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# Ecological engineering for rice pest suppression in China. A review

Pingyang Zhu<sup>1</sup> · Xusong Zheng<sup>2</sup> · Anne C. Johnson<sup>3</sup> · Guihua Chen<sup>4</sup> · Hongxing Xu<sup>2</sup> · Facheng Zhang<sup>4</sup> · Xiaoming Yao<sup>5</sup> · Konglun Heong<sup>6</sup> · Zhongxian Lu<sup>1,2</sup> · Geoff M. Gurr<sup>3</sup>

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## Abstract

Ecological engineering for pest suppression aimed at promoting ecosystem services of biological control, involves a range of environmentally-benign approaches to conserve and promote arthropod natural enemies and suppress pest populations, and thus reduce the need for insecticide use. Major components in rice pest management involve providing vegetation that favors parasitoid overwintering during the fallow seasons, growing nectar-producing flowering plants on the rice bunds to enhance the biocontrol function, and planting trap plants around rice fields to minimize the initial populations of pests. Complementary tactics involve using sex pheromone traps and mass-releasing *Trichogramma* spp. parasitoids to reduce the densities of Lepidoptera pests, and synergistically culturing ducks or fish to reduce other planthoppers. After a decade of laboratory and field research accompanied by on-farm demonstrations, ecological engineering for rice pest management has shown growth in both the underlying body of theory and practical adoption, especially in China. Ecological engineering approaches have been listed as a China National Recommendation by the Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA) since 2014. We feel this is worth documenting, especially because only a portion of that work has been reported in English-language journals so would otherwise remain “invisible” to the international scientific community. This study is the first time to systematically review the research that has allowed this rapid development and uptake in China, highlighting priorities for future research that will enhance the prospects for ecological engineering in this and other agricultural systems internationally.

**Keywords** Agricultural system · Environmentally benign approaches · Habitat management · Plant-based resources · Ecosystem service · Complementary tactics

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## 1 Introduction

Rice, the most important food crop in the world, is an essential staple food in China with cultivation dating back for more than six thousand years (Yuan 2014). The Green Revolution starting in the 1960s was aimed at meeting the increasing demand for food from rapid human population growth. Rice yields have been significantly increased with the wide-scale adoption of high-yielding varieties, and extensive use of chemical pesticides and fertilizers (Heong et al. 2015). However, the overuse of chemical pesticides results in severe threats to the sustainability and safety of agricultural production resulted from widespread insecticide resistance in pest populations a pressing problem (Conway and Pretty 1991; Xu et al. 2017). Even though it has become essential to reduce reliance on chemical pesticides to improve food security by improved pest management in rice. Compared to the overuse of chemical pesticides, conservation biological control (CBC) is a more sustainable practice that is a part of integrated pest management (IPM), and can be an effective means of reversing the negative effects of agricultural intensification. CBC aims to enhance pest control by improving resources for natural enemies and reducing the disadvantages of agricultural intensification for natural enemy populations (Holland et al. 2016; Shields et al. 2019). This can be achieved by a variety of management practices that has matured into an information-rich approach which includes ecological engineering (Gurr et al. 2004). Ecological engineering employs habitat management to promote ecosystem services of biological control by providing food, hosts, and shelter, for natural enemies of pests (Gurr et al. 2017; Westphal et al. 2015; Heong et al. 2021). Using practices to support biological control has been advocated since the 1960s (Pathak 1968; Yasumatsu and Torh 1968). Though largely overshadowed by Green Revolution technologies, China had made use of Integrated Pest Control (IPC, the predecessor of IPM) during the 1960s–1970s—this included cultural practices and biological control (Brader

1979). Since the end of 1970s, researchers in China increasingly realized the importance of trap crops and non-crop habitats in the rice ecosystem, especially the effects of weedy bunds on the natural enemies of rice herbivores (Brader 1979; Qiu et al. 1998; Yu et al. 1996; Zhuang 1989).

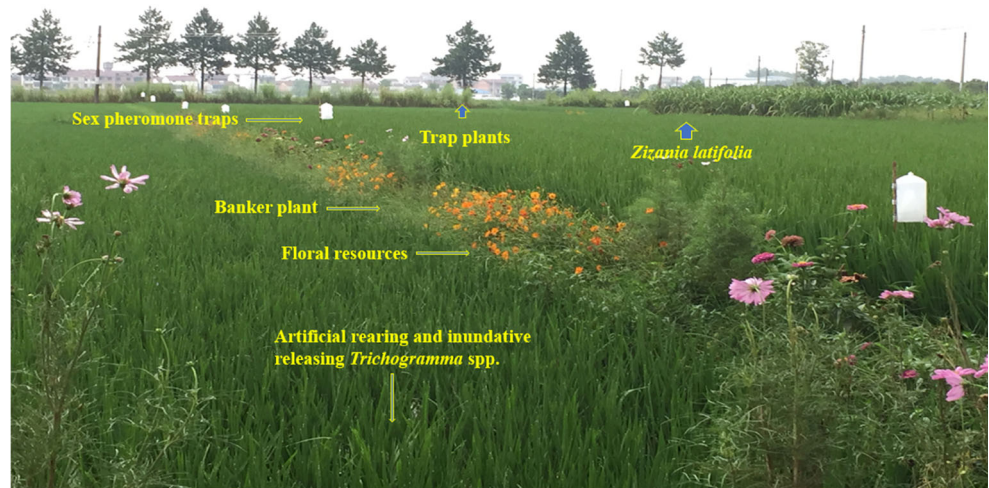
More generally, research on ecological engineering for pest control in various crop systems has developed markedly over the last 40 years though translation into widespread adoption was limited few crop species (Gurr et al. 2017; Wu et al. 2009; Zhao et al. 2016). The principles of ecological engineering were originally proposed by Shijun Ma in 1979 (Sun and Qi 2017), and the earliest study (for which data are available recorded in English) on ecological engineering for pest management was on cotton aphid control by ladybird beetles (Li and Du 1984). Over the past two decades, research has been conducted in many cropping systems. These laboratory and field studies have produced empirical evidence to support the concept of ecological engineering and refined the techniques of ecological engineering for pest management. Examples in China include wheat (Zhao et al. 2013), cotton (Liu et al. 2016; Liu et al. 2018), tea (Chen et al. 2019; Zhang et al. 2016a), soybean (Zhang and Swinton 2012), brassica vegetables (Li et al. 2016), and orchards (Wan et al. 2019a). As a formal program, ecological engineering techniques (EET) for rice pest management were initiated in China in 2008 with the first demonstration farm was established in Zhejiang Province, China (Fig. 1). Ecological engineering for rice pest management is now integrated with both theory and practice into a comprehensive system (Table 1). Ecological engineering techniques for rice pest management include ecological engineering techniques (EET) and supporting techniques for higher efficiency of EET. Ecological engineering techniques improve the ecosystem services of pest control by ecological approaches. In contrast, supporting techniques are those that operate by other mechanisms (releasing natural enemies and applying biopesticides) or that are implemented for wider, production-related issues (co-culture). These ecological engineering techniques can enhance the strength of ecosystem services and reduce the need for pesticide use (especially insecticides). This study is the first time to systematically review research on the practical introduction of ecological engineering for rice pest suppression in China with the aim of providing guidance for its implementation and replications in other crops and regions.

## 2 Ecological engineering techniques (EET) for rice pest management

### 2.1 Increasing crop system compatibility of pest management

Typically, intensified rice-based agricultural production systems are oversimplified farm landscapes where non-crop flora

**Fig. 1** The demonstration farm of ecological engineering for rice pest suppression in Zhejiang Province, China. Photograph by Pingyang Zhu.



is greatly reduced. In addition, the overuse of fertilizers and pesticides is widespread (Heong et al. 2015). These results in a weakening of contributions of ecosystem services by natural enemies of crop pests, which in turn results in frequent pest outbreaks (Lu et al. 2015). In recent decades, the acknowledgement of the importance of non-crop flora on farmlands has initiated research on enhancing ecosystem services provided by improved biodiversity in farmland (Lu et al. 2015; Wan et al. 2018). The practice of habitat manipulation for arthropod pest management is a critical component of ecological engineering for pest suppression aimed at improving the ecosystem services of biological control (Gurr et al. 2004; Gurr et al. 2017).

Habitat management introduces plant-based resources for natural enemies such as shelter, nectar, alternative prey, and pollen (Gurr et al. 2017). Increasing crop system compatibility in agroecosystems brings stability to arthropod communities and populations, which will better address pest suppression.

### 2.1.1 Shelter for natural enemies

Providing arthropod natural enemies with shelter allows them to overwinter near crop fields, prevents communities from being wiped out from insecticide use, and allows rapid recolonization during early crop stages or after disruptions. Pest suppression function has been enhanced in rice by growing green manure crops (the Chinese milk vetch *Astragalus sinicus*), which give shelter and food for natural enemies to overwinter after the rice season. Other examples of providing shelter include incorporating the rice straw to the field, maintaining graminaceous plants around rice fields, intercropping with *Zizania latifolia* and neighboring with vegetable crops (Table 1). Providing these forms of shelter for natural enemies has been shown to suppress pest populations so that densities do not reach threshold levels. Therefore, pesticides use can be avoided (Chen et al. 2016; Huang et al. 2005; Zhang et al. 2011).

