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Do diverse landscapes provide for effective natural pest control in subtropical rice?

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Abstract

1. While the biocontrol potential of natural enemies is well established, it is largely unknown how landscape-mediated effects on pest and natural enemy communities impact the cascade of biocontrol potential, crop injury, yield and profit, taking into account crop management and surrounding landscape composition.
2. We compared natural biocontrol with chemical control according to local farmers' practice, across the 'full cascade' from natural enemy and pest abundance to crop injury, yield loss, yield and economic performance. This 2-year study was conducted in 20 rice fields embedded in a gradient of landscapes from crop-dominated to semi-natural habitat-dominated, in subtropical China, the world's largest rice-producing region.
3. Natural enemies suppressed brown planthopper population growth in unsprayed plots, irrespective of landscape composition. However, crop injury was lower in pesticide treated plots than in unsprayed plots, and yields in sprayed plots were 20% higher than in unsprayed plots. Nevertheless, pesticide applications were only profitable in less than half of the cases when only costs for pesticides were considered, and in less than one third of the cases when costs for pesticides and labour were considered.
4. *Synthesis and applications*. Our findings question the cost-effectiveness of current chemical-based pest management in farming, and highlight opportunities for more ecologically based pest management strategies based on the widespread activity of natural enemies. Pest damage and biocontrol, however, are largely independent from the landscape context, which might be due to the small-scale character of Chinese rice landscapes. To maintain high levels of biocontrol, conserving this small-scale character appears more important than increasing the proportion of semi-natural habitat.

Yi Zou and Joop de Kraker have contributed equally to this manuscript.

KEYWORDS
agroecosystem, biological pest control, chemical, China, natural enemy, pest management, planthopper, yield

1 | INTRODUCTION

Rice is the staple food for two billion people in the world and higher yields are needed to keep up with a global increase in rice demand of 26% in the next 25 years, resulting from population growth (GRiSP, 2013). Therefore, rice production systems are undergoing further intensification, involving simplification of landscapes and increased inputs of fertilizers and pesticides (GRiSP, 2013). It is critical, however, that the production system, including the management of pests, remains sustainable and ecologically sound. The basis for sustainable pest management in rice is 'conservation biocontrol', that is, conserving locally occurring natural enemies to suppress pest populations (Gallagher, Ooi, Mew, Borromeo, & Kenmore, 2002; Matteson, 2000; Savary, Horgan, Willocquet, & Heong, 2012). Maintaining diverse landscapes with semi-natural habitats is considered an important mechanism for natural enemy conservation (Bianchi, Booij, & Tscharntke, 2006; Chaplin-Kramer, O'Rourke, Blitzer, & Kremen, 2011; Rusch et al., 2016; Tscharntke et al., 2007), and recently calls have been made for 'landscape manipulation' to control, amongst others, major rice pests in China (Zhao, Sandhu, Ouyang, & Ge, 2016). However, the effects of landscape diversity on pest control are not always significant and positive (Begg et al., 2017; Rusch, Bommarco, & Ekbom, 2017), and the relative importance of landscape diversity in conservation biocontrol may vary dramatically depending on type of crop, pest, natural enemy, crop management and landscape structure (Tscharntke et al., 2016).

Thus far, in tropical and subtropical Asian rice production systems, the relationship between landscape diversity and natural biological pest control has been studied only to a limited extent, and a sound knowledge base to deploy landscape diversity to enhance rice pest control is still lacking. Most empirical work has concentrated on the local scale of the rice field including the vegetation immediately surrounding it. Recently, for example, it was demonstrated that planting nectar-producing plants around rice fields in Thailand, Vietnam and China resulted in improved pest control, also in economic terms (Gurr et al., 2016), and similar results were reported for planting border crops in peri-urban rice systems in Shanghai, China (Wan et al., 2018). Only a handful of studies have addressed the effects of the wider landscape setting on pests and natural enemies in rice, and all were conducted in tropical Southeast Asia (Dominik et al., 2017; Dominik, Seppelt, Horgan, Settele, & Václavík, 2018; Heong, Hijmans, Villareal, & Catintig, 2010; Settle et al., 1996; Wilby et al., 2006). None of these studies included assessments of pest control level, crop injury, yield loss or economic performance of pest control. Moreover, landscape composition was in most studies represented in a relatively crude manner by percentage rice cover or agricultural land, based on visual assessments or low-resolution satellite data.

Landscapes can be conducive for natural biological pest control when early immigration of natural enemies in crops is fostered (Schellhorn, Bianchi, & Hsu, 2014). Settle et al. (1996) studied the dynamics of rice arthropods in two contrasting landscapes in Java, Indonesia. These landscapes differed in three major aspects: presence of non-rice habitats, synchrony of rice planting, and length of a dry fallow between rice crops. In one landscape, there was a long and extensive absence of alternative habitats for arthropods after harvest of the rice crop, whereas in the other landscape, alternative habitats (both rice and non-rice) were almost always nearby. In the latter case, generalist predators arrived in the rice fields soon after transplanting, first feeding on detritivore prey and later on herbivore prey. In the first case, these predators arrived much later and were less capable of suppressing rice pests. However, studies of arthropod diversity and abundance in rice fields in Vietnam (Wilby et al., 2006) and the Philippines (Dominik et al., 2017, 2018; Heong et al., 2010) only yielded weak and variable relationships between landscape composition and abundance and diversity of arthropod functional groups. This indicates that in landscapes with continuous rice cropping and low enough levels of pesticide use expansion of monoculture rice does not automatically impact diversity and functioning of the arthropod community and natural pest control in rice (Sann et al., 2018; Wilby et al., 2006). In contrast to the weak associations between the arthropod community structure in rice fields and landscape composition measured at a relatively small scale (in a 100–750 m radius), both Heong et al. (2010) and Dominik et al. (2018) found significant differences in arthropod community structure between major rice growing regions in the Philippines. These regions, however, do not only differ in large-scale landscape composition, but also in climate, cropping systems and crop management.

