



# Maintaining Diversity of Integrated Rice and Fish Production Confers Adaptability of Food Systems to Global Change

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Rice and fish are preferred foods, critical for healthy and nutritious diets, and provide the foundations of local and national economies across Asia. Although transformations, or “revolutions,” in agriculture and aquaculture over the past half-century have primarily relied upon intensified monoculture to increase rice and fish production, agroecological approaches that support biodiversity and utilize natural processes are particularly relevant for achieving a transformation toward food systems with more inclusive, nutrition-sensitive, and ecologically sound outcomes. Rice and fish production are frequently integrated within the same physical, temporal, and social spaces, with substantial variation amongst the types of production practice and their extent. In Cambodia, rice field fisheries that strongly rely upon natural processes persist in up to 80% of rice farmland, whereas more input and infrastructure dependent rice-shrimp culture is expanding within the rice farmland of Vietnam. We demonstrate how a diverse suite of integrated production practices contribute to sustainable and nutrition-sensitive food systems policy, research, and practice. We first develop a typology of integrated production practices illustrating the nature and degree of: (a) fish stocking, (b) water management, (c) use of synthetic inputs, and (d) institutions that control access to fish. Second, we summarize recent research and innovations that have improved the performance of each type of practice. Third, we synthesize data on the prevalence, outcomes, and trajectories of these practices in four South and Southeast Asian countries that rely heavily on fish and rice for food and nutrition security. Focusing on changes since the food systems transformation brought about by the Green Revolution,

we illustrate how integrated production practices continue to serve a variety of objectives to varying degrees: food and nutrition security, rural livelihood diversification and income improvement, and biodiversity conservation. Five shifts to support contemporary food system transformations [i.e., disaggregating (1) production practices and (2) objectives, (3) utilizing diverse metrics, (4) valuing emergent, place-based innovation, (5) building adaptive capacity] would accelerate progress toward Sustainable Development Goal 2, specifically through ensuring ecosystem maintenance, sustainable food production, and resilient agricultural practices with the capacity to adapt to global change.

**Keywords: food systems, integrated agri-aquaculture, inland fisheries, food security, food policy**

## INTRODUCTION

The world's food systems are simultaneously overreaching planetary boundaries and failing to meet nutritional needs (Gordon et al., 2017; Willett et al., 2019). In response, transformation of current food systems is increasingly called on to minimize environmental impacts and sustain livelihoods while also producing food of sufficient quantity and quality to meet the growing needs and demands of populations globally (Ericksen et al., 2010; IPES-Food, 2016; Schipanski et al., 2016). A food system incorporates “*all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation, and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes*” (HLPE, 2014). Transformation toward more sustainable and equitable food systems is a foundation of the Sustainable Development Goals, directly for the second goal “Zero Hunger” and as a critical enabler of many of the other goals (Caron et al., 2018). To reshape food systems to meet the environmental, economic, and social challenges of sustainability, we must shift away from a narrow productivity focus that dominated previous “revolutions” in agriculture (Pingali, 2012; Blesh et al., 2019), aquaculture (Troell et al., 2014), and fisheries (Ratner and Allison, 2012).

Agroecological practices are important in the package of solutions needed to transform food systems (IPES-Food, 2016; HLPE, 2019) and to build resilience of livelihoods and landscapes in the face of global change (Sinclair et al., 2019). Agroecological practices are diverse, but can be characterized by a generic set of agroecological principles, such as a preferential use of natural processes and a focus on local suitability, equity, and systems management (Altieri, 2002; HLPE, 2019). The principles are conceptualized in categories of technical and/or biophysical and of organizational, institutional and/or socio-economic attributes (Therond et al., 2017; AFD CIRAD, 2018) and their application occurs in varying degrees along a gradient (HLPE, 2019). These gradients can be used to develop a typology that organizes and describes the diversity of practices within a production sector, e.g., maize and livestock production in central United States (Blesh and Wolf, 2014). A typology of production practices can guide evaluation of the contribution of various practices to food systems objectives (Blesh and Wolf, 2014) and facilitate planning for transformation pathways to sustainable food systems. We

demonstrate this approach in the context of Asian agricultural landscapes and diets, which have been dominated by rice and fish for more than a millennium (Ruddle, 1982; Miao, 2010).

Rice cultivation occurs in a range of agroecosystems, including lowland areas that are seasonally inundated by rainfall and floodplains extending from the edges of rivers and lakes (Heckman, 1979; Fernando, 1993). These agroecosystems also provide habitats for a “*wide range of aquatic species (including finfish, crustaceans, mollusks, reptiles, insects, amphibians, and aquatic plants) used for consumption and/or sale*” (FAO, 2014). Rice-fish production practices (RFPPs) are those where the cultivation of rice takes place while allowing the simultaneous or rotational presence of: naturally occurring fish and other aquatic species that are harvested through fisheries; and/or introduced fish populations that are cultured (FAO, 2014). Throughout Asia, RFPPs have developed, persisted, and been transformed under a range of environmental, social, and agricultural policy contexts and comprise diverse fish species and rice varieties (e.g., Heckman, 1979; Halwart, 1998; Amilhat et al., 2009). Presence of fish within agri-food systems is observed globally (Halwart and Gupta, 2004) and is especially important in food insecure nations (Fisher et al., 2017). Despite this, incorporation of fish in agricultural food security programs is lacking (Fisher et al., 2017) and fish are rarely more than anecdotally mentioned in agroecology and food systems literature, despite their relative resource efficiency among animal sources of dietary protein and rich micronutrient content for diets (Kawarazuka and Béné, 2011; Béné et al., 2015).

In addition to the production of rice and fish for food and nutrition, RFPPs can provide a range of ecosystem services and farmer benefits, depending on the approach and application of agroecological principles. For example, RFPPs can make efficient use of scarce water and land resources (Frei and Becker, 2005), maintain biodiversity (Liu et al., 2013; Freed et al., 2020), regulate water flows and water quality (Zhang et al., 2012), and reduce the need for agrochemicals for rice production (Halwart, 1994; Cheng-Fang et al., 2008; Xie et al., 2011). RFPPs can also provide local food and nutrition security (Garaway et al., 2013; Halwart, 2013), income benefits (Hortle et al., 2008), generate more revenue per hectare than rice monoculture (Dwiyana and Mendoza, 2006), and produce higher rice yields (Halwart and Gupta, 2004; Dubois et al., 2019), although rice monoculture can be more cost and labor efficient (Dwiyana and Mendoza, 2006)

and in some contexts, the economic return from fish replacing a rice crop in a rotational system can be lower than the return from the second rice crop (Ahmed et al., 2011). RFPPs are not the only agroecological alternatives to rice monoculture: ecologically engineered farm design can enhance biodiversity and ecosystem function (Horgan et al., 2016); and alternate wetting and drying can reduce water and input use in irrigated systems (Tirol-Padre et al., 2018).

The nutritional, environmental, and cultural value of integrated rice and fish production has been recognized in contemporary agricultural discussions since the 1948 convening of the FAO Rice committee (Halwart and Gupta, 2004). However, interest in RFPPs has periodically waxed and waned, and has yet to gain traction alongside the more locked-in monoculture production focus (Halwart and Gupta, 2004; IPES-Food, 2016). This is at least in part due to the disciplinary approaches to agricultural and aquatic systems research and development that impedes integration among crops and wild and cultured aquatic resources (Amilhat et al., 2009; Tezzo et al., 2020). Currently, agricultural investments increasingly seek to achieve food and nutrition security as well as environmental sustainability objectives (Asian Development Bank, 2015; McCartney et al., 2019), leading to increased interest in agroecological approaches (e.g., FAO, 2019; HLPE, 2019). To assist in these efforts, we describe the range of RFPPs and evidence of their respective advantages, constraints, and contributions toward sustainable food systems outcomes. This focus is particularly urgent, given that the types of RFPPs that actively stock, enclose, and feed fish are expanding in China and elsewhere in Asia (Hu et al., 2015; Miao, 2016; FAO, 2019), without consideration of other types of RFPPs that are more aligned with agroecological principles.

To bridge the evidence gap constraining decision-making, we draw on literature to develop a typology to distinguish RFPPs based on the nature and degree of: water infrastructure and management, the use of inputs, the source of fish populations, and the institutions that control access to fish. We illustrate these variations across four RFPP types for which we also highlight current and potential research and innovation to improve delivery of food system outcomes (specifically, food and nutrition security, equitable and secure incomes, and ecological integrity). We review the trajectory of RFPPs in four case studies from South and Southeast Asian countries and examine the enabling and constraining factors determining the contributions of each RFPP to food systems objectives. We discuss how RFPPs might contribute to different pathways for food system transformation in rice producing nations, and explore ways in which research, innovation and policy might enable achievement of multiple food system objectives.

## RICE-FISH PRODUCTION PRACTICE TYPOLOGY

Rice-fish production practices vary substantially between different contexts and countries. Scholars have noted distinctions based on biophysical and technical attributes such as relative use of naturally occurring or stocked fish, water control

