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RESEARCH ARTICLE

Land consolidation impacts the abundance and richness of natural enemies but not pests in small-holder rice systems

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Abstract

1. Traditional small-holder agricultural landscapes in southern China are being consolidated to increase mechanisation levels in agriculture, but it is unclear how this influences rice arthropod communities in these landscapes.
2. Here, based on a six-year study in 20 rice fields, we evaluated the impact of land consolidation on arthropod communities, crop damage, and rice yield. We also analysed how effects of land consolidation were moderated by the proportion of large semi-natural habitat patches and insecticide use.
3. We found that, compared to consolidated fields, rice fields in traditional farmlands had a higher abundance and family richness of natural enemies, but a similar abundance of rice pests. Land consolidation did not significantly interact with the proportion of large semi-natural habitat patches or insecticide application, in terms of affecting arthropods. The proportion of semi-natural habitat reduced the negative effect of insecticide application on key rice pests, but no equivalent interaction occurred for natural enemies.
4. *Synthesis and applications*: Land consolidation can have negative impacts on the abundance and richness of natural enemies, but not pests in small-holder rice systems, and these impacts are independent from insecticide application and proportion of semi-natural habitat in the landscape. We recommend the implementation of agri-environmental measures or re-establishing field margin vegetation during the consolidation process to mitigate these potential negative effects, although trade-off between enhancing crop yields and preserving rice arthropod biodiversity should be considered. We encourage future research to focus on the detailed assessment of the function of linear habitats for a better understanding of the impact of land consolidation.

KEYWORDS
biocontrol, biodiversity, China, field margins, insects, landscape complexity, semi-natural habitat, yield

1 | INTRODUCTION

Traditional small-holder farmlands are rapidly changing as a consequence of land consolidation in China. Traditional farmlands in subtropical southern China have fields of irregular shapes, with field margins consisting of fine-scale linear habitats (Zou, 2024). These farmlands could support a high diversity of arthropods (Shi et al., 2021; Zou, 2024). Because traditional farmlands are usually difficult for mechanised management and have relatively inefficient irrigation systems, farmlands in these regions are undergoing consolidation (Tang et al., 2019). Land consolidation may merge smaller field to create larger ones, and/or it may change the traditional irregular-shaped fields to regular ones for machinery access, which is particularly true for south China (Zou, 2024; Figure 1). During the consolidation process, the removal of linear habitats may result in biodiversity loss (Li et al., 2019; Shi et al., 2021; Zhang et al., 2012). Compared to traditional lands, consolidated farmlands have a lower diversity of pollinators, probably due to the removal of flowering plants in field margins (Shi et al., 2021), and a lower diversity of aquatic arthropods due to the reduction of small irrigation ponds and ditches (Nam et al., 2019). Therefore, while farmland consolidation may increase agricultural efficiency (General Administration of Quality Supervision, 2014; Ministry of Natural Resources of the People's Republic of China, 2021), the potential impacts on biodiversity need to be evaluated (Zou, 2024).

Rice is the most important staple food that feeds almost half of the world's population (FAO, 2019), and China is the world's largest rice producer (Huang et al., 2014). Pest pressures strongly affect rice yield, and the use of natural enemy arthropods for biological pest control presents an environmentally friendly solution

