Change in ladybeetle abundance and biological control of wheat aphids over time in agricultural landscape

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ABSTRACT

The improvement of biocontrol services provided by natural enemies is important for realizing sustainable agriculture. While it has been well demonstrated that landscape context affects the occurrence of natural enemies in agricultural ecosystems, the response of natural enemies and their ability to suppress pest population growth over time has rarely been studied in relation to landscape composition and diversity. In this study, we investigated natural enemy (ladybeetle) and pest (wheat aphids) population abundance in wheat fields in the early period (defined as the main period for aphid colonization) and the late period (i.e., the main period for aphid reproduction) in different landscapes. Non-crop habitats surrounding wheat fields were found to enhance ladybeetle abundance. More specifically, the proportion of dwellings and woodlots were positively correlated with ladybeetle abundance in early period, and those of fallow and woodlot habitats were positively associated with ladybeetle abundance in late period. The most predictive spatial scales of ladybeetle abundance were landscape features within 0.5 and 2.0 km of wheat fields in the early and late periods, respectively. In contrast with the significantly negative correlation between ladybeetle abundance and aphid population growth during the late period, the relative low density of ladybeetles in the early period appeared to have no effect on aphid population growth. These findings suggest that non-crop habitats have differing effects on ladybeetle populations, both in their spatial scale and over time, and the continuity of functional habitat types is essential to support ladybeetle populations. While ladybeetles do indeed suppress aphid growth in the later part of the cycle, aphid control is also dependent on early colonization and constrained by external circumstances.

1. Introduction

Land-use patterns are well known to have significant effects on biological diversity and ecosystem services provided by beneficial insects in agricultural landscapes (Balvanera et al., 2006; Bianchi et al., 2006; Fahrig et al., 2011). The biological control of pests by natural enemies is one of the most important ecosystem services that suppress pest population and reduce the need for chemical pesticides (Naylor and Ehrlich, 1997; Landis et al., 2000; Losey and Vaughan, 2006; Zhang et al., 2007). Changes to landscape patterns caused by modern agricultural production methods and adjustment of cropping structures affect the abundance of pests and natural enemies, as well as the magnitude of biological control contributed by natural enemies in agricultural ecosystems (Chaplin-Kramer et al., 2011; Veres et al., 2013). For example, the recent expansion of main crop production for fuel and food security restructured the agricultural landscape, and had a negative effect on biological control services and increased the use of insecticides (Landis et al., 2008; Gardiner et al., 2009a; Meehan et al.,

2011; Zhao et al., 2015; Gurr et al., 2016; Landis, 2017). To optimize the level of natural biological control services, a landscape perspective is needed (Tscharntke et al., 2005).

In agricultural landscapes, non-crop habitats (such as woodlot, fallow land, and vegetation around dwelling) frequently help natural enemies complete their lifecycles (Landis et al., 2000; Pfannenstiel et al., 2012; Morandin et al., 2014). Landscapes with a high proportion of non-crop habitats usually show greater natural enemy abundance, diversity and better levels of biological control of pests by providing overwintering habitats, alternative prey, and other food resources (pollen or nectar) (Landis et al., 2000; Wackers, 2005). Nevertheless, these positive effects vary over time, with distance from the crop fields, and among insect species (Gardiner et al., 2009b; Chaplin-Kramer et al., 2013; Alignier et al., 2014). Habitats in a landscape mosaic serve different functions to different natural enemies, which differ depending on the spatial scale analyzed (Rusch et al., 2010; Vandermeer et al., 2010; Schellhorn et al., 2015). The common spatial scale of landscape features for predicting natural enemy population have been reported ranging

from 0.5 to 2.0 km (Gardiner et al., 2009a; Mitchell et al., 2014; Dong et al., 2015; Koh and Holland, 2015). Furthermore, the effect of landscape elements on pests and biological control also differ over time, further confounding the link between ecological services and landscape features (Roschewitz et al., 2005; Chaplin-Kramer et al., 2013; Midega et al., 2014). For example, Thies et al. (2005) reported that perennial habitats in complex landscapes enhanced parasitism of aphids in wheat at the milk-ripening stage, but facilitated aphid colonization at the wheat flowering stage, resulting in similar aphid densities across landscape types. Therefore, it is essential to identify the functions of different habitats at various periods and at different spatial scales, to promote the abundance of natural enemies and suppress pest densities at a particular stage (Kennedy and Storer, 2000; Chaplin-Kramer et al., 2011).

Suppressing pests' population growth and maintaining pest densities under the economic threshold is the goal of biological control (Murdoch et al., 1985; Ge, 2001), but few studies have used these metrics to evaluate landscape functions, especially for population dynamics (Chaplin-Kramer, 2010; Chaplin-Kramer et al., 2011; Chisholm et al., 2014). Evaluating the ecosystem services of a landscape based on pest density is difficult, not least because pest density varies from year to year, but also because landscape features affect pests in conflicting ways (Roschewitz et al., 2005; Thies et al., 2005; Carrière et al., 2012; Chaplin-Kramer et al., 2013; Plećaš et al., 2014). Fortunately, the population dynamic of pests summarizes the immigration, emigration, birth and death rate of the species, and in addition represents real conditions in the field (Chaplin-Kramer et al., 2011; Schellhorn et al., 2014). Compared with pest absolute density, differences in pest population growth across landscape gradients over time provide a reasonable method of detecting how landscape patterns affect the ecosystem services of pest control (Pulliam and Danielson, 1991).

