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Increasing the proportion of flower strips promotes natural enemies to enhance aphid biocontrol and wheat yields

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Research Article

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Abstract

Sowing flower strips adjacent to cropsis an effective practice for promoting natural enemies, enhancing biological pest control servicesand conserving biodiversity. However, few studies have considered the relationships of the proportion of flower strips with pest control servicesand crop yield. We conducted a three-year field experiment (including a control: 0% and three treatments: 5%, 10% and 15%) to determine the biocontrol service potential of sowing strips of *Cnidium monnieri* (L.) Cuss flowers adjacent to wheat and to reveal the relationships of the proportion of flower strips with pests, natural enemies, biological pest control services and wheat yield. Compared with the control (0%), flower strips promoted suppression of wheat aphid abundance by ladybugs and parasitoids. With an increasing proportion of flower strips, the predatory ladybug abundance and parasitism rates increased, while aphid abundance decreased. The relative biocontrol services index (RBSI) in the control (0%) was significantly lower than those in the treatments (5%, 10% and 15%). The wheat yield in the control (0%) was significantly lower than those in the treatments (5%, 10% and 15%). With an increasing proportion of flower strips, the RBSI and yield increased. In conclusion, sowing strips of *C. monnieri* flowers adjacent to wheat is a promising measure for providing considerable biocontrol services and increasing wheat yields. Specifically, natural enemies, biocontrol service potential and wheat yield were enhanced with an increasing proportion of flower strips. A 10% or 15% installment of flower strips is suggested to provide substantial biocontrol services and sustain wheat yields.

Key message

- Sowing strips of Cnidium monnieri (L.) flower adjacent to wheat as noncrop habitat in farmland ecosystems significantly promoted ladybugs and parasitoids to suppress wheat aphids.
- The relative biocontrol services index (RBSI) was proposed to quantitatively evaluate the extent or degree of aphid reduction in farmland ecosystems. With the increasing proportion of flower strips, the RBSI increased.
- The wheat yields bolstered with the increasing proportion of flower strips.
- A 10% or 15% installment of flower strips is suggested to provide substantial biocontrol services and sustain wheat yields.

Introduction

Agricultural intensification is an important measure to provide more food for the increasing human population. However, following the advancement of agricultural intensification, the input of harmful chemical pesticides has increased, causing issues such as pest resistance, pest resurgence and pest outbreaks and even having adverse effects on food production, environmental safety, biodiversity and the potential for biological pest control (Abrol and Shankar 2014; Crowder and Jabbour 2014; Emmerson et al. 2016; Geiger et al. 2010). Wheat (*Triticum aestivum* L.) is the third most important crop in China and worldwide, and wheat yield has been promoted by the progress in intensification. Wheat aphids, which

include *Sitobion miscanthi*, *Rhopalosiphum padi* and *Schizaphis graminum*, are the major pests in the main area of wheat grain production across China. These aphids damage wheat by removing its sap, and they generate honeydew and carry yellow dwarf virus, which further contribute to wheat yield and quality losses (Rabbinge et al. 1981). As a consequence, measures must be taken to overcome the issues above, such as lowering pesticide use on a large farmland scale and taking biodiversity protection and biological pest control into consideration to meet global challenges in future farming systems (Crowder and Jabbour 2014; Geiger et al. 2010; Pretty and Bharucha 2015).

Habitat management is a form of protective biological control in which an ecological infrastructure such as noncrop habitat is created to provide adult natural enemies with resources such as food (alternative prey or hosts) and shelter for avoiding adverse conditions (Landis et al. 2000). Exploiting noncrop habitats, especially flower strips, was found to be an effective method for enhancing biological pest control efficiency. For example, wildflower strips increased the species and abundance of natural insects compared with cropped habitats (Haaland et al. 2011) and highly, effectively promoted pest control, enhanced biocontrol services by 16% on average and reduced pest levels below the economic threshold (Albrecht et al. 2020; Tschumi et al. 2016b). Thus, tailored flower strips can be an effective and environmentally friendly agricultural practice for improving natural enemies and pest control stability and a promising management option for coordinating biodiversity conservation and ecological intensification (Tschumi et al. 2016b).

In a simple landscape where the noncrop habitat accounted for less than 20% of the total area, the biodiversity and associated ecological processes were significantly strengthened by the introduction of local habitat, such as set-aside land, but the set-aside management should also being improved to reduce the proportion of noncrop habitat (Tscharntke et al. 2011). In 1993, it was advised to set aside approximately 5–15% of arable land for rotation and at least 7% of arable land to provide ecological services (Albrecht et al. 2007; Aviron et al. 2009; ENCA 2008). However, few studies have revealed the relationships of the proportion of noncrop habitat in farmland ecosystems with pests and their enemies.

Cnidium monnieri (L.) Cuss is a native, wild and annual medicinal herb found throughout China and has been identified as an economically valuable flowering plant in farmland ecosystems that attracts many natural predators, such as ladybeetles (Coleoptera: Coccinellidae) and hoverfly larvae (Diptera: Syrphidae) (Yang et al. 2018). This finding provides a foundation for the development and utilization of this flowering plant species. Our previous studies showed that planting *C. monnieri* adjacent to cotton increases the abundance of predatory enemies (ladybugs, lacewings and hoverflies) and reduces aphid abundance (Yang et al. 2022). However, relevant research is still limited regarding the effects of sowing flower strips adjacent to wheat on aphids and their natural enemies and which proportion of flower strips should be sown in farmland ecosystems. To better understand the biological control effects of sowing strips of *C. monnieri* flowers in wheat farmland ecosystems, we conducted a three-year field experiment from 2020 to 2022 in Jiyang, Shandong Province, including three treatments (5%, 10%, and 15% flower strips) and a control (0% flower strips). The objectives of our experiment were to 1) determine the potential effects of sowing flower strips adjacent to wheat on predators, parasites and wheat aphids; 2)

determine the relationship between the proportion of flower strips and biological pest control services; and 3) determine the relationship between the proportion of flower strips and wheat yield.