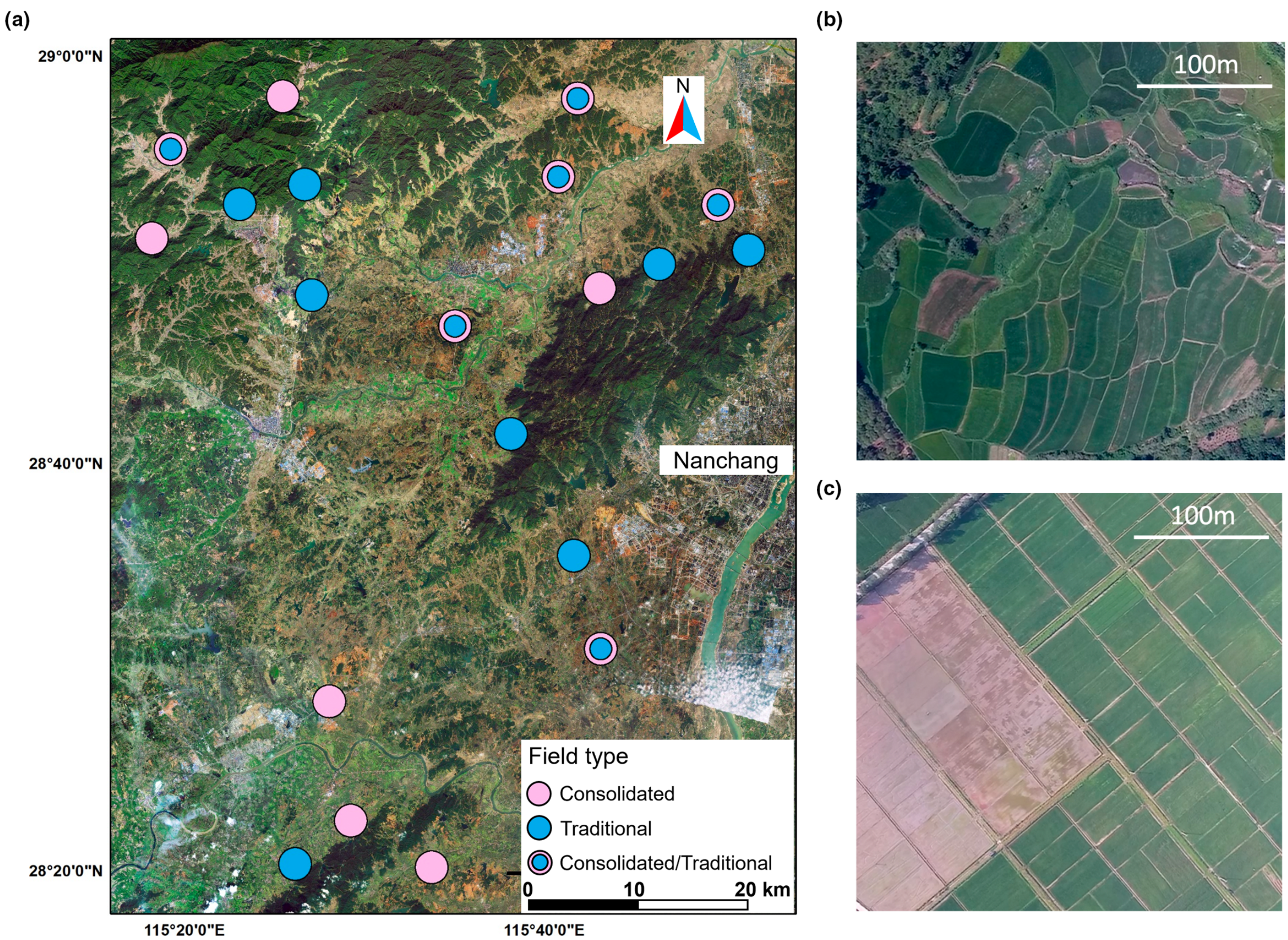

FIGURE 1 Locations of the 20 study sites with focal rice fields (a) and examples of landscapes dominated by traditional (b) and consolidated fields (c). Consolidated/traditional sites refer to the consolidation status of the experimental rice field changed during the six experimental years.

(Ali et al., 2019; Dale et al., 2020), with a high diversity of natural enemies leading to improved biological control (Jonsson et al., 2017; Wilby et al., 2005; Yuan et al., 2019). Natural enemies of rice pests, such as ground beetles, spiders, and parasitoids, require suitable source habitats, including linear habitats on field margins. For example, a study from multiple countries in Asia suggests that growing nectar-producing plants around rice fields enhances the presence of predators and parasitoids of rice pests (Gurr et al., 2016). Land consolidation that leads to the removal of vegetated field margins may negatively affect the natural enemies and hence reduce the biocontrol ability in rice fields (Marshall & Moonen, 2002). However, comprehensive assessments of the impact of land consolidation on the abundance and diversity of rice pests and their natural enemies in China are lacking (Zou, 2024).

Apart from linear habitats, large semi-natural habitat patches (e.g. primary or secondary forests, or substantial continuous herbaceous habitats) surrounding agricultural fields are considered beneficial for biodiversity (Bianchi et al., 2006; Tscharntke et al., 2012; Zhang et al., 2021; Zou, 2024). It is not clear whether these landscape-level large semi-natural habitats can compensate for the loss of biodiversity due to land consolidation. This question is relevant when managers are considering investing in agri-environment measure (AEM) or Ecological Engineering (EE), such as planting grass or flower strips to enhance the linear habitats, as a way to conserve farmland biodiversity and ecosystem services (Horgan et al., 2016; Kleijn & Sutherland, 2003; Uthes & Matzdorf, 2013; Zhu et al., 2022; Zou, 2024). For example, a meta-analysis based on European studies found that the effectiveness of AEM in improving pollinator diversity is determined by the ecological contrast (i.e. difference of plant richness or cover between AEM and non-AEM fields; Marja et al., 2019), suggesting an interactive effect between AEM and the 'stock' of biodiversity elsewhere in the landscape. We might therefore predict that the application of AEM in consolidated farmlands might be less effective for landscapes with a high proportion of large semi-natural habitat patches. However, these results may not extend to natural enemies of rice pests, because their dispersal ability (e.g. several 100 m for ground beetles; Elek et al., 2014) is often considerably lower than that of mobile pollinators (several kilometres; Garcia Bulle Bueno et al., 2022; Kraus et al., 2009). While fine-scale linear habitats have been reported to benefit natural enemy arthropods in rice fields (Dominik et al., 2018; Sattler et al., 2021), it remains unclear whether these benefits are influenced by the presence of large semi-natural habitat patches.

The application of insecticides is another important factor that affects the arthropod community in rice fields, and the application has increased with the world demand for agricultural production (GRiSP, 2013). Although insecticides are intended to eliminate pests and boost yield, they also remove natural enemies (Hill et al., 2017; Janssen & van Rijn, 2021; Theiling & Croft, 1988), and reduce arthropod diversity (Geiger et al., 2010; Mone et al., 2014; Sonoda et al., 2011). A previous study in smallholder agro-ecosystems of South China reported that although the application of insecticides reduces both rice pests and natural enemies, it results in relatively low yield gains, with these yield gains (or losses due to the absence of insecticide use) being independent of the large-scale landscape context (Zou, de Kraker, et al., 2020). However, it is not yet clear whether the effect of pesticide application on rice arthropods is affected by the landscape context. The effects of insecticides on the diversity of pests and natural enemies may differ between traditional and consolidated rice fields. Since arthropod diversity is likely higher in traditional than in consolidated farmlands, insecticides may cause more arthropod diversity loss in traditional than in consolidated farmlands and may lead to lower yield gains in traditional than in consolidated land. Furthermore, since arthropod species are influenced by large-scale landscape patches, rice arthropods in landscapes with a higher proportion of large semi-natural habitat patches might be less impacted by insecticide application, as these landscapes could offer more refuge sites (Tscharntke et al., 2012).

Because of the annual fluctuation of the arthropod population, a landscape study from a single year only provides a snapshot observation and may not reflect the longer-term patterns (Paredes et al., 2021; Zou, de Kraker, et al., 2020). A global synthesis study reported an inconsistent effect of landscape complexity on arthropod diversity and biological pest control (Karp et al., 2018), and one of the reasons is that such effect could be masked by annual variations (Karp et al., 2018; Paredes et al., 2021; Zou, de Kraker, et al., 2020). Therefore, long-term observations are essential to detect any consistent landscape effect.