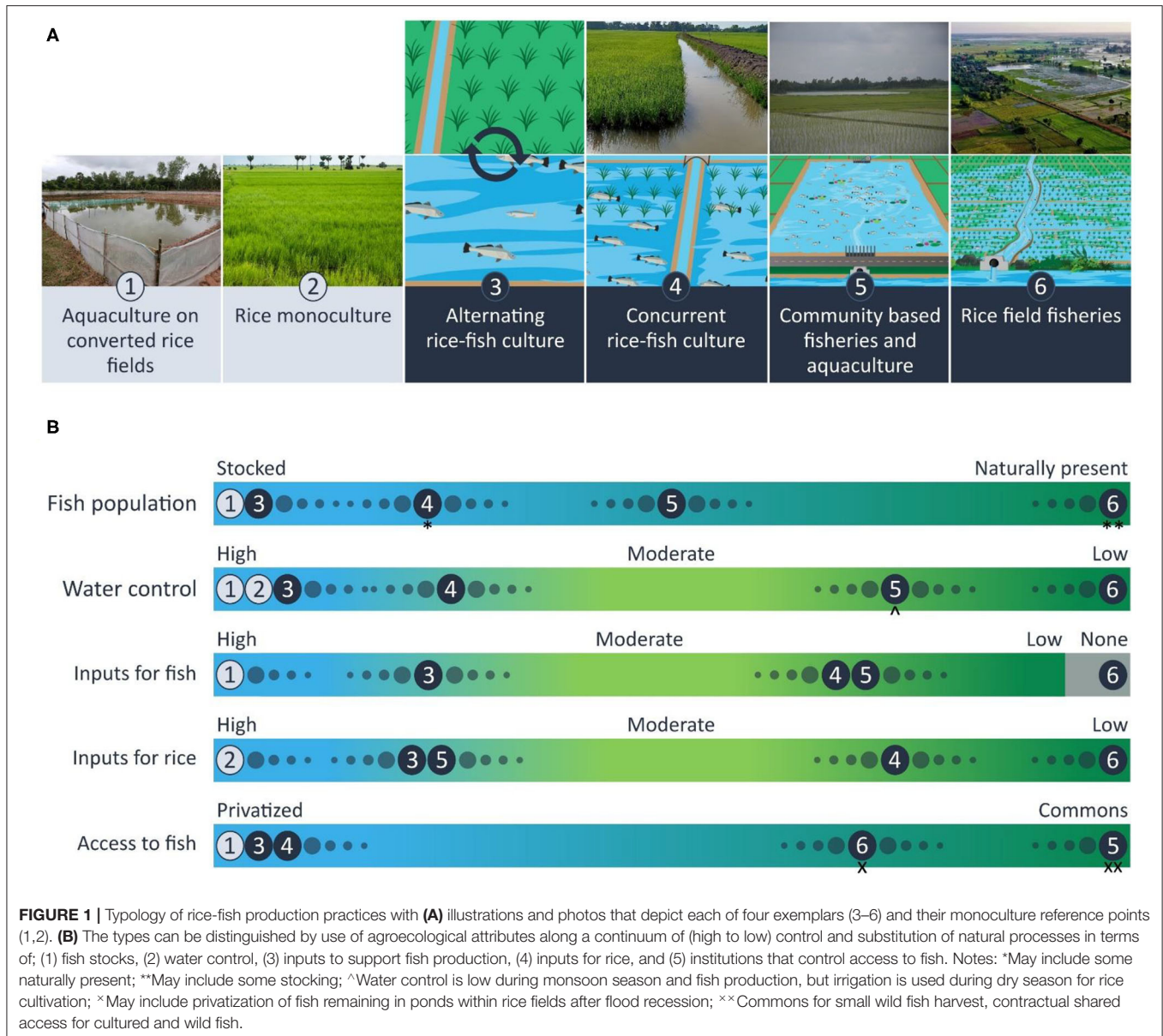
measures, intensity, and volumes of production inputs (e.g., Welcomme and Bartley, 1998; Koochafkan and Furtado, 2004) and organizational and institutional attributes such as the fit with, and use of, a range of governance institutions (e.g., Dey et al., 2013). Drawing on literature and field observations, we developed a typology of RFPPs along an agroecological continuum. The continuum runs from high levels of human control and substitution of natural processes to lower levels of control and greater reliance on natural processes for five variables; (1) fish stocks, (2) water control, (3) inputs to support fish production, (4) inputs for rice, and (5) institutions that control access to fish (**Figure 1**). Rice varieties, fish species, water access, and rice planting methods are also variable, but do not help to distinguish RFPPs as they vary as much (or more) within types than between them. The typology is not meant to be an exhaustive catalog of all factors that vary and all types of RFPPs, but instead aims to elucidate at a broad level distinguishing characteristics that influence RFPP performance in terms of food systems outcomes. The typology is also not meant to impose a “good-better-best” ordering of production practices, as RFPP suitability is highly context dependent. In addition, differing contexts and drivers of change can also result in variable outcomes within each RFPP type. In this sense, RFPPs are only one component necessary for delivering food systems objectives. Below, we describe in greater detail each exemplar RFPP in terms of the five aforementioned attributes.

### Rice Field Fisheries

Rice field fisheries lie on the “natural” end of the agroecological continuum. Rice field agroecosystems often contain both rice fields and water bodies such as canals, streams, ponds, and ditches. The harvest or capture of naturally occurring (or “wild”) fish, aquatic animals, and plants from these rice field agroecosystem habitats is referred to as “rice field fisheries” (Gregory, 1997). An important contributing factor to these fisheries is the natural inundation of rice fields that occurs following seasonal rainfall and/or rising water levels in rivers and other water bodies. During the inundation period, many fish and other aquatic species migrate from perennial water bodies to the shallow rice field wetlands to feed and spawn. Studies on the aquatic biodiversity of rice field fisheries across China and Southeast Asia reveal that between 32 and 147 species are caught and used (**Supplemental Table 1; Supplemental Figure 1**). Flood waters and fish may be considered a common pool resource even when occurring in privately owned rice fields. Wild fish are most prevalent when water management infrastructure (dikes and irrigation) and agrochemical use is minimal (Ali, 1990). Stocking may occur in rice field fisheries, but if it does occur is usually minimal. Small water bodies within or near the rice field may be managed as perennial refuges for fish, or may function as trap ponds from which fish are harvested when the pond is pumped or dries out.

Historically, rice field fisheries were the most widespread form of integrated rice and fish production (Coche, 1967; Ruddle, 1982), and are most common in rainfed and deepwater rice growing areas (Vo, 1975; Gregory, 1997). Rice field fisheries





have been an important source of food and nutrition security, and livelihoods for rural communities in low and middle income countries across Asia, including in Bangladesh (Dey et al., 2013), Cambodia (Freed et al., 2020), Lao PDR (Nguyen Khoa et al., 2005; Garaway et al., 2013), Myanmar (Gregory, 2017), and Vietnam (Berg et al., 2017; Nguyen et al., 2018). The level of formal recognition and management support for these fisheries varies greatly, with the greatest support occurring in Cambodia (e.g., Fisheries Administration, 2011; MAFF, 2014). While rice field fisheries are a long-standing RFPP, associated agricultural and water use practices and infrastructure have changed substantially in many places. Community fish refuges (Kim et al., 2019) and “fish friendly” irrigation (Baumgartner et al., 2016) are two examples of contemporary rice field fisheries research and innovations for improving

environmental connectivity, biodiversity conservation, and food and water security.

### Community-Based Fisheries and Aquaculture

Community-based fisheries and aquaculture straddles the intervention and natural ends of the agroecological continuum. This practice emerged out of three decades of research in Bangladesh on floodplain aquaculture and community-based fisheries management (Sheriff et al., 2010) and was introduced and adapted in Vietnam, Cambodia, Mali, and China, but was not as widely adopted or expansive as in Bangladesh (Joffre and Sheriff, 2011). Community-based fisheries and aquaculture occurs in lowland flood-prone areas where one crop of rice is grown only during dry months. During the monsoon, rice fields

are inundated to a depth of 2–3 m. The resulting inundated water bodies were traditionally common areas to harvest wild fish and aquatic plants. Under community-based fisheries and aquaculture, the water bodies are managed for both wild fish and fish culture through technical and water governance innovations that allow wild fish (and fishers) to remain while introducing a communal governance model for cultured fish production (Joffre and Sheriff, 2011). For example, inlets and outlets are fenced to keep cultured fish in while allowing passage for smaller wild fish. Community-based fisheries and aquaculture includes stocking the water body with fish; most commonly cultured fingerlings of carp species (e.g., *Hypophthalmichthys molitrix*, *Labeo rohita*), but also wild-sourced broodfish of mola (*Amblypharyngodon mola*), other small indigenous species such as darkina (*Esomus danricus*), chela (*Chle phulo*), puntius (*Puntius* spp.), and indigenous species of catfish (*Clarias* spp.) and snakehead (*Channa* spp.). Ongoing social (e.g., water governance), economic (e.g., market connections and resilience), and ecological (e.g., optimal stocking densities and biodiversity) innovations continue to be tested and refined in Bangladesh.

## Rice-Fish Culture

Rice-fish culture lies predominantly on the intervention end of the agroecological continuum, yet comprises a broad range with many variations in practice. Rice-fish culture is the deliberate introduction of fish from cultured or wild sources into a rice field. While some practices may include natural water flows to retain wild stocks and biodiversity, these are recused in areas with greater water control and physical barriers to prevent escape of cultured fish (Lu and Li, 2006). Water is actively managed to control inflow during the dry season, and dikes are used in the wet season to prevent flooding. In many contexts, rice-fish culture is privately managed by the rice farmers who own or lease the plot of land.

There are two main sub-types: concurrent culture and alternating culture. Concurrent culture is where rice and fish are cultivated together in the same space and at the same time. Alternating culture is where production cycles of rice and fish crops are sequential. It is possible for both concurrent and alternating culture to take place within the same rice plot, as in extended growing seasons for fish beyond the rice harvest, or multiple crops of fish with fewer crops of rice (e.g., Halwart and Gupta, 2004; Dwiyananda and Mendoza, 2008). Input use is often determined by the extent of intensification and the timing and duration of the fish culture (Halwart and Gupta, 2004). Fish are often fed when present at high densities and for fish grow-out, while low densities of fish and/or short duration fish culture are likely to require either no inputs or only the application of fertilizers to promote phytoplankton growth and enhance the natural food web that supports fish (Halwart and Gupta, 2004).

## Concurrent Rice-Fish Culture

In concurrent culture, also referred to as rice fish co-culture, the rice field is modified with the addition of small water bodies such as trenches, small ponds, or depressions that retain water for fish habitat when water levels become low in the rice field. Concurrent culture tends to use fewer agrochemical inputs than

alternating culture or rice monoculture and aquaculture. Fish can feed from the biodiversity in the flooded rice field and have a symbiotic relationship with rice crops; fish are eating insects and so reduce the pest load, and fish waste contributes nutrients to the water and soil. Concurrent rice-fish culture requires a relatively high degree of management, for water levels in the rice field and the fish shelter through irrigation and dikes. A drop in water levels in the rice field can undesirably shorten the duration of fish culture, especially toward the end of a monsoon season or as water availability declines during a dry season. In Asia, rice fish co-culture has been practiced for over a 1,000 years, with documented cases in China, Indonesia, Thailand, Vietnam, Philippines, Malaysia, Bangladesh, and Myanmar (Halwart and Gupta, 2004). Recent innovations for this long-standing practice focus on diversifying production through fish polyculture and integrated (i.e., plant and vegetable) farming (FAO, 2019).

## Alternating Rice-Fish Culture

Alternating culture of rice and fish allows the use of crop-specific inputs during both rice and fish culture. The use of inputs for both fish and rice is relatively common, and as such alternating culture is considered an intensive form of rice-fish culture. During fish culture, the rice field is managed as a shallow pond for fish. Feed and other inputs may be used to maintain and grow fish. Alternating culture also occurs in coastal areas, such as the “gher” in Bangladesh and rice-shrimp culture in Vietnam, in which a monsoon season rice crop is followed by a dry season shrimp crop that coincides with saline water intrusion in the rice field. Production of fish fingerlings in alternating culture has emerged as aquaculture growth has boosted the demand for fingerlings, particularly in Indonesia (Costa-Pierce, 1992) and Bangladesh (Barman and Little, 2006). Recent research investigates technical and social innovations that might improve institutional arrangements among stakeholders and across scales (Joffre et al., 2018; Nguyen et al., 2020). A primary focus of this research is to improve management of organic and agrochemical effluents from culture ponds and rice cropping (Joffre et al., 2018).