Materials and Methods

2.1 Study site and experimental design

The field experiment was carried out on a 90 × 130 m plot of farmland from 2020 to 2022 at the Jiyang Experimental Station of the Chinese Academy of Sciences, Shandong Province, China (116° 58’ E, 36° 58’ N). The research site was in a temperate, seasonal, semihumid monsoon climate, where the mean annual temperatures were approximately 15.5°C (2020), 16.0°C (2021) and 15.9°C (2022). The precipitation was approximately 630.0 mm (2020), 1043.6 mm (2021) and 906.8 mm (2022), concentrated in the summer months.

A completely randomized block design was set up in the experimental field plot. The test field was divided into three blocks with 12 plots overall. The total area of each plot was 380 m^2 (20 m length ×19 m width). A control (0%) plot was completely seeded with wheat (Jimai 22), while the 5% treatment plot was sown with one flower strip (1×20 m) and wheat (18×20 m); the 10% treatment plot was sown with two flower strips (on the east and west margins) and wheat (17×20 m); and the 15% treatment plot was sown with three flower strips (15%, on the east and west margins and in the central plot) and wheat (8×20 m) (Fig. 1). The wheat was sown in late October, while the flower (*C. monnieri*) strips were sown earlier, in late September. A ten-meter isolation belt was left to minimize the interference between plots, and a more than 10 m isolation belt was left between the experimental plot and its surroundings to minimize the interference from the environment (Fig. 1). The field was insecticide-free and managed with conventional management strategies during the whole wheat growing season. All vegetation between plots was removed by a cultivating machine when necessary to minimize the effects from the surroundings. Plants were watered and fertilized with compound fertilizer when needed.

2.2 Insect sampling

The abundance of aphids and parasitized aphids on 20 wheat tillers, as well as the abundance of predatory ladybugs (larvae pupae and adults) on wheat, were counted by visual observation using a 0.25 m^2 (0.5×0.5 m) metal sampling frame. The observation was carried out at distances 1, 2 and 3, which were 5 to 6 meters, 9 to 10 meters and 13 to 14 meters from the western edge of each plot, respectively (observation in the 15% treatment was carried out only at distances 1 and 3). Nine (0%, 5%, 10%) or eight (15%) sampling points were selected randomly at the above three or two distances. The observations were carried out from the booting stage (18 Apr 2020; 20 Apr 2021; 20 Apr 2022) to the milk-ripening stage of wheat (28 May 2020; 30 May 2021; 25 May 2022) with a 7–10 day time interval. The other four observations were carried out at the heading stage (26 Apr 2020; 28 Apr 2021; 28 Apr 2022), flowering stage (5 May 2020; 6 May 2021; 6 May 2022), early grain-filling stage (12 May 2020; 14 May 2021; 16 May 2022) and late grain-filling stage (19 May 2020; 22 May 2021) of wheat.

2.3 RBSI in farmland ecosystems

The biocontrol service index (BSI) was applied to determine the effects of natural enemies on the aphid population. An open treatment where natural enemies could have full access to the aphid-infested plants and a caged treatment where exclusion cages prevented natural enemies from colonizing plants and consuming aphids were adopted in the field experiment. The BSI equation is as follows:

$$\mathrm{BSI} = \frac{\sum_{p=i}^{n} \frac{Acp - Aop)}{Ac_p}}{\mathrm{n}} \quad [1]$$

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 the plot, and *n* is the number of replicates for a given site (Gardiner et al. 2009; Landis et al. 2008).

However, the initial abundance of aphids in the field experiment varied, which made it difficult to fit formula [1] to the data (Ao_0 was equal to Ac_0). To solve this problem, the relative biocontrol service index (RBSI) is proposed, and the equation is as follows:

$$\mathrm{RBSI} = \frac{\sum_{p=1}^{n} \frac{Ac_p - Ac_0 - (Ao_p - Ao_0)}{Acp - Ac_0}}{\mathrm{n}} \quad [2]$$

In the field experiment, an open (semicage) treatment (1 m length × 1 m width × 0.75 m height) and a caged (1 m length × 1 m width × 1.5 m height) treatment were set up with three distance categories (1–3). The semicages and cages were made of nylon mesh (10 μm mesh size), and the cages were fitted with a zipper on one side. Ac_0 is the number of aphids on the caged plant on day 0, Ao_0 is the number of aphids on the open plant on day 0, Ac_p is the number of aphids on the caged plant on day 14, Ao_p is the number of aphids on the open plant on day 14, *p* is the plot, and *n* is the number of replicates in the field experiment.

2.4 Wheat yield measurement

Corresponding to the insect sampling distances, the wheat grain samples for wheat yield measurement were collected manually with a 0.25 m^2 (0.5×0.5 m) sampling frame at distances 1 to 3 at harvest (three samples per distance in 2020 and 2021, four samples in 2022). All the samples were sun-dried before threshing. Later, the thousand-grain weight and wheat yield per unit (0.25 m^2) were measured by a balance with an accuracy of 0.001 g (JA1003, Shanghai, China) and 0.1 g (YH-A 20002, Zhejiang, China), respectively, after being oven-dried to an almost constant weight, where the degree of change in weight in two hours was less than 5% in 2020, 2021 and 2022.

2.5 Statistical analysis

First, the abundance of aphids, total ladybugs and parasitism rate (mummified aphids/total aphids) in the control and treatment plots on the different sampling dates from 2020 to 2022 were analyzed with

one-way ANOVA followed by Fisher's least significant difference (LSD) test to determine the effects of the four proportions of flower strips on the abundance of pests, predators and parasitoids in the wheat farmland ecosystem. The cumulative number of aphids among the five observations and the RBSI were also analyzed with one-way ANOVA followed by Fisher's LSD test. Linear regression models were fit to describe the relationships between the abundance of aphids and their natural enemies (ladybugs and parasitism rates) in the farmland ecosystem.

