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Ecological control service of the predatory natural enemy and its maintaining mechanism in rotation-intercropping ecosystem via wheat-maize-cotton

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ABSTRACT

Ecosystem can offer regulating services to change biodiversity patterns and ecological processes and then affect the prevalence of crop pests. Biological pest control could serve as an environmentally friendly ecological control service to suppress crop pests and decrease pesticide use by maintaining or increasing natural enemies. However, few study focus on the explicit process of natural enemies, pest dynamics, quantitative assessment and maintaining mechanism of ecological control service in multi-crop farmland landscape system for the whole crops growing cycle. Here, an experimental model of rotation-intercropping ecosystem via wheat-maize-cotton was planned for three consecutive years to response above questions. Our result found the rotation-intercropping ecosystem help to increase the abundances of the dominant natural enemy, *Propylea japonica* adults and then promoted aphid reduction in center cotton plots. In crops growing cycle, many predators maintained in wheat from Mid-April to late May, then the predator moved to inhabit in maize before wheat harvest during early June. During the intercropping period of maize and cotton, the predator would prefer to back and forth inhabit in maize and travel to cotton to actively prey on cotton pests. Quantitative evaluation of pest control based on a new built method of Ecological Control Service Index (ESI) found that crop diversity has highly efficient control function in rotation-intercropping ecosystem. The values of ESI at the peak of cotton aphids on center cotton plots were 0.80 in 2012, 0.31 in 2013 and 0.61 in 2014, respectively. The sustainably available prey resources in multi-crops ecosystem and maize as crop habitat with conditions of relative low temperature (28.5℃) and high humidity (68.3 %) are beneficial to maintain the predator natural enemy and ecological control service. Thus, our results suggest that giving full play to the ecological control service of crop diversity in rotation-intercropping ecosystem is beneficial to decrease crop pests and pesticide use, especially under the aggravating agricultural intensification. These findings support growing efforts from landowner, field manager and policy-makers to promote this ecosystem service via designing crops patterns and adjusting crops growing circle in regional agroecosystem.

1. Introduction

Humanity has always depended on the products and services provided by the ecosystems (Joseph Alcamo et al., 2005; Garcia et al., 2018). Provisioning services as important ecosystem services, are the products obtained from ecosystems, including the vast range of food products derived from plants, animals, and microbes (Daily, 1997). Farmland ecosystems by crop production could provide a variety of crop foods to meet the escalating needs of human population. But crop production usually suffers major losses to crop pests. Ecosystem can offer regulating services to change biodiversity patterns and ecological processes and then affect the prevalence of crop pests (Tscharntke et al.,

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2012; Karp et al., 2018; Snyder, 2019; Wan et al., 2019).

Agriculture can contribute to the conservation of high-diversity systems, which may provide important ecosystem services, biological pest control via complementarity and sampling effects (Tscharntke et al., 2005; Dainese et al., 2019). Biological pest control could serve as an environmentally friendly ecological control service to suppress crop pests by maintaining or increasing natural enemies. Biological pest control has primarily relied on local improvements in populations of natural enemies in agricultural landscape ecosystem (Thies and Tscharntke, 1999; Hossard et al., 2018). Agricultural landscape is the geographic space made of farmland as main body and surrounding land cover or land use as background, such as grassland, forest, shrub, wetland, building area etc (Ouyang and Ge, 2011). Landscape composition and configuration play the great role in determining the structure of ecological communities, ecosystem functioning and services (Batary et al., 2011). Knowing the ecological effects of agricultural landscape pattern or agricultural practice on population dynamics of insect pests and their natural enemies is fundamental for ecological regulation and management of insect pests (Ouyang et al., 2012).

In past years, agricultural intensification has resulted in the landscapes simplification via the expansion of farmland, enlargement of field size and removal of non-crop habitat, and the rapid decline of farmland biodiversity and a concentration of the remaining biodiversity in the field edges and non-crop habitats (Robinson and Sutherland, 2002; Benton et al., 2003; Bianchi et al., 2006). So, there is growing concern about biological pest control based on landscape-level crop diversity in areas where crops are grown intensively. For example, predator and parasitoid densities increased with crop diversity on small (100 − 250 m) and large (2,000–3,000 m) spatial scales respectively (Redlich et al., 2018). According to the experimental landscape system composed of multiple crops, our previous results indicated high crop species richness could suppress the pest population, indicating that crop species richness could enhance biological control services (Sheng et al., 2017). As crop rotation between wheat and legume fields is common worldwide, the findings emphasized the importance of creating an agricultural mosaic to enhance biodiversity permeability within the agricultural matrix (Rotem and Ziv, 2016). However, few study focus on the explicit process of natural enemies, dynamics of pest population, ecological control service and its maintaining mechanism in multi-crop farmland landscape system for the whole crops growing cycle.