Given their focus on tropical rice, rather limited scope and/or low resolution, these studies have left the question unanswered whether diverse landscapes may provide for effective natural biological pest control in subtropical rice systems with a winter fallow, such as in China, the world's largest producer of rice (GRiSP, 2013). From this knowledge gap, we derived two specific research questions:

- What is the effect of landscape composition on natural biological pest control in rice?
- How effective is natural biological pest control in rice, compared to farmers' chemical pest control practices?

We addressed these questions with a first-time comparison of natural biological and chemical pest control in rice along a landscape gradient. This comparison includes the 'full cascade' (Liere et al., 2015; Potschin & Haines-Young, 2011), from natural enemy and pest abundance to crop injury, yield loss, yield and economic performance (Figure 1).

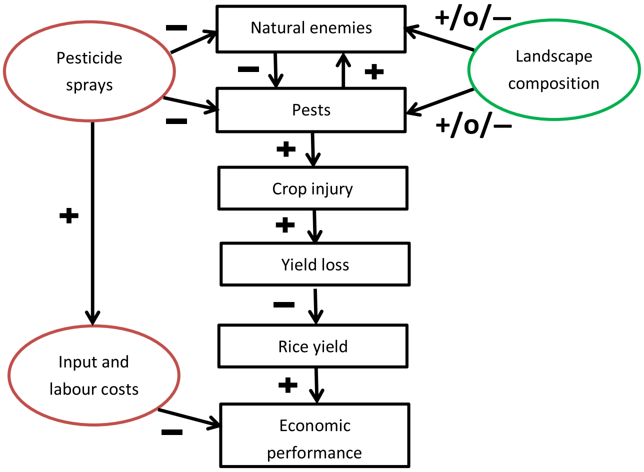

FIGURE 1 Flow chart of the 'full cascade' of rice pest control, from natural enemies to economic performance, and the effect of landscape composition and farmers' pesticide sprays. All indicated variables were measured

2 | MATERIALS AND METHODS

We addressed our two research questions by comparing natural biological and chemical pest control in rice in 20 landscape settings, covering a wide variation in the proportions of rice, other crops and semi-natural vegetation. Biological and chemical control treatments were represented by paired plots in each of the 20 landscape settings, which were either unsprayed allowing for undisturbed naturally occurring biological control or sprayed with pesticides according to farmers' practice. The entire study was conducted twice, in 2014 and 2015, to check for consistency of effects and relationships across years. Below, we detail our methods of data collection and analysis for each component of the system.

2.1 | Study sites, treatments and land-use survey

The study was conducted in Jiangxi Province, China in 2014 and 2015 (N28.35°–N28.99°, E115.26°–E115.82°). Within an area of about 75 × 75 km, we selected 20 irrigated rice fields covering a broad range in terms of surrounding landscape composition (Figure 2). The average size of the selected fields was 1,100 m^2 (*SD* = 87 m^2; range 450–1,980 m^2), and the minimum distance between two fields was 5.4 km. In south China, rice is grown either in a double cropping system with early rice (April to July) followed by late rice (July to October), or as a single rice crop (middle rice, from June to September) followed by oilseed rape or fallow (October to May). At the time of the study, the crop in all selected fields was middle rice. Crop establishment was either by transplanting (60% of cases) or direct seeding (40% of cases). In 2014, rice cultivars were not standardized and farmers were allowed to use the cultivar of their choice, while in 2015 all farmers used the hybrid middle rice variety YLY1 (Y-Liangyou-1). This variety as well as the varieties chosen by the farmers in 2014 is not resistant to rice planthoppers and the seeds were not treated with insecticides. Each field was split into two plots of similar size: in one plot no pesticides were applied and in the other plot farmers applied pesticides according to their normal pest management practices.

Land use around the focal fields was first quantified by remote sensing digital images from the data centre of the Chinese Academy of Sciences using ArcGIS 10.0, within a radius of 2,000 m, and then ground truthed in July 2014, resulting in land-use data with a resolution of 2.5 m. A total of 45 land-use types were distinguished and for the analysis pooled into ten categories: early rice, middle rice, horticulture, other arable land, forest, grassland, hedgerows, water, built-up and unused land (Appendix S1). These land-use categories take into account that different types of crop and non-crop habitat can differ in their effects on pests and natural enemies (Cohen & Crowder, 2017), and also account for the temporal dynamics of potential source habitats of rice pests (Schellhorn, Gagic, & Bommarco, 2015).

2.2 | Arthropod abundance

Arthropods were sampled with a modified blower-vac suction sampler, in combination with a circular enclosure with a 0.125 m^2 bottom area (Zou et al., 2016). In both, the sprayed and unsprayed plots, six random samples were taken at least 2 m away from the field margin and plot border. In both 2014 and 2015, samples were taken four times between late June and early September, at approximately 2-week intervals. The collected arthropod specimens were sorted and identified to the species level whenever possible (using Barrion & Litsinger, 1994), and allocated into four functional groups (pests, predators, parasitoids, and 'neutral' species neither known as rice herbivores or as natural enemies, and including mostly dipteran detritivores).

2.3 | Biological control services index

As an indicator of the level of biological pest control, we determined a 'biological control services index' (BSI; Gardiner et al., 2009) for each study site, based on the impact of natural enemies on brown planthopper (BPH, *Nilaparvata lugens*), the major rice pest in China (Cheng, 2015). We assessed this impact with an exclusion experiment in the unsprayed plots, using open and closed cages (cf. Claridge, Morgan, Steenkiste, Iman, & Damyanti, 2002). The exclusion experiment started 4 weeks after planting for transplanted rice fields, and 6 weeks after seeding for direct-seeded fields. At each site, equivalent numbers (either 8 or 12) of reproductive female BPHs were introduced in the cages. After 4 weeks (i.e. the generation time of BPH) the number of BPH in the cages was determined by destructive sampling. A more detailed description of cage set up can be found in Appendices S2 and S3.