The abundance of aphids on 20 tillers was converted into that on 100 tillers, and the abundance of predatory ladybugs in the 0.25 m^2 sampling frame was converted into that in a 1 m^2 sampling frame. The wheat yield in the 0.25 m^2 sampling frame was converted to reflect that in 1 m^2 sampling frame as well. The data for each sampling point in a plot were averaged. Before analysis, the aphid abundance data were log-transformed, and the percentage data (including parasitism rates and the RBSI) were arcsine square root-transformed to avoid data heteroscedasticity and ensure the normalization of residuals. All statistical analyses were conducted in SPSS software (PASW Statistics 18). Most of the graphs were generated in GraphPad Prism 8, except those showing the linear regression model results, which were created with OriginPro 2023.

Results

3.1 Effect of flower strip proportion on the abundance of natural enemies and wheat aphids.

3.1.1 Parasitism rate on different sampling dates

The survey of the field experiment showed that on the sampling date of the aphid prepeak stage, the parasitism rate (proportion of parasitized aphids to total aphids) in the control was significantly lower than that in the three treatments on 5 May 2020 ($F_{3,8}$ = 6.820, P = 0.014), 6 May 2021 ($F_{3,8}$ = 17.361, P = 0.001) and 28 April 2022 ($F_{3,8}$ = 9.323, P = 0.005). At the aphid peak stage, the parasitism rate in the control was (extremely in 2021) significantly lower than that in the three treatments (5%, 10% and 15%) on 12 May 2020 ($F_{3,8}$ = 9.046, P = 0.006), 14 May 2021 ($F_{3,8}$ = 225.544, P < 0.001) and 5 May 2022 ($F_{3,8}$ = 17.846, P = 0.001). The multiple comparison results showed that the parasitism rate in the 5% treatment was extremely significantly lower than that in the 10% (P < 0.001) and 15% (P < 0.001) treatments on 14 May 2021. On other sampling dates, the parasitism rate in the control was significantly lower than that in the 10% and 15% treatments ($F_{3,8}$ = 4.484, P = 0.040) in the late grain-filling stage on 19 May 2020. No significant difference was observed between the treatments and the control ($F_{3,8}$ = 3.089, P = 0.090, 22 May 2021; $F_{3,8}$ = 3.099, P = 0.089, 16 May 2022), except that the parasitism rate of the control was significantly lower than that of the 5% (P = 0.026, 16 May 2022), 10% (P = 0.049, 22 May 2021; P = 0.036, 16 May 2022) and 15% (P = 0.023, 22 May 2021) treatments. The parasitism rate in the control was extremely significantly lower than that in the 10% and 15% treatments ($F_{3,8}$ = 9.974, P = 0.004) on 20 April 2021 and that in the control was significantly lower than that in all treatments ($F_{3,8}$ = 5.176, P = 0.028) on 25 May 2022 (Fig. 2).

3.1.2 Abundance of ladybugs on different sampling dates

The ladybugs on wheat included *Propylaea japonica* (Thunberg) (Coleoptera: Coccinellidae), *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae), *Hippodamia variegata* (Goeze) (Coleoptera: Coccinellidae) and *Coccinella septempunctata* (L.) (Coleoptera: Coccinellidae). At the aphid peak stage, the abundance of total predatory ladybugs (including larvae, pupae and adults) in the control was significantly lower on 12 May 2020 ($F_{3,8}$ = 8.119, P = 0.008) and 14 May 2021 ($F_{3,8}$ = 7.357, P = 0.011) and extremely significantly lower on 6 May 2022 ($F_{3,8}$ = 21.835, P < 0.001) than that in the three treatments (5%, 10% and 15%). The multiple comparison results showed that the abundance of total predatory ladybugs in the 10% treatment was significantly lower than that in the 5% (P = 0.009) and 15% (P = 0.015) treatments. On other sampling dates, the abundance of total ladybugs in the control was significantly lower than that in the three treatments on 5 May 2020 ($F_{3,8}$ = 14.901, P = 0.001). At the aphid postpeak stage, the abundance of total ladybugs in the control was significantly lower than that in the treatments on 19 May 2020 ($F_{3,8}$ = 14.729, P = 0.001), 22 May 2021 ($F_{3,8}$ = 6.635, P = 0.015) and 16 May 2022 ($F_{3,8}$ = 5.084, P = 0.029), with that in the 5% treatment being significantly lower than that in the 15% treatment (P = 0.032) on 22 May 2021. The abundance of total predatory ladybugs in the control was significantly lower than that in the 15% treatment on 18 April 2020 ($F_{3,8}$ = 5.469, P = 0.024), and it was extremely significantly lower than that in the treatments (5%, 10% and 15%) on 25 May 2022 ($F_{3,8}$ = 22.182, P < 0.001) (Fig. 3).

3.1.3 Abundance of aphids on different sampling dates

The cumulative abundance of wheat aphids in the treatments (5%, 10% and 15%) was extremely significantly lower than that in the control (0%) ($F_{3,8}$ = 9.504, P = 0.005, 2020; $F_{3,8}$ = 75.392, P < 0.001, 2021; $F_{3,8}$ = 25.343, P < 0.001, 2022), and that in the 10% and 15% treatments was significantly lower than that in the 5% treatment (P = 0.003, P = 0.001) (Fig. 4 (a), Fig. 4 (c), Fig. 4 (e)).