Another important task to quantitatively evaluate the ecosystem service of pest control is to assess the extent or degree of pest reduction in multi-crop farmland landscape system. The pest reduction is by means of agricultural practice or landscape habitat management, which may directly inhibit pest population breeding and movement or control pest indirectly by protecting natural enemies. Biocontrol Services Index (BSI) was used to determine the impact of natural enemies on soybean aphid populations (Landis et al., 2000; Gardiner et al., 2009; Woltz et al., 2012). When Biocontrol Services Index (BSI) was calculated in field experiment under an ideal situation. However, it is hard to avoid potential interference factor or errors over during actual field experiments. In order to minimize potential interference factor or errors, a new method of Ecological Control Service Index (ESI) is proposed to evaluate the ecosystem service of pest control in multi-crops farmland. Biocontrol Services Index (BSI) was calculated with a hypothesis that migratory insects did not fly to and produce offspring on plants in the open treatment. While Ecological Control Service Index (ESI) is proposed to quantitatively evaluate the extent or degree of pest reduction resulting of agricultural practice or landscape habitat management.

In this study, an experimental model system was planned to study the explicit process of natural enemies, pest dynamics, quantitative assessment and maintaining mechanism of ecological control service in multi-crop farmland landscape system for the whole crops growing cycle. Wheat, cotton and maize are important crops in the world and provide the main agricultural landscape in Northern China. Three crops (wheat, maize and cotton) were constructed to a rotation-intercropping ecosystem. The cotton aphid, *Aphis gossypii* (Glover), is a serious sucking pest of cotton that could lead to substantial yield loss (Wu and Guo, 2005). the dominant predator, *Propylea japonica* is a prevalent mobile predator of aphids in wheat, maize and cotton and moves among crops in agricultural systems (Ge Feng, 1995; Liu et al., 2004; Gao et al., 2010). Much research on its predation on aphids in cotton has been reported (Ge Feng, 1995; Liu et al., 2004; Gao et al., 2010). However, the factors affecting intercrop movement and foraging behavior of *Propylea japonica* among wheat, cotton and maize remain to be elucidated from a landscape perspective. Our objectives were to: 1) confirm the effects of crop planting patterns on the predatory ladybird and its prey in rotation-intercropping ecosystem via wheat-maize-cotton; 2) evaluate ecological control service of the rotation-intercropping via wheat-maize-cotton based on a new built method; 3) explore maintaining mechanism of ecological control service via rotation-intercropping.

2. Methods

2.1. Study site and experimental design

The field experiment was performed during 2012–2014 at the Yucheng Experimental Station of the Chinese Academy of Sciences, Shandong Province, China (116°36′ E, 36°57′ N). The research site is in a temperate, seasonal, semi-humid monsoon climate, where the mean annual temperature is about 13.0 °C, the mean annual precipitation is about 580 mm, concentrated in the summer months. Winter wheat, maize and cotton are the primary crops at this Planting area.

An experimental model system was planned to study the explicit process of natural enemies, dynamics of pest population, ecological control service and its maintaining mechanism in multi-crop farmland landscape system. Three crops (wheat, maize and cotton) were constructed to a rotation-intercropping ecosystem. Plot treatments were designed based on crop planting patterns and crop growth cycle (Fig. 1). Crop planting patterns include one crop: cotton, two crops: wheat and cotton, three crops: wheat, maize and cotton. On the basis of crop growth cycle, cotton and maize were planted at the beginning of May, while wheat was planted in Mid-October last year. The field was 65 m × 100 m and divided into 12 15 m × 15 m plots. The spacing between neighboring plots was 5 m. All vegetation between plots was removed, when necessary, to minimize effects from the surrounding environment. Host plants used in the experiments were planted without pesticides at this research station. Plants were watered as needed and fertilized with a controlled release fertilizer.

2.2. Insect sampling and microclimate monitoring

The number of predatory ladybirds s and aphids on wheat, cotton and maize were monitored in each experimental plot of 15 m × 15 m from Mid-April to Mid- September in 2012, 2013, and 2014. In center cotton subplots of 12 15 m × 15 m plots, the number of predatory ladybirds, *Propylaea japonica* adults were sampled using stick trap, and the number of cotton aphids, *Aphis gossypii* on cotton leaves were counted by visual observation.

Temperature and humidity were monitored at ten-minutes intervals during summer season in rotation-intercropping ecosystem via wheat-maize-cotton. A two-channel micro-thermohygrometer was used, and the probe of right channel was set in maize leaves while the probe of the other one in cotton leaves.