## FISH, RICE, AND FOOD SYSTEM TRANSFORMATION

The Green Revolution and transformation of rice culture into intensively farmed monoculture began in Asia around 55 years ago (Hazell, 2009; Pingali, 2012). The changes to farming practices included increased use of agrochemicals and more rigid control of water flows and storage that reduced connectivity to floodplains and water bodies (e.g., Shankar et al., 2005; Tong, 2017). Resultant gains in rice production were substantial; across all developing countries rice yields increased 109% (Pingali, 2012), and across Asia total rice production rose steadily and rice prices decreased (Hazell, 2009). However, these farming practices also resulted in losses of long-standing integrated rice and fish production in, at least, Malaysia (Ali, 1990), Vietnam (Berg et al., 2017), and China (Lu and Li, 2006). In Bangladesh, Cambodia, Vietnam, and Myanmar, rice yield per hectare doubled between

1965 and 2000 and rice production tripled by 2013 (FAO, 2020c). Rapid growth in aquaculture production occurred around the same time globally (Troell et al., 2014) and across Asia (Ahmed and Lorica, 2002).

While these agriculture and aquaculture revolutions gained substantial investment and policy attention, inland capture fisheries persisted, but were underappreciated and largely ignored (Cambodia is a notable exception). Recent research illustrates the magnitude of inland capture fisheries contributions to food and nutrition security (Fluet-Chouinard et al., 2018). Yet, the low profile of inland fisheries in national and global policies, including their absence in the Sustainable Development Goals, persists to this day (Cooke et al., 2016; Funge-Smith and Bennett, 2019). This is most likely due to a combination of factors, including the difficulty of collecting reliable data to fulfill official statistics (Coates, 2002; Bartley et al., 2015), the popular crisis narrative of declining fisheries (Friend et al., 2009), and of the fact that fisheries are not easily amended to the Green Revolution approach of increasing productivity. This lack of policy support for fisheries greatly reduces the nutrition provision potential of food systems (Thilsted et al., 2016).

Current conditions are ripe for transformation in Asia's rice and fish sectors, yet there are multiple interpretations about what this transformation might entail. Rice producing regions are now contending with issues of climate change (Johnston et al., 2009) and factors exacerbating persistent rural poverty, such as increasing indebtedness and loss of land (Ingalls et al., 2018). Local, regional, and international demand for rice and fish are expected to increase for decades to come (Reardon and Timmer, 2014; Chan et al., 2017). Fish demand is tracking faster than population growth, with increases in per capita consumption associated also with rising incomes (Chan et al., 2017). Rice demand is expected to continue to grow as populations do, but at a slower rate given that as incomes rise, diets tend to diversify away from staples (Reardon and Timmer, 2014; Cramb and Newby, 2015). Growth in both rice and inland capture fishery production have recently slowed or reversed in the case study countries. Rice production seems to have peaked in Myanmar (in 2009) and Vietnam (in 2015) and production growth is slowing in Bangladesh and Cambodia (since 2010; FAO, 2020c). Inland capture fisheries production has begun to level off or gradually decline (since 2009 for Bangladesh, 2013 for Cambodia, 2016 for Myanmar, and 2001 for Vietnam; FAO, 2020a). As of 2013, capture fisheries still contributed substantially to inland fish production in Bangladesh (36%), Cambodia (86%), and Myanmar (49%; FAO, 2020a). While growth in aquaculture production has continued, the relative contributions of inland capture fisheries remain sizeable in terms of fish production (Edwards et al., 2019; Funge-Smith and Bennett, 2019), food provision (Arthur and Friend, 2011; Fluet-Chouinard et al., 2018), and nutrition (Halwart, 2006; Kawarazuka and Béné, 2011; Thilsted et al., 2016; Golden et al., 2019).

The Green Revolution aim of increased rice production was adopted to varying degrees in Bangladesh, Cambodia, Myanmar, and Vietnam. Yet, the cases below (illustrated in **Figures 2–6**) illustrate how each country also adopted different objectives and strategies for food system transformation, including different

policies, investments, and institutions that influenced the various roles RFPPs played. For each country we examine: (1) the changes to RFPPs and the trajectory of rice and fish sectors since 1980; (2) prevalent RFPPs, innovations, and evidence of RFPP contributions to food systems objectives; and (3) current gaps to achieving food system objectives and the potential pathways for rice and fish production to address these challenges.

## Cambodia

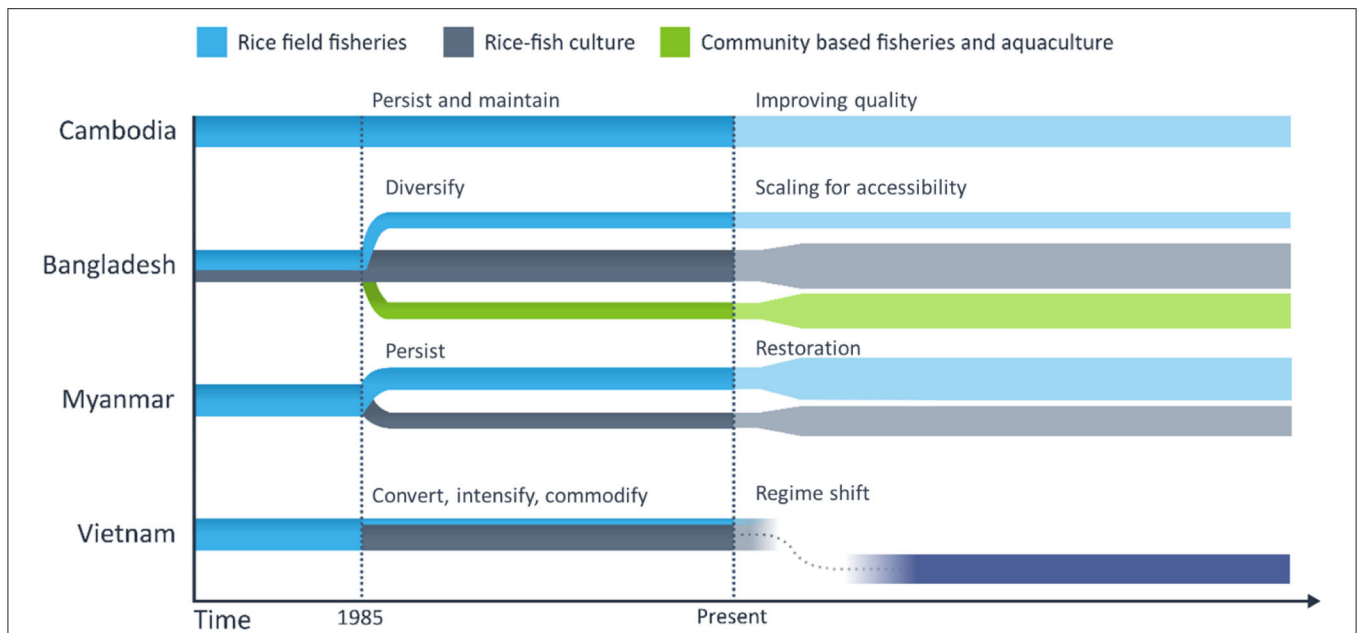
Rice field fisheries have been maintained, initially as consequence of socio-political crisis, but more recently through deliberate policy recognizing their importance as a productive fishery, their provision of food and nutrition security, the cultural appreciation of wild sourced foods, as well as the difficulty to compete with already advanced aquaculture in neighboring countries. Regaining food self-sufficiency was Cambodia's initial food system objective following the Khmer Rouge crisis, while a longer-term objective has been to employ the large rural population. Rice and fisheries contributed to Cambodia's substantial GDP growth from the 1990s, although the contribution from these sectors has declined in recent years (The World Bank, 2017a).

Rice field fisheries are prevalent in Cambodia's 2.6 million hectare wet season rice landscape, due to relatively little irrigation (17% of total area) and expansive rainfed lowlands (80% of total area; MAFF, 2017, 2018) with relatively little flood control. Official estimates place rice field fisheries at 30% of national inland fisheries production, while field-based studies estimate a higher contribution equivalent to 60–70% (Chheng et al., 2016; Freed et al., 2020). It is estimated that more than 50% of Cambodian rural households engage in fishing at least occasionally (Nasielski et al., 2016). Cambodia law stipulates that wild aquatic species in flooded rice landscapes are a common pool resource available to anyone who chooses to fish, provided non-destructive gear is used as stipulated by law. At least 150 wild aquatic species are present within the rice field landscape of Cambodia's Tonle Sap Region, including finfish, snakes, frogs, bivalves, prawn, crab, turtle, waterbirds, insects, and aquatic plants (Freed et al., 2020). The majority of aquatic species are used for food, and in sum these fisheries can provide more than 60% of the fish and other aquatic animals consumed within local farming-fishing households (Freed et al., 2020).

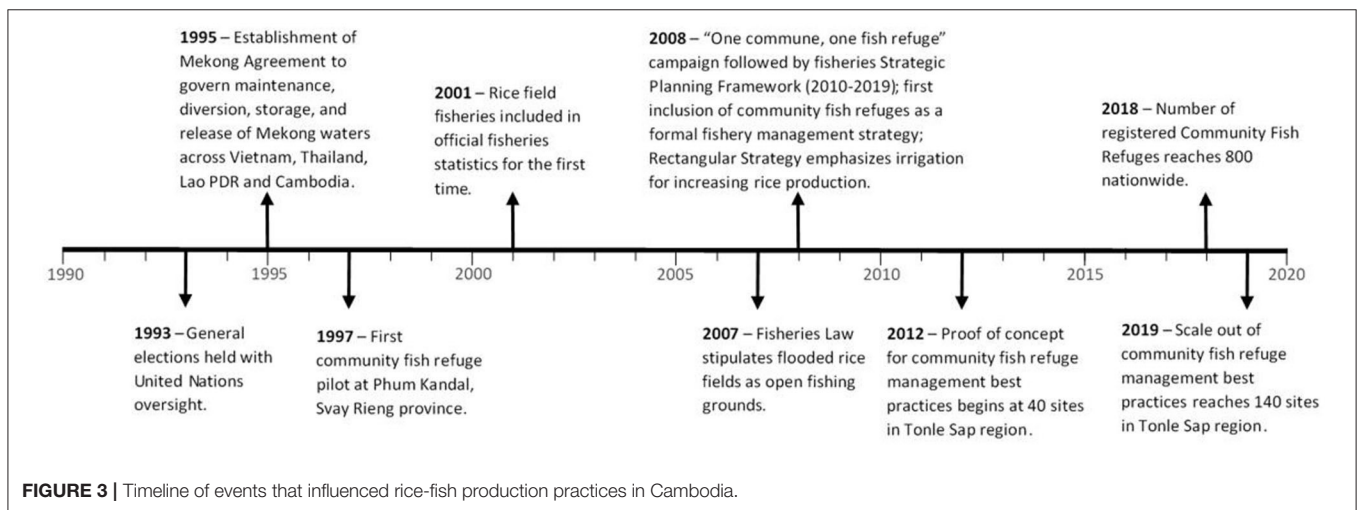
Cambodia's government has formally recognized, in the form of an enhancement strategy, the values and potential of rice field fisheries for national food production and food and nutrition security (Fisheries Administration, 2011; CARD, and TWG-SP&FS, 2014). The enhancement strategy centers around scaling community fish refuges, which are perennial water bodies (i.e., a small pond or part of a large reservoir) that provide habitats for fish within the rice field landscape (**Figure 3**). Research and pilots implemented throughout the Tonle Sap region have informed the development of best management practices for community fish refuges, including co-management, community engagement, and fisheries management strategies as well as habitat improvement and conservation measures (Kim et al., 2019).