In this study, we conducted a 6-year field experiment in consolidated and traditional farmlands in a region with a gradient of semi-natural habitat. Each experimental field contained insecticide-sprayed and unsprayed plots. The main objective of this study is to assess the effect of land consolidation on arthropod pest and natural enemy communities in the rice field. We also aim to assess the influence of land consolidation on rice crop damage and rice yield improvement from insecticide spraying. Our additional objectives are to determine whether such possible effects interact with the application of insecticides and the presence of semi-natural habitat in the wider landscape. We have the following hypotheses:

1. Consolidated land has lower arthropod richness and abundance than traditional land;
2. the presence of large semi-natural habitat patches in the wider landscape reduces the negative effect of land consolidation on arthropod richness and abundance, due to the provision of alternative habitat for the removed field margin vegetation (Tscharntke et al., 2005);
3. the effect of insecticide application in reducing rice arthropods is weaker in the consolidated lands, due to the removal of linear habitat elements;
4. the negative effect of insecticide application on arthropod abundance and richness is mitigated by the increase of semi-natural habitat due to the landscape complementation or supplementation effect (Tscharntke et al., 2012);

2 | MATERIALS AND METHODS

2.1 | Study area and land-use

The study was conducted in 20 landscapes centred on focal rice fields in Jiangxi province, China (28°20′–28°59′ N, 115°15′–115°49′ E). In the study region, rice is grown in single-cropping (middle rice, grown in June to September followed by oilseed rape or fallow) or double-cropping systems (early rice in April to July followed by late rice in July to October). In this study, all selected fields were single-cropping rice. The minimum distance between the centres of two landscapes was 5.4 km. Most of the focal rice fields were located in the centre of the landscape throughout the 6 years, but in some cases the focal field with few changed locations slightly (<100 m) between different years due to crop rotation. Among these 20 rice fields, 14 fields had a consistent consolidation status between the different years, while six changed their status due to the change of farmers (and hence location) or due to the undergoing of the consolidation project during the experimental period (Figure 1a). In total, we had 54 year-fields with consolidated status and 62 year-fields with traditional status, with both types distributed across a gradient of semi-natural habitat cover. Consolidated fields were rectangular in shape, generally with concrete field margins or irrigation channels, while traditional fields were irregular in shape with traditional field margins covered by wild grass and flowers (see Figure S1 in Supporting Information). The field size on both consolidated and traditional land is similar, with the mean (and SD) size (excluding field margins) of the experimental fields were $1184 \pm 313\,m^2$ (consolidated) and $1027 \pm 426\,m^2$ (traditional). The landscapes spanned a gradient in semi-natural habitat (forest and grassland) ranging from 2% to 73% at a radius of 1 km (Figure 1a; see Table S1). All experimental fields had very similar elevation levels (40 ± 17 m).

The study was conducted for 6 years: 2014, 2015, 2016, 2017, 2020 and 2021. Except for 2014 when farmers used their own rice variety, all farmers used the same middle rice hybrid variety (Y-Liangyou-1) in the following experimental years. The experimental rice fields were evenly divided into two plots, assigned as "insecticide sprayed (S)" and "insecticide unsprayed (U)" treatments. If the field was too small (smaller than $667\,m^2$, i.e. 1 μ in Chinese measurement units) to divide into two plots, two neighbouring fields belonging to the same farmer were selected as the "S" and "U" treatments. In the "S" plots, the farmers managed the crop according to their normal pest management practices, with approximately three pesticide applications per growing season (see Zou, de Kraker, et al., 2020). In U plots, no chemical insecticides were used, while fungicides and herbicides were allowed. All other management practices were identical between two plots. Pesticide application is determined by individual farmers and is also universally guided by the central government at the provincial level. We recorded the frequency of pesticide application for the year 2015, 2016 and 2020 of our study plots, and the frequency of pesticide application is ubiquitous in both traditional (mean and SD = 2.7 ± 1.1) and consolidated land (3.0 ± 1.3).

Land-use around the focal rice fields was first quantified by the analysis of digital remote sensing images with a resolution of 2.5 m obtained from the data center of the Chinese Academy of Sciences using ArcGIS 10.0 at a radius of 2 km. Land-use maps were ground-truthed in 2014, resulting in a total of 45 land-use types but not including fine-scale linear habitats at the margins of traditional fields (see Zou, de Kraker, et al., 2020). For our analysis, we calculated the proportion of large semi-natural habitat patches (i.e. forest and grassland, hereafter refer to semi-natural habitat) at the scale of 1 km radius around each focal field, as representative of availability of large non-cropped habitat patches (Dainese et al., 2019). This 1-km scale guarantees that land-use information can be obtained for all our study sites where the experimental fields were not centered in the landscape sector. Nonetheless, we additionally analysed the land use for a radius of 0.5 and 2 km to check the consistency of our results at different scales. Land use image analysis conducted at study sites in 2020 confirmed that the proportion of semi-natural habitat in landscapes did not change during the study period (Shi et al., 2022). Although the aerial imagery did not have sufficient resolution to digitise field margins reliably, the availability of linear field margin habitats is practically entirely determined by consolidation status (i.e. it varies starkly between these categories and very little within them). The typical width of traditional margins is 1–1.5 m, which leads to approximate coverage of 7%–11% if a landscape has 100% rice fields. Linear field margins in consolidated fields are usually removed for concrete infrastructure or irrigation channels but may occasionally be left unconcreted.

No permission for fieldwork is needed in this study.

2.2 | Arthropod sampling

Arthropods were sampled by a modified leaf blower-vac combined with a bucket ($0.125\,m^2$ at the bottom area), which allows the calculation of absolute density (Zou et al., 2016). Each year, four sampling rounds were conducted at 2–3 week intervals, during the middle rice growth stage of the jointing stage (late June to early July), heading stage (late July), flowering stage (middle August) and filling stage (late August to early September). In each plot, six samples were taken (except for five samples in 2020 and 2021), and sampling locations were evenly distributed across the plot and at least 5 m from the field edge. All arthropods were identified to the family level, which was found to be a useful proxy for species level biodiversity for the mega-diverse arthropods (Zou, van der Werf, et al., 2020). Unidentified individuals were sorted to order level (6.3% by overall abundance). These unidentified individuals were included in the abundance analysis, but excluded from the richness analysis. All arthropods were classified into three functional groups: pests, natural enemies, and neutral species mainly according to the family level (see also Zou, de Kraker, et al., 2020), but species belonging to multiple functional guilds within a family were distinguished (e.g. *Miridae*).

