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Review

Balancing food security, vertebrate biodiversity, and healthy rice agroecosystems in Southeast Asia

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ABSTRACT

Rice is the dominant food staple and an important economic resource throughout Asia. Lowland rice production also provides important wetland habitats in support of biodiversity that may provide ecosystem services back to the rice agroecosystems. This review summarizes the literature on the ecosystem benefits that amphibians, birds, bats, and rodents support in the context of the Southeast Asia rice agroecosystems. The literature provides evidence that these taxonomic groups contribute to cultural, regulatory, and provisioning services in support of smallholder farmers and may allow for economic benefits through reduced use of chemical inputs into crops. We encourage a multipronged research approach to bring stakeholders together to provide structured and scalable education programs that will lead to improved human and agroecosystem health through the promotion of understanding the positive feedbacks from biodiversity in these important agricultural wetland habitats.

1. Introduction

1.1. Rice in Asia – balancing food security and healthy agroecosystems

Rice is the dominant food staple in Asia. In Asia, there are 52 million ha of lowland irrigated rice (GRiSP, 2013) that provides food security to smallholder farmers while also having the potential to preserve wetland habitat for wildlife. Globally, all wetland habitats are at grave risk, and as a result, there are great concerns on the rates of loss of biological diversity. A report from the 13th Meeting of the Conference of the Contracting Parties to the Ramsar Convention on Wetlands (COP13) highlighted that 35% of wetlands have been lost since 1970 (Gardner et al., 2018). A follow-up report in 2021 (Courouble et al., 2021) highlighted the conversion of wetlands to agricultural land use as an important process, with greater than 50% of wetlands at a global level being negatively impacted by agriculture either directly through land use conversion or indirectly through runoff of pesticides (Jayasiri et al., 2022; Vandergragt et al., 2020) and inflow of plastics (Wagner et al., 2014).

Rice agricultural systems provide important human-modified wetlands for wildlife, including undomesticated vertebrates. In an ecosystem service context, flooded rice wetland environments potentially provide important "supporting services" for wildlife through their extensive water networks. The border habits of agricultural lands in Europe are well documented as keys to the preservation and conservation of wildlife. For example, the growth of native herbs, grasses, and wildflowers along these margins provides refuges for important pollinators and bird species (Landis et al., 2000). In Asian lowland rice agroecosystems, there has been a relative paucity of studies investigating the benefits of heterogeneous agricultural landscapes on biodiversity. One exception has been studies on the benefits of ecologically engineering lowland rice margins by growing wildflowers and cultivating additional vegetables along the

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bunds and the wider margins of rice fields (Gurr et al., 2016; Horgan et al., 2022). Ecologically engineering rice field margins have reportedly positive spill-over benefits to farmers through increased bird activity that may lead to increased pest control in rice fields (Horgan et al., 2017).

In this review, we will focus primarily on vertebrate faunal biodiversity. Our aim is to set our sights beyond Sustainable Development Goal (SDG) 2, which focuses on ending hunger and achieving food security via the promotion of sustainable agriculture, ideas that are also synonymous with the One Health initiative (Lebov et al., 2017). Often, agricultural scientists are motivated to achieve food security but pay insufficient attention to the need to have a healthy and resilient agroecosystem that supports biodiversity. Given the documented loss in global biodiversity, especially in tropical zones (Hughes, 2017), resulting from deforestation for agriculture and mining, we need to set our sights on how best to integrate SDG 2 and SDG 15 in this region of intensification of rice agriculture. These goals emphasize the need to promote sustainable use of terrestrial ecosystems and halt biodiversity loss. The tropics cover 40% of the world's land mass and are home to 91% of terrestrial birds and >75% of amphibians and terrestrial mammals (Barlow et al., 2018). In addition, ecologists who address SDG 15 in terrestrial agricultural systems need to balance their efforts so that SDG 2 is not compromised. This issue has also been clearly captured in target 10 of the Convention on Biological Diversity 2030 framework (Keping, 2023).

Conversion of land to agricultural use has been identified as a significant driver of biodiversity loss (Jaureguiberry et al., 2022). Milled rice demand will increase by an additional 100 million tons year^{-1} by 2050, and most of this extra production will occur in Asia (FAO, 2020); therefore, failure to act on finding sustainable growth practices will lead to significant further biodiversity loss. However, there is cause for optimism, as a growing volume of research has indicated that, if managed effectively, agroecosystems can be more resilient and generate positive effects on biodiversity (de la Riva et al., 2023).