2.3. Ecological control service index in farmland landscape system

Key to quantitatively evaluate the ecosystem service of pest control is to assess the extent or degree of pest reduction. The pest reduction is by means of agricultural practice or landscape habitat management, which may directly inhibit pest population breeding and movement or

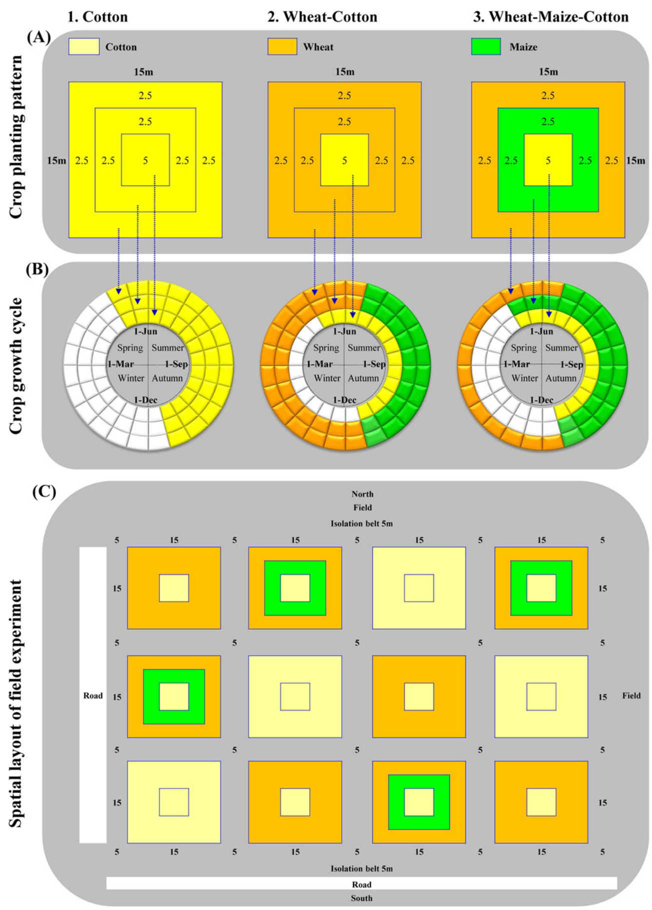

Fig. 1. Spatial layout of the field experiment. (A) Crop planting patterns, 1. one crop: cotton, 2. two crops: wheat and cotton, 3. three crops: wheat, maize and cotton. (B) Crop growth cycle, cotton and maize were planted at the beginning of May, while wheat was planted in Mid-October last year. (C) The field was 65 m × 100 m and divided into 12 15 m × 15 m plots. The spacing between neighboring plots was 5 m. Yellow, orange and green areas in plot indicate the planting of cotton, wheat and maize (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

control pest indirectly by protecting natural enemies. Biocontrol Services Index (BSI) was used to determine the impact of natural enemies on soybean aphid populations (Habitat Management toLandis et al., 2008; Gardiner et al., 2009). In the field experiment, two treatments were compared: an open treatment where natural enemies had full access to aphid-infested soybean plants, and a caged treatment where exclusion cages prevented natural enemies from colonizing plants and consuming aphids (Habitat Management toLandis et al., 2008). BSI is supposed to the relative reduction in aphid density caused by predator access over a period of 7 or 14 days:

$$BSI = \frac{\left(\sum_{p=1}^{n} \frac{(Ac_p - Ao_p)}{Ac_p}\right)}{n}$$

Where Ac is the number of aphids on the caged plant on day 7 or 14, Ao is the number of aphids on the open plant on day 7 or 14, p is plot, and n is the number of replicates for a given site. At each location, treatments (n replications) were established when fields reached an average of 10 aphids per plant, and plants in both treatments were manipulated to start with this aphid density at day 0. Aphid counts were made 7 and 14 days after the treatments were established. When Biocontrol Services Index (BSI) was calculated in field experiment under an ideal situation, a hypothesis was that migratory aphids did not fly to and produce offspring on plants in the open treatment.

However, it is hard to avoid potential interference factor or errors over a period of 7 or 14 or more days in actual field experiments, such as above migratory aphids into the open treatment. In order to minimize potential interference factor or errors, Ecological Control Service Index (ESI) is proposed to quantitatively evaluate the extent or degree of pest reduction resulting of agricultural practice or landscape habitat management. ESI equations are following,

$$\overline{A}_c = \left(\frac{\sum_{i=1}^{n} A_{c,i}}{n}\right), \text{ and } \overline{A}_t = \left(\frac{\sum_{j=1}^{m} A_{t,j}}{m}\right)$$

$$ESI_j = \frac{\overline{A}_c - A_{t,j}}{\overline{A}_c}, \text{ and } ESI = \frac{\overline{A}_c - \overline{A}_t}{\overline{A}_c} \text{ or,}$$

$$ESI = \frac{\left(\frac{\sum_{i=1}^{n} A_{c,i}}{n}\right) - \left(\frac{\sum_{j=1}^{m} A_{t,j}}{m}\right)}{\left(\frac{\sum_{i=1}^{n} A_{c,i}}{n}\right)}$$