2.3 | Crop damage and rice yield

Visible crop damage was recorded, consisting of dead hearts and rolled leaves, which are caused by rice stem borers, *Chilo suppressalis*, and rice leaf folder, *Cnaphalocrocis medinalis*, respectively (Lou et al., 2013). Crop damage was assessed during 5 years (2014, 2015, 2016, 2017 and 2020). In the sampling year of 2014 to 2017, crop damage was assessed during each of the arthropod sampling rounds, while in 2020 it was evaluated during rice yield assessment. For the assessment of crop damage, 12 randomly selected 0.2 × 0.2 m quadrants located at least 5 m from the field edge were selected (131 ± 2 rice tillers).

Rice yield was estimated by five 0.5 m^2 (1 m^2 in 2020 and 2021) random placed iron hula hoop quadrants and harvesting the rice in the ripening stage. The grains were oven-dried at 60°C for 24 h and then weighted. Yield estimations were conducted separately for the S and U plots, and the yield loss was calculated as the relative yield for the insecticide unsprayed (Y_U) to sprayed (Y_S) plot ($Y_S - Y_U/Y_S$; Zou, de Kraker, et al., 2020).

2.4 | Data analysis

We used generalised linear mixed models (GLMM) to analyse the effect of consolidation status on eight different response variables: the abundance and richness of arthropod pests and natural enemies, the pest-natural enemy ratio, crop damage, yield and yield loss. Arthropod and crop damage data from sub-samples within the same plot and the four sampling rounds per year were pooled. Although pooled data eliminates the information of variance within each year, it reflects the cumulative arthropod effect (e.g. pest pressure) and also gives us a better estimation of the mean value (Zou, de Kraker, et al., 2020). Furthermore, we also found that the distribution of the pooled data conformed better to the GLMM assumptions, and gave us more discrimination to show the main effects we were interested in. Although our aim is not to compare results across different sampling years, we treated the sampling year as a random variable to account for within-year variance (e.g. the different in rice variety in 2014, and different sampling frequency for crop damage in 2020). Arthropod richness was calculated as the family richness for all pests, natural enemies, and all arthropods. The abundance of pests and natural enemies (individuals per m^2) and pest-natural enemy ratio were log10-transformed. Because more than 70% of all pest individuals consisted of rice plant hoppers (*Delphacidae*), the abundance of pests was further divided into dominant (*Delphacidae*) and other pests. Crop damage was expressed as the proportion of dead hearts (i.e. ratio of number of dead hearts and total number of tillers), and the proportion of rolled leaves (i.e. ratio of number of rolled leaves and total number of leaves). We used a Poisson error distribution for richness-based response variables and a Gaussian error distribution for all other models.

Explanatory variables for the full GLMM included consolidation status (consolidated vs. traditional), proportion of semi-natural habitat, insecticide application (S vs. U, except explanatory variable "yield loss"), and their two- and three-way interactions. "Year" and "Site" were included as crossed random effects. We applied model selection based on the AICc criterion, whereby the model with the lowest AICc receives most support from the data (Burnham & Anderson, 2002). We report results from models with the lowest AICc, and those exhibiting a ΔAICc <2, and the weighted value based on non-shrinkage natural average (Rusch et al., 2011). All models were checked by inspecting residual plots (Zuur et al., 2009).

All analyses were conducted in R (version 4.2.0; R Core Team, 2020). The package "lme4" (version 1.1–30; Bates et al., 2015) was used for mixed models with Poisson error distribution, and "lmerTest" (version 3.1–3 which shows the *p*-value in the results; Kuznetsova et al., 2017) was used for mixed models with Gaussian error distribution. The package "MuMIn" (version 1.47.1; Bartoń, 2022) was used to conduct the model selection and model average.

3 | RESULTS

Overall, we collected 141,587 arthropod individuals (80 families), containing 67,610 pest (28 families), 27,482 natural enemy individuals (36 families), and 38,023 neutral arthropods (13 families). *Delphacidae* was the most abundant family with 47,489 individuals, of which *Sogatella furcifera* (white-backed planthopper) and *Nilaparvata lugens* (brown planthopper) made up 59% and 38%, respectively, then followed by *Thripidae* and *Cicadellidae* (9328 and 4670 individuals, respectively). *Veliidae* (water striders) was the most abundant natural enemy family with 8578 individuals, followed by *Lycosidae* (wolf spider) and *Tetragnathidae* (long-jawed orb-weavers) with 3517 and 2434 individuals, respectively (see Table S2).

Results of land consolidation effects showed that traditional fields had a significantly higher total arthropod family richness, and abundance and family richness of natural enemies than consolidated fields (Table 1; Figure 2). However, the abundance and family richness of pests, crop damage or yield were not statistically different between traditional and consolidated fields (Table 1; Figures 2 and 3).

Insecticide application had a significant negative effect on the family richness and abundance of pests and natural enemies, as well as the pest: natural enemy ratio (Table 1, Figure 2). On average, there was a 10.8% yield loss due to not spraying, with the average yield of 7.14 ± 0.30 ton/ha and 6.07 ± 0.30 ton/ha in the S and U plots (Figure 3).

None of the selected models included interactions between land consolidation status and proportion of semi-natural habitat, or between land consolidation and insecticide application status (Table 1; Figures 2–4). Results for the consolidation effect and its lack of

TABLE 1 The most parsimonious models showing the response of arthropod diversity and abundance, crop damage and rice yield in response to consolidation status (C: consolidated), proportion of semi-natural habitat (SNH) in a radius of 1 km and insecticide application status (S: insecticide sprayed).