Given the relative paucity of published studies on vertebrate faunal biodiversity in rice agricultural lands of developing countries, particularly in biodiversity hotspots such as Southeast Asia (Myers, 1988), this review will report on studies in lowland rice agroecosystems over the past decades on vertebrate faunal ecology and biodiversity in this region. A key focus is identifying the likely positive ecosystem services provided by vertebrate fauna in intensive lowland rice production in Southeast Asia.

1.2. Agricultural land use and vertebrate faunal biodiversity are closely interwoven

The Millennium Ecosystem Assessment (2005), followed by the Global Assessment Report on Biodiversity and Ecosystem Service (IPBES, 2019), puts forward several non-mutually exclusive mechanisms through which the environment provides ecosystem services. These reports, as well as a United Nations (UN) Report on Biodiversity (Secretariat of the Convention on Biological Diversity, 2020), also highlighted the dire situation that the world is facing involving species loss. Although the increased land area devoted to agriculture contributes to this loss, the UN World Health Organization has recognized the interrelationship between agricultural biodiversity (faunal and floral) and food security (Hodgkin et al., 2015). Together, the reports referred to identify several areas where wildlife positively interact with rice agroecosystems, including through (1) regulating services, such as pest and vector control, (2) provisioning services, including providing food security, where local wildlife supplements human diet and food security in many parts of the world, (3) acting as bio-indicators for overuse of chemical inputs into agricultural and potentially urban systems, (4) providing potential medicinal/pharmaceutical services, and (5) promoting cultural ecosystem services associated with traditional and non-traditional uses in arts, medicine, and mental well-being. Recommendations include interdisciplinary development of alternative approaches for more sustainable agriculture methods that integrate natural biological processes and agriculture practices.

This review will cover what is understood about the positive interactions that tetrapod vertebrates (amphibians, reptiles, birds, and mammals) provide to lowland rice agricultural environments in Southeast Asia (Settele and Settle, 2018; Tekken et al., 2017). Although fish also provide important ecosystem services in these rice-growing regions, importantly as a food resource and as nutrient provisioners, because they are also often farmed in these systems, their interactions in the rice wetland growing systems have been covered elsewhere (Ahmed et al., 2021; Fernando, 1993).

2. Amphibians

Among the ever-increasing and documented endangered vertebrate groups, amphibians rank among the most at risk (Alroy, 2015; Mendelson et al., 2006; Stuart et al., 2004). Research is just beginning to understand how amphibians provide beneficial natural and agricultural ecosystem services (Bambaradeniya and Amerasinghe, 2003; Hocking and Babbitt, 2014; Propper et al., 2020; Shuman-Goodier et al., 2019; Valencia-Aguilar et al., 2013). Many anuran (frog) amphibian species utilize rice fields as habitat in the absence of natural wetlands (Naito et al., 2012) and can provide provisioning and cultural services by acting as food, medicinal, cultural, pet, and/or art resources in many parts of the world. Amphibians can also provide supportive ecosystem services through effects on algal biomass and nutrient cycling (Fang et al., 2021; Hocking and Babbitt, 2014; Lin and Wu, 2020; Sha et al., 2017; Teng et al., 2016). Amphibian species can also provide pest control services (Khatiwada et al., 2016), indicating that they act as regulators against rice pests and potential vectors of disease. Critically, these aquatic species act as bio-monitors for the risk of negative health outcomes for wildlife and humans resulting from chemical exposures used in the agroecosystems (Ito et al., 2020; Mesleard et al., 2016). Together, these studies demonstrate the importance of anuran amphibians supporting dynamic and healthy rice agroecosystems.