One of Cambodia's primary food system challenges is to ensure more secure farming livelihoods, as evidenced by the





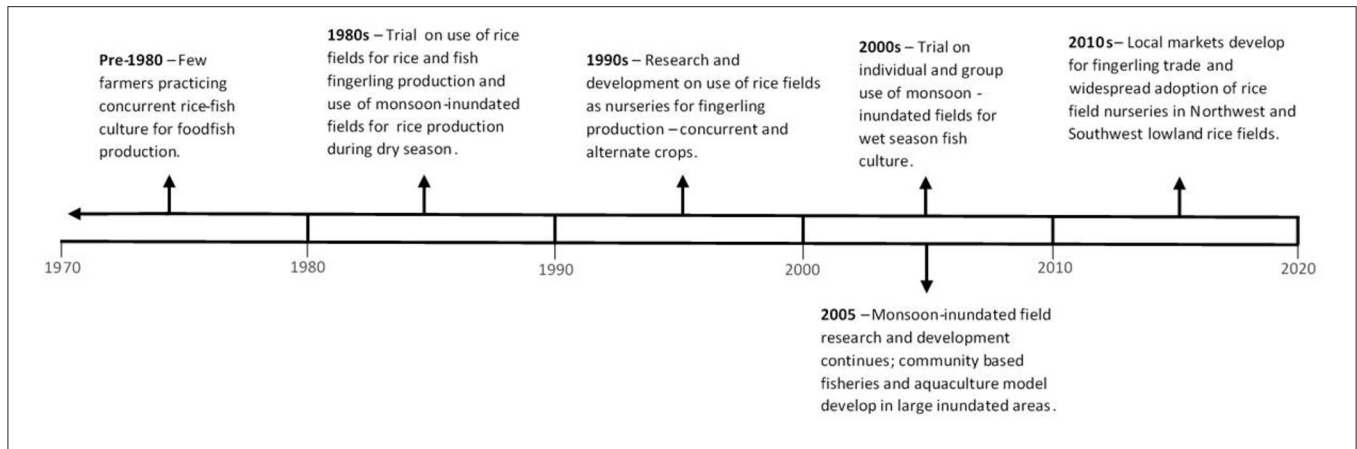
**FIGURE 2 |** Transformation pathways for rice-fish production practices. Starting from similar initial practices (predominantly rice field fisheries), rice-fish production in the four case study countries transitioned or transformed along different pathways according to their context and the objectives that followed from the Green Revolution (ca. 1985) onwards. During the present opportunity for food systems transformations, four potential pathways are foreseen, once again depending on the context and objectives in the push for sustainable food systems.



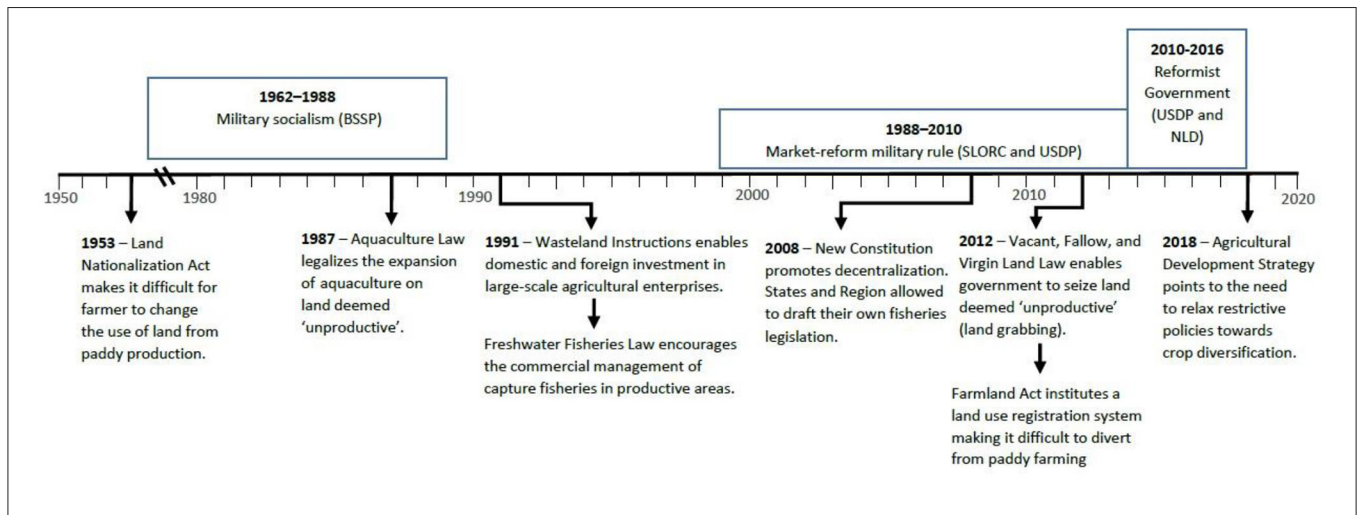
**FIGURE 3 |** Timeline of events that influenced rice-fish production practices in Cambodia.

concentration of poverty in rural areas, pronounced rural migration (Ingalls et al., 2018), and low Gross National Income per capita (\$1,063, the lowest among the four case study countries; The World Bank, 2017b). Another challenge is to improve nutritional outcomes. Despite relatively high availability of freshwater fish per capita (**Supplementary Table 2**; FAO, 2020a), Cambodia performs poorly in terms of childhood stunting (ranked third among case study countries; GHI, 2019) and prevalence of maternal anemia (ranked fourth among case study countries; WHO, 2016). Potential impediments to achieving nutritional benefits from the relatively high fish

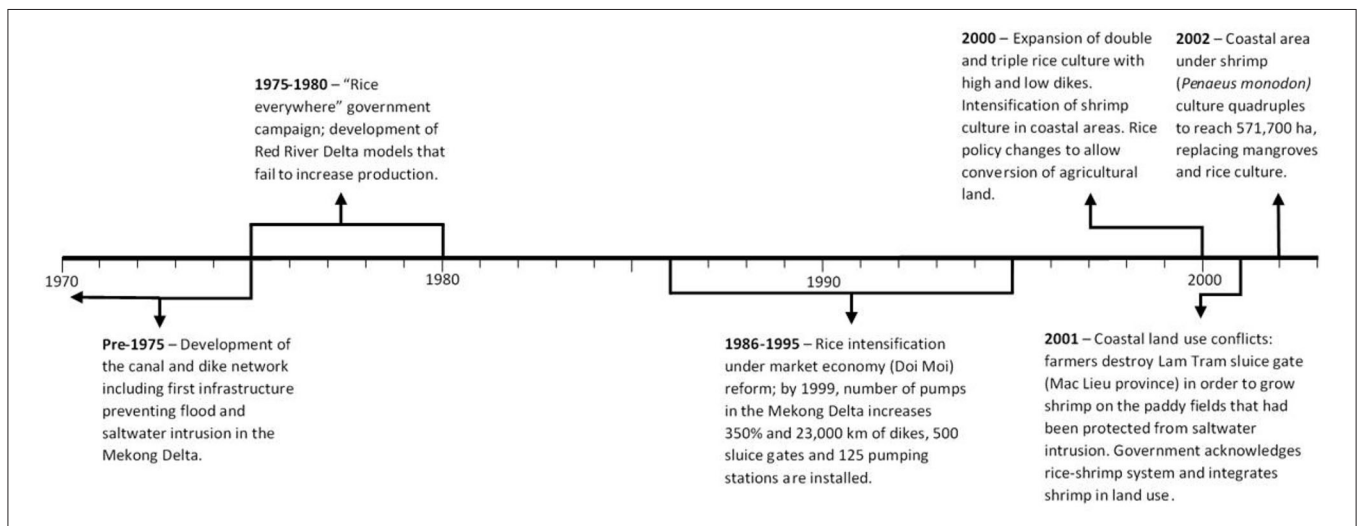
consumption rate include demographic or geographical pockets of low fish consumption (for example, low fish consumption in children under 2 years of age) and issues of food safety, sanitation infrastructure, and lack of available clean water (Kawarazuka and Béné, 2011; Vyas et al., 2016). A transformation focused on availability of affordable fish for consumption and production of high-quality rice and fish for income generation could address these nutritional and livelihood challenges. Production of high-value rice and fish and ensuring their quality along the value chain could also improve international trade in the face of the large volumes of cheap rice and fish produced in



**FIGURE 4** | Timeline of events that influenced emerging rice-fish production practices in Bangladesh.



**FIGURE 5** | Timeline of events that influenced and ultimately restricted rice-fish production practices in Myanmar.



**FIGURE 6** | Timeline of events that influenced rice-fish production practices in Vietnam’s Mekong Delta.



nearby countries. Quality assurance would most likely require substantial investments, properly targeted incentives for value chain development, and improvements in regulatory policies and their implementation (Ponte et al., 2014).

Water demand is a growing challenge due to recurrent dry periods and increased frequency and/or severity of adverse conditions during rice cultivation (Chhinh et al., 2014; Thangrak et al., 2020), the limited capacity of existing reservoirs in the Tonle Sap basin (Johnston et al., 2014), “water-scavenging” irrigation at farm level (Mukherji et al., 2009), and large scale upstream hydropower development affecting the Mekong and its inflow into the Tonle Sap (Arias et al., 2014). This last factor has already been linked to an expected decline in food and nutrition security through loss of fish availability (Golden et al., 2019). Local mitigation measures such as effective water management, “fish friendly” designs for irrigation development (McCartney et al., 2019), and continued community fish refuge support and scaling of best management practices (Kim et al., 2019) are essential for sustaining rice field fisheries. Some policies have recognized the benefits of rice field fisheries and supported innovations to enhance performance. However, more policy consistency is needed to ensure irrigation and agricultural intensification are not carried out at the expense of natural water flow and biodiversity, for example the directive on irrigation development (MAFF, 2017) and the promotion of rice dry season crop intensification in the Tonle Sap region (RGC, 2008).