In the field experiment, control and treatment were compared, where $A_{c,i}$ is the number of pest insect on the plant of control plot i, n is the number of replicates for given control plots, $\overline{A}_c$ is the average value of numbers of n control plots. $A_{t,j}$ is the number of pest insect on the plant of treatment plot j, m is the number of replicates for given treatment plots, $\overline{A}_t$ is the average value of numbers of m treatment plots. ESI_j is the extent or degree of pest reduction for the number of pest insect on the plant of treatment plot j compared to the average value of numbers of n control plots. $ESI$is the extent or degree of pest reduction for the average value of numbers of m treatment plots compared to the average value of numbers of n control plots. In the field experiment, ESI_j is used to assess the extent or degree of pest reduction on the plant of treatment plot j. And ESI is used to assess total or average extent or degree of pest reduction in particular treatment.

2.4. Statistical analysis

Statistical analysis and mathematic model were applied to study the explicit process of natural enemies, dynamics of pest population, ecological control service and its maintaining mechanism in multi-crop farmland landscape system. Firstly, to determine effects of three crop planting patterns on the predatory ladybird, *Propylaea japonica* adults in center cotton plots, the numbers of the predator, *P. japonica* adults by stick traps among three crop planting patterns at sample dates in 2012, 2013, and 2014 were analyzed with one way ANOVA. Secondly, to know the roles of the rotation-intercropping via wheat-maize-cotton comparing to monoculture cotton, independent samples t Test were used to analyze the densities of cotton aphids, *Aphis gossypii* in center cotton plots by visual observation in 2012, 2013, and 2014. Thirdly, Ecological Control Service Index (ESI) is used to assess total or average extent or degree of aphids reduction for the average value of numbers of 4 treatment plots (rotation-intercropping via wheat-maize-cotton) compared to the average value of numbers of 4 control plots (monoculture cotton). Fourthly, after wheat harvest in rotation-intercropping ecosystem via wheat-maize-cotton, independent samples t Test were used to analyze the densities of the predatory ladybird, *P. japonica* adults between in maize plots and in cotton plots during the sample dates. All statistical analyses were conducted using SPSS software (IBM SPSS Statistics 20.0, 2011).

3. Results

3.1. Effect of crop planting patterns on predatory ladybird and its prey

Abundances of the predatory ladybird, *P. japonica* adults in center cotton plots of planting pattern with three crops (wheat-maize-cotton) were significant more than those with one crop (cotton) and two crops (wheat-cotton) during the sample dates on 7 Jun (Fig. 2 A, $F = 53.973$, $p < 0.001$) and 17 Jun (Fig. 2 A, $F = 6.802$, $p = 0.029$) in 2012, on 7