On different sampling dates, the abundance of wheat aphids in the treatments (5%, 10% and 15%) was extremely significantly lower than that in the control (0%) on 12 May 2020 ($F_{3,8}$ = 7.642, P = 0.010), 14 May 2021 ($F_{3,8}$ = 43.854, P < 0.001) and 6 May 2022 ($F_{3,8}$ = 6.841, P = 0.013) (aphid peak stage). The multiple comparison results showed that the abundance of aphids in the 5% treatment was significantly higher than that in the 10% (P = 0.012) and 15% (P = 0.001) treatments in 2021. There were no significant differences between the treatments and the control ($F_{3,8}$ = 2.289, P = 0.155), except that the aphid abundance in the 15% treatment was significantly lower than that in the control (P = 0.039) on 5 May 2020, the aphid abundance in the 10% and 15% treatments was significantly lower than that in the 5% treatment and the control on 6 May 2021 ($F_{3,8}$ = 8.388, P = 0.007), and the aphid abundance in the 10% and 15% treatments was significantly lower than that in the control ($F_{3,8}$ = 4.108, P = 0.049) on 28 April 2022 (aphid prepeak stage). On other sampling dates, the aphid abundance in the 10% and 15% treatments was significantly lower than that in the 5% treatment and the control on 20 April 2021 ($F_{3,8}$ = 6.124, P = 0.018), and that in all treatments (5%, 10% and 15%) was significantly lower than that in the control on 21 April 2022 ($F_{3,8}$ = 4.857, P = 0.033) and on 25 May 2022 ($F_{3,8}$ = 18.693, P = 0.001), with that

in the 15% treatment being significantly higher than that in the 5% (P = 0.012) and 10% (P = 0.010) treatments. The abundance of aphids in the control was significantly higher than that in the treatments ($F_{3,8}$ = 10.646, P = 0.004), with that in the 5% treatment being significantly higher than that in the 10% treatment (P = 0.028), on 28 April 2021 (Fig. 4 (b), Fig. 4 (d), Fig. 4 (f)).

3.2 RBSI under the four flower strip proportions

The RBSI significantly differed between the treatments (5%, 10% and 15%) and the control 14 days after the cage experiment was established ($F_{3,8}$ = 19.970, P < 0.001, 2021; $F_{3,8}$ = 79.339, P < 0.001, 2022). The multiple comparisons results showed that the RBSI in the control was significantly lower than that in the 5% treatment (P = 0.009, 2021; P < 0.001, 2022), 10% treatment (P < 0.001, 2021; P < 0.001, 2022) and 15% treatment (P < 0.001, 2021; P < 0.001, 2022), and the RBSI in the 5% treatment was lower than that in the 10% treatment (P = 0.017, 2021; P=0.038, 2022) and 15% treatment (P = 0.009, 2021; P = 0.038, 2022). (Fig. 5 (a) and Fig. 5 (b)).

3.3 Relationships between aphids and their natural enemies in the wheat farmland ecosystem

A negative linear relationship was detected between parasitism rates and wheat aphids (y = - 7923 * x + 2.859, P < 0.001) (Fig. 6 (a). A negative linear relationship was found between ladybugs and aphids (y = - 0.9703 * x + 2.8938, P < 0.001) (Fig. 6 (b)). The abundance of aphids decreased with an increasing abundance of predators and parasites.

3.4 Wheat yields under the four flower strip proportions

The thousand-grain weight in the control was extremely significantly lower than that in the three treatments (5%, 10% and 15%) ($F_{3,8}$ = 12.280, P = 0.002; $F_{3,8}$ = 5.981, P = 0.019; $F_{3,8}$ = 21.408, P < 0.001) in 2020, 2021 and 2022, with that in the 5% treatment being significantly lower than that in the 10% (P = 0.044, 2022) and 15% (P = 0.031, 2020; P = 0.005, 2022) treatments (Fig. 7 (a)). The wheat yield (1 m^2) in the control (0%) was significantly lower than that in the three treatments (5%, 10% and 15%) ($F_{3,8}$ = 21.698, P < 0.001; $F_{3,8}$ = 16.864, P = 0.001; $F_{3,8}$ = 50.782, P < 0.001) in 2020 and 2021, with that in the 5% treatment being significantly lower than that in the 10% (P = 0.009, 2022) and 15% (P = 0.045, 2020; P = 0.001, 2022) treatments (Fig. 7 (b)).

Discussion

Habitat management is an effective method for the conservation of biodiversity, natural enemy protection and biological pest control (Landis et al. 2000). Designing the composition and configuration of farmland landscapes is recommended to maintain the diversity of generalist (e.g., predatory ladybugs) and specialist (e.g., parasites) enemies (Martin et al. 2015; Tscharntke et al. 2008). In a simple farmland landscape where crops accounted for more than 80% of the farmland (Zhao et al. 2013a), flowering

plants were used to inhibit the abundance of pests by enhancing the abundance of predatory enemies such as ladybugs, hoverflies (Cai et al. 2021; Ribeiro and Gontijo 2017; Yang et al. 2022; Zhang et al. 2022), lacewings (Herrera et al. 2022; Zhang et al. 2022) and parasitic enemies (Herrera et al. 2022; Yang et al. 2019), which enhanced the biological control capacity of the landscape ecosystem (Haaland et al. 2011; Tschumi et al. 2016b). In our study, we demonstrated that sowing strips of *C. monnieri* flowers adjacent to wheat in farmland promoted the abundance of natural enemies (ladybugs and parasitoids) and suppressed the abundance of wheat aphids. With an increasing proportion of flower strips, the abundance of enemies increased, and that of aphids decreased. The above results may be explained by three factors. Firstly, *C. monnieri* evaporated the plant volatile (1,2-diethylbenzene and pdiethylbenzene), which attracted the ladybugs move ahead into the field (Cai 2020; Cai et al. 2021; Zhang et al. 2022). Secondly, flowers of *C. monnieri* helping increase the abundance of *Harmonia axyridis* offspring, shorten the growth period of its larvae, prolong its life span(Su et al. 2023; Yang et al. 2021). Thirdly, the flowers enhance the parasite rates and prolong the life span of parasitoids (Su 2022). Linear regression results revealed a negative relationship between enemies (ladybugs and parasitoids) and aphids, which indicated that the promotion of natural enemies helps suppress aphids (Zhang et al. 2022) (Fig. 6).