### 2.1.2 Alternative hosts for natural enemies

The banker plant system, as a form of CBC, consists of a non-crop plant which is consciously nourished a non-pest herbivore as an alternative host for natural enemies of the target crop pest (Frank 2010). Banker plants support the temporal continuity of key natural enemy species by providing, during the winter fallow and early in the rice season, prey and hosts that support these beneficial arthropods during periods when the rice herbivores are absent or scarce (Zheng et al. 2017a). Banker plants thereby prevent the local extinction of natural enemies of rice pests, and build up natural enemy densities. In a banker plant system, the alternative host or prey is ideally a specialist to the banker plant so that it does not pose a risk to the focal or other crops, and the natural enemies need to have the ability to disperse across the crop field and a wide enough host/prey range to attack the focal pest.

Two banker plant systems used in rice production are the *Zizania latifolia* – *Saccharosydne procerus* – *Anagrus* spp. (ZSA) (Fig. 2a) and *Leersia sayanuka* – *Nilaparvata muii* – *Anagrus* spp. & *Typhus chinensis* (LNA&T) (Fig. 2b) (Table 1). Laboratory studies showed that BPH was unable to complete its life cycle on *L. sayanuka*, and *N. muii* could not complete its life cycle on rice. Thus, planting *L. sayanuka* poses no risk of it serving as an alternative host to the rice pest *N. lugens*. BPH densities in field studies were found to be significantly lower in rice fields grown with the banker plant compared to control rice fields without the banker plant (Zheng et al. 2017a). The ZSA system involves the intercropping of rice with the aquatic vegetable *Z. latifolia*. Green slender planthopper, *Saccharosydne procerus*, is the main pest of *Z. latifolia*, but it does not feed on rice, and shares the egg parasitoid *Anagrus* spp. with rice plant- and leafhoppers and provides *Anagrus* spp. with food in winter (Yu et al. 1999; Zheng et al. 1999). If well chosen, plants such as *Zizania* serve the dual function of providing shelter to a range of natural enemy taxa as well as supporting hosts of more specific parasitoid species.

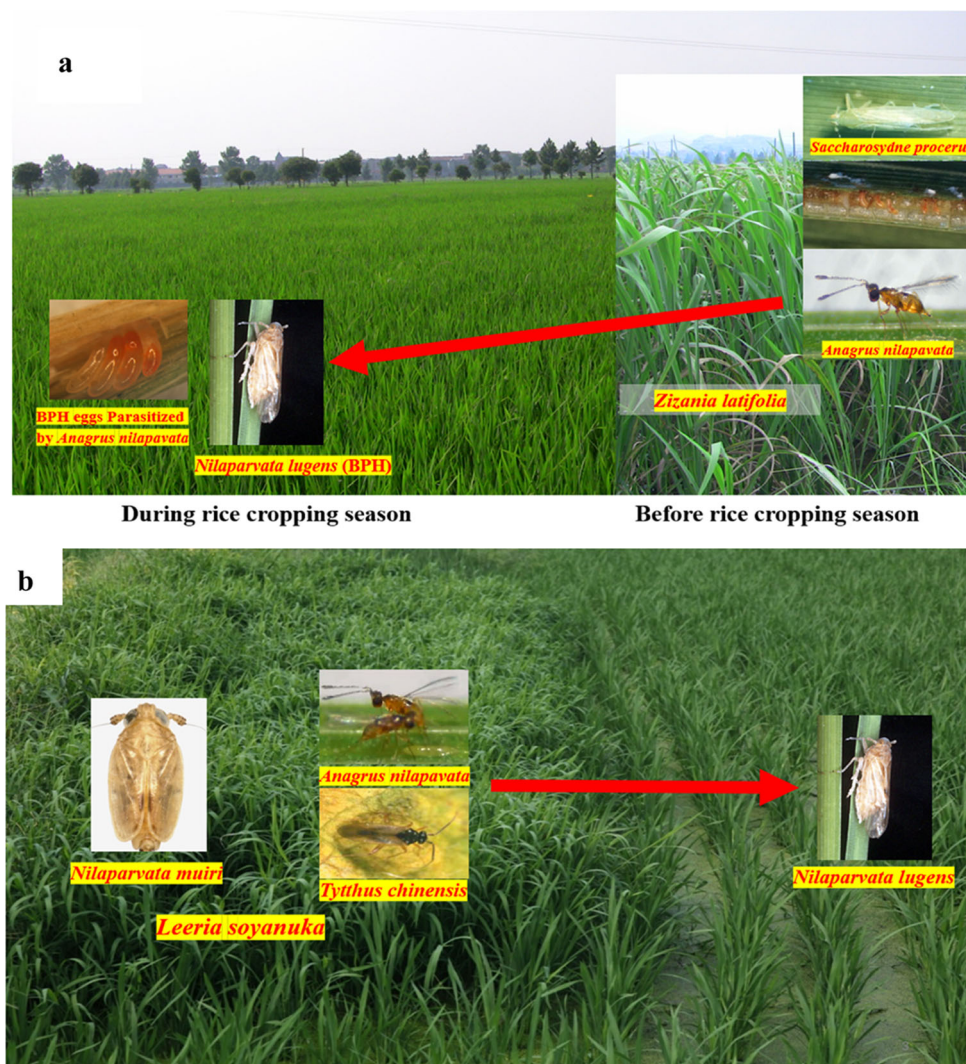
**Table 1** Ecological engineering techniques for rice pest suppression used in China. \*RPHs, rice planthoppers, *Nilaparvata lugens* (Stål); *Sogatella furcifera* (Horváth); and *Laodelphax striatellus* (Fallen); BPH, brown planthopper, *Nilaparvata lugens* (Stål); WBPH, white-backed planthopper, *Sogatella furcifera* (Horváth); RSB, rice stem borer, *Chilo suppressalis* (Walker); PSB, pink rice borer, *Sesamia inferens* (Walker); YRB, yellow rice borer, *Scirpophaga incertulas* (Walker); RLF, rice leaf folder, *Chnathalacrocis medinalis* (Guenee). §References are in additional information.

Objectives	Techniques	Target natural enemies	Target pests*	Details	References§
<b>Ecological engineering techniques (EET)</b>					
<b>Increasing crop system compatibility on pest management</b>					
Shelter for natural enemies	Growing green manure crops after rice season (the Chinese milk vetch <i>Astragalus sinicus</i> )	Spiders/predators/parasitoids	Rice pests	The number of species, densities, and diversity of arthropod natural enemies are significantly higher in Chinese milk vetch fields than those in winter fallow fields.	1
	Maintaining graminaceous plants around rice fields	<i>Oligosita</i> spp. <i>Anagrus</i> spp. spiders	RPHs, RLF, RSB	Abundant <i>Oligosita</i> spp. on <i>Digitaria sanguinalis</i> and <i>Eleusine indica</i> , and <i>Anagrus</i> spp. on <i>Alopecurus aequalis</i> and <i>Leersia hexandra</i> .	2
	Intercropping <i>Zizania latifolia</i>	spiders	rice	<i>Zizania latifolia</i> fields provided refugia and breeding sites for spiders to overwinter. Spiders in the rice field adjacent to <i>Z. latifolia</i> increased by about 30%.	3
	Neighboring with vegetable crops	Spiders/predators	RLF, RPHs	The densities of arthropod natural enemies are significantly higher when rice neighbored with white melon ( <i>Cucurbita pepo</i> ) and flowering Chinese cabbage ( <i>Brassica campestris</i> )	4
Alternative hosts for natural enemies using the banker plant system	<i>Z. latifolia</i> – <i>Saccharosydne procerus</i> – <i>Anagrus</i> spp. <i>Leersia sayanuka</i> – <i>Nilaparvata muiri</i> – <i>Anagrus</i> spp. and <i>Typhus chinensis</i>	<i>Anagrus</i> spp. <i>Anagrus</i> spp. and <i>T. chinensis</i>	RPHs RPHs	<i>Z. latifolia</i> supports the non-pest herbivore of rice <i>S. procerus</i> that is an alternative host for <i>Anagrus</i> spp. Parasitoids of rice planthoppers, allowing parasitoid to build up early in the season. <i>N. muiri</i> , a planthopper only feeds on <i>L. sayanuka</i> , could be chosen as the alternative host of for <i>A. nilaparvatae</i> . The rice planthopper could not complete its life cycle on <i>L. sayanuka</i> , while <i>N. muiri</i> could not complete its life cycle on rice. Rice planthopper densities were significantly lower in rice fields with LNA&T banker plant system.	5, 6 7, 8
Floral resources for natural enemies	Sesame ( <i>Sesamum indicum</i> ) Soybean ( <i>Glycine max</i> ) Corn pollen with water Sesame ( <i>S. indicum</i> ) Sesame ( <i>S. indicum</i> ) Sesame ( <i>S. indicum</i> ) Sesame ( <i>S. indicum</i> )	<i>Anagrus opabilis</i> and <i>A. nilaparvatae</i> <i>A. nilaparvatae</i> <i>A. nilaparvatae</i> <i>Cyrtorhinus lividipennis</i>	RPHs RPHs RPHs RPHs RLF RSB RSB, RLF	Significantly attracted by the volatiles from sesame. The longevity and fecundity of adult females with sesame flowers are improved considerably. The longevity and fecundity of <i>A. nilaparvatae</i> are significantly improved. The longevity and fecundity of <i>A. nilaparvatae</i> are significantly improved. The longevity and fecundity of <i>C. lividipennis</i> are extended, egg consumption is increased, the nymphal period duration is shortened, the 4th instar nymph's predation on BPH eggs is significantly increased in the presence of sesame. Adult survival of the larval parasitoids is significantly increased when fed on <i>S. indicum</i> flowers. Sesame increased the fecundity of <i>T. chilonis</i> and did not favor the Lepidoptera pests, like RSB and RLF.	9 10 10 11, 12 13

Table 1 (continued)