Our review supports the finding that amphibians provide several ecosystem services in the rice agroecosystems. Both introduced and native species utilize rice wetland habitat (Propper et al., 2023), and preliminary survey data suggest that cultivation practices may influence the abundance of amphibians in rice agroecosystems. Some species of frogs in rice fields also provide provisioning ecosystem services through human food, markets, and cultural resources (Propper et al., 2020). Local peoples have been documented collecting anuran species to be eaten in the Philippines and other Southeast Asian countries (Nurhasan et al., 2010). Other studies in South Asia have demonstrated the importance of amphibians as regulators of ecosystem services in rice agriculture. A study of 60 rice fields in India found that six species provided pest control services (Seshadri et al., 2020). In Nepal, the stomach contents of 13 species of frogs inhabiting rice fields (Khatiwada et al., 2016) were found to contain both rice pests and disease vectors. In the Philippines, we found that a native species has the potential to provide regulatory services, but not all species provide a positive ecosystem service: the most abundant and incidentally invasive species eat predators of pests, and therefore, its high population numbers could lead to suppression of natural pest control (Shuman-Goodier et al., 2019). We propose that more effort should be placed into conserving native amphibian populations, which can result in outcomes that benefit both rice farmers and native wildlife communities.

Other studies in Southeast Asia indicate that amphibians provide bio-indicator ecosystem services for pesticide risk in intensive rice production systems. Developmental and reproductive assays using amphibians that inhabit rice fields, such as the non-native cane toad or native Fejervarya species, may be used to monitor the physiological effects of pesticides in wildlife populations (Salvani et al., 2023; Shuman-Goodier et al., 2021). Other species across the globe have been used to study the impacts of pesticides on amphibians, and many pesticides have been observed to produce negative impacts on behavior, physiology, growth, reproduction, and survivorship (Baker et al., 2013; Egea-Serrano et al., 2012; Shuman-Goodier and Propper, 2016; Shuman-Goodier et al., 2017).

Our findings suggest that to maintain sustainable rice agricultural practices, all stakeholders need to collaborate in a bilateral framework to fully understand the depth of the potential for biodiversity's role in ecosystem services. We found that farmers in the Philippines understood that frog populations were diminishing and provided them with important sources of food and income (Propper et al., 2020). Furthermore, across the globe, amphibians are known to have cultural significance in myth, medicine, and art (Adil et al., 2022). Increasing frog abundance in rice fields can also potentially reduce the need for pesticides while increasing rice yields (Teng et al., 2016). Together, these studies suggest that farmers have knowledge about the abundance of amphibians in their fields, the impact of different cultivation practices on those populations over time, and the ecosystem services they provide.

3. Birds

Birds often gain a negative reputation with regard to their impact on crop yield but can also provide positive ecosystem services to farmers. The general dogma of smallholder rice farmers in Southeast Asia that “all birds eat rice” adds further pressure on avian biodiversity (Bourdin et al., 2015). The occurrence of a large flock of Eurasian tree sparrow (*Passer montanus*) around rice fields fuels the belief that they are exclusively eating the rice crop, even though ecological studies suggest a varied and seasonal diet (Summers-Smith, 1995). However, there is evidence that birds provide both regulatory and provisioning services in rice fields. Global ecological studies show a strong affiliation between rice fields and insectivorous species and/or birds which prefer wetland habitats (Elphick et al., 2010b). Keeping rice fields continually flooded throughout the year provides an alternative wetland habitat for bird species (Elphick, 2000; Stafford et al., 2010; Taylor and Schultz, 2010) and plays an important role in conserving populations of rare species, such as the critically endangered Giant Ibis (*Thaumatibis gigantea*) in Cambodia (Sakmay, 2015), or as stopover sites for passing migratory species (Wood et al., 2010). Water birds provide enhanced nutrient recycling, reducing the need for fertilizer (Navedo et al., 2015), or can control rice pests, such as the golden apple snail (*Pomacea canaliculata*) (Sawangproh et al., 2012; Teo, 2001). Ecological engineering through the development of high-diversity vegetation patches along the edges of rice fields increased bird diversity in the fields, with several of these bird species observed foraging for arthropods and snails (Horgan et al., 2017). Birds may also provide important cultural services where they act as symbols of good luck (Tekken et al., 2017). The understanding of bird communities and their effect within rice fields is currently disproportionately represented by studies from the United States of America and Europe (Elphick et al., 2010a; Ibáñez et al., 2010). Studies on the community and ecology of birds within rice agroecosystems and crop management to support these species should be extended to bird diversity hotspots such as Southeast Asia. While the need to conduct long-term cataloging of species is essential in understanding the importance of irrigated rice fields to avian biodiversity, it is also necessary to include strong research methodology to evaluate both the ecosystem services and risks to birds in rice agroecosystems.