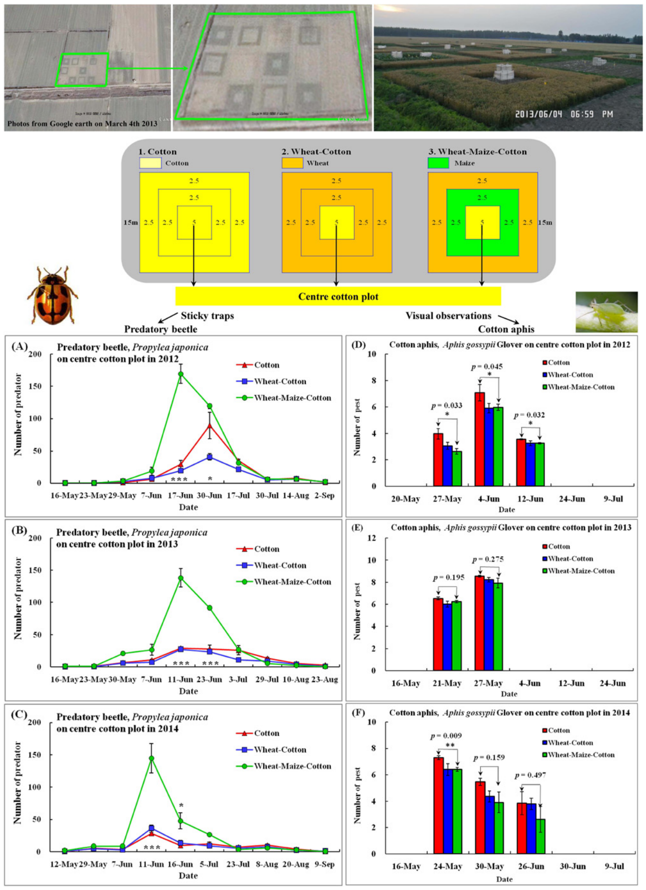

Fig. 2. Population dynamics of predatory ladybird and cotton aphids among three crop planting patterns. Dynamics of the predatory ladybird, *Propylaea japonica* adults in center cotton plots by stick traps in 2012 (A), 2013 (B), and 2014 (C). *, ** and *** denote significant differences among three crop planting patterns at p < 0.05, p < 0.01 and p < 0.001. Data are presented per stick trap in center cotton plots (mean ± SE) with separate field plots used as replicates. Dynamics of cotton aphids, *Aphis gossypii* in center cotton plots by visual observation in 2012 (D), 2013 (E), and 2014 (F). *, ** and *** denote significant differences of aphids densities between two crop planting patterns, one crop: cotton and three crops: wheat, maize and cotton at p < 0.05, p < 0.01 and p < 0.001. The data for aphid density were log-transformed (ln(n +1)). Data are presented per 100 cotton plants in center cotton plots (mean ± SE) with separate field plots used as replicates.

Jun (Fig. 2 B, F = 43.010, p < 0.001) and 11 Jun (Fig. 2 B, F = 62.903, p < 0.001) in 2013, and on 7 Jun (Fig. 2 C, F = 17.887, p = 0.001) and 11 Jun (Fig. 2 C, F = 5.463, p = 0.028) in 2014.

Densities of the cotton aphids, *Aphis gossypii* in center cotton plots of planting pattern with three crops (wheat-maize-cotton) were significant less than those with one crop (cotton) during the sample dates on 27 May (Fig. 2 D, t = -3.194, p = 0.033), 4 Jun. (Fig. 2 D, t = -2.875, p = 0.045) and 12 Jun. (Fig. 2 D, t = -3.236, p = 0.032) in 2012, and on 24 May (Fig. 2 F, t =-3.758, p = 0.009) in 2014.

3.2. Ecological control service of rotation-intercropping via wheat-maize-cotton

Calculation method was constructed to assess the quantitative control of aphids by their natural enemies between multi-crop cultivation (wheat-maize-cotton as treatment) and monoculture (cotton as control) (Fig. 3 **A**). Ecocontrol service indexes at the peak of cotton aphids on center cotton plots were 0.80 in 2012, 0.31 in 2013 and 0.61 in 2014, respectively (Fig. 3 **B**).

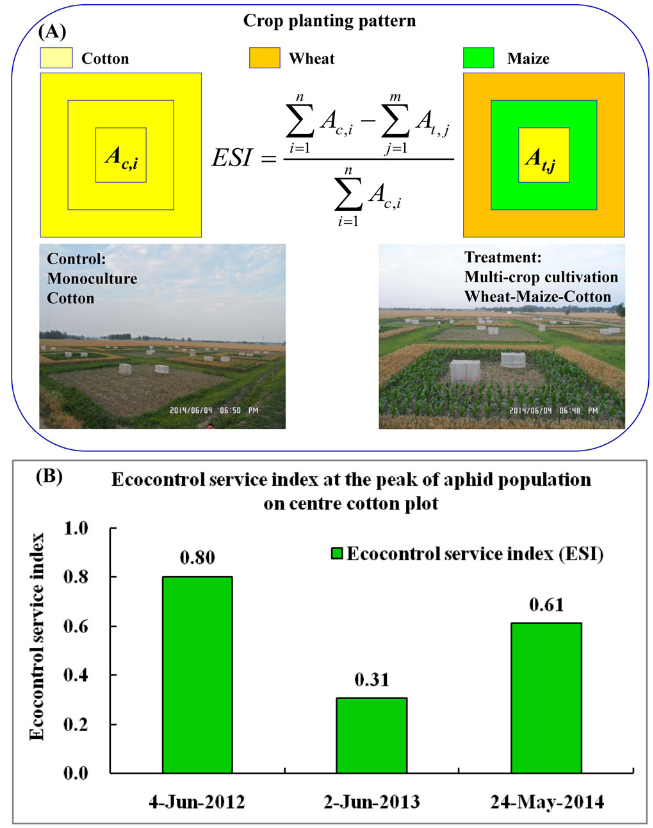

Fig. 3. Ecocontrol service index of rotation-intercropping via wheat-maize-cotton to monoculture cotton. (A) Calculation method for ecocontrol service index. (B) Ecocontrol service indexes at the peak of cotton aphids on center cotton plots in 2012, 2013 and 2014.