BPH numbers at the start and at the end of the experiment were used to calculate the BSI for each site. The BSI represents the proportional reduction of the BPH population due to natural enemies and is calculated as:

$$\mathrm{BSI}_i = 1 - \frac{\overline{N_{o,i}}}{\overline{N_{c,i}}},$$

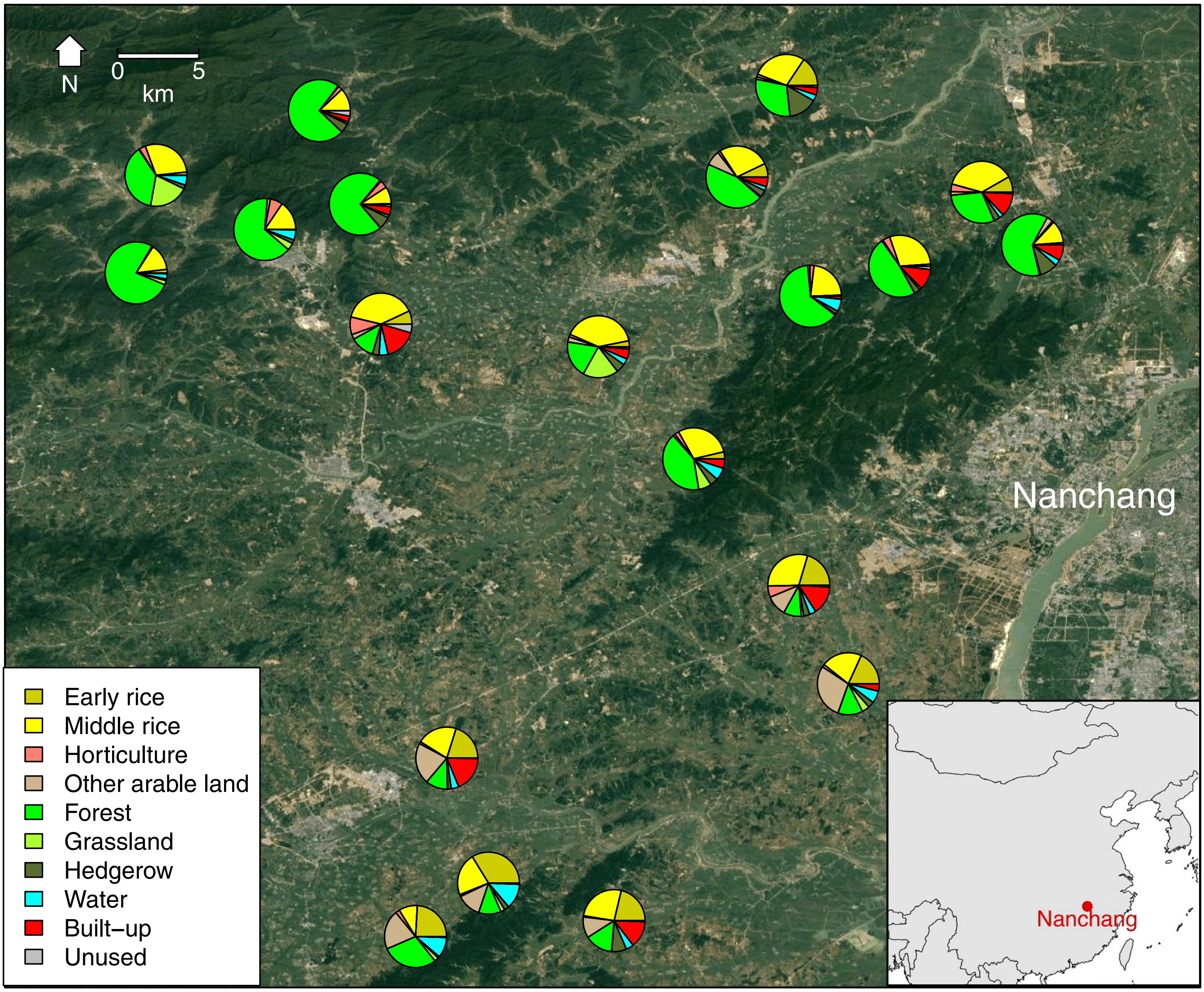

FIGURE 2 Location and landscape composition (2,000 m radius) of the 20 study sites near Nanchang, Jiangxi Province, China

where $\overline{N_{o,i}}$ is the average number of BPH in the open cages at site *i* and $\overline{N_{c,i}}$ is the average number of BPH in the closed cages at site *i*.

2.4 | Crop injury, rice yield, yield loss and economic performance of chemical pest control

Crop injury in sprayed and unsprayed plots was assessed by recording the incidence of dead hearts (caused by rice stemborer, *Chilo suppressalis*) and rolled leaves (caused by rice leaffolder, *Cnaphalocrocis medinalis*), the two major types of visible crop injury in rice (Lou, Zhang, Zhang, Hu, & Zhang, 2013). In each plot, 12 randomly selected 0.2 × 0.2 m quadrants with 154 ± 3 (mean ± *SEM* throughout manuscript) rice tillers each were assessed and incidence was calculated as the percentage of tillers with dead hearts or rolled leaves. In both years, the assessment was conducted four times, at the same time as the arthropod sampling.

Rice yield was assessed at the end of the ripening stage in both sprayed and unsprayed plots. In each plot, five 0.5 m^2 quadrants were randomly placed and all panicles harvested. The rice grains were oven-dried at 60°C for 24 hr and weighed. Yield loss was calculated as the difference between the yield in the sprayed plots (Y_S) and the unsprayed plots (Y_u), relative to the yield in the sprayed plots: $(Y_S - Y_u)/Y_S$. A relative metric was used to account for site effects on yield level (e.g. soil fertility).