To address the paucity of avian studies in Southeast Asian rice agroecosystems, a series of studies were conducted on the avian diversity of rice fields within the Philippines (Smedley, 2017). One study showed that intensification of rice cropping had a measurable impact on local bird communities. In areas where the rice cropping frequency was increased to produce an additional crop every two years (five crops over two years vs. four crops over two years), there was an increase in the number of individual Eurasian tree sparrows, a perceived pest of rice, within these sites compared to conventional cropping areas. On the other hand, the mean abundance of waterbird species was lower (Propper et al., 2023). Another important finding in this study was the impressively high level of avian biodiversity in these rice “wetlands”. During the 15-month study conducted over four sites, 53 avian species were recorded (Propper et al., 2023; Smedley, 2017).

In another study, the effect of alternative wetting and drying (AWD) on avian biodiversity and abundance was investigated (Table 1). AWD is an important method of water management in irrigated rice fields that reduces water use and significantly reduces greenhouse gas emissions (Lampayan et al., 2015). Bird surveys were conducted during the dry season crop (January–April) of 2013 and 2014 on rice fields at six AWD locations in Bohol, Philippines (Smedley, 2017). In the AWD system, rice fields were irrigated weekly and allowed to dry but retained sufficient water within the soil to supply moisture to the rice plants. Whereas, in the conventionally flooded systems, rice fields were continuously flooded. The AWD rice fields were paired at three different locations along the irrigation channel, relative to their distance from the local dam, the main source of irrigation which released water weekly. The avian diversity and abundance were simultaneously compared to six conventionally irrigated fields, utilizing a community irrigation system (CIS), that were also paired at the three locations along the irrigation channel. The entire irrigation catchment area was just over 10,000 ha.

No significant difference was recorded in either avian diversity or abundance between the AWD and CIS sites, with high avian diversity recorded at both sites (Table 1, Smedley, 2017). Several feeding guilds were represented that might be expected to respond differently to the different water management systems. However, no difference was observed. One explanation may be because surface water is only temporarily depleted in AWD systems, waterbird species predominantly use rice fields as feeding habitats (Fasola and Ruiz, 1996), and the lack of an observable effect from AWD on their abundance indicates that they are still able to find food within the fields. In fact, the reduction in surface water would enable birds with smaller bills access to probe for food (Ma et al., 2010). Overall, the findings from this study suggest that wider adoption of AWD can maintain important wetland habitat to support the local avian fauna and benefit local communities through a reduction in water demand. However, further studies are needed to investigate the effect of AWD over a much larger scale.

Research in Southeast Asia on the importance of lowland irrigated rice landscapes for avian biodiversity is sparse. Studies in southern Luzon, Philippines, demonstrate that birds may be an important positive ecosystem resource for rice farming in Southeast Asia (Propper et al., 2023; Smedley, 2017). Additionally, this research provided clear evidence that flooded rice fields provide an important wetland landscape that maintains high avian biodiversity in Southeast Asia. In addition, ecological engineering, aimed at managing invertebrate pests of rice through the development of high-diversity vegetation patches along the edges of rice fields, increased bird diversity in the fields, with many of the bird species foraging for arthropods and snails (Horgan et al., 2017).

Table 1
Mean number of species recorded between an alternate wetting and drying (AWD) crop and a crop utilizing a community irrigation system (CIS) across six fields over two dry seasons.

Species category	AWD cropping system	CIS cropping system
Waterbirds	10.67 (9–13)	10.00 (7–15)
Granivorous	3.00 (3–3)	3.33 (3–4)
Other	16.67 (13–20)	17.33 (15–19)
Total	30.33 (25–36)	30.67 (25–37)

Cumulative number of species recorded per site is given in parenthesis. General species categorization of all birds, including those identified only at the family level, during four months of data collection. A total of 69 surveys were conducted per site. Waterbirds including water associated species.