Variable	C	SNH	S	C:SNH	C:S	SNH:S
Arthropod Richness	−0.09 ± 0.042*	0.19 ± 0.107	−0.12 ± 0.031***	—	—	—
Pest richness	—	—	−0.09 ± 0.054	—	—	—
Natural enemy richness	−0.14 ± 0.050**	0.24 ± 0.121	−0.14 ± 0.042***	—	—	—
Delphacidae abundance	—	0.08 ± 0.280	−0.51 ± 0.116***	—	—	0.52 ± 0.277
Other pest abundance	—	—	−0.19 ± 0.050***	—	—	—
Natural enemy abundance	−0.12 ± 0.036**	0.24 ± 0.087*	−0.16 ± 0.033***	—	—	—
Pest: Natural enemy ratio	—	−0.77 ± 0.514	−0.72 ± 0.220**	—	—	1.12 ± 0.527*
Dead hearts%	—	—	—	—	—	—
Rolled leaves%	—	—	−0.02 ± 0.005***	—	—	—
Yield	—	−0.57 ± 0.606	1.07 ± 0.303**	-	—	−0.81 ± 0.701
Yield loss	—	—	/	—	/	/

Note: The "—" indicates factors not included in the best models and the "/" indicates factors not applicable for the initial analysis. Values show the estimated coefficient and standard errors; asterisks indicate significance levels (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Traditional fields and insecticide unsprayed plots are set as reference levels.

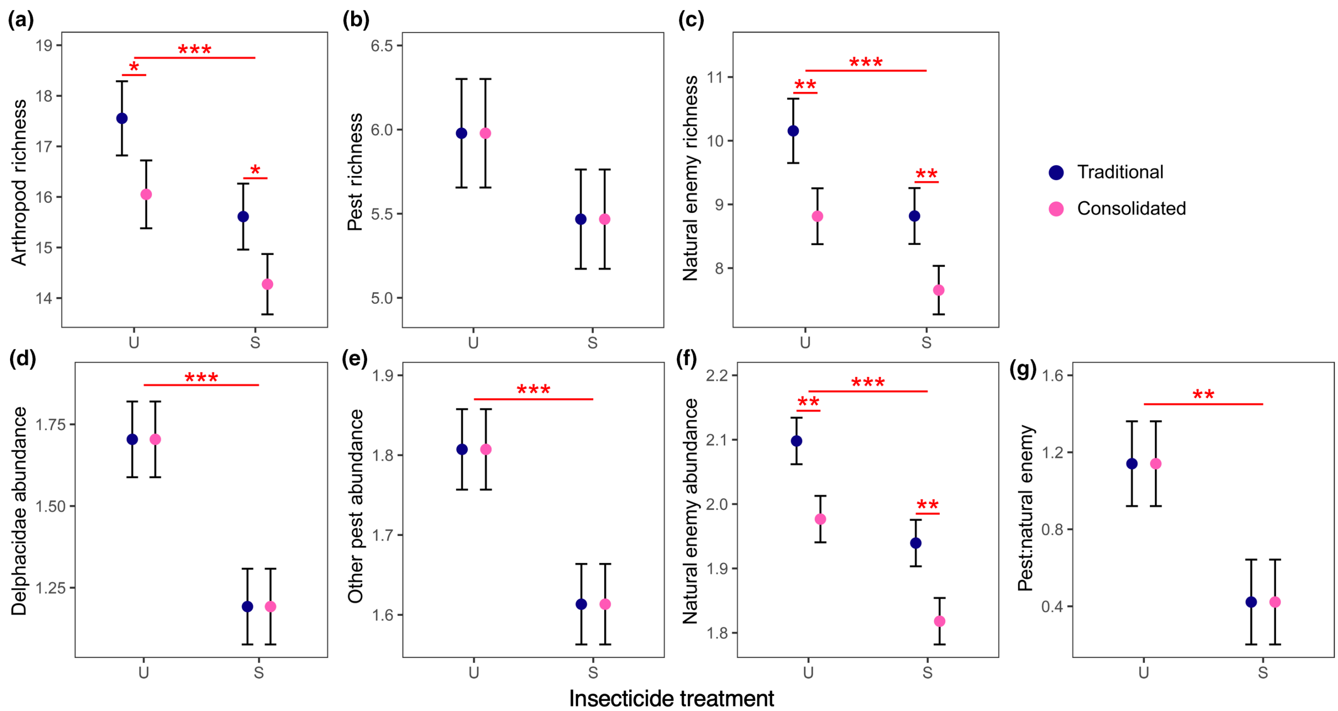

FIGURE 2 Effects of land consolidation (consolidated vs. traditional) and insecticide application status (U: insecticide unsprayed, S: insecticide sprayed) on arthropod community variables: (a) arthropod richness, (b) pest richness, (c) natural enemy richness, and log10-transformed, (d) *Delphacidae* abundance, (e) other pest abundance, (f) natural enemy abundance and (g) pest-natural enemy ratio. Asterisks indicate significance levels (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$). Values and error bars refer to the mean and SE of coefficients from the most parsimonious models (Table 1).

interaction with semi-natural habitat and insecticide use were consistent among the top models with lowest AICc values and those models with ΔAICc <2 and their weighted average, as well as at different landscape scales (see Tables S3 and S4).