Objectives	Techniques	Target natural enemies	Target pests*	Details	References <sup>§</sup>
	Creeping woodsorrel ( <i>Oxalis corniculata</i> )	<i>T. chilonis</i>	RSB, RLF	The longevity and fecundity are extended.	14
	<b>Reducing the negative effects</b>				
Reducing insecticide use	Keeping the early rice stages insecticide free			No significant effects were found in the growth and yields of rice by reducing 1–2 times insecticide sprays in the early rice stage;	15, 16
Host plant-related measures	Employing the three controls nutrient management (TCNM) (control fertilizer, control seedlings, and control pests by nutrient management) Application of silicon fertilizer		RPHs, RLF	Reduction of the average nitrogen usage by 200 kg/ha to 250 kg/ha; The average yields increased by more than 5%; The damages of dominant pests were significantly lower.	17 18
	<b>Minimizing the initial population of pest</b>				
	Growing of trap plants		WBPH, RSB	Inhibit oviposition of WBPH; Contribute to the suppression of RSB directly through impeding larval feeding and indirectly by delaying stem penetration, resulting in prolonged exposure to natural enemies.	19 20 21
	<b>Applying biological control agents</b>				
Supporting techniques for higher efficiency of EET	Artificial rearing and inundative releasing natural enemies Rice-duck co-culture system Rice-fish co-culture systems Use of sex pheromone traps	<i>Trichogramma</i> species	RSB, PSB, YRB RSB, RLF rice pests rice pests RSB, RLF	Lay eggs on vetiver grass <i>Vetiveria zizanioides</i> , but they could not complete their life cycles; low nutrients in vetiver grass. <i>Trichogramma</i> species have been studied extensively (details in Table S1). Reduce ineffective rice tillers, promote the gas exchange and the soil effective component decomposition, enhance the resistance of rice, reduce rice pests, increase the ripening rate and thousand kernel weight of rice and improve rice quality. Prolong tillering stage by 10–12 days; increase rice spike rates and yields, reduce the use of chemicals through reducing rice pest occurrence and complementary nutrient use. The control effects were more than 50%; reduce insecticide sprays by 1 or 2 times a season	22, 23, 24 25, 26, 27, 28 29, 30 31, 32
	<b>Applying biopesticides</b>				
	<i>Bacillus thuringiensis</i> (Bt) <i>Mamestra brassicae</i> nuclear polyhedrosis virus (MbNPV)		RSB, RLF RSB, RLF	The efficacies on RSB and RLF are 65.31–96.69% and 88–97.17%, respectively. Control effects on RLF over 86% at 7 d after spraying and on RSB over 88% at 30 d after spraying	33 34, 35, 36

**Fig. 2** Banker plant systems used in rice production. **a** The *Zizania latifolia* – *Saccharosydne procerus* – *Anagrus* spp. (ZSA) system, BPH refers to the brown planthopper *Nilaparvata lugens*; **b** *Leersia sayanuka* – *Nilaparvata muii* – *Anagrus* spp. & *Typhus chinensis* (LNA&T) system. Photographs by the authors.



### 2.1.3 Floral resources for natural enemies

Floral resources can enhance the effectiveness of natural enemies since they attract them, prolong their longevity, and increase their fecundity (Lu et al. 2014). Accordingly, the inclusion of suitable flowering plants in non-crop habitats can improve the activity and impact of natural enemies. A growing number of studies have demonstrated the abundance and fecundity of natural enemies were increased in the presence of floral resources (Lu et al. 2014; Wang et al. 2017; Zhao et al. 2016), particularly in the rice-based ecosystem (Table 1), with measurable benefits in terms of pest densities, rice yield, reduced pesticide use, and overall economic advantage (Gurr et al. 2016). Sesame (*Sesamum indicum*) has been the most popular flowering plant used in ecological engineering techniques for rice pest management because it serves as a lucrative dual income crop and has been listed as a central component of the nationally recommended sustainable management

of rice insect pests by ecological engineering techniques in China (MARA 2014).

### 2.2 Keeping the early rice stages insecticide free

Neutral insects, especially detritivore chironomid midges, whose population could be as many as 4.5 million per  $\text{hm}^2$  in a rice field, can be an essential food source for predators early in the rice season (Li et al. 2010; Wu et al. 1994). Populations of natural enemies and neutral insects are easily reduced by injudicious use of insecticides. This decrease in the biodiversity of arthropods early in the season allows a natural build-up of pests like rice planthoppers and rice leaf folders later in the crop (Way and Heong 1994). Generally, in the first 30 days after transplanting, pest densities are low, and insecticide applications do not impact on crop yield, therefore, are not necessary (Xu et al. 2017; ZQTSB 2017). Many field studies have indicated that applying less than 1–2 insecticide

sprays in the early rice stage will not affect the growth and yields of rice (Guo et al. 2013; Hu et al. 1996).

### 2.3 Cultural methods

The overuse of nitrogen fertilizers in rice is common across Asia and is most acute in China (Cheng 2009; Ding et al. 2018; Wang et al. 2019). The adoption of hybrid rice for high yields resulted in significant increases in the use of nitrogen across Asia (Wang and Peng 2017). Higher levels of nitrogen in rice also increased herbivore feeding, survival rates, and reproduction (Lu et al. 2007). In many areas, outbreaks of pests, including planthoppers, leaf rollers, and stem borers, have been closely linked to excessive use of nitrogen (Hu et al. 2016; Lu et al. 2007; Lu and Heong 2009). High nitrogen use also negatively impact natural enemy performance, which increases the risk of BPH outbreaks (Zhu et al. 2017b). The high-efficiency technology system for nitrogen fertilizer applications in rice fields has been developed (Zhong et al. 2010). Optimum nitrogen estimated by this system limits the number of ineffective tillers, and improves yield while minimizing disease occurrence and pest damage (Huang et al. 2010; Zhong et al. 2010).

Nitrogen (N), phosphorus (P), and potassium (K) are essential nutrients for rice that must be applied in rice fields to maintain productivity (Rashid et al. 2016), but the unbalanced and excessive use of N, P, and K is common in rice production (Xu et al. 2017). Balanced application of the essential nutrients improves utilization efficiency of nitrogen fertilizer in the rice field, as well as potassium fertilizer, in turn, improves rice plant vigor, and enhances rice resistance to rice leaf folder and other pests (de Kraker et al. 2000). There is also a positive relationship between rice resistance to pests and the application of silicon fertilizer (Liu et al. 2017). Silicon also plays important roles in rice plant defense against abiotic stress (Tripathi et al. 2014), such as lodging (Deng et al. 2011), heat and drought (Agarie et al. 1998). Silicon fertilizer can contribute to pest control by inhibiting feeding and oviposition of pests, as well as enhancing the attraction of parasitoids (Liu et al. 2017) (Table 1).

### 2.4 Minimizing initial pest population using trap plants

The stem borers including RSB, pink rice borer (PRB) *Sesamia inferen* and yellow rice borer (YRB) *Scirpophaga incertulas*, lay eggs on vetiver grass *Vetiveria zizanioides*, but the larvae cannot complete their life cycle feeding on this grass making it a useful “dead-end host” (Chen et al. 2007; Gao et al. 2015; Lu et al. 2017; Zheng et al. 2009). The underlying mechanisms are (1) bioactive substances in vetiver grass are toxic and inhibit RSB larval growth; (2) extracts of vetiver grass disturb the dynamic equilibrium of Superoxide

Dismutase (SOD), Catalase (CAT), and Peroxidase (POD), and inhibit the esterase and cytochrome P450 enzyme activities, leading to a loss of the larvae function in detoxification and metabolism; (3) vetiver grass has lower nutritional value than rice; and (4) the *V. zizanioides* extract inhibits RSBF; the protective efficacies were 66.7% in an outdoor pot-cultivation test (Gao et al. 2011, 2015; Lu et al. 2017). With these characteristics, planting vetiver grass around paddy fields can attract stem borer adults to lay eggs on its leaves and reduce the population in rice fields (Lu et al. 2018). The best planting period is from late March to early April in temperate regions of China (planting 4–8 weeks before rice planting in the spring), and the appropriate planting coverage is 6–10% of the rice field (Chen et al. 2007). The optimal planting pattern is in clusters with spacing of 3–5 m and line spacing of 50–60 m (Zheng et al. 2017c). The aim of planting this trap crop is to keep the density of the stem borers in the rice to below the thresholds in order to avoid using pesticides.

## 3 Supporting techniques for higher efficiency of EET

### 3.1 Applying biological control agents

#### 3.1.1 Inundative releasing *Trichogramma* wasps

*Trichogramma* species have been studied extensively and play a vital role in insect pest management in China (Lou et al. 2013). Research into releasing *Trichogramma* spp. for the control of main Lepidoptera pests in rice fields has been conducted since the 1950s in China (Table S1). Constraints on the use of *Trichogramma* spp. include appropriate species selection, population rejuvenation, and field application techniques (Babendreier et al. 2019). In recent years, applications of *Trichogramma* have gained renewed interest (Xu et al. 2017; Babendreier et al. 2019). Technologies for releasing *Trichogramma* into rice fields have advanced in recent years incorporating unmanned aerial vehicles “drones” for rapid dispersal and release (Xu et al. 2017) as well as nectar food supplements to maximise post-release longevity. Research into species selection, the interval of release timing and density and release heights could contribute to further improvements in the large-scale use of *Trichogramma* spp. in rice (Xu et al. 2017).