4. Bats

Bats are diverse and abundant in agricultural landscapes (Williams-Guillén et al., 2015), including major rice-growing areas of Southeast Asia (Kingston, 2010). Because many species of bats are insectivorous, they are capable of providing regulatory ecosystem services through their consumption of pests in the rice agroecosystems (Kunz et al., 2011; Tuneu-Corral et al., 2023). Some bats forage over 30 km from their communal roost and reach altitudes as high as 200 m above ground level in pursuit of migrating planthoppers (Nguyen et al., 2019; Utthammachai et al., 2008). Other bat species forage locally, closer to ground level and to their roost, which could be in a building, nearby cave, under the fronds of a palm, or in human-made bat houses in some regions (Chhay, 2012). Regardless of the distance traveled, bats hunting in the open air are generally opportunistic foragers seeking dense aggregations of prey and consuming species in proportion to their availability (Aizpurua et al., 2018). As a natural surveillance system, they act as bio-indicators for pest outbreaks because they are likely the first to detect the arrival of dispersing crop pests (Maslo et al., 2017). For example, regular DNA sequencing of pipistrelle guano provided an early warning of the arrival of the rice weevil (*Lissorhoptrus oryzophilus*) in Spain (Montauban et al., 2021) and therefore could provide similar surveillance services for irrigated rice that is often devastated by planthoppers. In Thailand, high-flying wrinkle-lipped bats (*Chaerephon plicatus*) consume rice brown planthoppers (Leelapaibul et al., 2005; Srilopan et al., 2018), an ecosystem service estimated to be valued at 1.2 billion USD annually (Wanger et al., 2014). At ground level, aerial-hawking bats are notoriously abundant over open water, exploiting the dusk and dawn emergence of water-borne insects, including mosquitoes, which are important vectors of human diseases (dengue and malaria) common in irrigated rice-growing areas (Ohba et al., 2015; Puig-Montserrat et al., 2020). In addition to the direct consumption of insect crop pests, the ultrasonic pulses emitted by echolocating bats over rice paddies may indirectly suppress the dispersal and reproduction of ultrasound-hearing insects (Nakano et al., 2015; Zha et al., 2013). Recently, an experimental field study emitting bat-mimicking ultrasonic pulses over long green onion crops in Japan significantly reduced crop infestation by *Spodoptera exigua* (Nakano et al., 2022).

Bats also provide provisioning resources through their guano, which provides fertilizer rich in phosphorous and other nutrients (Reid et al., 2022). The practice of farming free-ranging lesser Asian house bats *Scotophilus kuhlii* in order to harvest their guano has been developed by smallholder farming communities in many parts of Cambodia and several areas of southern Vietnam (Furey et al., 2016; Thi et al., 2014). This practice dates back to at least the 1960s (Baker-Munton, 2018) and involves creating roosting substrates for the bats, which typically comprise bundles of dried sugar palm (*Borassus flabellifer*) leaves. These are gathered to create dome-shaped bundles which are traditionally placed under the crown of sugar palm trees, although a variety of larger structures have been employed more recently to accommodate the roost material in both countries (Propper et al., 2023).

Bats potentially provide several ecosystem services, including regulating activities and provisioning resources. Eleven species of bats were found across a farming landscape in southern Luzon, Philippines (Propper et al., 2023), with seven identified through mist netting or acoustic monitoring of their echolocation calls (Sedlock et al., 2019). Bats across these rice fields were found to follow arthropod activity in a guild-specific fashion (Sedlock et al., 2019). Some species preferred foraging over flooded rice paddies with open water and young plants, and others foraged during the later rice growth stages. This study and those mentioned above demonstrate that bats provide regulatory services—directly through consumption and indirectly by modifying insect pest behavior—in controlling pests in rice fields; however, studies regarding the diet of bats that forage over rice fields and pursue migrating pests across the landscape are limited to a few countries. The use of DNA technology to analyze bat guano may be very helpful in identifying additional bat species that are providing ecosystem services.

Farmers in parts of Southeast Asia are gaining economic benefits from bat guano as an important resource used for fertilizer, making it a provisioning resource. A study in Cambodia demonstrated that farmers build structures to attract bats in order to harvest guano (Pisey, 2017). A single bat farm can provide roosts for thousands of bats, and depending on the size of its bat population, it can produce tens of kilograms of guano day^{-1}. The farmers can use the guano themselves or sell the guano, thereby increasing their own economic security. Nearby rice farms also potentially benefited from the increased number of bats brought in by the structures, as the increase in bat numbers led to more bats foraging over the rice fields, which may reduce both rice pests and insect vectors of human diseases. Therefore, the “farming” of bats may lead to both provisioning and regulatory services, with spillover benefits to rice agroecosystems. In addition to providing provisioning through the local use of guano as fertilizer and economic support, the increase in bat numbers feedback into the regulatory pest and vector control services (Pisey, 2017). However, fewer Asian house bats commonly roost on house roofs, and farmers will continue to use the ecosystem services bats provide.