In 2015, we furthermore assessed the economic performance of farmers' pest management practices for 17 of our 20 study sites. In monthly interviews with farmers, the pesticides used and the cost, number and timing of the applications were determined, and photos were taken of the pesticides' packaging. The net economic benefit of chemical control was calculated as:

$$\mathrm{NB}_i = \left(Y_{S,i} - Y_{U,i}\right) \times P - T_i \times L - \sum_{j=1}^{T_i} C_{ij},$$

where NB is the net benefit (CNY/ha); Y_S and Y_U are rice yield in sprayed and unsprayed plots (tonnes/ha), P is the rice price (CNY/tonne), T_i is the number of applications (dimensionless) at site *i*; L is the labour cost per application (CNY/ha), and C_{ij} is the pesticide input cost of each application *j* (CNY/ha) at site *i*. For *P* we used the market price of middle rice in 2015, which was 2,760 CNY per tonne (Department of Agriculture and Rural Affairs of Jiangxi Province, http://nync.jiangxi.gov.cn/News.shtml?p5=284116, Accessed on 1 November 2015), and for *L* we used 375 CNY/ha (Wang, 2017).

2.5 | Data analysis

The relationship between landscape composition and arthropod densities and crop injury was analysed with mixed-effects models. Response variables included the densities of the most abundant pest group, (a) planthoppers (Delphacidae), the two most abundant predator groups, (b) long-jawed spiders (Tetragnathidae) and (c) sheet weavers (Linyphiidae), (d) all pests, (e) all predators, (f) all parasitoids, (g) pest-enemy ratio – calculated by dividing total pest abundance by total natural enemy abundance, (h) incidence of rolled leaves and (i) incidence of dead hearts.

As explanatory landscape composition variables, we included all land use categories that are ecologically meaningful, that is, which may serve as habitat for rice arthropods: the proportion of (a) early rice, (b) middle rice, (c) horticulture, (d) other arable land, (e) forest, (f) hedgerows, (g) grassland, and (h) water. Interactions between landscape composition and year, and landscape composition and treatment were added. Study site was added as a random variable. The relationship between landscape composition and biological control (BSI) and yield loss was analysed with multiple linear regression. Explanatory variables were the same landscape composition variables as mentioned above, and the interaction with year was added. All variables were standardized (*z*-scored transformation) prior to analysis. We selected candidate models based on the corrected Akaike's information criterion (AICc) < 2, and then weighted these candidate models based on non-shrinkage natural average (Grueber, Nakagawa, Laws, & Jamieson, 2011; Rusch, Valantin-Morison, Sarthou, & Roger-Estrade, 2011). Analysis of correlation among the explanatory landscape composition variables showed that collinearity was limited (Appendix S4), and not expected to be problematic, with r exceeding 0.7 only in one instance (Dormann et al., 2013). However, as a check we also analysed the same relations with landscape composition using principle component analysis (PCA), to remove collinearity among the explanatory variables (e.g. Moreira et al., 2012). For the PCA, the original set of land use variables was first transformed to principal components, and the first two components (PC1 and PC2), which accumulated explained >50% of the total variance (Appendix S5), were included as explanatory variables.

Analyses were conducted at five spatial scales, taking the landscape composition in a radius of 100, 200, 500, 1,000 and 2,000 m around the focal fields. All models were validated by checking the residuals according to the protocol of Zuur, Ieno, Walker, Saveliev, and Smith (2009) to ensure that deviance residuals met normality and homoscedasticity assumptions.

The effect of farmers' pesticide applications on (a) pest density, (b) predator density, (c) parasitoid density, (d) density of neutral species, (e) pest-enemy ratio, (f) incidence of rolled leaves, (g) incidence of dead hearts and (h) rice yield was assessed with mixed-effects models with Gaussian error distribution. Arthropod catches from blower-vac sampling were pooled across the six samples per plot and the four sampling times. Year and treatment (sprayed vs. unsprayed) were included as fixed effects and study site as a random effect. The interaction between year and treatment was included as well.

Differences between the numbers of BPH in open and closed cages at the same site were assessed with a paired-sample *t* test, after log-transformation of the numbers to obtain normality and meet homogeneity of variance requirements.

Generalized linear models (GLM) with Gaussian error distribution were used to analyse the effects of pests on rice yield. Explanatory variables included were: (a) planthopper density (Delphacidae), (b) rice leaffolder density (*C. medinalis*), (c) rice stemborer density (*Chilo suppressalis*), (d) leafhopper density (Cicadellidae), (e) density of other pests, (f) year, and (g) treatment. Interactions between treatment and other explanatory variables were also included. Model selection was based on the AIC_c value, whereby the model with the lowest AIC_c receives most support from the data (Burnham & Anderson, 2002).

All analyses were conducted in R (R Core Team, 2014). Mixed models were fitted using the "lme" function in the "nlme" package (Pinheiro, Bates, DebRoy, & Sarkar, 2014), and model selection and averaging was conducted using the "dredge" function in "MuMIN" package (Bartoń, 2015).

3 | RESULTS

3.1 | Arthropod abundance

Arthropod sampling in 2014 and 2015 yielded a total of 33,602 specimens (Appendix S6), and included rice pests (45%), predators (11%), parasitoids (2%) and neutral species (42%). Planthoppers were the most abundant group among the pests, accounting for 92% of the specimens. Within the planthoppers (Delphacidae), white-backed planthopper *Sogatella furcifera* adults represented 57% of the specimens and BPH adults 21%. A total of 21 families of predators were identified in the samples. These predator groups are all generalists and known to prey on the major pest species (Barrion & Litsinger, 1994). Long-jawed spiders (Tetragnathidae) and sheet weaving spiders (Linyphiidae) were the dominant predator groups, accounting for 24% and 22% of the specimens respectively.

Results from analyses with the original land-use variables showed that no significant associations at any spatial scale were found between densities of parasitoids or long-jawed spiders and any of the landscape composition variables, and only sporadic significant associations were found between the densities of planthoppers and all pests and landscape composition variables (Figure 3; Appendix S7). For all predators and the pest-enemy ratio multiple significant associations were found, but most of these associations were not consistent across the 2 years. The densities of sheet weaving spiders, however, were positively associated with the proportion of early rice in both years and at four spatial scales (100–1,000 m radius). Analysis with principal components yielded similar results (Appendix S8), and will therefore hereafter not referred to in the main text.