3.3. Maintaining mechanism of ecological control service via rotation-intercropping

The predatory ladybird, *P. japonica* adults inhabited in wheat before harvest (Fig. 4 A, B, C). The date of wheat harvest was on June 7th for three years in field experiment. After wheat harvest in rotation-intercropping ecosystem via wheat-maize-cotton, the densities of the predatory ladybird, *P. japonica* adults in maize plots were significant more than those in cotton plots during the sample dates on 12 Jun. (Fig. 4 A, t = 7.731, p = 0.002) and 12 Jun. (Fig. 4 A, t = 13.835, p < 0.001) in 2012, on 11 Jun. (Fig. 4 B, t = 27.684, p < 0.001) and 20 Jun. (Fig. 4 B, t = 16.487, p < 0.001) in 2013 and on 12 Jun. (Fig. 4 C, t = 18.723, p < 0.001) and 24 Jun. (Fig. 4 C, t = 3.110, p = 0.021) in 2014 (Fig. 4).

Temperature and humidity were measured in field experiment. The mean temperature from 20 Jun. to 30 Jun. in maize leaves (28.5°C) was lower than that in cotton leaves (29.3°C), while the humidity during the same periods in maize leaves (68.3 %) was higher than that in cotton leaves (62.1 %) (Fig. 5).

4. Discussion

Based on field experiment of three consecutive years in rotation-intercropping ecosystem via wheat-maize-cotton, our research had confirmed the effects of crop planting patterns on the predatory ladybird and its prey, evaluated ecological control service of the rotation-intercropping, and explored the maintaining mechanism of ecological control service.

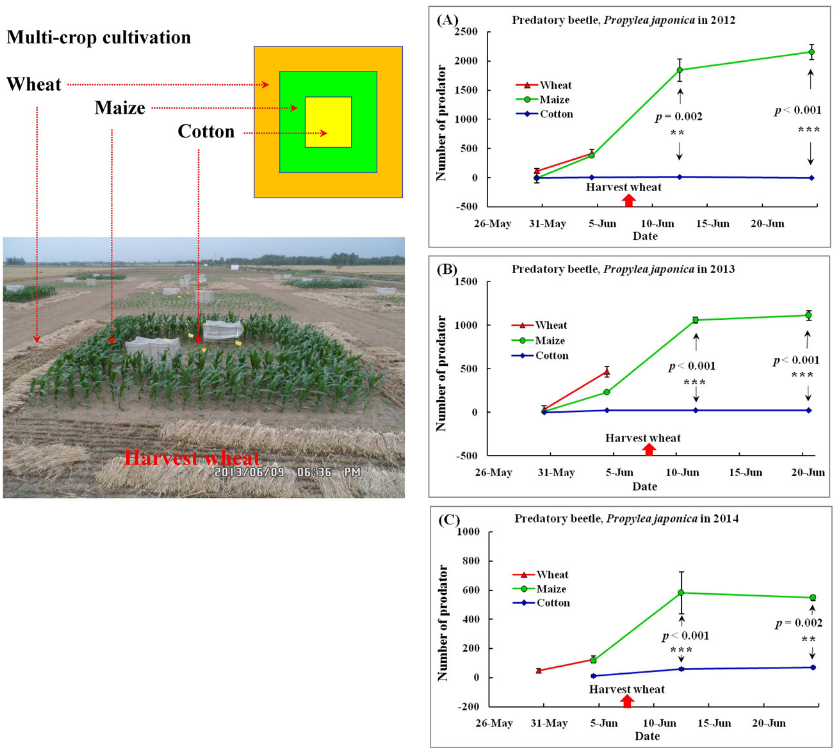

Fig. 4. Population dynamics of predatory ladybird in rotation-intercropping ecosystem via wheat-maize-cotton. Dynamics of the predatory ladybird, *Propylaea japonica* adults in among wheat, cotton and maize in rotation-intercropping ecosystem by visual observation in 2012 (A), 2013 (B), and 2014 (C). *, ** and *** denote significant differences among three crops at the same planting pattern at $p < 0.05$, $p < 0.01$ and $p < 0.001$. Data are presented per 100 plants in center cotton plots (mean ± SE) with separate field plots used as replicates.

4.1. Dynamics of the predatory natural enemy in rotation-intercropping ecosystem

The movement of insect from one place to another underlies their abundance and distribution in space and time in agricultural landscapes (Mazzi and Dorn, 2012). Landscape-moderated spillover of organisms across habitats, including between managed and natural ecosystems, influences landscape-wide community structure and associated processes (Tscharntke et al., 2012). Usually cross-habitat spillover of organisms was focused on, which is the movement (including both dispersal and foraging) of organisms from one distinct habitat type to another. Our previous experiment researched the agricultural ecosystem composed of cotton and maize and only investigated the moving process of the predatory natural enemy, *P. japonica* adults between the two crops during short period from Mid-May to late-September (Ouyang et al., 2012). In this research we concerned the cross-crop