#### 3.1.2 Agroecological intensification by co-culture systems

Rice co-culture systems incorporating, such as rice-duck, rice-fish, rice-soft shelled turtle, rice-crab, or all combinations, can provide benefits compared to traditional rice monocultures, especially due to the animal component of the system consuming pest species (Khumairoh et al. 2021; Xu et al. 2017)

(Table 1). The rice-fish co-culture model has a long history in China (Huang et al. 2014). Recent studies show the rice-fish co-culture can decrease herbivore insect abundance, reduce weed abundance, richness of species and biomass, increase invertebrate predator abundance, reduce pesticide use, and enhance both soil and grain quality in terms of increasing available nitrogen, phosphorus, potassium, total nitrogen, and organic matter content of the soil environment in rice-fish production systems, as well as increasing head rice rate, milled rice rate, and protein content of grain quality in rice-fish production systems (Li et al. 2022; Wan et al. 2019b; Xie et al. 2011). Rice-fish co-culture has been demonstrated to provide a more than 10% higher net income than rice monoculture (Wan et al. 2019b). The rice-duck co-culture model is but widespread and sporadic in China but has been widely promoted during the last two decades. It can reduce fertilizer use by over 30% and pesticide use by 50%, and significantly improve rice quality in terms of no herbicide and less pesticide used, and increasing coarse rice rate, head rice rate, gel consistency, and chalkiness rate of grain quality in rice-duck production systems, compared with the conventional farming model (Huang et al. 2014). The ongoing exploration of co-culture models means new co-culture models in the rice ecosystem regularly appear, like rice-crab (Guo et al. 2015), rice-crayfish (Jiang and Cao 2021), rice-soft shelled turtle (Zhang et al. 2016b), and rice-frog (Fang et al. 2021) (Fig. 3).

### 3.2 Minimizing initial pest population using sex pheromones

Some pest control strategies involve changing pest behavior through chemicals, visual, or audio signals (Rodriguez-Saona and Stelinski 2009). Like other IPM techniques, the use of methods to manipulate insect behavior previously was not given much attention due to the low cost and convenience of using insecticides.

In many insect species, especially lepidopteran pests, the females emit the sex pheromone to attract the males (Rodriguez-Saona and Stelinski 2009). In rice fields, sex pheromones for controlling the rice stem borer (RSB) *Chilo suppressalis* and rice leaf folder (RLF) *Cnaphalocrocis medinalis* have been developed (Xu et al. 2017). The use of dry traps which have low maintenance needs during the rice season has advantages over conventional traps which need regular replacement of water or lures (Si et al. 2016; Zhu et al. 2013). The results of field applications of sex pheromone traps show that the control effects were more than 50% better when combined with other pest management strategies at a large scale rather than when used as a sole means of pest suppression. Use of sex pheromone traps combined with other pest control strategies against RSB and RLF can reduce insecticide spraying to just one to two times a season, with a cost

comparable to that of using chemical pesticides (Du et al. 2013; Si et al. 2016).

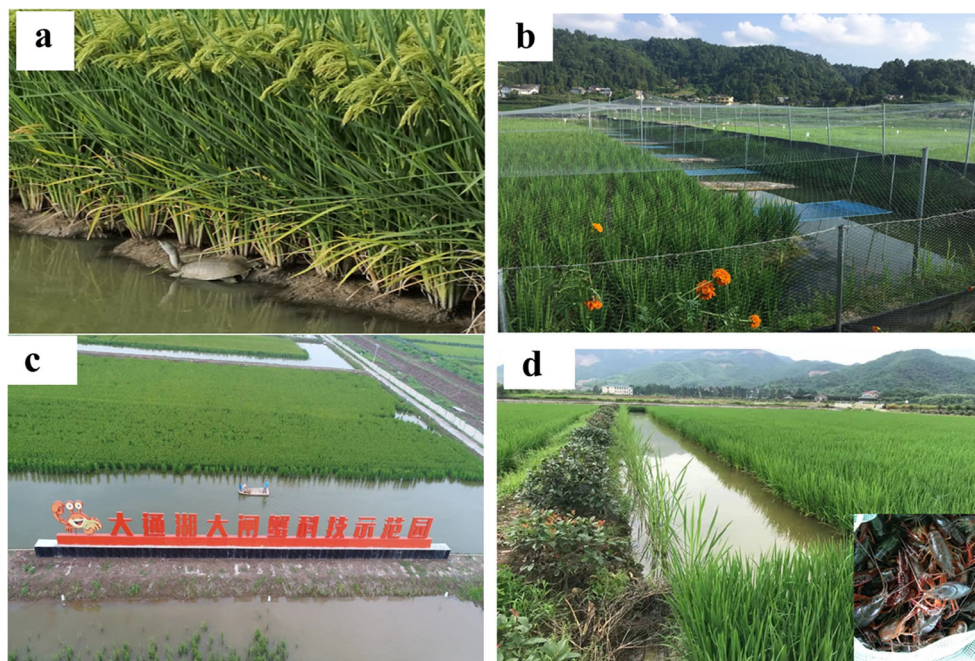
### 3.3 Biopesticides

Biopesticides are increasingly popular in China as they meet the increasing consumer demand for food-safety. *Bacillus thuringiensis* (Bt) is the most popular biopesticide and is officially recommended to control rice stem borers and rice leaf folder in China (Xu et al. 2017). *Mamestra brassicae* nuclear polyhedrosis virus (MbNPV), *Beauveria bassiana*, and *Empedobacter brevis* show high insecticidal activities on rice Lepidoptera insect pests (Wang et al. 2016; Xu et al. 2017; Zheng et al. 2016) (Table 1). *Cnaphalocrocis medinalis* granulovirus (CnmeGV) is also another potentially effective biopesticide to control RLF (Liu et al. 2013; Zhang et al. 2014). The ideal biopesticide application methods in rice involve the following: using Bt and *Bacillus subtilis* before the transplanting of rice seedlings to prevent and reduce the occurrence of field diseases and pests; using Bt to control rice Lepidoptera insect pests and use of the fungus *Beauveria bassiana* to control rice planthoppers during the rice-growing season when necessary.

## 4 Case study of ecological engineering for rice pest suppression

The Zhejiang Academy of Agricultural Sciences (ZAAS) and the Jinhua Plant Protection Station (JPPS) in collaboration with the International Rice Research Institute (IRRI) and Charles Sturt University (CSU) initiated a pioneering attempt to manage rice insect pests by developing a program for ecological engineering for rice pest suppression in 2008. The experimental site was located at Si Ping village, Jinhua city, Zhejiang province, set in an area with nearby mountains and high-quality water resources. Although the original ecosystem had not been greatly disturbed, the areas used for rice production had been impacted by intensive cultivation and the overuse of chemical fertilizers and pesticides. The main techniques included manipulation of vegetation to promote natural enemies, specifically, planting nectar-rich plants like sesame (*Sesamum indicum*), zero insecticide sprays during the first 30 days after transplanting and reducing over 20% of nitrogen fertilizer than conventional application. The goal was to reduce the use of chemical pesticide by 60–80%, to keep yield losses by major pests to less than 3%, and to gradually recover the natural pest control function of the ecosystem. The field studies were done on a farm scale at Si Ping village since 2008. After that, similar field studies were tested at several farms during 2009 to 2018 in Zhejiang province, such as Ningbo, Xiaoshan, Lishui, Wenling, and Wenzhou. The scale of each study site was over 10 ha.

**Fig. 3** Co-culture models in rice ecosystems of China. **a** Rice-soft shelled turtle, photo by Hongxing Xu; **b** rice-frog, photo by Pingyang Zhu; **c** rice-crab, photo by Xusong Zheng; and **d** rice-crayfish, photo by Xusong Zheng.



#### 4.1 Improved biological control

Field surveys showed that the numbers of *Anagrus* spp. and invertebrate predators, including damselflies (e.g., *Ischnura senegalensis*, *Agriocnemis femina*) in the ecological engineering fields, were over four times higher than those in the farmer's fields with conventional agricultural operations (Chen et al. 2016).

The population density of the dominant frog species, *Fejervarya multistriata*, in ecological engineering for rice pest suppression fields was over three times than those in the farmer's fields (Kong et al. 2016). The number of RPH egg parasitoids near the ridge was doubled than those in the farmer's fields in the tiller stage and the filling stage of rice, but the population of RPH was reduced over five times by implementing ecological engineering for rice pest management than those in the farmer's fields in the tiller stage and the filling stage of rice (Zhu et al. 2015). A 5-year follow-up survey showed that the numbers of functional guilds of predatory Odonata and Tetragnathidae, as well as the larval parasitoids of RLF in ecological engineering for rice pest suppression fields, were significantly higher (1.63–8.94 times, 0–3.69 times, 1.20–2.47 times, respectively) than those in the control fields (Zhu et al. 2017c). Furthermore, the ecological engineering strategy promoted the breeding of aquatic predators and neutral insects in rice fields, because of the technique of keeping the early rice stages insecticide free could increase the biodiversity and the population density of aquatic predators and neutral insects, as well as the techniques of growing green manure crops after rice season, maintaining graminaceous plants around rice fields and intercropping *Zizania latifolia*

could provide a stable habitat with plant-based resources for such as shelter, nectar, alternative prey, and pollen (Zhu et al. 2017a).

#### 4.2 Reduced insecticide applications

Applying ecological engineering for rice pest suppression dramatically reduced chemical insecticide applications. Chemical insecticides were not used at all in 2009 and 2011 against rice planthoppers, and the overall number of insecticides was reduced by more than 75% in ecological engineering for rice pest suppression fields compared to the control fields in Jinhua, Zhejiang (Chen et al. 2016).