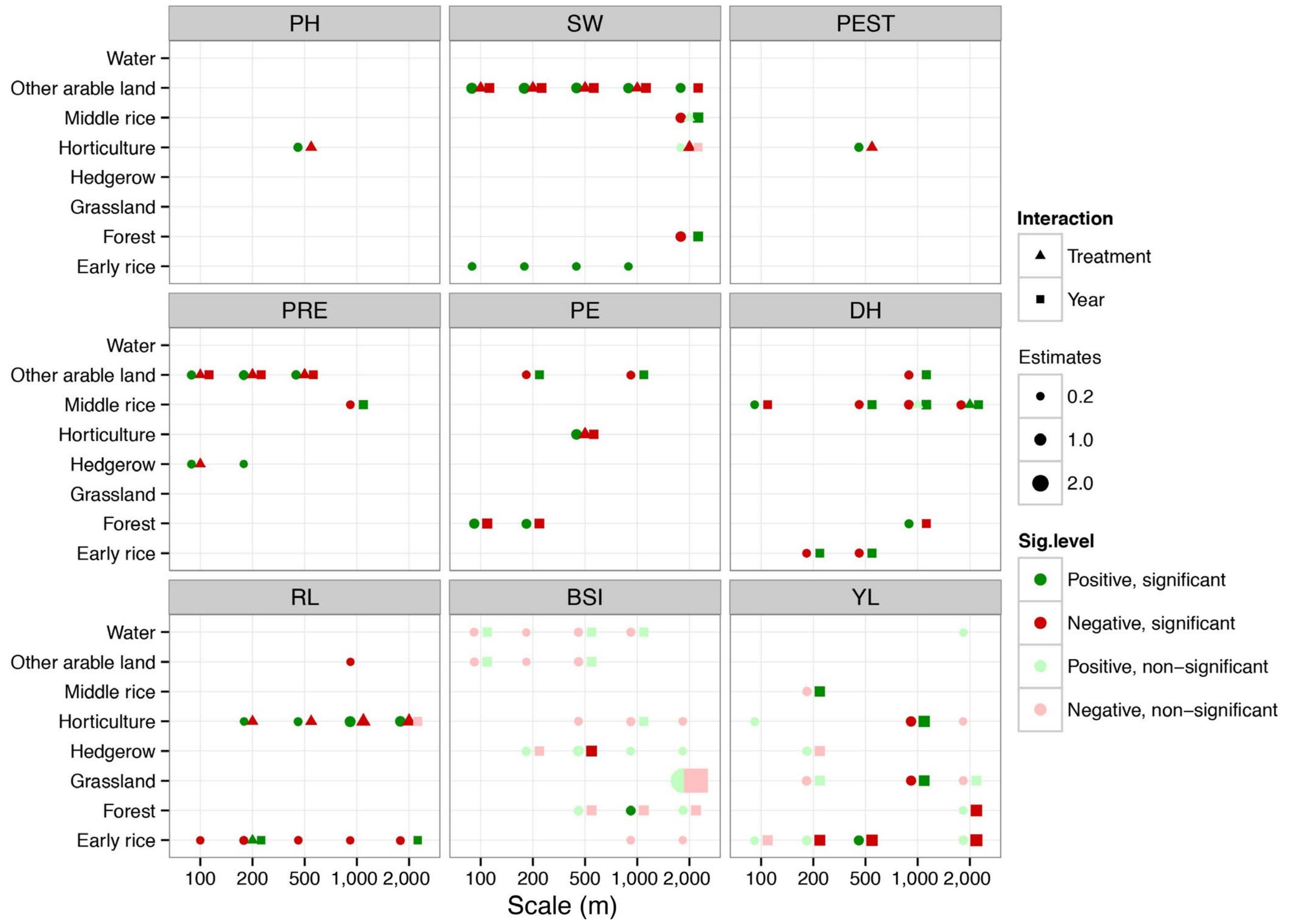

FIGURE 3 Relationship between densities of plant hopper (PH), sheet weavers (SW), all pests (PEST), all predators (PRE), pest-enemy ratio (PE), incidence of dead hearts (DH) and rolled leaves (RL) biological control services index (BSI) and yield loss (YL), and landscape variables, and interactions with treatment and year at a 100, 200, 500, 1,000 and 2,000 m radius. The size of the symbol represents the value of estimated coefficients and the colour indicates whether the coefficient is significant ($p < .05$), positive or negative, or not significant ($p > .05$). Triangles indicate interactions between landscape and treatment (base: unsprayed), and squares indicate interactions between landscape and year (base: 2014). The values of the parameter estimates are presented in Appendix S7

Farmers' chemical pest control practices resulted in both years in significantly lower densities of pests, predators, and parasitoids, as well as lower pest-enemy ratios in sprayed plots as compared to unsprayed plots (Figure 4a–e; Appendix S9). Neutral species were not significantly affected by farmers' pesticide applications.

3.2 | Biological control services index

The exclusion cage experiment showed a large impact of natural enemies on rice pest populations with significantly lower numbers of BPH in open cages as compared to closed cages, both in 2014 and 2015 (Figure 5). BSI was 0.76 ± 0.07 in 2014 (range 0.58–0.99) and 0.97 ± 0.01 in 2015 (range 0.81–0.99), indicating highly effective biological control. No significant associations were found between BSI and any of the land use categories that were consistent across both years or multiple spatial scales (Figure 3; Appendix S7). There was a significant negative correlation between BSI and overall pest density (Pearson's $r = -.5$, $p = .001$), between BSI and the incidence of rolled leaves (Pearson's $r = -.38$, $p = .02$), and a marginally significant negative correlation between BSI and yield loss in unsprayed plots (Pearson $r = -.3$, $p = .08$). These results suggest substantial biocontrol potential in the studied rice fields and a significant effect of biocontrol on pest density, crop injury and yield loss in the absence of pesticide treatments.