The RBSI is an improvement of the BSI proposed to quantitatively evaluate the extent or degree of pest reduction in our system. It can be used in situations where the initial quantities of aphids are not exactly the same (but similar) in field experiments (Gardiner et al. 2009; Landis et al. 2008). In our study, sowing flower strips in wheat agroecosystems improved the RBSI, which indicates that floral resources can help to promote biological control services (Gardiner et al. 2009; Landis et al. 2008; Seree et al. 2022; Yang et al. 2022; Zhao et al. 2013a) (Fig. 5). Regarding wheat yields, according to two indicators (thousand-grain weight and wheat yield in 1 m^2), we found that planting flower strips could help sustain field yields in the agroecosystem. With an increasing proportion of flower strips, crop production improved (Gagic et al. 2017; Rundloef et al. 2018; Tschumi et al. 2016a), and sowing 10% and 15% flower strips adjacent to wheat was significantly superior to sowing 5%. Overall, 10% and 15% flower strips in agroecosystems can provide similar ecological services and sustain equivalent wheat yields.

The diversification of agroecosystems enhances the diversity of natural enemy communities and biological pest control (Batary et al. 2011; Crowder and Jabbour 2014). In general, biological pest control services are provided by natural enemies in the process of food production. The solution for improving the biological control capacity demands that we maintain a better balance among landscape components. Habitat management, which depends on the design and arrangement of different habitats, is an available method for creating a beneficial environment for enemies but that is harmful to pests (Landis et al. 2000; Zhao et al. 2013b). The high connectivity of crop–noncrop mosaics may favor long-term protective biological control and sustainable crop production, but experimental evidence for detailed recommendations is needed to determine the composition and configuration in agricultural landscapes (Tscharntke et al. 2008). Simulations and empirical studies have shown that pest pressure decreases with increasing area of noncrop habitat, and more research is needed to find the threshold of noncrop habitat acreage (Bianchi and van der Werf 2005). In a simple landscape where the noncrop habitat was

less than 20%, the biodiversity and associated ecological processes were significantly strengthened by the introduction of local habitat, such as set-aside land (Tscharntke et al. 2011), and the abundance of predatory enemies (Syrphidae) and aphid mummies increased with an increasing proportion of flowering species (Seree et al. 2022). Although some researchers argued that the set-aside habitat would promote pests and other harmful species (Firbank et al. 2003; Shield and Bacon 1998), set-aside land was beneficial for biodiversity, especially spiders and birds, while attracting few or no pest species (Van Buskirk and Willi 2004). Twenty percent noncrop habitat seems to be a rough threshold for the promotion of biodiversity and sustainable services; however, future set-aside land management should aim to reduce the proportion of noncrop habitat in farmland ecosystems (Holzschuh et al. 2008; Tscharntke et al. 2011) and use more economically valuable plants (ENCA 2008). According to our study, sowing 10% flower strips in the farmland ecosystem was a rough threshold for providing sufficient biological pest control services and sustaining wheat yields, which differed from the suggestion that applying 5–10% flower strips in agricultural landscapes would enhance the number of natural beneficial arthropods (Abivardi 2008).

Sowing flower strips in farmland landscapes is a promising strategy for increasing landscape diversity in intensified farmland ecosystems in order to enhance both biological control services and food production (Albrecht et al. 2020; Gardiner et al. 2009; Haaland et al. 2011; Landis et al. 2000). An increased proportion of flower strips could help to improve food production by enhancing biocontrol services, promoting pollination (Albrecht et al. 2020; Gagic et al. 2017; Rundloef et al. 2018; Tschumi et al. 2016a; Uyttenbroeck et al. 2015) and reducing the use of pesticides and other associated risks (Frank 2010). Overall, the selection of flowering plant species and the spatial arrangement of flower strips and crops are two important aspects of enhancing biological pest control, pollination services and food production (Ouyang et al. 2016). In addition, *C. monnieri* is a flowering plant used in traditional herbal medicine with known phytochemistry, pharmacology, and toxicity. Its fruits contain at least 350 extractable compounds, conferring increased economic value to *C. monnieri* (Li et al. 2015). Its highly adaptable and manageable trait (once its seeds are sown onto the soil, the fruit matures can sprout after falling down onto the soil) makes it useful for a wider range of applications. To some extent, the economic value of flowering plants can offset the loss of yields from noncrop habitat land use and make it easier to promote the application of flower strips in agricultural production. The future selection on the noncrop resource should consider the adaptable and manageable trait to better play the application value in the agricultural production and biodiversity conservation processes.

Conclusion

The application of strips of *C. monnieri* flowers in wheat farmland ecosystems is a promising and beneficial practice for promoting natural enemies, enhancing ecological control and sustaining crop yields. *C. monnieri* has the potential to be applied in wheat farmland ecosystems to provide substantial biological pest control services. The proportion of natural habitat in agricultural ecosystems is suggested to be 10% or 15% because such a proportion can provide substantial biological pest control services and sustain crop yields. The findings of our study provide some evidence for recommending a suitable

proportion of noncrop habitat in a larger agricultural production area that better balances food production activities and biodiversity conservation. However, future studies should also seek to answer the question regarding control distance and field layouts in the *C. monnieri* and wheat farmland ecosystem and the combination effects of *C. monnieri* and other noncrop plants (e.g.flowering plants, banker plants and repellent plant) to play the better role in pest control and sustain crop yields in wheat and other farmland ecosystems and the additional economic value of the noncrop plants.

Declarations

Author contribution statement

FG acquired the funding and performed in supervision. FG, FO, XRZ and YYY took part in conceptualization. XYL collected the field data. XYL and ZL performed the statistical analyses. XYL wrote the original draft. FG, FO, ZL, XRZ, YYY and XYL took art in writing, reviewing and editing. All the authors revised and approved the manuscript.