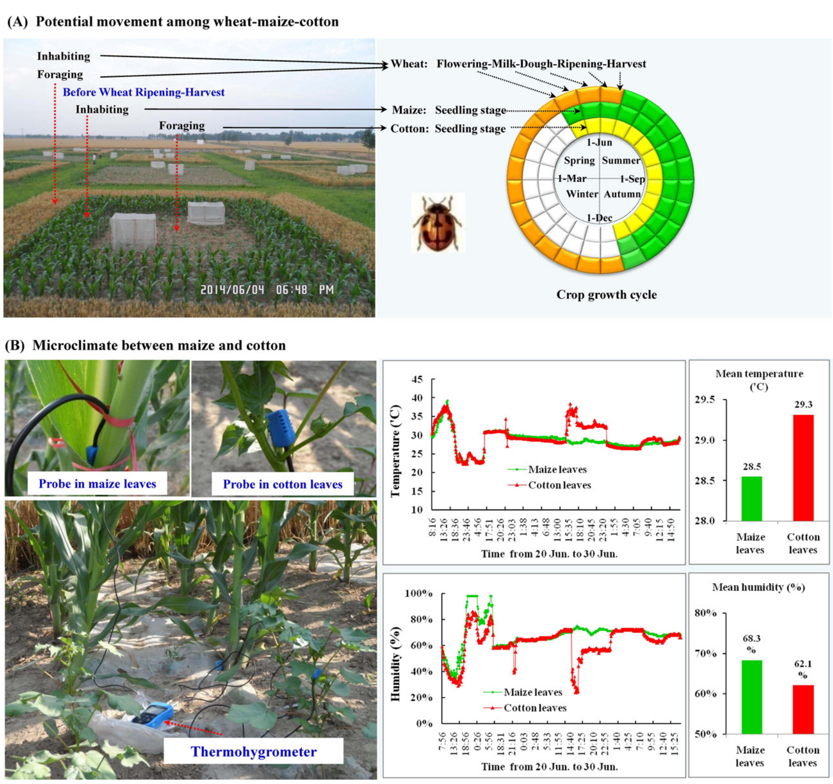

Fig. 5. Potential movement of predatory ladybird and microclimate in rotation-intercropping ecosystem via wheat-maize-cotton. (A) Potential movement of predatory ladybird, *Propylaea japonica* adults in rotation-intercropping ecosystem. (B) microclimate including temperature and humidity in rotation-intercropping ecosystem via wheat-maize-cotton.

spillover of the predatory natural enemy, *P. japonica* adults in rotation-intercropping ecosystem via wheat-maize-cotton. Our result showed that in the whole crops growing cycle, many the predatory natural enemy, *P. japonica* adults maintained in wheat planting area from Mid-April to late May, then the predator moved to inhabit in maize planting area before wheat harvest during early June. During the simultaneous planting or intercropping period of maize and cotton, the predatory natural enemy, *P. japonica* adults prefer to inhabit maize and travel to cotton to actively prey on cotton pests such as aphids.

4.2. Ecological control service of rotation-intercropping ecosystem

Landscape-level crop diversification was a promising tool for ecological intensification, whereby biodiversity and ecosystem services are enhanced (Redlich et al., 2018). In this study, our result found that the rotation-intercropping ecosystem via wheat-maize-cotton help to preserve and increase the abundances of the predatory natural enemy, *P. japonica* adults and then promoted aphid reduction in center cotton plots. A meta-analysis indicated that the positive response of natural enemies did not necessarily translate into pest control, since pest abundances showed no significant response to landscape complexity (Strip intercropping peanut with maize et al., 2011). But our study found that the positive response of the predatory natural enemy, *P. japonica* adults and the negative response of aphid on cotton to crop diversity. Using ecological control service index (ESI) to quantitatively evaluate the ecosystem service of pest control, we found the efficient control function in rotation-intercropping ecosystem via wheat-maize-cotton. Our previous results also indicated that peanut/maize strip intercropping could enhance the predator number and suppress pest (Ju et al., 2019). Biocontrol Services Index (BSI) was usually used to determine the impact of natural enemies on pest populations and supposed to the relative reduction in aphid density caused by predator access over a short period such as 7 or 14 days (Habitat Management toLandis et al., 2008). BSI was carried out according to two treatments: the open treatment where natural enemies had full access to pest-infested crops, and the caged treatment where exclusion cages prevented natural enemies from colonizing crops and consuming pests. Using BSI will be to meet two challenges in rotation-intercropping ecosystem. Firstly, estimating BSI need to set the same initial value (pest number) and install a lot of cages, which could increase amount of work and time to finish the experiment as arrange more study sites across regional scales. Secondly, the migratory pests such as winged aphids may fly to and produce offspring on corps in the open treatment. It would result in the different initial value of pest number between the open and the caged treatments. As a result, it is difficult to objectively evaluate the ecological control service of natural enemies in multi-crops ecosystem. While Ecological Control Service Index (ESI) is proposed to quantitatively evaluate the extent or degree of pest reduction resulting of agricultural practice, crop growing circle, crop diversity or landscape habitat management. Using ESI could avoid potential interference factor or errors over a period of 7 or 14 or more days in actual field experiments. And ESI can be used to assess the overall effect of agricultural practice on pests and be suitable for more research sites and more complex trials. By quantitatively evaluate the ecosystem service of pest control, the values of ESI at the peak of cotton aphids on center cotton plots were 0.80 in 2012, 0.31 in 2013 and 0.61 in 2014, respectively. The results signified the extent or degree of pest reduction from 31 % to 80 % in multi-crop farmland landscape system. However, the ESI values were different across years in the farmland. Because the ecological control service to suppress crop pests are often affected by ambient climatic conditions.