Results of effects of semi-natural habitat proportion showed that there was a significant positive association between the abundance of natural enemies and the proportion of semi-natural habitat (Table 1; Figures 4 and 5b). However, the family richness of natural

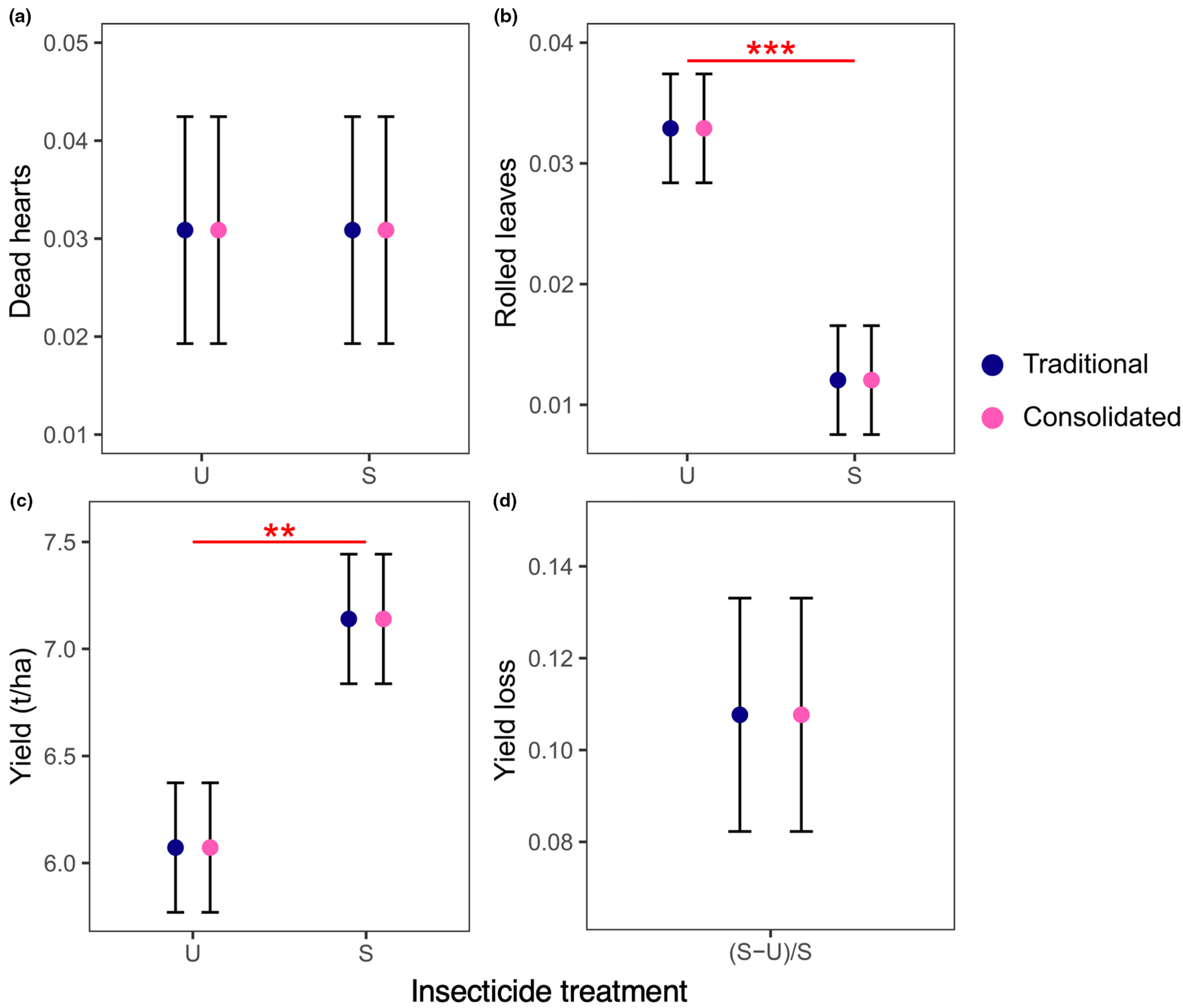

FIGURE 3 Effects of land consolidation (consolidated vs. traditional) and insecticide application status (U: insecticide unsprayed, S: insecticide sprayed) on rice-related variables: (a) proportion of dead hearts, (b) proportion of rolled leaves, (c) rice yield, and (d) yield loss. Asterisks indicate significance levels (**$p<0.01$; ***$p<0.001$). Values and error bars refer to the mean and SE of coefficients from the most parsimonious model (Table 1).

enemies and all arthropods were not significantly associated with the proportion of semi-natural habitat (Table 1). The abundance of *Delphacidae* was positively associated, and rice yield negatively associated with the proportion of semi-natural habitat, respectively, but these associations were only significant in insecticide sprayed fields (Table 1; Figure 5a,d). The relationships between pest: natural enemy ratio and proportion of semi-natural habitat were significantly different between the S and U plots, even if the relationships were not significant in either plot (Table 1; Figure 5c). Significance of results of effects of semi-natural habitat proportion and its interaction with insecticide application was mostly consistent for the top models with the lowest AICc values and those models with ΔAICc <2 and their weighted average, or at different landscape scales, although the effect of semi-natural habitats on family richness was stronger on a small scale (see Tables S3 and S4).

4 | DISCUSSION

We examined the effect of land consolidation on arthropod family richness and abundance, crop damage and yield in small-holder rice agroecosystem in South China, and how these relationships are moderated by the proportion of semi-natural habitat and insecticide use. We found that: (1) traditional farmland supported a higher family richness and abundance of rice natural enemies than consolidated farmland, but there was no difference in the abundance of rice pests and yield; (2) the effects of land consolidation on the arthropod family richness and abundance did not differ by increasing the proportion of semi-natural habitat, nor by insecticide application; (3) the effects of insecticide application on the abundance of key rice pest and rice yield decreased with increasing semi-natural habitat, but an equivalent interaction was not found for the abundance of natural enemies.