## Bangladesh

Integrated rice and fish production practices diversified during the Green Revolution in Bangladesh due to aims of livelihood diversification alongside irrigation development for food system transformation. Diversification pursued due to famine, very low income per capita (the second lowest among all nations in 1975; World Bank Group, 2015), high levels of landlessness, and very small farm size. Bangladesh's economy also diversified away from agriculture (World Bank Group, 2015). However, rice and fish remain important agricultural products and dietary staples. Fisheries, and aquaculture in particular, may be considered key sectors for livelihood diversification and food and nutrition security, especially in rural areas. Around 11% of Bangladesh's population is employed in fisheries full or part-time (DoF, 2018). Aquaculture in particular provides rural income opportunities for landholders and landless alike (Belton et al., 2014). Improved fishery and aquaculture production remains a policy objective of Bangladesh for enhancing both employment and income, and food and nutrition security. Fisheries and aquaculture remain important contributors to agricultural gross domestic product and recently became productive enough to consider the nation's fish supply as self-sufficient (DoF, 2018).

Rice field fisheries in Bangladesh were once widespread, but diminished as dry season fish habitat was lost to intensification of dry season rice cultivation (Dey et al., 2013). Rice-fish culture is prevalent in southern Bangladesh, supporting the livelihoods of an estimated 600,000 people, including farmers, fish traders, and processors (Karim et al., 2014). Referred to in Bangla language as a “gher” farming system, rice-fish culture in this region consists primarily of alternating culture and most commonly incorporates

shrimp and prawn, selected for their export value and high income potential for producers (Rahman et al., 2006; Belton, 2016; Faruque et al., 2017). The widespread production of shrimp and prawn has led to the development of hatcheries and irrigation infrastructure, adoption of compatible rice varieties, and more employment opportunities.

Two additional RFPPs, rice field nurseries and community based fisheries and aquaculture (covering approximately 3,000 and 50,000 hectares, respectively), are emerging through innovations responding to investment, climatic, demographic and/or economic changes (Figure 4). The rice field nursery model emerged in the 1980s and 1990s, when farmers opted to pilot fingerling production that required less investment than fish grow-out and was more amenable to the rice production cycle, using lower water depths and shorter growing periods (Barman and Little, 2006). Increased demand for fingerlings, availability of inputs including fry and commercial feed, and the relatively low risk and quick return on investment also encouraged farmer adoption of rice field nurseries. Currently, little information is published on the environmental, food security, and income benefits of these nurseries.

Community based fisheries and aquaculture emerged largely in Bangladesh's northwest (e.g., Rajshahi district) and central regions (e.g., Cumilla district; Toufique and Gregory, 2008; Dey et al., 2013). Innovation of the management model was essential for this RFPP's success. A community based committee is formed from diverse stakeholders, receives training, and develops functional rules and regulations with support from formal institutions such as local government, Department of Fisheries, non-governmental organizations, and members of civil society (Joffre and Sheriff, 2011). Governance is challenging, especially to ensure inclusion of fishers and landless individuals and equity of benefit sharing (e.g., Toufique and Gregory, 2008). When managed inclusively, employment opportunities are generated and fishers gain additional fishing opportunity for up to 6 months each year (Haque and Dey, 2017). Successful examples have demonstrated that community based fisheries and aquaculture increased expenditure equality by 15% among community participants (Haque and Dey, 2016). In addition, the increased fish production bolstered fish consumption, especially for landless non-fishers (33% increase in annual per capita fish consumption) and improved household incomes from fish by a factor of 3.7 (Haque and Dey, 2017).

Adequate nutrition remains a challenge in Bangladesh, particularly in terms of hunger and maternal anemia (ranked fourth and third among the four case study countries, respectively; WHO, 2016; GHI, 2019). Natural disasters and climate change effects are also key challenges, with diverse patterns affecting food production across the country (Dastagir, 2015; Raihan et al., 2020). Scaling of RFPPs with an emphasis on resilience to climate change and accessibility for local consumption could ensure the contribution of rice and fish production to improved nutrition. Community based fisheries and aquaculture is a suitable candidate for scaling, considering the demonstrated positive benefits for household consumption. Effective scaling will require development of policy conducive to RFPPs and producer-focused initiatives such as dissemination of

farm management best practices, market development for inputs and outputs of fish culture, as well as initiatives to support the entire value chain (e.g., transportation facilities and financial and information technology instruments).

## Myanmar

Rice production has remained the primary focus of agricultural and food policy in Myanmar since the Green Revolution, despite delivering relatively low yields and economic returns per unit of land area (Ministry of Agriculture, Livestock and Irrigation, 2018; World Bank, 2018). Rice and fish are the fourth largest contributors to gross domestic product and are the main sources of rural incomes (Raitzer et al., 2015; FAO, 2020b). The government has declared revitalization of the agriculture sector as a priority, following the impacts of a tumultuous political history (Figure 5).

Rice field fisheries have continued as an abundant but “hidden harvest” in Myanmar. Myanmar’s 2012 Farmland Act has reinforced the stringent conditions required for the conversion of rice fields for any other permanent purpose (Gregory, 2017), constraining physical modifications to the rice farming landscape for fisheries enhancement or integration of aquaculture. Nevertheless, informal rice field fisheries are very common (Gregory, 2017; Oo and Mackay, 2018). While not officially recognized, rice field fisheries remain important for food and nutrition security in rice farming regions and may in fact constitute a large proportion of inland fisheries production in Myanmar. A survey of 180 leasable fishing lots in the Ayeyarwady Region found that 34% of these lots included seasonally flooded wetlands that were used for rice cultivation during the dry season. Fish productivity in these areas was comparable to the most productive seasonal floodplains in Bangladesh and Cambodia (Tezzo et al., 2018). Most households participating in rice field fisheries benefitted from savings due to self-supply of fish and income from selling surplus catch (Gregory, 2017). Fishery decline is observed, however, likely due to large numbers of fishers, increasing use of agrochemicals, and electrofishing (Gregory, 2017). Rice-fish culture is also present in Myanmar, but much less prominent. Shrimp are produced in saline zones through alternating rice-fish culture, but very little rice-fish culture occurs in fresh and brackish water areas (Gregory, 2017). The number of farmers practicing concurrent rice-fish culture in freshwater regions is currently limited due to restrictions in the 2012 Farmland Act.

Myanmar is showing signs of shifting from a monoculture focus to diversified production. Recent on-farm piloting of concurrent rice-fish culture showed positive benefits for rice yield, agrochemical reduction, and mean gross margin (which was 25% greater than that of rice monoculture; Dubois et al., 2019). These results highlight the improved resource efficiency and potential economic benefits of adopting concurrent rice-fish culture in the Ayeyarwady Delta without compromising rice production. Approximately 70% of the fish produced in the research trials was sold to the local market and purchased by rural and peri-urban consumers, while 30% was consumed by the farming households (Dubois et al., 2019), indicating the potential

to improve the diets of rice farming households and contribute to food and nutrition security in the region.

Economic inequality and food insecurity remain important challenges. Myanmar has the highest income inequality among the four case study countries (19.9% as of 2018; UNDP, 2020). Hunger and malnutrition affect large segments of the population and food insecurity remains a serious problem among resource poor people (Robertson et al., 2018). Inequalities in fish consumption exist, with the poorest households consuming less than one-quarter of the amount consumed by wealthier households (Wilson and Wai, 2013). In terms of environmental challenges, the central dry zone of Myanmar faces water availability limitations (Boori et al., 2017), while coastal regions face saline intrusion along with sea level rise (Oo et al., 2018).

Further studies are needed to assess the extent and benefits of RFPPs in Myanmar. Rice field fisheries likely make substantial contributions to food and nutrition security. Concurrent rice-fish culture could maintain rice production relative to rice monoculture, with the added benefit of fish as a more nutritious food and higher value commodity, however this has yet to be tested at scale (Dubois et al., 2019). Monoculture-focused policy and practices have limited the extent of RFPPs and land use regulations limit widespread adoption of rice-fish culture. The fast modernization of the agriculture sector may constitute another significant barrier to RFPPs. Further research on the current status and benefits of RFPPs to women and men in farming and non-farming households could provide guidance for policy makers to facilitate adoption and/or restoration of RFPPs toward local incomes and food and nutrition security.

## Vietnam

Transformation of fish and rice sectors have been pronounced since the Green Revolution in Vietnam. The improvement in rice yields and production secured self-sufficiency and exportation, and the Mekong delta remains the “rice bowl” of the country, producing 50% of Vietnam’s paddy rice (25 million tons) and 90% of its rice exports (Demont and Rustaert, 2017; Thang, 2017). The once prolific rice field fisheries of Vietnam’s Mekong delta declined in tandem with rice intensification. Although the delta once produced up to 90% of total inland fisheries production in southern Vietnam (Taki, 1975), rural households in the delta have experienced significant decreases in wild fish catch and consumption (Berg et al., 2017; Nguyen et al., 2018).

Environmental and infrastructure changes have been profound as well. The Mekong Delta now hosts over 10,000 km of canals and 20,000 km of dykes, and irrigation infrastructure encompasses 90% of its cropland (Nguyen et al., 2020). Saline water intrusion is increasing in the delta due to land subsidence (to which groundwater extraction for irrigation is a contributing factor; Minderhoud et al., 2017), sea level rise, high levels of downstream sand mining, and reduced upstream flow of water and sediment (largely due to hydropower infrastructure along the Mekong and its tributaries; Eslami et al., 2019). Variability in soil fertility and large areas of acid sulfate soil further constrain the intensification of rice culture in the delta (Husson et al., 2000).

Policy mandates and market incentives have operated to convert and intensify RFPPs in the Mekong Delta. Intensification and commodification of fish (including prawn and shrimp) production followed the initial Green Revolution push for rice production and commodification (Figure 6). In response to the low farm-gate prices for the high-yield but low quality rice (Demont and Rustaert, 2017) and increased use of inputs that keep farmer incomes low (Berg et al., 2017), farmers have diversified production in increasing numbers since the early 2000s. The high value and salt tolerance of shrimp motivated farmers to convert a large area planned for rice intensification to shrimp aquaculture and alternating rice-shrimp culture (Hoanh et al., 2003).