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Foundings

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflict of 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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Figures

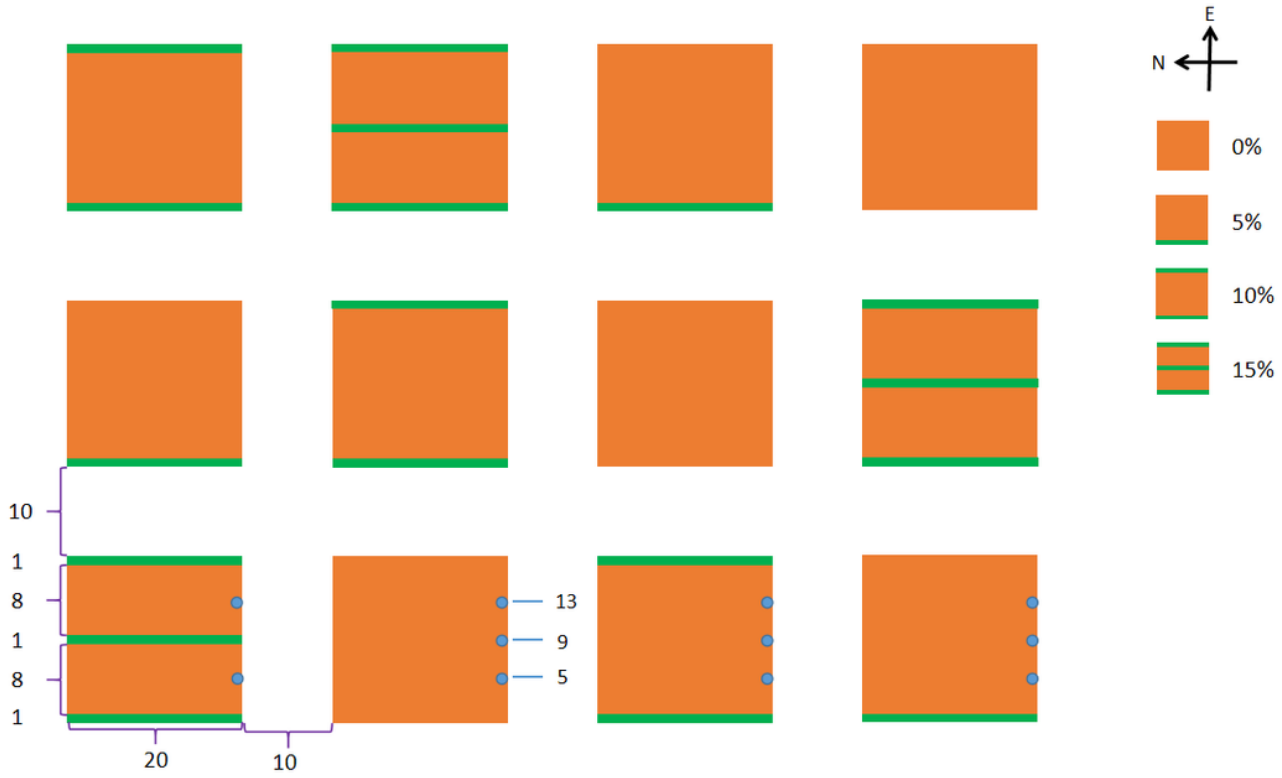


Figure 1

Spatial layout of the farmland experiment and the location of flower strips from2020 to 2022. The field measured 90 m ×130 m and was divided into twelve 20 m × 19 m plots (The green:flower strips; brown: wheat; blue: distance categories of 1-3 (5 m, 9 m, and 13 m); isolation belt: 10 m).

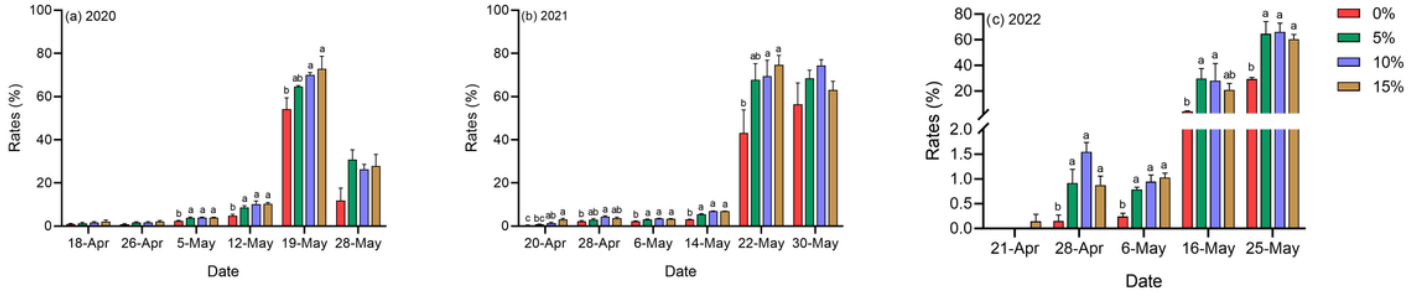


Figure 2

Parasitism rate (percentage of parasitized aphids among total aphids; mean ± SE; *N = 3*) on different sampling dates under four flower strip proportions in 2020 (a), 2021 (b) and 2022 (c). a, b and c indicate significant differences among the treatments.

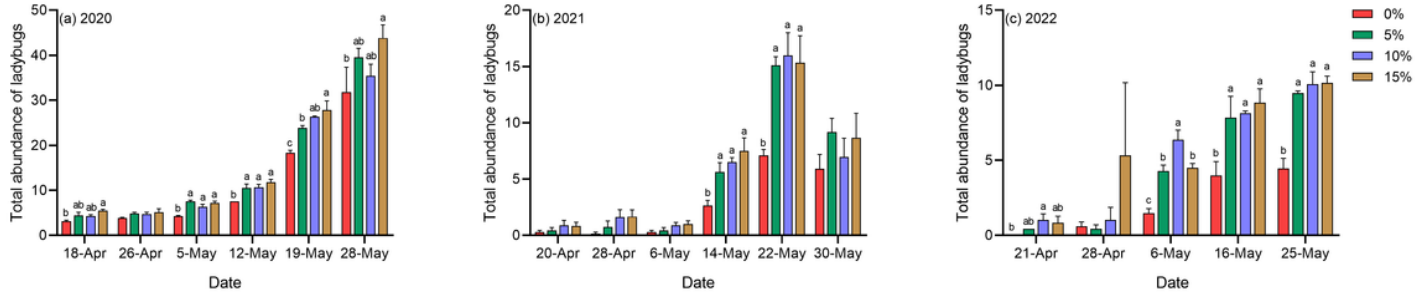


Figure 3

Total abundance dynamics of predatory ladybugs (mean ± SE; *N = 3*) on different sampling dates under four flower strip proportions in 2020 (a), 2021 (b) and 2022 (c). a, b and c indicate significant differences among the treatments.