3.3 | Crop injury, rice yield and yield loss

No significant associations were found between incidence of dead hearts and yield loss and any of the land use categories that were consistent across both years (Figure 3; Appendix S7). Incidence of rolled leaves, however, was negatively associated with the proportion of early rice and positively associated with the proportion of horticulture at multiple spatial scales. Crop injury (incidence of dead hearts and rolled leaves) was significantly lower in sprayed than unsprayed plots, and yield was 20% higher in the sprayed plots than the unsprayed plots (Figure 4f–h; Appendix S9). Rice yield was negatively associated with planthopper

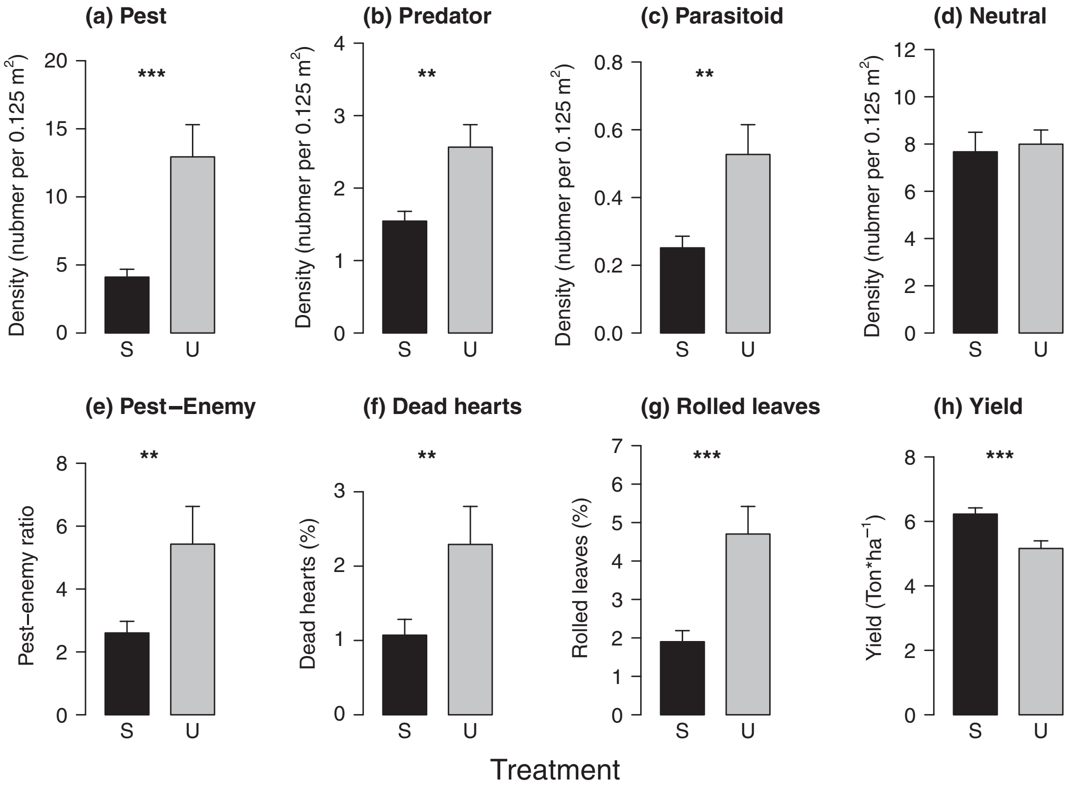

FIGURE 4 Density of pest (a) predator (b) parasitoid (c) and neutral (d) arthropods, pest-enemy ratio (e) incidence of dead hearts (f) and rolled leaves (g) and rice yield in sprayed (S) and unsprayed (U) plots, comprising both 2014 and 2015 data. Bars represent mean ± *SEM* of 20 study sites. Asterisks indicate significant differences between S and U (***p* < .01, ****p* < .001; Appendix S9)

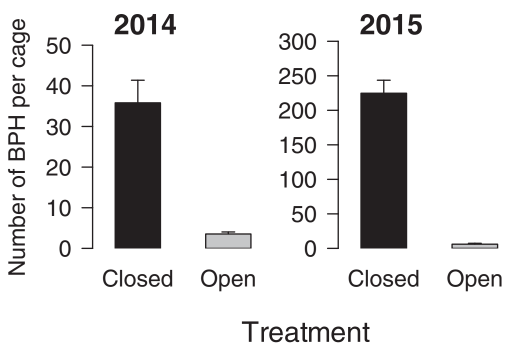

FIGURE 5 Number of adult brown planthoppers (BPH) in closed and open cages, 4 weeks after the start of the exclusion experiment, in 2014 and 2015. Bars represent mean ± *SEM* of all study sites and the difference was significant ($p < .001$) for both years

density ($\beta = -.05 \pm .01$, $p < .001$) and leaffolder density ($\beta = -1.7 \pm .95$, $p = .07$). There was no significant interaction between pesticide treatment and pest density on rice yield. There was a significant positive association between yield loss (relative difference in yield between sprayed and unsprayed) and the difference in pest density between sprayed and unsprayed plots (linear regression $R^2 = .37$, $p = .005$; Appendix S10). Yield loss was also significantly correlated with the difference in incidence of rolled leaves between sprayed and unsprayed plots ($R^2 = .16$, $p = .02$), and marginally significantly with the difference in incidence of dead hearts ($R^2 = .11$, $p = .06$).

3.4 | Economic performance of chemical pest control

In 2015, the farmers applied 3.2 ± 0.25 (range 2–5) times pesticides in the sprayed plots, typically using tank mixes with multiple components. Of all pesticide components sprayed, 74.4% were insecticides, 24.6% fungicides and 1% herbicides (Appendix S11). In the transplanted rice fields, about 50% of the insecticide sprays were applied within 40 days after transplanting.

When only taking the input costs of the pesticides into account, the net benefit of farmers' chemical pest control was positive in 47% of the cases (8 out of 17), with an overall mean of 652 ± 680 CNY/ha (Figure 6). However, when also the labour cost of applying the pesticides was considered, chemical pest control was only profitable in 29% of the cases (5 out of 17). Overall, the mean net benefit of spraying, when taking into account both the pesticide and labour costs (−561 ± 676 CNY/ha), was negative and not significantly different from zero.