Extensive alternating rice-shrimp culture now covers 160,000 hectares (Hai et al., 2016), or about 5% of the wet season rice cultivation area of Vietnam (General Statistics Office, 2016). Freshwater finfish aquaculture has also increased in the delta (Nguyen et al., 2020), as have alternating culture of freshwater prawn and rice (Nguyen et al., 2020) and concurrent culture of rice- freshwater prawn followed by shrimp (*Penaeus vannamei* or *Penaeus monodon*) is also increasing in the coastal zone of the Mekong Delta (Hai et al., 2017). Net returns of alternating rice-shrimp culture can be as high as \$3,000 per hectare annually (AMDI, 2016). When compared with rice monoculture, rice-shrimp culture can improve economic and social equity and provide significantly higher net income at the household level, but may be difficult for poorer households to implement because of the high initial investment and reliance on household labor (Grassi et al., 2017). Although the shrimp sector is known for “boom and bust” cycles, alternating rice-shrimp culture in Vietnam appears to be more stable, at least in part because it is less prone to disease outbreaks than intensive aquaculture (Joffre and Bosma, 2009; Duc et al., 2015). While the rice may be consumed locally, nationally, or internationally, the shrimp are exported and rarely consumed locally, limiting the direct contribution to food and nutrition (Vu, 2012). Nonetheless, of the four countries we examine here, Vietnam has the lowest rates of childhood stunting and maternal anemia (WHO, 2016; GHI, 2019), due in part to increases in animal source food consumption in recent decades (Stür and Gray, 2015).

Currently, climate change, freshwater availability, and water quality are the greatest challenges for Vietnam’s rice and fish sectors. Semi-intensive rice-shrimp culture can release exotic species, nutrient loads, and anti-biotic and agrochemical residues, even though rice-shrimp producers tend to report lower application of pesticides and antibiotics than in intensive shrimp culture (Be et al., 1999; Binh et al., 2018; Braun et al., 2019). Promotion of rice-shrimp management practices that limit nutrient discharge and restore connectivity between the plot and the wider ecosystem (e.g., Joffre et al., 2018) could mitigate some of the environmental and health concerns of high-input practices.

Recent severe drought and increasing saline intrusion is causing crop loss, particularly for rice (South China Morning Post, 2020). Alternating rice-shrimp culture may expand in the delta as saltwater intrusion continues, but it may be replaced by shrimp monoculture in areas where the duration

of saline intrusion increases. The Ministry of Agriculture and Rural Development plans to develop the rice-shrimp area in the Mekong Delta to 250,000 hectares producing 125,000–150,000 metric tons by 2030, rendering a value of up to \$1.3 billion and providing stable jobs for over 1 million people in rural areas (AMDI, 2016). At the same time, if there are no adaptation efforts, profit from intensive and semi-intensive shrimp farming is estimated to fall by \$41 per hectare by 2050 due to climate change (affected in particular by increasing temperatures and lack of fresh water; Kam et al., 2012). Rising temperatures are anticipated to not only adversely affect shrimp, but also rice yields (Nhan et al., 2011). Although expansion of other RFPPs could further contribute to food system sustainability, continuing salinization and subsidence of the delta may require more dramatic shifts or a conversion to alternative production practices.

## DISCUSSION

Food and nutrition security challenges are intensifying in the face of increasing demand for food as well as climate change and associated water stress and environmental degradation (Hanjra and Qureshi, 2010; Myers et al., 2017). In its current form, agriculture is overreaching the limits of global environmental sustainability (Gordon et al., 2017; Gerten et al., 2020). The typology and case studies in this review demonstrate how long-standing, adapting, and emergent agroecological practices can contribute to addressing these challenges in rice and fish producing nations. Reflecting on the Green Revolution approach to transforming food systems, the typology and case studies illustrate five shifts in approach, set out below, that could nudge food systems toward greater sustainability and better nutritional outcomes.

The first shift toward sustainable and nutrition-sensitive food systems is to apply an agroecological lens when identifying the range of production practices that can be enabled, improved, and scaled. The Green Revolution primarily promoted high-input practices and in doing so, sidelined other practices that are evidenced to effectively manage water availability, soil fertility, and pest control (Tilman, 1998; Tilman et al., 2002). The RFPP typology we developed illustrates the range and diversity of available agricultural practices for rice and fish production, including nutrition-sensitive practices. This typology broadens the solution space under consideration and illustrates opportunities for new practices or strengthening of agroecological features associated with existing practices.

The second shift in the approach to food system transformations is to account for the diversity of food system objectives. The Green Revolution focused primarily on the objective of increasing quantities of staple crops (Hazell, 2009; Pingali, 2012). Our review illustrates that, alongside this production goal, national food systems were also attuned to other objectives: nutrition gains and biodiversity conservation in Cambodia; livelihood diversification in Bangladesh;



self-sufficiency in Myanmar; export value in Vietnam; and improving rural incomes in all cases. The contemporary demands for more sustainable and nutrition-sensitive food systems explicitly prioritize a much broader suite of objectives than the Green Revolution (De Schutter, 2017) and present an opportunity to build upon the breadth of food systems objectives found in the national food systems of Cambodia, Bangladesh, Myanmar, and Vietnam. The degree to which each objective will continue to be prioritized depends on the influence of divergent views of what constitutes a sustainable food system (Béné et al., 2019) and potential transformation pathways (Bezner Kerr, 2012; Blythe et al., 2018) within investments and policy.

The third shift is to align decision-making and planning tools with the broader range of recognized objectives, particularly through adjustments of metrics and evaluation frameworks. Food systems decisions during the Green Revolution were evaluated against indicators and targets relating to production, yield, Gross Domestic Product, and (in some cases) employment (IPES-Food, 2016; De Schutter, 2017). As public and private actors increase commitments toward sustainable food systems (Asian Development Bank, 2015; McCartney et al., 2019), evaluation metrics must align with, and ensure accountability to, a broader set of nutrition, equity, and environmental targets. In addition to evaluating food system performance, a shift in approach to metrics can improve tracking of feedback loops among food system components and outcomes and can facilitate course-checking and course-correction. Existing measures must also be refined to better distinguish among production practices, especially to better account for fisheries and diverse aquatic foods (Thilsted et al., 2016; Funge-Smith and Bennett, 2019). For example, in rice and fish producing nations, rice monoculture and aquaculture areas are often well-represented in national statistics, but areas of integrated and agroecological production such as rice field fisheries remain largely unrepresented or misrepresented as rice monoculture.

The fourth shift brings equity to the fore through contextualized and inclusive approaches to research and innovation. The Green Revolution has been criticized for relying on generic technologies and innovations that are disseminated globally with too little consideration for social, ecological, and agricultural context and diversity (Horlings and Marsden, 2011). Transformations devoid of agroecological practices are prone to excluding and marginalizing certain stakeholders, most notably vulnerable rural farming households (Bezner Kerr, 2012), and can enhance social and environmental inequalities (Bezner Kerr, 2012; Blythe et al., 2018). An emerging paradigm shift in agronomy emphasizes support for local innovation to develop emergent and adaptive solutions that suit the heterogeneity of farmer-fisher contexts and objectives (Sinclair and Coe, 2019). Ensuring the alignment of innovations, institutions, and policies is also necessary for effective transformation (Horlings and Marsden, 2011; Bezner Kerr, 2012; Joffre et al., 2018). The suite of production practices represented in the RFPP typology allow for continued testing and refining of innovations to further

improve nutrition, equity, and environmental outcomes. The innovations emerging from RFPPs demonstrate gains or promise in enhancing management of landscape connectivity (in the Mekong Delta; Joffre et al., 2018; Nguyen et al., 2020), equity and inclusivity (in Bangladesh; Haque and Dey, 2016), and enabling adaptation in the face of changing environmental and sociopolitical conditions (in Myanmar; Dubois et al., 2019). Even for the long-standing rice field fisheries in Cambodia, innovation and research have enabled adaptation to the contemporary agricultural, ecological, and institutional context (Kim et al., 2019).

To support this contextualized and inclusive approach to research and innovation, research must more consistently investigate food and nutrition provision, equitable benefit sharing, and environmental outcomes of different production practices. These shifts in research focus will help meet Blesh et al. (2019) call for “*place-based, adaptive, and participatory solutions that simultaneously attend to local institutional capacities, agroecosystem diversification and ecological management, and the quality of local diets.*” For example, rice field fisheries outcomes can vary due to environmental conditions (both natural biophysical characteristics and managed attributes such as barriers to water flow and migration) and fishing practices, including access to fishing grounds (Freed et al., 2020), and also differ from outcomes of other RFPPs. Understanding the range of outcomes produced under variable contexts and among practices would help guide decision-making on whether to invest in enhancing a rice field fishery, an alternative RFPP, or another farming approach. Research is also needed on actors and practices along the rest of the value chain, institutions, and policies, to determine their influence on food systems equity and sustainability (Ericksen et al., 2010; Horlings and Marsden, 2011; De Schutter, 2017).

Finally, the fifth shift in the approach to food systems transformations is to build adaptive capacity to cope with evolving challenges and harness opportunities that arise during the implementation period. Substantial environmental change is occurring across South and Southeast Asia, e.g., salinization in the deltas in Vietnam, Myanmar, and Bangladesh (Dastagir, 2015; Minderhoud et al., 2017; Oo et al., 2018; Eslami et al., 2019); increasing frequency and severity of already disastrous extreme weather events in Bangladesh (Dastagir, 2015; Raihan et al., 2020); and water scarcity in parts of Myanmar and Cambodia (Chhinh et al., 2014; Boori et al., 2017; Thangrak et al., 2020). RFPPs can help maintain adaptive capacity in the face of environmental change, especially in coastal Bangladesh and Vietnam (Hai et al., 2016; Faruque et al., 2017). This adaptability is a unique feature of diversified agroecological production practices, in contrast to the “lock-in” effect observed in monoculture systems (Chhetri et al., 2010; De Schutter, 2017; Magrini et al., 2018). A lock-in, or the “*cumulative outcome of technological trajectories adopted by farmers and promoted by extension services, agricultural policies, and agricultural research systems*” (Chhetri et al., 2010), requires concerted efforts across institutions, disciplines, and scales to break (Chhetri et al., 2010; Meynard et al., 2018).



## CONCLUSION

Systems perspectives to the concurrent environmental and food and nutrition security challenges we now face are gaining traction in policy arenas, providing an opportunity to embrace diversity in visions of agricultural change. Enabling the contribution of agroecological approaches to transforming food systems has the potential to improve progress toward the “Zero Hunger” Sustainable Development Goal (SDG). The evidence we synthesize demonstrates this for rice and fish producing regions. Integrated and agroecological rice-fish production practices can contribute to productivity and income for small-scale food producers and to ecosystem maintenance and capacity for adaptation to climate change and natural disasters, in alignment with SDG targets 2.3 and 2.4. Implementation of the five shifts we propose for food system transformations could maintain or further improve sufficient rice yields and production of rice and fish. Beyond that, these shifts support ecological integrity and biodiversity conservation alongside the provision of a broad range of nutrition and livelihood benefits, commensurate with a holistic vision of sustainable food systems.

