, insect-trapping lamps have not been accepted by local farmers, because the rate of killing pests is somewhat slower than that achieved using pesticides. Combining insect-trapping lamps with pesticides cost US$53.7–78.7 hm^{-2}, a little higher than using only pesticides. To enable such environmentally friendly technology to be applied, we suggest that the insect-trapping lamps could be provided by the government and are managed by a professional pest management team. If this were done, pest control could be coordinated by professional staff at county level who have their wages paid by the government. These government-funded professionals could monitor the occurrence of pests and the responsible use of pesticides. Meanwhile, we suggest that peasant farmers could be hired to collect the pests captured by the insect-trapping lamps. Their salaries could be paid by the farmers, who would pay US$36.6–40.7 hm^{-2} year^{-1} for this pest control. This approach could reduce the use of pesticides and the labor of farmers, thereby reducing the probability of farmers being exposed to poisonous pesticides, and improving health and safety for producers.

5 CONCLUSION

In conclusion, the use of insect-trapping lamps can be effective for capturing nocturnal phototactic pests, especially Lepidoptera, Coleoptera and Orthoptera species. Reducing pesticides by 25–35% combined with the use of insect-trapping lamps did not reduce yields but actually increased them, with pesticides being applied at 2 days before winter wheat planting, at 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage. A 35–65% reduction of pesticides plus the use of insect-trapping lamps had no adverse effect on crop yields, and thus had the potential to reduce the costs of pest control and produce the greatest economic benefit, with pesticides being applied only at 2–3 days before the winter wheat flowering stage and at the summer maize big flare stage. When no pesticides were used in the insect-trapping control area, although the annual yields were lower than those in plots in which pesticides were used, they were still >15 t hm^{-2}. Our findings may provide a theoretical basis for, and data supporting, approaches to reduce the use of pesticides while still controlling pests, as well as to restore the ecological balance in the winter wheat–summer maize rotation system.

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