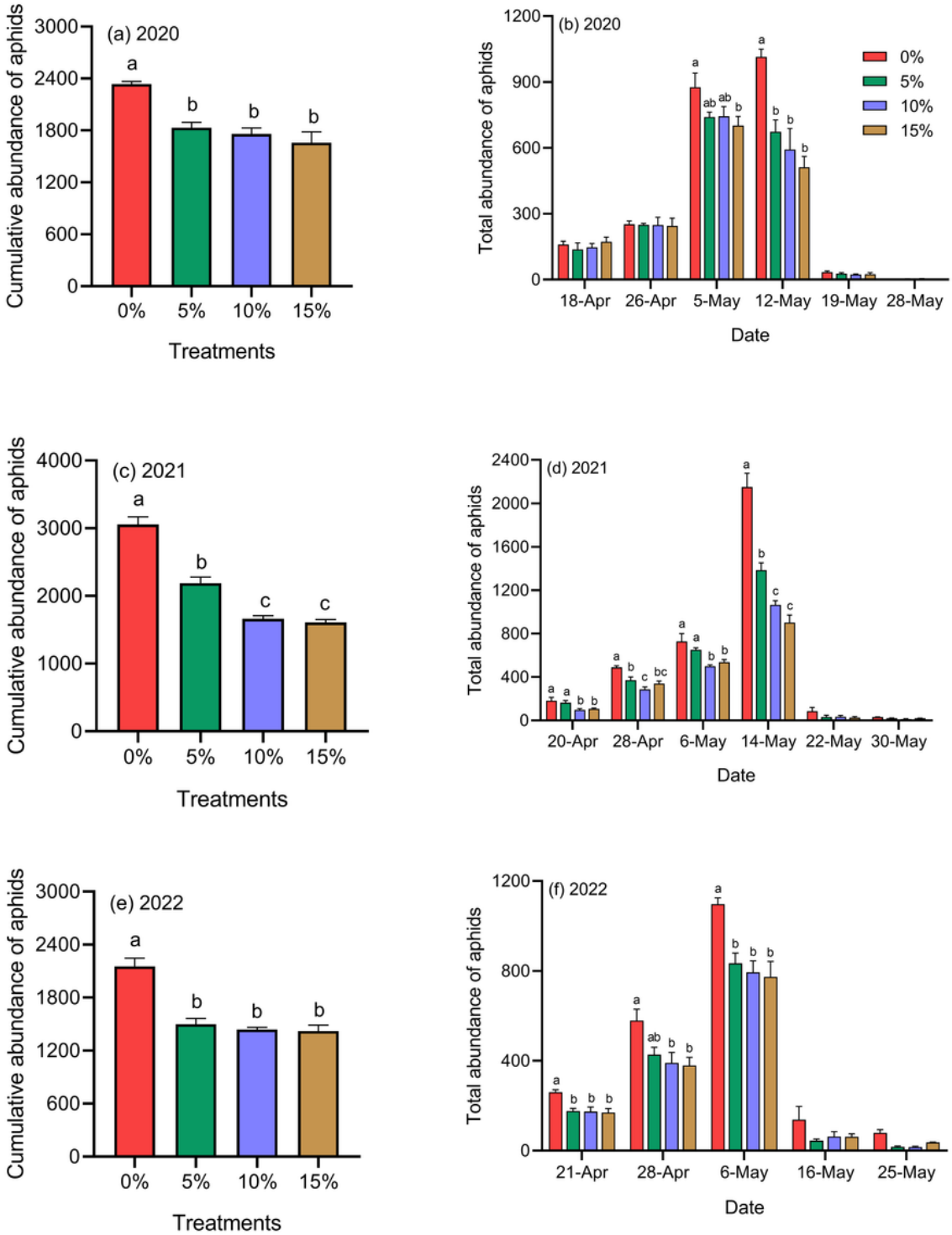


Figure 4

Abundance dynamics (mean ± SE; *N = 3*) of wheat aphids in 100 wheat tillers under four flower strip proportions on different sampling dates. The one-way ANOVA and multiple comparisons result of the cumulative abundance of aphids (5 times) among the four planting proportions in 2020, 2021 and 2022 areshown in (a), (c) and (e) and on different sampling dates shown in (b), (d) and (f). a, b and c indicate significant differences among the four proportions.