## AUTHOR CONTRIBUTIONS

SF, YK, and PC contributed to conceptualization and methodology. SF conducted formal analysis. All authors contributed to writing and editing.

## REFERENCES

- AFD and CIRAD (2018). *Supporting the Agro-Ecological Transition in the Global South*. Paris.
- Ahmed, M., and Loricca, M. H. (2002). Improving developing country food security through aquaculture development - lessons from Asia. *Food Policy* 27, 125–141. doi: 10.1016/S0306-9192(02)00007-6
- Ahmed, N., Zander, K. K., and Garnett, S. T. (2011). Socioeconomic aspects of rice-fish farming in Bangladesh: opportunities, challenges and production efficiency. *Aust. J. Agric. Resour. Econ.* 55, 199–219. doi: 10.1111/j.1467-8489.2011.00535.x
- Ali, A. B. (1990). Some ecological aspects of fish populations in tropical ricefields. *Hydrobiologia* 190, 215–222. doi: 10.1007/BF00008188
- Altieri, M. A. (2002). Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agric. Ecosyst. Environ.* 93, 1–24. doi: 10.1016/S0167-8809(02)00085-3
- AMDI (2016). *Development of Rice-Shrimp Farming in the Mekong River*. Vietnam.
- Amilhat, E., Lorenzen, K., Morales, E. J., Yakupitiyage, A., and Little, D. C. (2009). Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) I. Characterisation of systems. *Aquaculture* 296, 219–226. doi: 10.1016/j.aquaculture.2009.08.014
- Arias, M. E., Cochrane, T. A., and Elliott, V. (2014). Modelling future changes of habitat and fauna in the tonle sap wetland of the mekong. *Environ. Conserv.* 41, 165–175. doi: 10.1017/S0376892913000283
- Arthur, R. I., and Friend, R. M. (2011). Inland capture fisheries in the mekong and their place and potential within food-led regional development. *Glob. Environ. Chang.* 21, 219–226. doi: 10.1016/j.gloenvcha.2010.07.014
- Asian Development Bank (2015). *Operational Plan for Agriculture and Natural Resources: Promoting Sustainable Food Security in Asia and the Pacific in 2015-2020*. Mandaluyong City: Asian Development Bank.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2020.576179/full#supplementary-material>

- Barman, B. K., and Little, D. C. (2006). Nile tilapia (*Oreochromis niloticus*) seed production in irrigated rice-fields in Northwest Bangladesh—an approach appropriate for poorer farmers? *Aquaculture* 261, 72–79. doi: 10.1016/j.aquaculture.2006.06.018
- Bartley, D. M., De Graaf, G. J., Valbo-Jørgensen, J., and Marmulla, G. (2015). Inland capture fisheries: status and data issues. *Fish. Manag. Ecol.* 22, 71–77. doi: 10.1111/fme.12104
- Baumgartner, L., Marsden, T., Millar, J., Thorncraft, G., Phonekhampheng, O., Homsombath, K., et al. (2016). *Development of Fish Passage Technology to Increase Fisheries Production on Floodplains in the Lower Mekong Basin*. Final Report, Project FIS/2009/041. Canberra, ACT: ACIAR, 75.
- Be, T., Dung, L., and Brennan, D. (1999). Environmental costs of shrimp culture in the rice-growing regions of the Mekong Delta. *Aquac. Econ. Manag.* 3, 31–42. doi: 10.1080/13657309909380231
- Belton, B. (2016). Shrimp, prawn and the political economy of social wellbeing in rural Bangladesh. *J. Rural Stud.* 45, 230–242. doi: 10.1016/j.jrurstud.2016.03.014
- Belton, B., Ahmed, N., and Murshed-e-Jahan, K. (2014). *Aquaculture, Employment, Poverty, Food Security and Well-Being in Bangladesh: A Comparative Study*. Penang: CGIAR Research Program on Aquatic Agricultural Systems. Program Report: AAS-2014-39.
- Béné, C., Barange, M., Subasinghe, R., Pinstrip-Andersen, P., Merino, G., Hemre, G. I., et al. (2015). Feeding 9 billion by 2050 – putting fish back on the menu. *Food Secur.* 7, 261–274. doi: 10.1007/s12571-015-0427-z
- Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., et al. (2019). When food systems meet sustainability – current narratives and implications for actions. *World Dev.* 113, 116–130. doi: 10.1016/j.worlddev.2018.08.011
- Berg, H., Ekman Söderholm, A., Söderström, A. S., and Tam, N. T. (2017). Recognizing wetland ecosystem services for sustainable rice

- farming in the Mekong Delta, Vietnam. *Sustain. Sci.* 12, 137–154. doi: 10.1007/s11625-016-0409-x
- Bezner Kerr, R. (2012). Lessons from the old green revolution for the new: social, environmental and nutritional issues for agricultural change in Africa. *Prog. Dev. Stud.* 12, 213–229. doi: 10.1177/146499341101200308
- Binh, V., Dang, N., Anh, N., Ky, L., and Thai, P. (2018). Antibiotics in the aquatic environment of Vietnam: sources, concentrations, risk and control strategy. *Chemosphere* 197, 438–450. doi: 10.1016/j.chemosphere.2018.01.061
- Blesh, J., Hoey, L., Jones, A. D., Friedmann, H., and Perfecto, I. (2019). Development pathways toward “zero hunger.” *World Dev.* 118, 1–14. doi: 10.1016/j.worlddev.2019.02.004
- Blesh, J., and Wolf, S. A. (2014). Transitions to agroecological farming systems in the mississippi river basin: toward an integrated socioecological analysis. *Agric. Hum. Values* 31, 621–635. doi: 10.1007/s10460-014-9517-3
- Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N. J., Moore, M. L., et al. (2018). The dark side of transformation: latent risks in contemporary sustainability discourse. *Antipode* 50, 1206–1223. doi: 10.1111/anti.12405
- Boori, M. S., Choudhary, K., Evers, M., and Paringer, R. (2017). A review of food security and flood risk dynamics in central dry zone area of Myanmar. *Procedia Eng.* 201, 231–238. doi: 10.1016/j.proeng.2017.09.600
- Braun, G., Braun, M., Kruse, J., Amelung, W., Renaud, F. G., Khoi, C. M., et al. (2019). Pesticides and antibiotics in permanent rice, alternating rice-shrimp and permanent shrimp systems of the coastal Mekong Delta, Vietnam. *Environ. Int.* 127, 442–451. doi: 10.1016/j.envint.2019.03.038
- CARD, and TWG-SP&FS (2014). *National Strategy for Food Security and Nutrition 2014–2018*. Phnom Penh: Council for Agricultural and Rural Development and Technical Working Group for Social Protection and Food Security and Nutrition.
- Caron, P., Ferrero y de Loma-Osorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., et al. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. *Agron. Sustain. Dev.* 38:41. doi: 10.1007/s13593-018-0519-1
- Chan, C., Tran, N., Dao, C., Sulser, T., Phillips, M., Batka, M., et al. (2017). *Fish to 2050 in the ASEAN Region*. Washington, DC.
- Cheng-Fang, L., Cou-Gui, C., Jin-Ping, W., Ming, Z., Wei-Ling, Y., and Ahmad, S. (2008). Nitrogen losses from integrated rice-duck and rice-fish ecosystems in southern China. *Plant Soil* 307, 207–217. doi: 10.1007/s11104-008-9597-1
- Chheng, P., Un, S., Tress, J., Simpson, V., and Sieu, C. (2016). *Fish Productivity by Aquatic Habitat and Estimated Fish Production in Cambodia*. Phnom Penh.
- Chhetri, N. B., Easterling, W. E., Terando, A., and Mearns, L. (2010). Modeling path dependence in agricultural adaptation to climate variability and change. *Ann. Assoc. Am. Geogr.* 100, 894–907. doi: 10.1080/00045608.2010.500547
- Chhinh, N., Cheb, H., and Heng, N. (2014). Drought risk in Cambodia: assessing costs and a potential solution. *Asian J. Agric. Dev.* 11, 1–16. doi: 10.22004/ag.econ.202425
- Coates, D. (2002). *Inland Capture Fishery Statistics of Southeast Asia: Current Status and Information Needs*. Bangkok.
- Coche, A. G. (1967). Fish culture in rice fields a world-wide synthesis. *Hydrobiologia* 30, 1–44. doi: 10.1007/BF00135009
- Cooke, S. J., Allison, E. H., Beard, T. D., Arlinghaus, R., Arthington, A. H., Bartley, D. M., et al. (2016). On the sustainability of inland fisheries: finding a future for the forgotten. *Ambio* 45, 753–764. doi: 10.1007/s13280-016-0787-4
- Costa-Pierce, B. A. (1992). “Rice-fish systems as intensive nurseries,” in *Rice-Fish Research and Development in Asia. ICLARM Conference Proceedings*, eds C. R. dela Cruz, C. Lightfoot, B. A. Costa-Pierce, V. R. Carangal, and M. P. Bimbao (Makati city: ICLARM), 117–130.
- Cramb, R., and Newby, J. (2015). “Trajectories of rice-farming households in mainland Southeast Asia,” in *Trajectories of Rice-Based Farming Systems in Mainland Southeast Asia*, ed R. Cramb (Canberra, ACT: Australian Centre for International Agricultural Research), 35–72.
- Dastagir, M. R. (2015). Modeling recent climate change induced extreme events in Bangladesh: a review. *Weather Clim. Extrem.* 7, 49–60. doi: 10.1016/j.wace.2014.10.003
- De Schutter, O. (2017). The political economy of food systems reform. *Eur. Rev. Agric. Econ.* 44, 705–731. doi: 10.1093/erae/jbx009
- Demont, M., and Rustaert, P. (2017). Restructuring the Vietnamese rice sector: towards increasing sustainability. *Sustainability* 9:325. doi: 10.3390/su9020325
- Dey, M. M., Spielman, D. J., Haque, A. B. M. M., Rahman, M. S., and Valmonte-Santos, R. (2013). Change and diversity in smallholder rice-fish systems: recent evidence and policy lessons from Bangladesh. *Food Policy* 43, 108–117. doi: 10.1016/j.foodpol.2013.08.011
- DoF (2018). *Yearbook of Fisheries Statistics of Bangladesh 2017–2018*. Vol. 35, Fisheries Resources Survey System (FRSS), Department of Fisheries. Dhaka: Ministry of Fisheries. p. 129.
- Dubois, M. J., Akester, M., Leemans, K., Teoh, S. J., Stuart, A., Thant, A. M., et al. (2019). Integrating fish into irrigation infrastructure projects in Myanmar: rice-fish what if...? *Mar. Freshw. Res.* 70, 1229–1240. doi: 10.1071/MF19182
- Duc, P., Thi, T., Hoa, T., Phuong, N., Bosma, R., Hien, V., et al. (2015). Virus diseases risk-factors associated with shrimp farming practices in rice-shrimp and intensive culture systems in Mekong Delta Viet Nam. *Int. J. Sci. Res. Publ.* 5, 1–6.
- Dwiyana, E., and Mendoza, T. C. (2006). Comparative productivity, profitability and efficiency of rice monoculture and rice-fish culture systems. *J. Sustain. Agric.* 29, 145–166. doi: 10.1300/J064v29n01\_11
- Dwiyana, E., and Mendoza, T. C. (2008). Determinants of productivity and profitability of rice-fish farming systems. *Asia Life Sci.* 17, 21–42.
- Edwards, P., Zhang, W., Belton, B., and Little, D. C. (2019). Misunderstandings, myths and mantras in aquaculture: its contribution to world food supplies has been systematically over reported. *Mar. Policy* 106:103547. doi: 10.1016/j.marpol.2019.103547
- Ericksen, P., Stewart, B., Dixon, J., Barling, D., Loring, P., Anderson, M., et al. (2010). “The value of a food system approach,” in *Food Security and Global Environmental Change*, eds J. Ingram and P. Ericksen (London: Earthscan), 25–45.
- Eslami, S., Hoekstra, P., Trung, N., Kantoush, S., Van Binh, D., Quang, T., et al. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Sci. Rep.* 9:18746. doi: 10.1038/s41598-019-55018-9
- FAO (2014). *A Regional Rice Strategy for Sustainable Food Security in Asia and the Pacific*. Bangkok.
- FAO (2019). *Report of the Special Session on Advancing Integrated Agriculture Aquaculture Through Agroecology, Montpellier, France, 25 August 2018*. Rome.
- FAO (2020a). *FAO FishStatJ Database*. Available online at: <http://www.fao.org/fishery/statistics/software/FishStatJ/en> (accessed October 19, 2020).
- FAO (2020b). *FAO in Myanmar*. Available online at: <http://www.fao.org/myanmar/fao-in-myanmar/myanmar/en/> (accessed October 19, 2020).
- FAO (2020c). *FAOSTAT Database*. Available online at: <http://www.fao.org/faostat/en/home> (accessed October 19, 2020).
- Faruque, G., Sarwer, R. H., Karim, M., Phillips, M., Collis, W. J., Belton, B., et al. (2017). The evolution of aquatic agricultural systems in Southwest Bangladesh in response to salinity and other drivers of change. *Int. J. Agric. Sustain.* 15, 185–207. doi: 10.1080/14735903.2016.1193424
- Fernando, C. H. (1993). Rice field ecology and fish culture - an overview. *Hydrobiologia* 259, 91–113. doi: 10.1007/BF00008375
- Fisher, B., Naidoo, R., Guernier, J., Johnson, K., Mullins, D., Robinson, D., et al. (2017). Integrating fisheries and agricultural programs for food security. *Agric. Food Secur.* 6, 10–16. doi: 10.1186/s40066-016-0078-0
- Fisheries Administration (2011). *Cambodia Strategic Planning Framework for Fisheries 2010–2019*. Phnom Penh.
- Fluet-Chouinard, E., Funge-Smith, S., and McIntyre, P. B. (2018). Global hidden harvest of freshwater fish revealed by household surveys. *Proc. Natl. Acad. Sci. U.S.A.* 115, 7623–7628. doi: 10.1073/pnas.1721097115
- Freed, S., Kura, Y., Sean, V., Mith, S., Cohen, P., Kim, M., et al. (2020). Rice field fisheries: wild aquatic species diversity, food provision services and contribution to inland fisheries. *Fish. Res.* 229:105615. doi: 10.1016/j.fishres.2020.105615
- Frei, M., and Becker, K. (2005). A greenhouse experiment on growth and yield effects in integrated rice–fish culture. *Aquaculture* 244, 119–128. doi: 10.1016/j.aquaculture.2004.11.014
- Friend, R. M., Arthur, R. I., and Keskinen, M. (2009) “Songs of the doomed: the continuing neglect of capture fisheries in hydropower development in the Mekong,” in *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*, eds F. Molle, T. Foran, and M. Käkönen (London: Earthscan), 307–331. doi: 10.4324/9781849770866