#### 4.3 Increased economic benefits

With the application of ecological engineering, pest populations were lower throughout the rice-growing season, and compared with the control fields no yield loss was found (Gurr et al. 2016). Insecticide use was reduced by 75%, with cost savings for insecticides and labor amounting to over US \$400 per hectare per year (Chen et al. 2016). With the concerted efforts of the research team and agricultural extension services, ecological engineering for rice pest suppression has been further recognized in society. Rice from EET fields could fetch a price over five times higher than the normal market price, as the benefits of reduced pesticides use are highly valued by the public with the improvement of living standard (Liu et al. 2014). Similar positive results were also observed in other sites in Zhejiang province with the same design as Jinhua, such as Xiaoshan, Lishui, Wenling, and Wenzhou.

### 4.4 EET trade-offs

Certainly, ecological engineering techniques for rice pest suppression improve the ecosystem services of rice pest control. The trade-offs of EET are also worthy of note, even though no independent evidence has been reports to date. But there are anecdotal reports that snake densities are enhanced in some sites where ecological engineering is implemented (possibly reflecting increased frog densities as a result of lower insecticide use). Farmers from EET rice area also give the feedback that the population of egret is much high in the rice field where ecological engineering is implemented, especially early in the rice planting season (possibly reflecting increased small animal densities, such as frogs, earthworm, and minnows). In addition, effects of weedy rice bunds on rat population also should be considered. The systematic review of all underlying risks is necessary for the future work.

## 5 The current situation of ecological engineering for rice pest suppression in China

Ecological engineering for rice pest suppression was standardized by Jinhua city local standard in 2014 (JQTSB 2014) and by Zhejiang province local standard in 2017 (ZQTSB 2017), promoting the popularization of ecological engineering for rice pest suppression in Zhejiang province. Over 80,000 ha of rice fields, which accounts for about 10% of the rice planting area of Zhejiang province, employed the whole-process technical scheme of ecological engineering for rice pest suppression in 2018. The measures included (1) maintaining functional graminaceous weeds around rice fields to provide native arthropod natural enemies with shelter and alternative hosts in winter, and during pesticide applications; (2) intercropping zizania (*Zizania latifolia*) in rice fields as a shelter for spiders, frogs, and *Anagrus* parasitoids of leaf- and planthoppers; (3) inter-planting nectar crops such as sesame

**Fig. 4** Ecological engineering for rice pest suppression was promoted by different ways in China. **a** By demonstration for agricultural extension services and farmers, **b** by setting up a mini museum of rice field biodiversity for visitors and farmers, **c** by DVD video for agricultural extension services and farmers, **d** by online video for agricultural extension services and farmers, **e** by operation diagram for agricultural extension services and farmers. Photographs by Pingyang Zhu.



on field bunds to enhance biological control functioning of *Trichogramma* and *Anagrus* parasitoids and the predator *Cyrtorhinus lividipennis*; (4) planting vetiver grass (*Vetiveria zizanioides*) as a trap plant to attract rice stem borers to lay eggs; (5) inundative releases of *Trichogramma* spp. When necessary to enhance biological control of lepidopteran pests of rice.

Insecticide use has been reduced by 50% across the scheme of ecological engineering for rice pest suppression. Ecological engineering for rice pest suppression also has been promoted energetically by the General Station of Plant Protection and Quarantine of Zhejiang Province and the local Plant Protection Station in Zhejiang as the main technology for green methodologies for the prevention and control of rice pests by various ways (Fig. 4). Over 900 demonstration sites had been established by 2018, which extended over 538,000 ha of rice fields (data from the General Station of Plant Protection and Quarantine of Zhejiang Province, count by rice fields which adopted more than one ecological engineering measure). Now, in a national recommended technology by the Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA 2014), ecological engineering for rice pest suppression has been extended to over 3,000,000 ha of rice fields in southern China, such as Jiangxi province, Jiangsu province, Hunan province, Hubei province, Anhui province, Shanghai, Guizhou province, Yunnan province, and Guangxi province since 2014 (Fu et al. 2021).

## 6 Conclusions and perspectives

New research directions for pest suppression based on ecological engineering techniques have been explored in recent decades and especially this century (Gurr et al. 2004; Heong et al. 2021). The benefits of these techniques extend over multiple trophic levels, promoting natural enemies, suppressing pests, and enhancing crop productivity. In some cases, studies have shown more comprehensive benefits, including reduced insecticide use and financial advantage. Reflecting this, the new concept of “green plant protection” has been widely accepted in China (Lu et al. 2012). It emphasizes the support and safeguards needed to obtain high-yield, good quality, and ecologically sustainable agricultural systems. Ecological engineering for rice pest suppression has been recommended as one of the key strategies for the sustainable management of rice pests by the National Agriculture Technology Extension and Service Centre since 2013, and has been listed as a national recommended technology by the Ministry of Agriculture and Rural Affairs of China since 2014 (MARA 2014). Only a portion of that work has been reported in English-language journals so would otherwise remain “invisible” to the international scientific community, hence the need to document the work in the current form in

order to allow for its expansion to worldwide rice production areas.

Although ecological engineering has gained increasing acceptance among biological control experts and agriculture practitioners (Lu et al. 2015; Settele et al. 2019), there are still important knowledge gaps, including the wider use of floral resources. A growing number of studies have demonstrated the abundance and fecundity of natural enemies increased in the presence of a range of floral resources (Lu et al. 2014; Wang et al. 2017; Zhu et al. 2018). Foremost is the fact that all work has been dependent upon the empirical testing of multiple candidate plants to identify suitable species for each pest-nature enemy interaction in each agroecosystem. It is labor- and time-consuming, and sometimes, decisions are made on a weak evidence base. Ecological engineering for rice pest suppression still needs a scientific evaluation system so that it can be promoted and applied in a broader range of agroecosystems.

Ecologically based pest management in agroecosystems has become increasingly important worldwide (Pretty 2018; Reddy 2017; Zhao et al. 2016). Ecological engineering for rice pest suppression also has been explored in other Asian rice production systems (Ginigaddara 2018), such as the Philippines (Horgan 2017), Indonesia (Sparta et al. 2021), Vietnam (Horgan et al. 2022; Settele et al. 2019), Bangladesh (Ali et al. 2019), and India (Chandrasekar et al. 2017). The present account of ecological engineering for rice pest suppression in China provides a framework for its expansion to other areas and for adaptation for use in a wider range of crop systems.

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**Code availability** Not applicable

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Conflict of interest** The authors declare no competing interests.