Here, we investigated effects of landscape composition and diversity on abundance of the dominant natural enemy group (ladybeetles) and aphid population growth rate at two different stages in wheat fields. In northern China, aphids mainly including *Rhopalosiphum padi* (L.), *Sitobion avenae* (Fabricius), *Schizaphis graminum* (Rondani) and *Metopolophium dirhodum* (W.) are the critical herbivore pests in winter wheat fields, and ladybeetles predominantly *Propylea japonica* Thunberg, *Harmonia axyridis* Pallas, and *Coccinella septempunctata* L. are the most important natural enemies (Dong et al., 2015; Zhao et al., 2015). Each spring, aphids disperse from their overwintering locations, colonize wheat fields at the stem elongating stage, and reach peak populations at the flowering stage. Natural enemies establish their community and provide biological control several days after aphid colonization (Zhang et al., 2013). We surveyed population density of ladybeetles and wheat aphids in wheat fields in northern China in 2015 and 2016. Our goal was to determine: (1) what effect non-crop habitats in the surrounding landscape had on the occurrence of natural enemies, and how these effects vary over time and across spatial scales; (2) whether landscape diversity benefits ladybeetle population abundance in wheat fields; and (3) what degree of suppression ladybeetles in wheat fields have on aphid population growth.

2. Methods

2.1. Study sites

From mid-April through mid-May in 2015 and 2016, we surveyed the abundance of ladybeetles and aphids in 24 wheat fields (17 fields in 2015 and 7 in 2016) in Hebei Province, near Beijing and Tianjin Cities in northern China (Fig. S1). The study area is one of the major winter wheat producing area in China with a climate of temperate semi-humid monsoon, and landscape mosaic mainly consist of crop lands, fallow lands, shelterbelts and villages during the spring-summer season. The fields selected for study along a gradient of landscape compositions ranging from monotonous landscapes dominated by wheat fields to complex landscapes with large area of non-crop habitats. Each year, the minimum distance between any two neighboring fields was more than 5 km. Fields ranged from 0.5 to 34.3 ha (average = 9.3), and no insecticides were applied on any of the fields during the sampling period.

2.2. Ladybeetle and aphid sampling

Aphid and ladybeetle densities were sampled three times each year, being from April 16 to May 13, in 2015, and from April 24 to May 18, in 2016, at intervals of about 10 days. We split the data into two periods: the early period (late April-early May, at wheat elongating and the period when aphids colonize into wheat fields) and the late period (early to mid-May, at wheat flowering and the main period of aphid reproduction). More specifically, the early period was in late April of 2015 and from late April to early May in 2016, respectively, and the late period ranged from early May to middle May in both years. At each site, the wheat field was randomly divided into three plots (20 × 30 m^2 for each, an interval of 10 m between two neighboring plots) and the population abundances of aphids and ladybeetles were surveyed by visual observation in five randomly-selected points within each plot, in which 10 tillers were surveyed for each point. Each selected tiller was at least 10 m from any field edge to minish edge effects (Janković et al., 2017; Pfister et al., 2017), and these counts were then converted into individuals per 100 tillers.

From the insect sampling data, we calculated aphid and ladybeetle densities in each time period. To measure aphid population growth in each time period, we subtracted the $\log_{10}(x + 1)$-transformed aphid densities at the end of each period from that at the beginning of each period. For ladybeetle density, we summed the number of adults and larvae within each time period.

2.3. Landscape investigation

The geographical coordinates of the center of each wheat field were collected using a handheld GIS unit (Model MG758, Beijing UniStrong Science & Technology Co., Ltd., China). We obtained satellite imagery for the surrounding areas out to a radius of 2.0 km from Google Earth maps using these coordinates, and printed imagery maps, marking the land cover types on the maps through ground verification to eliminate any inaccuracy caused by land use changes between the image date and study period (Liu et al., 2016a). We then digitized the extent of each of the habitat types surrounding each study site, summarizing the data at each of four spatial scales ranging from 0.5 to 2.0 km at 0.5 km intervals ranging outward from the field center, using ArcGIS 10.2 software (ESRI, 2013). We classified the land use within these zones into 12 categories: wheat, vegetables, greenhouses, fruit trees, pea, maize, poplar trees, reforested areas, fallow land, water bodies, roads, and dwellings.

From landscape habitat data, we calculated a landscape diversity index that was dependent not only on the number of habitats in each landscape, but also on the evenness of each kind of habitat (Wu, 2007; Dale and Fortin, 2014). Specifically, we calculated Simpson's diversity index (D) to reflect the diversity of landscape context for each spatial scale, the equation for Simpson's index is

$$D = \frac{1}{\sum (p_i)^2},$$

p_i is the proportion of habitat in the ith land-use category based on the 12 landscape categories (Gardiner et al., 2009a). The proportion of each category and Simpson's index at each radius were calculated using FRAGSTATS 4.2 (McGarigal et al., 2012).

2.4. Statistical analysis

We conducted a principal components analysis (PCA) to reduce the