4 | DISCUSSION

4.1 | Main findings and conclusions

In this study, we present unique data on natural biocontrol in rice across the 'full cascade' from natural enemy and pest abundance in

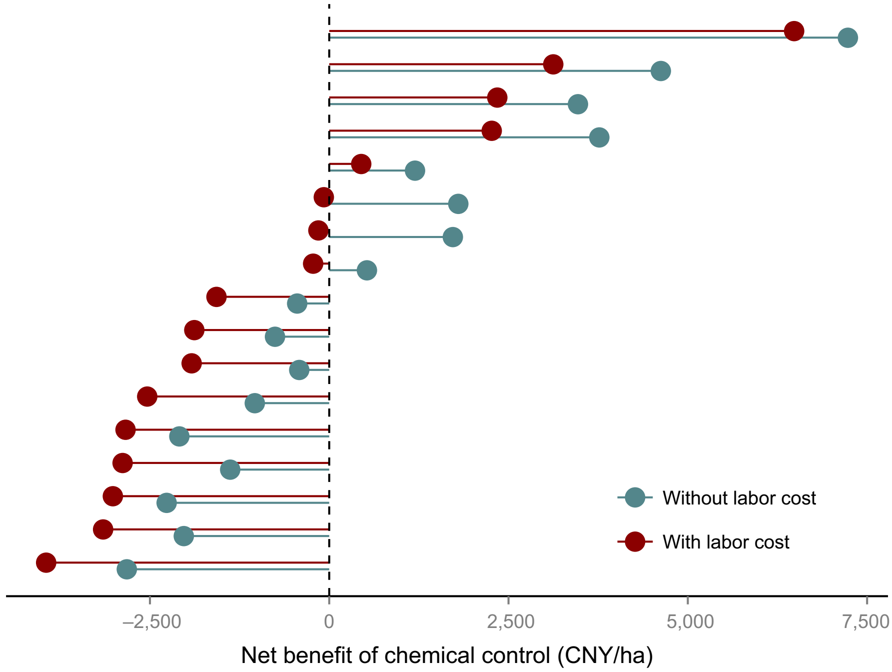

FIGURE 6 Net benefit of farmers' chemical control, without and with labour costs of spraying included. The results from 17 study sites are presented as a cumulative distribution function

rice to crop injury, yield loss, yield and economic performance, along a landscape composition gradient. We show that landscape composition did not consistently affect biological control, but also that the level of pest control by natural enemies was high, irrespective of landscape composition. Nevertheless, yields were on average 20% higher in plots treated with pesticides according to farmers' practices than in unsprayed plots. When costs of pesticides were accounted for, however, pesticide applications were only profitable in 47% of the cases, while pesticides were profitable in 29% of the cases when costs for pesticides and labour were considered. As a substantial part of the data points lie relatively close to the *y*-axis (net benefit = 0, Figure 6), the percentage of cases in which the net benefit is positive will be sensitive to changes in these costs or the price of rice. The observed variation in profitability can have many causes, including between-field variation in soil fertility and fertilizer application. However, under the conditions of our study, the mean net benefit of farmers' pesticide applications was not significantly different from zero. These findings question the cost-effectiveness of current farmer-practiced chemical-based pest management, and highlight opportunities for more ecologically-based pest management strategies based on the widespread activity of natural enemies.

Our findings on biological and chemical control of pests confirm earlier studies conducted in tropical (Way & Javier, 2001) and subtropical Asian rice systems (Lu et al., 2015). This correspondence includes the various elements of the cascade from natural enemy abundance to net revenues of pest control, such as the abundance and dominance of arthropod natural enemy and pest species (Lou et al., 2013; Luo, Fu, & Traore, 2014), the level of biocontrol of BPH (Gallagher et al., 2002; Way & Javier, 2001), the average yield levels (GRiSP, 2013), and the (lack of) profitability of chemical control (Heong, Escalada, Chien, & Reyes, 2015). However, studying the full cascade from arthropod abundance to yield loss is rarely done in landscape studies (Chisholm, Gardiner, Moon, & Crowder, 2014; Liere et al., 2015), and to our knowledge this is the first study that includes an assessment of economic performance and a comparison of natural pest control with farmers' pest control practices. Since economic return of management actions is a major criterion for farmer decision making, the assessment of the profitability of pest management practices is key to understanding, and potentially influencing, farmers' decision making.

We are confident of the validity of our conclusions for three reasons. First, the relationships established between the variables of the cascade (Figure 1) were consistent with each other. For example, relative yield loss was positively associated with pest density, whereas rice yield was negatively associated with planthopper and leaffolder density. While BSI might overestimate actual biological control services in the field due to the potential escape of planthoppers from the open cages, the negative correlation between BSI and pest density and between BSI and pest injury (incidence of rolled leaves), suggests that this index is a valid proxy of biological control services. Second, the quality of our landscape data collection was higher than in most previous studies on the effect of landscape composition on natural pest control in rice (Dominik et al., 2017; Heong et al., 2010; Settle et al., 1996; Wilby et al., 2006), due to the use of high-resolution GIS data, ground-truthing, detailed land-use classification, and by considering the landscape within a radius of up to 2,000 m around the focal fields. Third, it turned out to be crucial to conduct our study twice, in 2014 and 2015, as few of the significant effects of landscape composition were consistent across these 2 years, suggesting that many of the effects found in one-time studies may be statistical artefacts or one-off cases. This finding is in line with findings of a recent global meta-study (Karp et al., 2018).

Our study area in Jiangxi Province is representative of irrigated rice production in sub-tropical China, which is by far the largest rice producing region in the world (GRiSP, 2013). However, caution must be exercised in extrapolating our conclusions to the tropical and temperate rice producing regions in Asia, as important differences in rice field ecology exist between these agro-climatic zones (Cheng, 2015; Way & Heong, 1994). Another important limitation to our conclusions is that these should not be extrapolated beyond the range of landscape simplification included in our study (i.e. up to 70% of land cultivated).