4.3. Maintaining mechanism of ecological control service in rotation-intercropping ecosystem

Maintaining mechanisms for natural enemy enhancement or ecological control service has been a core concern. Nowadays, researchers have understood the importance of biodiversity-ecosystem function relationships and have a firmer theoretical foundation to design habitat management strategies for pest suppression in agricultural systems (Gurr et al., 2017). In this study, we explored the relationships between crop diversity (crop patterns and crops planting circle) and ecological control service. Our results suggest that designing rotation-intercropping ecosystem of multi-crops could maintain and increase the ecological control service of the predatory natural enemy to mitigate negative effects from the aggravating agricultural intensification. Ecological resources generally provided in habitat manipulation research and practice are readily captured in the SNAP mnemonic: shelter, nectar, alternative prey/hosts, and pollen (Gurr et al., 2017). Under the aggravating agricultural intensification, most crop habitats, especially annual crops, are not favorable for natural enemies because they are instable and have low heterogeneity with frequent disturbance (Thorbek and Bilde, 2004). Our results showed that many predatory ladybirds, *P. japonica* adults inhabited in wheat before harvest. And after wheat harvest in rotation-intercropping ecosystem via wheat-maize-cotton, the densities of the predatory ladybird, *P. japonica* adults in maize plots were significant more than those in cotton plots during the sample dates. The mean temperature in maize leaves was lower than that in cotton leaves, while the humidity during the same periods in maize leaves was lower than that in cotton leaves. Our results suggest that in rotation-intercropping ecosystem via wheat-maize-cotton, maize can serve as a habitat or refuge sources for the predatory ladybird, *P. japonica*, and benefits predators to provide potential to enhance biological control for insect pests in cotton. The sustainably available prey resources in multi-crops ecosystem and maize as crop habitat with conditions of relative low temperature (28.5℃) and high humidity (68.3 %) are beneficial to the maintenance of the population number and ecological control service of the predatory natural enemy, *P. japonica* adults.

5. Conclusion

Landscape structure, crop diversity or crop planting patterns in the agricultural ecosystem can influence the structure of ecological communities, population dynamics, ecosystem functioning and services (Batary et al., 2011; Rotem and Ziv, 2016). In this study, our result found that the rotation-intercropping ecosystem via wheat-maize-cotton help to increase the abundances of the predatory natural enemy, *P. japonica* adults and then promoted aphid reduction in center cotton plots. In the whole crops growing cycle, many the predatory natural enemy, *P. japonica* adults maintained in wheat planting area from Mid-April to late May, then the predator moved to inhabit in maize planting area before wheat harvest during early June. Our study found that the positive response of the predatory natural enemy, *P. japonica* adults and the negative response of aphid on cotton to crop diversity. By quantitative evaluation the ecosystem service of pest control, we found crop diversity has the highly efficient control function in rotation-intercropping ecosystem via wheat-maize-cotton. The sustainably available prey resources in multi-crops ecosystem and low temperature and high humidity habitat conditions are beneficial to the maintenance of the population number and ecological control service of the predatory natural enemy, *P. japonica* adults. In theory, our research has systematically revealed the explicit process of natural enemies, pest dynamics, quantitative assessment and maintaining mechanism of ecological control service in rotation-intercropping ecosystem via wheat-maize-cotton for the whole crops growing cycle. In practice, an environmentally friendly ecological control service was found to maintain or increase natural enemies and reduce the pest populations via designing crops patterns and crops growing circle in rotation-intercropping ecosystem. Thus, our results suggest that giving full play to the ecological control service of crop diversity in rotation-intercropping ecosystem is beneficial to decrease crop pests and pesticide use, especially under the aggravating agricultural intensification. These findings support growing efforts from landowner, field manager and policy-makers to promote this ecosystem service via designing crops patterns and adjusting crops growing circle in agroecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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