Bats provide several key ecosystem services back to the rice agroecosystems that enhance farmers' food and economic security (Wanger et al., 2014). Unfortunately, many of Southeast Asia's bat species are listed on the Union for the Conservation of Nature's (IUCN) Red List for concern (Kingston, 2010). Understanding how the natural history of specific bat species may support rice agroecosystems will provide a strong platform to enable local farmers to receive valuable ecosystem services from one of the two flying groups of vertebrates remaining on earth.

5. Rats

Most studies on rodents in ecosystem habitats focus on the negative impacts (Stenseth et al., 2003). These effects include direct damage to rice fields through digging into the banks (Stuart et al., 2007) or eating the rice plants or seeds (Singleton, 2003; Singleton et al., 2010). Post-harvest damage by rodents can also severely impact the income of smallholder farmers (Belmain et al., 2015), and rodents are carriers of important diseases that affect humans (Meerburg et al., 2009). For these reasons, farmers often perceive all rodents as pests. A review of the impacts of rodent species in agricultural landscapes concluded that although rodents make up approximately 42% of mammalian species, less than 10% of rodent species are significant agricultural pests (Singleton et al., 2007). Indeed, in the greater agricultural landscape, there are many rodent species that provide ecosystem services, including provisioning as a food resource (Fiedler, 1990), improving water flow and organic matter decomposition as ecosystem engineers (Dickman, 1999; Reichman and Seabloom, 2002), and being functionally important as dispersers of fungal spores (Blitzer et al., 2012) and tree seeds (Yu et al., 2014).

The native endemic species of rodents in Luzon Island, Philippines, potentially provide important positive ecosystem regulatory service benefits to rice farmers and the rice agroecosystems. An example is *Chrotomys* spp. that preys on golden apple snails and non-native giant earthworms, which are both major pests in Luzon (Stuart et al., 2007). The giant earthworms occur in the traditional rice terraces of northern Luzon, and their burrowing activity destabilizes the banks of these iconic terraces. The native *Chrotomys* species therefore provide a positive ecosystem service to farmers.

A second example is the interaction between an introduced rodent species that is now a major pest of rice and an endemic rodent species that lives in forest margins of rice crops but does not eat rice. The introduced rodent, *Rattus tanezumi,* is a major pest species of rice crops in the Philippines. This species causes considerable losses to both lowland and upland rice crops (Htwe et al., 2012; Singleton et al., 2008). A larger native species of rodent, *Rattus everetti,* appears to inhibit this pest rodent from establishing in forest and agro-forest habitats (Stuart et al., 2016) and therefore provides a regulatory service. These are important refuge habitats for *R. tanezumi* after the rice crop has been harvested and the rice stubble has been cleared from the fields. If at a landscape scale, the habitat is managed so that it is favorable to *R. everetti*, then perhaps the rate of growth of *R. tanezumi* populations may be substantially reduced. These results complement the findings of studies in eastern Australia, indicating that the native bush rat, *Rattus fuscipes*, can outcompete the introduced black rat, *Rattus rattus,* in a littoral rainforest (Stokes et al., 2009). These findings form the basis of a study to reintroduce bush rats in urban Sydney to examine the interaction between these two species at an urban bushland boundary (Banks and Smith, 2015).

The findings presented above suggest that native rodent species can provide positive ecosystem services. In Southeast Asian rice landscapes, sustained habitat disturbance in agroforests adjacent to rice fields would favor *R. tanezumi*, while the regeneration of agroforests toward a more natural state would favor endemic native species and consequently reduce losses caused by rodents and giant worms in adjacent rice crops. One challenge is to encourage farmers to promote the growth of native flora along the margins of their rice crops to encourage beneficial rodent species. The perceptions of Filipino farmers who manage rice are that all rodent species are pests of their rice crops and stored rice (Stuart et al., 2011). The scientific evidence indicates otherwise. A targeted extension campaign is recommended to provide educational outreach to farmers to promote ecosystem services from these beneficial species.