4.2 | Explanations for the lack of a landscape effect

Only few associations were found between any of the response variables and the explanatory landscape composition variables that were consistent across the 2 years and across more than two adjacent spatial scales. One case concerns the positive association between the abundance of sheet weaving spiders (Linyphiidae) in middle rice and the proportion of early rice in the surrounding landscape, at four spatial levels. Ecologically, this might be interpreted as a carry-over effect between rice crops, and the ballooning dispersal behaviour of these spiders may explain why this association extends over a wide spatial range (100–1,000 m radius; Bianchi, Walters, Cunningham, Hemerik, & Schellhorn, 2017). However, this positive association was rather weak (with coefficient values of about 0.2) and did not translate in a negative association between pest abundance or yield loss and the proportion of early rice. The negative association between the incidence of rolled leaves and the proportion of early rice at all spatial scales tested might be a consequence of the enhanced abundance of the sheet weaving spiders, but could also be due to a trap crop effect of early rice on immigrant leaffolders and, more importantly, did not translate into a consistent significant effect of landscape composition on yield loss.

To understand why landscape composition in our study did not have a clear, consistent and significant effect on natural pest control, we apply the insights into rice landscape ecology provided by Settle et al. (1996). According to these insights, the importance of permanent non-rice habitats in ensuring effective levels of natural pest control in rice depends on (a) the length and spatial extent of the fallow in between rice crops, (b) the arrival times of major pest species, and (c) the intensity of insecticide spraying, in particular during the first weeks after crop establishment. In the landscape settings we studied, the importance of permanent non-rice habitats may have been limited for four reasons. First, the presence of rice stubble cover or oil seed rape as a winter crop and the relatively short break between the harvest of late rice and the planting of early rice reduces the need for permanent non-rice habitat for winter survival of natural enemies. Second, major pests such as BPH and rice leaffolders are migratory and arrive late in the season relative to their major natural enemies which are residential (Cheng, 2015), allowing these generalist natural enemies time to rebuild population levels after the winter fallow. Third, the number of insecticide sprays during the first 40 days after transplanting was relatively low (1.6 ± 0.2), creating less need for replenishment of natural enemy populations from non-rice habitats after spraying. Fourth, even the most simplified landscape settings in our study still included a relatively large proportion of alternative habitats due to the small-scale character of Chinese rice landscapes, with fields of generally less than 0.1 ha separated by vegetated bunds. The minimum proportion of semi-natural habitat was 20% and the maximum proportion of cultivated land was 70%. According to Cohen and Crowder (2017), a landscape can be considered simplified when there is less than 20% semi-natural habitat, and complex when there is more than 20% semi-natural habitat.

4.3 | Implications and outlook

We found that even in landscape settings dominated by rice cultivation and with widespread and rather frequent use of insecticides, the level of natural pest control is still high and effective. Maintaining this level probably requires conservation of the small-scale character of Chinese rice landscapes and preventing further intensification of insecticide use in rice. Current levels of insecticide use by Chinese farmers are estimated to be at least 40% too high as compared to what is economically rational (GRiSP, 2013), and also our study showed that farmers' chemical control practices are in most cases not profitable despite a 20% yield increase compared to unsprayed rice (Figure 4h). This concerns specifically the application of insecticides, as, although farmers also applied fungicides, we did not observe any substantial symptoms of rice diseases. Our study questions the need of insecticide application in rice cultivation in tropical and subtropical China, and abandoning insecticide use should be considered as a serious option. However, Chinese farmers generally do not factor in costs of labour and produce rice primarily for domestic consumption (Wang, 2017), and are therefore probably unwilling to take the risk of occasionally losing a substantial part of their harvest due to infestation by pests such as planthoppers and leaffolders. In subtropical China, this risk is substantially higher than in tropical rice systems. According to Way and Javier (2001) and Cheng (2015) the lower reliability of natural pest control in subtropical Chinese rice systems is due to the fallow period resulting in generally lower abundance of natural enemies in rice fields and the sometimes very high influx levels of migratory pests such as brown planthopper and rice leaffolder. This vulnerability is enhanced by the high application rates of nitrogen fertilizer, which boosts the host plant quality for pests, compared to tropical Asian countries (Cheng, 2015; Way & Javier, 2001). These application levels could be substantially reduced when applied on the basis of need only (Cheng, 2015), which would reduce the growth rate of pests via bottom-up plant quality effects (Costamagna, van der Werf, Bianchi, & Landis, 2007). Such an agrochemical reduction can be expected from the ongoing modernization of Chinese agriculture, emphasizing rational pesticide and fertilizer use, and the currently strong growth of organic rice farming (Wang, 2017).

To further improve our understanding of natural pest control in subtropical rice and in particular the role of landscape composition, we suggest to concentrate follow-up research on the four explanatory factors we proposed for the lack of effect of landscape composition: the intensity of (early) insecticide applications, the length and spatial extent of the winter fallow, the arrival time of major pests relative to natural enemies, and the intensity of landscape simplification in terms of the percentage of non-rice permanent habitats. Another venue for further research would be to study the role of landscape configuration in natural pest control, as recent findings from both fine-grained European agricultural landscapes (Martin et al., 2019) and tropical rice landscapes (Dominik et al., 2018) suggest that configuration may have a stronger effect than landscape composition.

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AUTHORS' CONTRIBUTIONS

Y.Z., J.d.K., F.J.J.A.B., H.X., J.H., X.D., L.H. and W.v.d.W. conceived and designed the experiments. Y.Z., and H.X. performed the experiments. Y.Z. analysed the data. Y.Z., J.d.K., F.J.J.A.B., H.X. and W.v.d.W. wrote the manuscript.

DATA AVAILABILITY STATEMENT

Data available vis the DANS Repository https://doi.org/10.17026/dans-zde-gnpd (Zou et al., 2019).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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