In line with our hypothesis #1, we found that the abundance and richness of natural enemies were lower in rice fields in consolidated farmlands than in traditional farmlands. This finding aligns with previous studies reporting negative effects of land consolidation on pollinator communities (Shi et al., 2021), aquatic arthropods (Nam et al., 2019), and birds (Denac & Kmecl, 2021). The main reason might be that land consolidation eliminated natural vegetation cover on the field margins, while these field margins can provide nesting habitat and food sources for natural enemies (Marshall & Moonen, 2002; Vickery et al., 2009). Results are, to some extent, also consistent with the study by Dominik et al. (2018), who highlighted the importance of rice bunds in supporting natural enemies of rice pests. However, we did not observe significant differences in pest abundance, pest richness, and crop damage between traditional and consolidated fields. A possible explanation is that the majority of rice pests, such as planthoppers (oligophagous), leafhoppers, and rice leaf rollers (polyphagous), are migratory pests (Cook & Perfect, 1989; Sogawa, 2015; Sun et al., 2022) and that their population size in rice fields is more affected by the large-scale semi-natural habitat patches but less affected by fine-scale linear habitat field margins. We suggest that proper management schemes, such as AEM/EE could be introduced to compensate for the negative effect of land consolidation on natural enemies (Horgan et al., 2016; Kleijn & Sutherland, 2003; Landis, 2017; Zhu et al., 2022). However, while we did not observe a direct correlation between the reduction of natural enemies and an increase in the number of rice pests due to land consolidation, further investigation into the effectiveness of natural enemies in biological pest control is necessary before implementing AEM/EE strategies (Zou, 2024).

We did not observe significant differences in rice yield between consolidated and traditional farmlands. Although this result seems

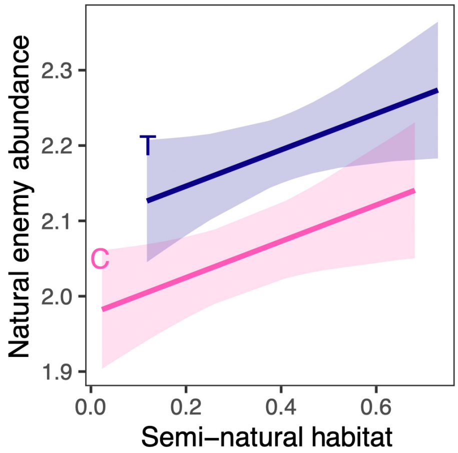

FIGURE 4 Effects between semi-natural habitat proportion and land consolidation status (T: traditional in blue, C: consolidated in pink) on natural enemy abundance (log10-transformed number of individuals per m^2) in unsprayed rice fields. Solid lines indicate significant relationships ($p < 0.05$). Shade areas refer to 95% CI.

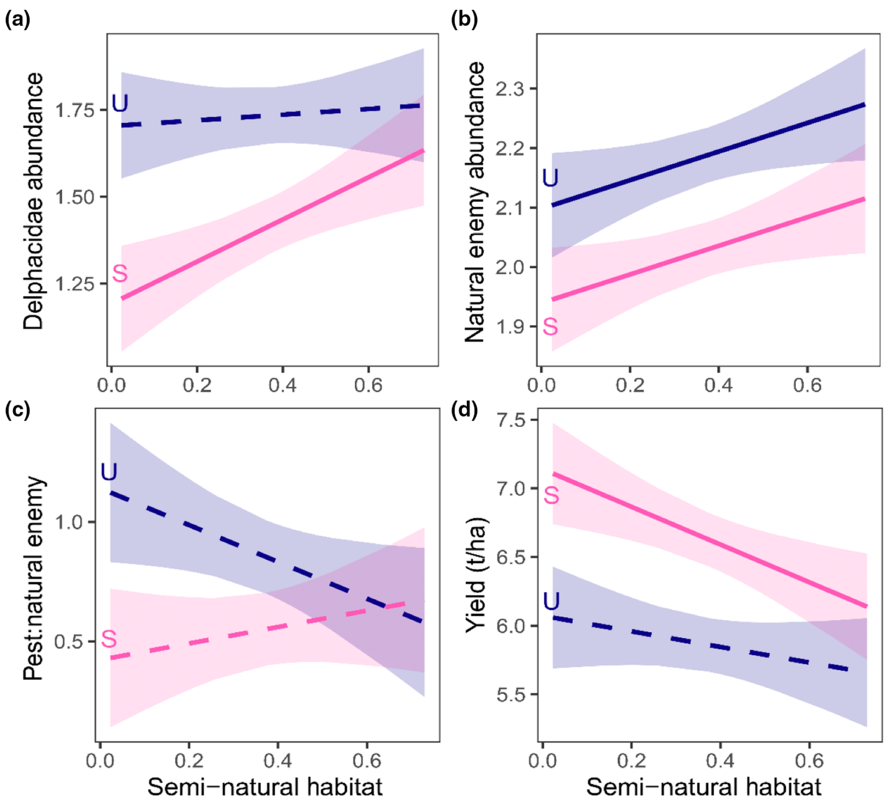

FIGURE 5 Effects between semi-natural habitat proportion and insecticide application (U: insecticide unsprayed in blue, S: insecticide sprayed in pink) on (a) *Delphacidae* abundance (log10-transformed), (b) natural enemy abundance (log10-transformed), (c) pest to natural enemy ratio (log10-transformed), and (d) yield. Solid lines indicate significant relationships ($p < 0.05$), and dashed lines non-significant relationships. Shade areas refer to 95% CI.

counterintuitive to many previous studies that land consolidation improved land use efficiency as well as crop yield (He et al., 2020; Jiang et al., 2022; Tang et al., 2019; Vitikainen, 2004), land consolidation can also reportedly reduce crop yield due to the decline in soil fertility (Du et al., 2018). The effect of land consolidation on yield depends on the comprehensive effect of agricultural management intensity, soil fertility and pesticide application. In our study region, agricultural management intensity, soil fertility, and pesticide application in consolidated fields were consistent with the traditional ones, which can also explain a similar yield for two field types. Nonetheless, since consolidated fields are much easier to manage with farm machinery than in traditional fields, rice production on farms in traditional farmland is much labour intensive than in farms with a high level of mechanisation in consolidated farmland (Tang et al., 2019). Although land consolidation is typically assessed based on economic, social, and agronomic factors, it is crucial to consider ecological effects, especially the negative effects on natural enemies.