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## References

- Agarie S, Uchida H, Agata W, Kubota F, Kaufman PB (1998) Effects of silicon on transpiration and leaf conductance in rice plants (*Oryza sativa* L.). *Plant Prod Sci* 1(2):89–95. <https://doi.org/10.1626/pp.s.1.89>
- Ali MP, Bari MN, Haque SS, Kabir MMM, Afrin S, Nowrin F, Islam MS, Landis DA (2019) Establishing next-generation pest control services in rice fields: eco-agriculture. *Sci Rep-UK* 9(1):10180. <https://doi.org/10.1038/s41598-019-46688-6>
- Babendreier D, Wan M, Tang R, Gu R, Tambo J, Liu Z, Grossrieder M, Kansime M, Wood A, Zhang F, Romney D (2019) Impact assessment of biological control-based integrated pest management in rice and maize in the Greater Mekong Subregion. *Insects* 10(8):226. <https://doi.org/10.3390/insects10080226>
- Brader L (1979) Integrated pest control in the developing world. *Annu Rev Entomol* 24:225–254. <https://doi.org/10.1146/annurev.en.24.010179.001301>
- Chandrasekar K, Muthukrishnan N, Soundararajan RP (2017) Ecological engineering cropping methods for enhancing predator, *Cyrtorhinus lividipennis* (Reuter) and suppression of planthopper, *Nilaparvata lugens* (Stal) in rice—effect of border cropping systems. *Int J Curr Microbiol App Sci* 6(12):330–338. <https://doi.org/10.20546/ijemas.2017.612.039>
- Chen XM, Peng CR, Yao FX, Guan XJ, Wang HL, Deng GQ (2007) Study on the technique and effect of vetiver for trapping and killing rice borer. *Acta Agriculturae Jiangxi* 19(12):51–52 (in Chinese). <https://doi.org/10.3969/j.issn.1001-8581.2007.12.015>
- Chen GH, Zhu PY, Zheng XS, Yao XM, Zhang FC, Sheng XQ, Xu HX, Lu ZX (2016) The practice of ecological engineering on the control of rice insect pests in Jinhua. *China Plant Prot* 36(1):31–36 (in Chinese). <https://doi.org/10.3969/j.issn.1672-6820.2016.01.006>
- Chen LL, Yuan P, Pozsgai G, Chen P, Zhu H, You MS (2019) The impact of cover crops on the predatory mite *Anystis baccarum* (Acari, Anystidae) and the leafhopper pest *Empoasca onukii* (Hemiptera, Cicadellidae) in a tea plantation. *Pest Manag Sci* 75(5):3371–3380. <https://doi.org/10.1002/ps.5489>
- Cheng JA (2009) Rice planthopper problems and relevant causes in China. In: *Planthoppers: new threats to the sustainability of intensive rice production systems in Asia*. International Rice Research Institute, Philippines, pp 157–178
- Conway GR, Pretty JN (1991) *Unwelcome harvest: agriculture and pollution*. Earthscan Publications Ltd, London
- de Kraker J, Rabbinge R, van Huis A, van Lenteren JC, Heong KL (2000) Impact of nitrogenous-fertilization on the population dynamics and natural control of rice leaf folders (Lep.: Pyralidae). *Int J Pest Manage* 46(3):225–235. <https://doi.org/10.1080/096708700415571>
- Deng JL, Fu GL, Yan YH (2011) The effect of silicon fertilizer on SiO<sub>2</sub> content and flexural strength of rice stems. *J Anhui Agric Sci* 39(5):2696–2698 (in Chinese). <https://doi.org/10.13989/j.cnki.0517-6611.2011.05.115>
- Ding W, Xu X, He P, Ullah S, Zhang J, Cui Z, Zhou W (2018) Improving yield and nitrogen use efficiency through alternative fertilization options for rice in China: a meta-analysis. *Field Crop Res* 227:11–18. <https://doi.org/10.1016/j.fcr.2018.08.001>
- Du YJ, Guo R, Han QR (2013) The application technique of insect sex pheromone control of rice stem borer and rice leaf folder. *China Plant Prot* 33(11):39–42 (in Chinese). <https://doi.org/10.3969/j.issn.1672-6820.2013.11.011>
- Fang K, Gao H, Sha Z, Dai W, Yi X, Chen H, Cao L (2021) Mitigating global warming potential with increase net ecosystem economic budget by integrated rice-frog farming in eastern China. *Agric Ecosyst Environ* 308:107235. <https://doi.org/10.1016/j.agee.2020.107235>
- Frank SD (2010) Biological control of arthropod pests using banker plant systems: past progress and future directions. *Biol Control* 52(1):8–16. <https://doi.org/10.1016/j.biocontrol.2009.09.011>
- Fu Q, He JC, Lu ZX, Barrion AT (2021) Identification and utilization of natural enemies of rice pests in China. Zhejiang Science and Technology Press, Hangzhou
- Gao GC, Xu HX, Zheng XS, Yang YJ, Lu ZX, Qiu HP (2011) The antifungal activity of *Vetiveria zizanioides* extracts against plant pathogenic fungi. *Acta Agriculturae Zhejiangensis* 23(3):568–571 (in Chinese). <https://doi.org/10.3969/j.issn.1004-1524.2011.03.026>
- Gao GC, Li J, Zheng XS, Xu HX, Yang YJ, Tian JC, Lu ZX (2015) Effects of extracts from *Vetiveria zizanioides* on growth and development, activities of protective enzymes of *C. suppressalis*. *Bull Sci Technol* 31(5):97–101 (in Chinese). <https://doi.org/10.3969/j.issn.1001-7119.2015.05.021>
- Ginigaddara G (2018) Ecological intensification in Asian rice production systems. In: *Sustainable Agriculture Reviews* 31. Springer, pp 1–23
- Guo R, Han M, Shu F (2013) Strategies and measures of green control of rice pests based on reduction of pesticides application in paddy field. *China Plant Prot* 33(10):38–41 (in Chinese). <https://doi.org/10.3969/j.issn.1672-6820.2013.10.007>
- Guo K, Zhao W, Li W, Zhao Y, Zhang P, Zhang C (2015) Food web structure and trophic levels in polyculture rice-crab fields. *Chin J Ocean Limnol* 33(3):735–740. <https://doi.org/10.1007/s00343-015-4205-8>
- Gurr GM, Wratten SD, Altieri MA (2004) *Ecological engineering for pest management: advances in habitat manipulation for arthropods*. CSIRO publishing, Collingwood, Vic, Australia
- Gurr GM, Lu ZX, Zheng XS, Xu H, Zhu P, Chen G, Yao X, Cheng J, Zhu Z, Catindig JL, Villareal S, van Chien H, Cuong LQ, Channoo C, Chengwattana N, Lan LP, Hai LH, Chaiwong J, Nicol HI et al (2016) Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat Plants* 16014:16014. <https://doi.org/10.1038/nplants.2016.14>
- Gurr GM, Wratten SD, Landis DA, You M (2017) Habitat management to suppress pest populations: progress and prospects. *Annu Rev Entomol* 62(1):91–109. <https://doi.org/10.1146/annurev-ento-031616-035050>
- Heong KL, Wong L, Delos Reyes JH (2015) Addressing planthopper threats to Asian rice farming and food security: fixing insecticide misuse. In: *Rice planthoppers: ecology, management, socio economics and policy*. Springer & Zhejiang University Press, China, pp 65–76
- Heong KL, Lu ZX, Chien HV, Escalada M, Settele J, Cheng JA (2021) Ecological engineering for rice insect pest management: the need to communicate widely, improve farmers' ecological literacy and policy reforms to sustain adoption. *Agronomy* 11(11):2208. <https://doi.org/10.3390/agronomy11112208>

- Holland JM, Bianchi FJJA, Entling MH, Moonen AC, Smitha BM, Jeanneret P (2016) Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Manag Sci* 72(9):1638–1651. <https://doi.org/10.1002/ps.4318>
- Horgan FG (2017) Insect herbivores of rice: their natural regulation and ecologically based management. In: *Rice production worldwide*. Springer, pp 279–302
- Horgan FG, Vu Q, Mundaca EA, Crisol-Martínez E (2022) Restoration of rice ecosystem services: ‘ecological engineering for pest management’ incentives and practices in the mekong delta region of Vietnam. *Agronomy* 12:1042. <https://doi.org/10.3390/agronomy12051042>
- Hu GW, Guo YJ, Li SS, Wu JC (1996) The principle and practice of reducing chemical application in paddy field (part 2). *Entomol Knowl* 33(2):65–69 (in Chinese). CNKI:SUN:KCZS.0.1996-02-000
- Hu XF, Cheng C, Luo F, Chang YY, Teng Q, Men DY, Liu L, Yang MY (2016) Effects of different fertilization practices on the incidence of rice pests and diseases: a three-year case study in Shanghai, in subtropical southeastern China. *Field Crop Res* 196:33–50. <https://doi.org/10.1016/j.fcr.2016.06.004>
- Huang DC, Zeng L, Liang GW, Chen ZN (2005) Population dynamics of pests and their enemies in different cultivated rice fields. *Chin J Appl Ecol* 16(11):2122–2125 (in Chinese). CNKI:SUN:YYSB.0.2005-11-021
- Huang NR, Hu XY, Zhong XH, Cao KW, Lin QS, Chen RB, Huang DS, Cheng FH, Tian K, Chen WF (2010) Progress in demonstration and extension of “three controls” technology for rice. *Guangdong Agricultural Sciences* 37(12):21–23 (in Chinese). <https://doi.org/10.3969/j.issn.1004-874X.2010.12.006>
- Huang S, Wang L, Liu L, Fu Q, Zhu D (2014) Nonchemical pest control in China rice: a review. *Agron Sustain Dev* 34(2):275–291. <https://doi.org/10.1007/s13593-013-0199-9>
- Jiang Y, Cao CG (2021) Crayfish–rice integrated system of production: an agriculture success story in China. A review. *Agron Sustain Dev* 41(5): 68. <https://doi.org/10.1007/s13593-021-00724-w>
- Jinhua Quality and Technology Supervision Bureau (JQTSB) (2014) Technical regulation of green management against rice pest and weeds. *Jinhua Quality and Technology Supervision Bureau*. DB3307/T 73—2014, Jinhua
- Khumairoh U, Lantinga EA, Handriyadi I, Schulte RPO, Groot JJC (2021) Agro-ecological mechanisms for weed and pest suppression and nutrient recycling in high yielding complex rice systems. *Agric Ecosyst Environ* 313:107385. <https://doi.org/10.1016/j.agee.2021.107385>
- Kong SS, Zheng SJ, Zhu PY, Zheng XS, Zheng RQ, Lu ZX (2016) Survey of amphibian diversity in the paddy field on controlling rice pests by ecological engineering. *China Plant Prot* 36(10):10–14 (in Chinese). <https://doi.org/10.3969/j.issn.1672-6820.2016.10.002>
- Li B, Du DS (1984) Preliminary investigation of application of grey system in ecological engineering—the impact of ladybird beetle on cotton aphid. *J Huazhong U Sci-Med* 12:1–8 [http://en.cnki.com.cn/Article\\_en/CJFDTOTAL-HZLG198403000.htm](http://en.cnki.com.cn/Article_en/CJFDTOTAL-HZLG198403000.htm)
- Li ZY, Yang H, Lai FQ, Fu Q, Hu Y (2010) Occurrence and population dynamics of chironomid midges in the early rice field. *Chin J Rice Sci* 24(6):630–634 (in Chinese). <https://doi.org/10.3969/j.issn.1001-7216.2010.06.011>
- Li Z, Feng X, Liu SS, You M, Furlong MJ (2016) Biology, ecology, and management of the diamondback moth in China. *Annu Rev Entomol* 61(1):277–296. <https://doi.org/10.1146/annurev-ento-010715-023622>
- Li WB, He ZF, Wu LP, Liu S, Luo L, Ye X, Gao H, Ma C (2022) Impacts of co-culture of rice and aquatic animals on rice yield and quality: a meta-analysis of field trials. *Field Crop Res* 280(1):108468. <https://doi.org/10.1016/j.fcr.2022.108468>
- Liu Q, Xu J, Wang Y, Li CM, Han G, Qi JH, Sun J, Ma TB (2013) Synergism of CmGV and *Bacillus thuringiensis* against larvae of *Cnaphalocrocis medinalis* Guenée. *Journal of Yangzhou University: Agricultural and Life Science Edition*, 34(4):89–93 (in Chinese). CNKI:SUN:JSNX.0.2013-04-019
- Liu GL, Zhang XM, Zhao LW, Zhang JL, Wang XT, Chen YB, Zheng XS (2014) Application of ecological engineering technology for managing rice pests and the benefit analysis. *J Zhejiang Agric Sci* 55(12):1809–1811 (in Chinese). <https://doi.org/10.3969/j.issn.0528-9017.2014.12.009>
- Liu B, Yang L, Yang F, Wang Q, Yang Y, Lu Y, Gardiner MM (2016) Landscape diversity enhances parasitism of cotton bollworm (*Helicoverpa armigera*) eggs by *Trichogramma chilonis* in cotton. *Biol Control* 93(1):15–23. <https://doi.org/10.1016/j.biocontrol.2015.11.004>
- Liu J, Zhu JW, Zhang PJ, Han L, Reynolds OL, Zeng R, Wu J, Shao Y, You M, Gurr GM (2017) Silicon supplementation alters the composition of herbivore induced plant volatiles and enhances attraction of parasitoids to infested rice plants. *Front Plant Sci* 8:1265. <https://doi.org/10.3389/fpls.2017.01265>
- Liu B, Yang L, Zeng Y, Yang F, Yang Y, Lu Y (2018) Secondary crops and non-crop habitats within landscapes enhance the abundance and diversity of generalist predators. *Agric Ecosyst Environ* 258:30–39. <https://doi.org/10.1016/j.agee.2018.02.007>
- Lou YG, Zhang GR, Zhang WQ, Hu Y, Zhang J (2013) Biological control of rice insect pests in China. *Biol Control* 67(1):8–20. <https://doi.org/10.1016/j.biocontrol.2013.06.011>
- Lu ZX, Heong KL (2009) Effects of nitrogen-enriched rice plants on ecological fitness of planthoppers. In: *Planthoppers: new threats to the sustainability of intensive rice production systems in Asia*. International Rice Research Institute, Philippines, pp 247–256
- Lu ZX, Yu XP, Heong KL et al (2007) Effect of nitrogen fertilizer on herbivores and its stimulation to major insect pests in rice. *Rice Sci* 14(1):56–66. [https://doi.org/10.1016/S1672-6308\(07\)60009-2](https://doi.org/10.1016/S1672-6308(07)60009-2)
- Lu ZX, Yang YJ, Yang PY et al (2012) China’s ‘green plant protection’ initiative: coordinated promotion of biodiversity-related technologies. In: *Biodiversity and insect pests: key issues for sustainable management*. John Wiley & Sons Ltd, pp 230–240
- Lu ZX, Zhu PY, Gurr GM, Zheng XS, Read DMY, Heong KL, Yang YJ, Xu HX (2014) Mechanisms for flowering plants to benefit arthropod natural enemies of insect pests: prospects for enhanced use in agriculture. *Insect Sci* 21(1):1–12. <https://doi.org/10.1111/1744-7917.12000>
- Lu ZX, Zhu PY, Gurr GM, Zheng X, Chen G, Heong KL (2015) Rice pest management by ecological engineering: a pioneering attempt in China. In: *Rice planthoppers: ecology, management, socio economics and policy*. Springer & Zhejiang University Press, China, pp 161–178
- Lu YH, Gao GC, Zheng XS, Lu ZX (2017) The lethal mechanism of trap plant *Vetiveria zizanioides* against the larvae of *Chilo suppressalis*. *Sci Agric Sin* 50(3):486–495 (in Chinese). CNKI:SUN:ZNYK.0.2017-03-007
- Lu YH, Zheng XS, Lu ZX (2018) The potential of vetiver grass as a biological control for the rice stem borers *Chilo suppressalis* and *Sesamia inferens*. *Chinese Journal of Applied Entomology* 55(6): 1111–1117 (in Chinese). <https://doi.org/10.7679/j.issn.2095-1353.2018.134>
- Ministry of Agriculture and Rural Affairs of the People’s Republic of China (MARA) (2014) The dominant cultivar and recommended cultivation technique of agriculture in China, 2014. China Agriculture Press, Beijing, p 248
- Pathak M (1968) Ecology of common insect pests of rice. *Annu Rev Entomol* 13(1):257–294. <https://doi.org/10.1146/annurev.en.13.010168.001353>
- Pretty J (2018) Intensification for redesigned and sustainable agricultural systems. *Science* 362:908. <https://doi.org/10.1126/science.aav0294>