6. Conclusions

Our review highlights the urgent need to rethink how rice landscapes are managed in Southeast Asia. We highlight that they are often overlooked biodiversity hubs that bristle with life. The unique semi-aquatic nature of rice farming systems means that rice landscapes offer habitats to numerous native species, some of which are threatened or endangered. The vertebrate diversity that inhabits this agroecosystem provides many positive ecosystem services to smallholder rice farmers (Table 2). However, research has also highlighted that today's prevalent rice farming practices across Asia often have one of the highest ecological footprints among agricultural commodities in the region, exacerbating the biodiversity crisis (de Miranda et al., 2015). In other areas of the world, rice agricultural practices have also led to a demonstrable loss of diversity (Azman et al., 2019). In Southeast Asia, as mechanization increases, there is a need also to evaluate the impact of how related changes in farming practices affect biodiversity. Furthermore, because of the large land area grown for rice, and the disproportionate share of agro-chemical inputs used to produce it in Southeast Asia, improving the environmental sustainability of rice landscapes would significantly benefit biological diversity conservation in the region. For example, we suggest that significant resources should be devoted to establishing routine monitoring for concentrations of pesticides in rice surface water, sediment, and local wildlife (Jayasiri et al., 2022) and to identify their biological effects in wildlife communities. In countries where there may be limited resources for monitoring chemical applications, using tools that are available to understand the potential impacts of exposure for wildlife, such as the United States Environmental Protection Agency's publicly accessible toxicity database, the Ecotoxicology Knowledgebase (ECOTOX) (Olker et al., 2022), can provide some predictive capacity for understanding the risk to the local fauna from chemical exposures. This approach would support delivering jointly upon the SDG 2 and SDG 15 2030 targets (Duru et al., 2015).

A key aim of this review is to increase our understanding of biological diversity in rice landscapes and the ecosystem services such biodiversity provides. However, our knowledge in many areas remains heavily constrained, posing significant challenges to design future interventions that aim at enhancing biodiversity in rice-based landscapes. Therefore, future programmes should also increase investment in research to improve the understanding of rice agroecosystems, biodiversity, and their attendant ecosystem services. For example, there is an urgent need to assess the role that border habitats around flooded rice play in biodiversity conservation, especially for amphibians, threatened by high agro-chemical use, habitat loss, and a Chytrid fungus that triggers mass deaths (Li et al., 2021; Shuman-Goodier and Propper, 2016). In Europe, where border habitats of agricultural lands are well documented, these regions are known to play a key role in the preservation and conservation of wildlife. The growth of native herbs, grasses, and wildflowers along these margins provides an important refuge for pollinators, as well as birds that feed on them (Phillips et al., 2020). It is highly likely that increased heterogeneity around rice areas would also benefit wildlife biodiversity, but this hypothesis needs quantification. Our review focused on Southeast Asia. A major concern is that there have been few studies on the potential ecosystem service benefits provided by vertebrate biodiversity in the two countries where the largest areas of agricultural land are under rice production – China and India. In China, a recent study highlighted the importance of coastal deltas for bird conservation for both resident and migratory birds and these deltas are compromised by the amount of nutrients and pesticides flowing from agricultural lands into these important wetlands (Hou et al., 2022). In South Asia, we previously highlighted some studies in India (Seshadri et al., 2020) and Nepal (Khatiwada et al., 2016). Although we have not included East and South Asia in our review, more research needs to be done in these regions. Given that milled rice demand will increase by an additional 100 million tons year^{-1} by 2050 and that most of this extra production will occur in Asia (FAO, 2020), failure to act could lead to the further deterioration of global biodiversity.

Table 2
The types of ecosystem services identified in this review for each taxon found in Southeast Asia rice fields.

Taxa/Ecosystem service	Specific outcome
Amphibian (frogs)	
Regulating	Pest and vector control
Provisioning	Food/economic/nitrogen cycling
Bio-indicators	Pesticide monitoring
Cultural	Calling indicates water availability for planting
Avian (birds)	
Regulating	Pest and vector control
Provisioning	Food/economic/nitrogen cycling
Cultural	Symbols of good luck
Chiropterans (bats)	
Regulating	Pest and vector control
Provisioning	Food/economic (guano)/nitrogen cycling
Bio-indicators	Pest surveillance
Rodents (rats and mice)	
Regulating	Pest control/ecosystem engineering
Provisioning	Food/economic/nitrogen cycling

Abbreviations

Not applicable.

Availability of data and materials

Data will be shared upon request to the authors.

Authors' contributions

All authors contributed to the writing of the manuscript; C.P., G.R.S., and A.S. reviewed and edited the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Author Grant R. Singleton (Editorial Board member) was not involved in the journal's review nor decisions related to this manuscript.

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