Contrary to our hypothesis #2, we did not find that the increase of large semi-natural habitats reduces the negative effect of land consolidation on arthropod abundance and family richness. This finding was consistent across different landscape scales. The result is consistent with Shi et al. (2021), who also found no interactions between land consolidation and semi-natural habitat affecting pollinators. The lack of interaction between land consolidation and semi-natural habitat implies that the effect of fine-scale linear habitats on biodiversity in rice is independent of large semi-natural habitat patches. However, results showed that large semi-natural habitat patches increase the natural enemy abundance for both consolidated and traditional fields, indicating that two types of habitat might have some additive effects, that is, that increasing large SNH patches might 'offset' the negative effect of consolidation (Shi et al., 2021).

We found that the consolidation status did not significantly interact with the status of insecticide application, in affecting arthropod family richness and abundance, crop damage, or yield. Contrary to our hypothesis #3, these results revealed that the adverse effects of insecticide application on arthropods were consistent in both consolidated and traditional fields. This outcome is expected as pests, crop damage, and yields were similar in both types of fields. Regarding natural enemies, the results indicated that insecticides eliminated an equal amount of natural enemy richness in both traditional and consolidated fields, despite traditional fields having a higher richness of natural enemies.

The abundance of rice plant hoppers and natural enemies increased with increasing proportion of semi-natural habitat but the rice yield decreased. This interactive effect agrees with our hypothesis #4, indicating that semi-natural habitats might offer alternative sites for rice arthropods from pesticide exposure. These positive relationships may be explained if semi-natural habitats support both natural enemies and rice plant hoppers (Tscharntke et al., 2016). Natural enemies may benefit from food and hibernation sources in semi-natural habitat (Bianchi et al., 2006), even though natural enemies do not always show consistent responses to semi-natural habitat (Karp et al., 2018). Semi-natural habitat may also contain grasses that may support white-backed planthoppers (*Sogatella furcifera*), which was the most abundant rice pest, which can then colonise rice fields from semi-natural habitats (Kisimoto & Sogawa, 1995). An alternative explanation could be that a high proportion of semi-natural habitats translated into a relatively low proportion of rice crops, resulting in an overall concentration effect for migratory pests in the relatively small rice area in landscapes with a high proportion of semi-natural habitat. However, this relationship was only observed in insecticide sprayed rice plots, presumably because in insecticide sprayed plots the pest population replied more on immigration from semi-natural habitat. A negative relationship between the proportion of semi-natural habitat and crop yield has also been reported elsewhere (Martin et al., 2013, 2016), and this may be explained by a higher pest abundance in rice fields in landscapes with a high proportion of semi-natural habitat, which may also explain our results of rice yield in insecticide sprayed plots. Although our results showed uniformly higher pest abundance and lower crop yield in insecticide unsprayed plots, the interactive effect between pest:natural enemy ratio and SNH showed potential biological pest control in landscapes with a high proportion of large semi-natural patches.

Here, we compared the rice arthropod communities between consolidated and traditional fields. However, we did not quantify the amount of linear habitats in different fields due to their small size, and digitizing each field patch and its margins was impractical for us. However, a further detailed assessment of the impact of changes in linear habitats on rice arthropods, for example, from a configuration aspect (Dominik et al., 2018; Martin et al., 2019), will help us understand the mechanisms behind landscape consolidation. Artificial intelligence (AI)-based land use digitalisation tool may be able to handle this task for these extremely small-sized fields (Chen et al., 2020). Furthermore, since each habitat type may support different arthropod groups in distinct ways (Dominik et al., 2022; Ernoult et al., 2013; Guo et al., 2022), a more detailed examination of how each group responds to changes in linear habitats is encouraged for future studies.

5 | CONCLUSIONS

A growing proportion of agricultural land in China is currently being consolidated to support agricultural mechanisation and the associated gains in labour efficiency and productivity. Our study showed that land consolidation reduces the abundance and family richness of natural enemies, but had less impact on pests in the small-holder rice systems. However, biodiversity loss caused by land consolidation was not reduced by an increase of large semi-natural habitat in the surrounding landscape, although additive effects (between consolation and SNH) were observed for the abundance of the natural enemies. To counteract the negative impacts of land consolidation on farmland biodiversity, the introduction of fine-scale AEM or EE and re-establishing vegetation on field margins in consolidated landscapes may help to conserve the abundance and diversity of rice natural enemies (Horgan et al., 2016; Zhu et al., 2022; Zou, 2024), although trade-off between enhancing crop yields and preserving biodiversity should be considered. We encourage future research to focus on the detailed assessment of linear habitats, to better understand the complex interactions between agricultural practices, biodiversity and biological control services.

AUTHOR CONTRIBUTIONS

Yi Zou, Haijun Xiao, Felix JJA Bianchi and Wopke van der Werf conceived and designed the experiments; Shanxing Gong, Yulin Zhu, Daomeng Fu, Haijun Xiao and Yi Zou collected the data; Shanxing Gong and Yi Zou analysed the data with advice from Jenny A. Hodgson, Felix JJA Bianchi and Wopke van der Werf; Shanxing Gong and Yi Zou wrote the manuscript with significant contributions from all other co-authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. Yi Zou is an Associate Editor of *Journal of Applied Ecology* but took no part in the peer review and decision-making processes for this paper.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.73n5tb34m (Gong et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Photo examples show traditional Chinese small-holder agricultural fields (a) and fields during the consolidation process (b).

Table S1. Land consolidation status and proportion of semi-natural habitat (SNH) of each site in each year.

Table S2. Number of arthropod individuals (identify to family level) sampled in consolidated (54 year-fields) and traditional (62 year-fields) farmland.

Table S3. The most parsimonious models (ΔAICc <2) and their average for response variables related to arthropod communities, crop damage and rice yield.

Table S4. The most parsimonious models (lowest AICc value) for response variables related to arthropod communities, crop damage and rice yield.

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