- Qiu DS, Gu DX, Zhang GR, Zhang WQ, Pu ZL (1998) The effects of species pools on the community reestablishment of predatory arthropods in rice fields. *Acta Scientiarum Naturalium Universitatis Sunyatseni* 37(5):70–73 [http://www.cnki.com.cn/Article\\_en/CJFDTOTAL-ZSDZ805.016.htm](http://www.cnki.com.cn/Article_en/CJFDTOTAL-ZSDZ805.016.htm)
- Rashid MM, Jahan M, Islam KS (2016) Impact of nitrogen, phosphorus and potassium on brown planthopper and tolerance of its host rice plants. *Rice Sci* 23(3):119–131. <https://doi.org/10.1016/j.rsci.2016.04.001>
- Reddy PP (2017) *Agro-ecological approaches to pest management for sustainable agriculture*. Springer
- Rodriguez-Saona CR, Stelinski LL (2009) Behavior-modifying strategies IPM: theory and practice. In: *Integrated pest management: innovation-development process: volume 1*. Springer Netherlands, Dordrecht, pp 263–315
- Settele J, Spangenberg JH, Heong KL, Kühn I, Klotz S, Arida G, Burkhard B, Bustamante JV, Cabbigat J, Canh LX, Catindig JLA, van Chien H, Cuong LQ, Escalada M, Görg C, Grescho V, Grossmann S, Hadi BAR, Hai LH et al (2019) Rice ecosystem services in South-East Asia: the legato project, its approaches and main results with a focus on biocontrol services. In: *Atlas of ecosystem services: drivers, risks, and societal responses*. Springer International Publishing, Cham, pp 373–382
- Shields MW, Johnson AC, Pandey S, Cullen R, González-Chang M, Wratten SD, Gurr GM (2019) History, current situation and challenges for conservation biological control. *Biol Control* 131:25–35. <https://doi.org/10.1016/j.biocontrol.2018.12.010>
- Si ZS, Gong XY, Zhao YF, Zhai HW (2016) Efficacy of sex pheromone with new type sex attractant trap on rice *Chilo Suppressalis*. *China Rice* 22(4):102–104 (in Chinese). <https://doi.org/10.3969/j.issn.1006-8082.2016.04.032>
- Sparta A, Khumairoh U, Valbuena D, Groot JCJ (2021) Potential economic and nutritional benefits of complex rice systems for small-scale farmers in West Sumatra, Indonesia. *Biol Agric Hort* 37(1):40–54. <https://doi.org/10.1080/01448765.2020.1833755>
- Sun HL, Qi Y (2017) From eco-agriculture to eco-civilization construction: In memory of Prof. Ma Shijun's 100 years birthday and the 36th anniversary of eco-engineering theory publication. *Chin J Eco-Agric* 25(1):8–12 (in Chinese). <https://doi.org/10.13930/j.cnki.cjea.161065>
- Tripathi DK, Singh VP, Gangwar S, Prasad SM, Maurya JN, Chauhan DK (2014) Role of silicon in enrichment of plant nutrients and protection from biotic and abiotic stresses. In: *Improvement of crops in the era of climatic changes*. Springer, New York, pp 39–56
- Wan NF, Cai YM, Shen YJ, Ji XY, Wu XW, Zheng XR, Cheng W, Li J, Jiang YP, Chen X, Weiner J, Jiang JX, Nie M, Ju RT, Yuan T, Tang JJ, Tian WD, Zhang H, Li B (2018) Increasing plant diversity with border crops reduces insecticide use and increases crop yield in urban agriculture. *Elife* 7:e35103. <https://doi.org/10.7554/eLife.35103>
- Wan NF, Ji XY, Deng JY, Kiaer LP, Cai YM, Jiang JX (2019a) Plant diversification promotes biocontrol services in peach orchards by shaping the ecological niches of insect herbivores and their natural enemies. *Ecol Indic* 99:387–392. <https://doi.org/10.1016/j.ecolind.2017.11.047>
- Wan NF, Li SX, Li T, Cavalieri A, Weiner J, Zheng XQ, Ji XY, Zhang JQ, Zhang HL, Zhang H, Bai NL, Chen YJ, Zhang HY, Tao XB, Zhang HL, Lv WG, Jiang JX, Li B (2019b) Ecological intensification of rice production through rice-fish co-culture. *J Clean Prod* 234:1002–1012. <https://doi.org/10.1016/j.jclepro.2019.06.238>
- Wang F, Peng SB (2017) Yield potential and nitrogen use efficiency of China's "Super" rice. *J Integr Agr* 16(5):60345–60347. [https://doi.org/10.1016/S2095-3119\(16\)61561-7](https://doi.org/10.1016/S2095-3119(16)61561-7)
- Wang GR, Han RP, Huang FD, Li B, Chen YJ, Xu HX, Lu ZX (2016) Effects of different insecticides on rice leaf folder on late single-season rice. *China Rice* 22(4):105–106 (in Chinese). <https://doi.org/10.3969/j.issn.1006-8082.2016.04.033>
- Wang JH, Li G, Qiu LF, Che SC, Shao JL, Zhong L (2017) Attractiveness of flowering shrubs in urban green space in Beijing to natural enemies of insect pests. *Chin J Appl Entomol* 54(1):126–134 (in Chinese). CNKI:SUN:KCZS.0.2017-01-016
- Wang J, Fu PH, Wang F, Fahad S, Mohapatra PK, Chen Y, Zhang C, Peng S, Cui K, Nie L, Huang J (2019) Optimizing nitrogen management to balance rice yield and environmental risk in the Yangtze River's middle reaches. *Environ Sci Pollut R* 26(5):4901–4912. <https://doi.org/10.1007/s11356-018-3943-5>
- Way MJ, Heong KL (1994) The role of biodiversity in the dynamics and management of insect pests of tropical irrigated rice—a review. *B Entomol Res* 84(4):567–588. <https://doi.org/10.1017/S000748530003282X>
- Westphal C, Vidal S, Horgan FG, Gurr GM, Escalada M, van Chien H, Tschamtker T, Heong KL, Settele J (2015) Promoting multiple ecosystem services with flower strips and participatory approaches in rice production landscapes. *Basic Appl Ecol* 16(8):681–689. <https://doi.org/10.1016/j.baec.2015.10.004>
- Wu JC, Hu GW, Tang J, Shu ZL, Yang JS, Wan ZN, Ren ZC (1994) Studies on the regulation effect of neutral insect on the community food web in paddy field. *Acta Ecol Sin* 14(4):381–386 (in Chinese). CNKI:SUN:STXB.0.1994-04-005
- Wu K, Lu Y, Wang Z (2009) Advance in integrated pest management of crops in China. *Chin Bull Entomol* 46(6):831–836 (in Chinese). CNKI:SUN:KCZS.0.2009-06-014
- Xie J, Hu LL, Tang JJ, Wu X, Li N, Yuan Y, Yang H, Zhang J, Luo S, Chen X (2011) Ecological mechanisms underlying the sustainability of the agricultural heritage rice-fish coculture system. *Proc Natl Acad Sci USA* 108(50):E1381–E1387. <https://doi.org/10.1073/pnas.1111043108>
- Xu HX, Yang YJ, Lu YH, Zheng XS, Tian JC, Lai FX, Fu Q, Lu ZX (2017) Sustainable management of rice insect pests by non-chemical-insecticide technologies in China. *Rice Sci* 24(2):61–72. <https://doi.org/10.1016/j.rsci.2017.01.001>
- Yasumatsu K, Torh T (1968) Impact of parasites, predators, and diseases on rice pests. *Annu Rev Entomol* 13(1):295–324. <https://doi.org/10.1146/annurev.en.13.010168.001455>
- Yu XP, Hu C, Heong KL (1996) The effects of non-crop habitats on crop pests and their natural enemies. *Chin J Biol Control* 12(3):130–133 (in Chinese). CNKI:SUN:ZSWF.0.1996-03-010
- Yu XP, Zheng XS, Chen JM, Lu ZX, Hu JC (1999) A study on the relationship between egg parasitoid, anagrus nilaparvatae and green slender planthopper, *Saccharosydne procerus*, a species of insect pest of wild rice, *Zizania Caduciflora*. *Acta Entomol Sin* 42(4):387–393 (in Chinese). CNKI:SUN:KCXB.0.1999-04-007
- Yuan LP (2014) Development of hybrid rice to ensure food security. *Rice Sci* 21(1):1–2. [https://doi.org/10.1016/S1672-6308\(13\)60167-5](https://doi.org/10.1016/S1672-6308(13)60167-5)
- Zhang W, Swinton SM (2012) Optimal control of soybean aphid in the presence of natural enemies and the implied value of their ecosystem services. *J Environ Manage* 96(1):7–16. <https://doi.org/10.1016/j.jenvman.2011.10.008>
- Zhang J, Liang GW, Zeng L (2011) Effects of rice-planting neighboring with vegetable crops on the population dynamics of *Cnaphalocrocis medinalis*, plant hopper, and their predatory enemies. *Chin J Ecol* 30(2):281–289 (in Chinese). <https://doi.org/10.3760/cma.j.issn.1674-2907.2007.13.004>
- Zhang S, Jia XW, Sun SF, Pang Y, Chen QJ, Yang K (2014) Phylogenetic analysis and epidemiologic investigation of a *Cnaphalocrocis medinalis* granulovirus strain. *J Environ Entomol* 36(5):756–762 (in Chinese). <https://doi.org/10.3969/j.issn.1674-0858.2014.05.15>
- Zhang ZQ, Zhou C, Xu YY, Huang X, Zhang L, Mu W (2016a) Effects of intercropping tea with aromatic plants on population dynamics of