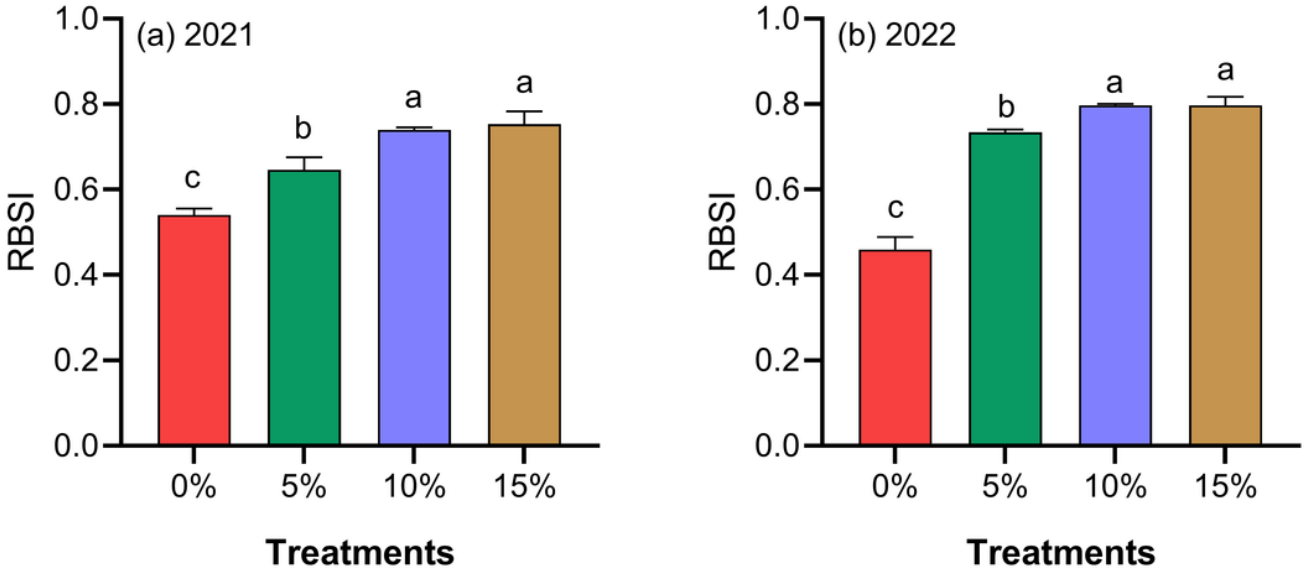


Figure 5

Relative biocontrol service index (RBSI; mean ± SE; *N = 3*) under four flower strip proportions in 2021 (a) and 2022 (b). a, b and c indicate significant differences among the four proportions.

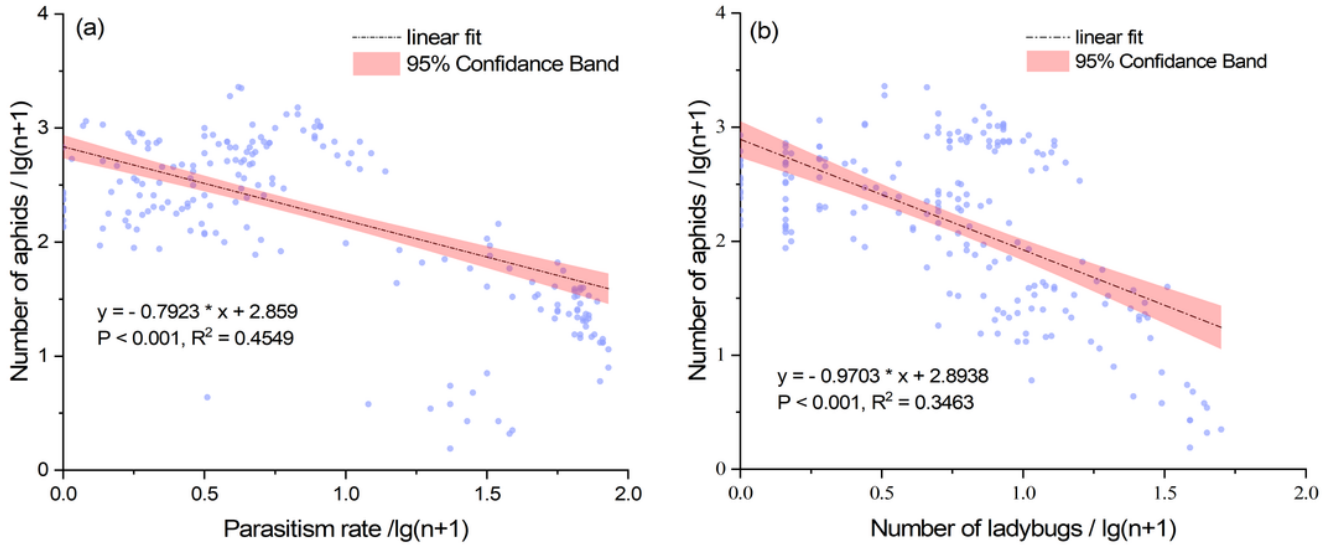


Figure 6

Linear regression models depicting the relationships between the abundance of aphids and the total abundance of ladybugs in 2020 to 2022 (a) and the parasitism rate in 2020 to 2022 (b).

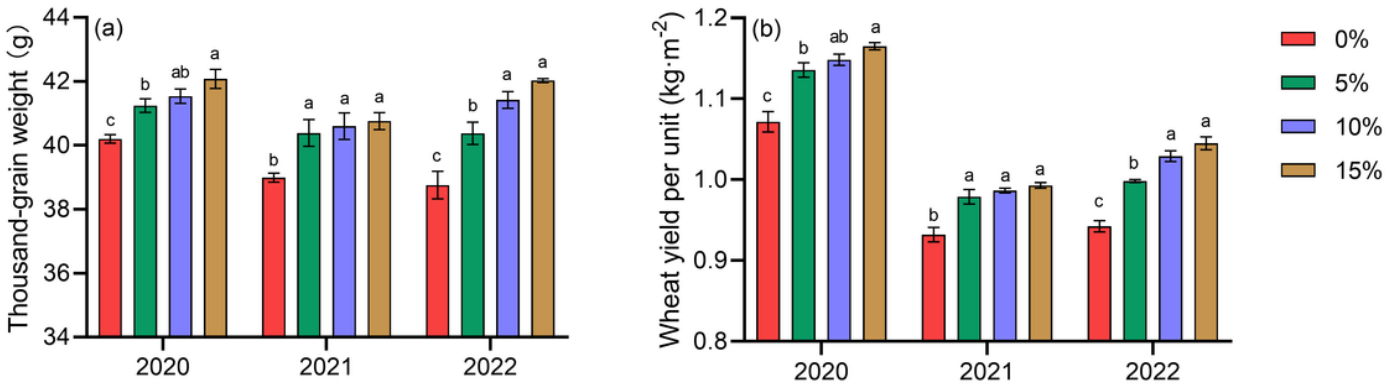


Figure 7

Thousand-grain weight (a) and wheat yield per 1 m^2 (b) in 2020, 2021 and 2022 (mean ± SE; *N = 3*). a, b and c indicate significant differences among the four proportions.