- arthropods in Chinese tea plantations. *J Pest Sci* 90(1):227–237. <https://doi.org/10.1007/s10340-016-0783-2>
- Zhang J, Hu LL, Ren WZ, Guo L, Tang J, Shu M, Chen X (2016b) Rice-soft shell turtle coculture effects on yield and its environment. *Agric Ecosyst Environ* 224:116–122. <https://doi.org/10.1016/j.agee.2016.03.045>
- Zhao ZH, Hui C, He DH, Ge F (2013) Effects of position within wheat field and adjacent habitats on the density and diversity of cereal aphids and their natural enemies. *BioControl* 58(6):765–776. <https://doi.org/10.1007/s10526-013-9536-9>
- Zhao ZH, Reddy GVP, Hui C, Li BL (2016) Approaches and mechanisms for ecologically based pest management across multiple scales. *Agric Ecosyst Environ* 230:199–209. <https://doi.org/10.1016/j.agee.2016.06.010>
- Zhejiang Quality and Technology Supervision Bureau (ZQTSB) (2017) Technical regulation for rice insect pest management by Ecological Engineering. Zhejiang: Zhejiang Quality and Technology Supervision Bureau. DB33/T 2069—2017. <https://wenku.baidu.com/view/e8131c2774a20029bd64783e0912a21615797fd6.html>
- Zheng XS, Yu XP, Lu ZX, Chen JM (1999) Dispersal patterns of natural enemies of rice planthoppers between zizania and rice fields. *Acta Agriculturae Zhejiangensis* 11(6):339–343 (in Chinese). CNKI: SUN:ZJNB.0.1999-06-012
- Zheng XS, Xu HX, Chen GH, Lu ZX (2009) Potential function of sudan grass and Vetiver grass as trap crops for suppressing population of stripped stem borer, *Chilo suppressalis* in rice. *Chin J Biol Control* 25(4):299–303 (in Chinese). <https://doi.org/10.3321/j.issn:1005-9261.2009.04.003>
- Zheng JJ, Huang LS, Li GJ, Guo R (2016) A preliminary study of *Mamestra brassicae* nuclear polyhedrosis virus (MBNPV) on insecticidal effect for *Cnaphalocrocis medinalis* Guenée. *China Plant Prot* 36(11):39–42 (in Chinese). CNKI:SUN:ZBJS.0.2016-11-008
- Zheng XS, Lu YH, Zhu PY, Zhang F, Tian J, Xu H, Chen G, Nansen C, Lu Z (2017a) Use of banker plant system for sustainable management of the most important insect pest in rice fields in China. *Sci Rep-UK* 7:45581. <https://doi.org/10.1038/srep45581>
- Zheng XS, Lu YH, Zhong LQ, Huang XF, Xu FS, Yao XM, Xu HX, Lu ZX et al (2017c) Optimal planting pattern of trap plant vetiver grass, *Vetiveria zizanioides* to control rice striped stemborer, *Chilo suppressalis*. *Plant Prot* 43(6):103–108 (in Chinese). <https://doi.org/10.3969/j.issn.0529-1542.2017.06.016>
- Zhong XH, Liang XM, Huang NR, Tian K, Mai YX, Liang XY (2010) Specification of chemical fertiliser-reduction technology for rice. *Guangdong Agric Sci* 37(12):71–73 (in Chinese). <https://doi.org/10.3724/SP.J.1142.2010.40491>
- Zhu PY, Sheng XQ, Feng F, Li YH, Chen GH (2013) Trapping technique of insect sex pheromone on striped stem borer and rice leaf folder. *J Zhejiang Agric Sci* 54(7):825–826, 829 (in Chinese). <https://doi.org/10.3969/j.issn.0528-9017.2013.07.023>
- Zhu PY, Zheng XS, Yao XM, Xu HX, Zhang FC, Chen GH, Lu ZX (2015) Ecological engineering technology for enhancement of biological control capacity of egg parasitoids against rice planthoppers in paddy fields. *China Plant Prot* 35(7):27–32 (in Chinese). CNKI: SUN:ZBJS.0.2015-07-005
- Zhu PY, Zheng XS, Zhang FC, Xu HX, Yao XM, Yang YJ, Chen GH, Lu ZX (2017a). Aquatic insect populations in paddy fields as affected by management of rice insect pests through ecological engineering technology. *Chin J Rice Sci* 31(2):207–215 (in Chinese). <https://doi.org/10.16819/j.1001-7216.2017.6065>
- Zhu PY, Heong KL, Villareal S, Lu ZX (2017b) Application of nitrogen fertilizer affects natural control of the rice brown planthopper *Nilaparvata lugens* (Stål) by arthropod natural enemies. *Acta Ecol Sin* 37(16):5542–5549 (in Chinese). <https://doi.org/10.5846/stxb201605220984>
- Zhu PY, Zheng XS, Zhang FC, Barrion AT, Xu HX, Yang YJ, Chen GH, Lu ZX (2017c) Natural enemy functional guilds of rice leaf folder (*Cnaphalocrocis medinalis*) enhanced in paddy field with sustainable pest management by ecological engineering. *Chin J Biol Control* 33(3):351–363 (in Chinese). 10.16409/j.cnki.2095-039x.2017.03.009
- Zhu PY, Zheng XS, Zhang FC, Xu H, Yang Y, Chen G, Lu Z, Johnson AC, Gurr GM (2018) Quantifying the respective and additive effects of nectar plant crop borders and withholding insecticides on biological control of pests in subtropical rice. *J Pest Sci* 91(2):575–584. <https://doi.org/10.1007/s10340-017-0946-9>
- Zhuang X (1989) Studies on the relationship between the insect community and the grasses on the rice field ridges. *Acta Ecologica Sinica* 9(1):35–40 (in Chinese). <https://www.ecologica.cn/stxb/article/abstract/890106>

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