- Funge-Smith, S., and Bennett, A. (2019). A fresh look at inland fisheries and their role in food security and livelihoods. *Fish Fish* 20, 1–20. doi: 10.1111/faf.12403
- Garaway, C. J., Photitay, C., Roger, K., Khamshivily, L., and Halwart, M. (2013). Biodiversity and nutrition in rice-based ecosystems; the case of lao PDR. *Hum. Ecol.* 41, 547–562. doi: 10.1007/s10745-013-9602-z
- General Statistics Office (2016). *Agriculture, Forestry and Fishing Database*. General Statistics Office of Vietnam. Available online at: <https://www.gso.gov.vn/en/agriculture-forestry-and-fishery/> (accessed October 19, 2020).
- Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., et al. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustain.* 3, 200–208. doi: 10.1038/s41893-019-0465-1 (accessed October 19, 2020).
- GHI (2019). *Global Hunger Index*. Available online at: <https://www.globalhungerindex.org/results.html> (accessed 19 October 2020).
- Golden, C. D., Shaper, A., Vaitla, B., Smith, M. R., Myers, S. S., Stebbins, E., et al. (2019). Impacts of mainstream hydropower development on fisheries and human nutrition in the lower mekong. *Front. Sustain. Food Syst.* 3, 1–10. doi: 10.3389/fsufs.2019.00093
- Gordon, L. J., Bignet, V., Crona, B., Henriksen, P. J. G., Van Holt, T., Jonell, M., et al. (2017). Rewiring food systems to enhance human health and biosphere stewardship. *Environ. Res. Lett.* 12:100201. doi: 10.1088/1748-9326/aa81dc
- Grassi, F., Paris, T. R., and Chi, T. T. N. (2017). *Rice-Rice and Rice-Shrimp Production: A Gender Perspective on Labour, Time Use and Access to Technologies and Services in Southern Vietnam*. Rome: Food and Agriculture Organization of the United Nations.
- Gregory, R. (1997). *Ricefield Fisheries Handbook*. Los Banos: International Rice Research Inst.; Phnom Penh: Ministry of Agriculture, Forestry and Fisheries.
- Gregory, R. (2017). *Development of Rice Fish Systems (RFS) in the Ayeyarwaddy Delta. Rice Fish Systems Characterisation Study*. Yangon.
- Hai, T., Huong, H., Viet, L., Huong, D., and Phuong, N. (2017). Giant freshwater prawn (*Macrobrachium rosenbergii* de Man, 1879) farming in brackish water areas of the Mekong Delta, Vietnam. *Can Tho Univ. J. Sci.* 7, 82–90. doi: 10.22144/ctu.jen.2017.053
- Hai, T., Minh, T., Phu, T., and Phuong, N. (2016). “Shrimp industry in Vietnam,” in *Progress of Shrimp and Prawn Aquaculture in the World*, eds C. Liao, N. Chao, and E. Leano (Keelung; Manila; Louisiana: National Taiwan Ocean University; The Fisheries Society; World Aquaculture Society), 181–204.
- Halwart, M. (1994). *Fish as Biocontrol Agents in Rice: The Potential of Common Carp *Cyprinus carpio* (L.) and Nile Tilapia *Oreochromis niloticus* (L.)*. Weikersheim: Margraf Verlag.
- Halwart, M. (1998). Trends in rice-fish farming. *FAO Aquac. Newslett.* 18 (Rome: Food and Agriculture Organisation of the United Nations). 3–11.
- Halwart, M. (2006). Biodiversity and nutrition in rice-based aquatic ecosystems. *J. Food Compos. Anal.* 19, 747–751. doi: 10.1016/j.jfca.2006.03.012
- Halwart, M. (2013). “Valuing aquatic biodiversity in agricultural landscapes,” in *Diversifying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*, eds J. Fanzo, D. Hunter, T. Borelli, and F. Mattei (Abingdon: Routledge), 88–108.
- Halwart, M., and Gupta, M. (2004). *Culture of Fish in Rice Fields*. Rome: FAO; Penang: WorldFish.
- Hanjra, M., and Qureshi, M. (2010). Global water crisis and future food security in an era of climate change. *Food Policy* 35, 365–377. doi: 10.1016/j.foodpol.2010.05.006
- Haque, A. B. M. M., and Dey, M. M. (2016). Impact of the community-based fish culture system on expenditure and inequality: evidence from Bangladesh. *J. World Aquac. Soc.* 47, 646–657. doi: 10.1111/jwas.12317
- Haque, A. B. M. M., and Dey, M. M. (2017). Impacts of community-based fish culture in seasonal floodplains on income, food security and employment in Bangladesh. *Food Secur.* 9, 25–38. doi: 10.1007/s12571-016-0629-z
- Hazell, P. B. R. (2009). *The Asian Green Revolution*. Available online at: <https://www.ifpri.org/publication/asian-green-revolution> (accessed October 19, 2020).
- Heckman, C. W. (1979). *Rice Field Ecology in Northeastern Thailand*. ed J. Illies. Dordrecht: Springer Science+Business Media.
- HLPE (2014). *Food Losses and Waste in the Context of Sustainable Food Systems*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.
- HLPE (2019). *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.
- Hoanh, C. T., Tuong, T. P., Gallop, K. M., Gowing, J. W., Kam, S. P., Khiem, N. T., et al. (2003). Livelihood impacts of water policy changes: evidence from a coastal area of the Mekong river delta. *Water Policy* 5, 475–488. doi: 10.2166/wp.2003.0030
- Horgan, F. G., Ramal, A. F., Bernal, C. C., Villegas, J. M., Stuart, A. M., and Almazan, M. L. P. (2016). “Applying ecological engineering for sustainable and resilient rice production systems,” in *Procedia Food Science*, eds C. N. Walpita, P. Sorgeloos, I. Karunasagar and K. K. D. S. Ranaweera (Belihuloya: Elsevier Srl), 7–15. doi: 10.1016/j.profoo.2016.02.002
- Horlings, L. G., and Marsden, T. K. (2011). Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could “feed the world.” *Glob. Environ. Chang.* 21, 441–452. doi: 10.1016/j.gloenvcha.2011.01.004
- Hortle, K., Troeung, R., and Lieng, S. (2008). *Yield and Value of the Wild Fishery of Rice Fields in Battambang Province, Near the Tonle Sap Lake*. Vientiane.
- Hu, L., Tang, J., Zhang, J., Ren, W., Guo, L., Halwart, M., et al. (2015). Development of rice-fish system: Today and tomorrow. *Chinese J. Eco Agric.* 23, 268–275.
- Husson, O., Verburg, P., Phung, M., and Van Mensvoort, M. (2000). Spatial variability of acid sulphate soils in the plain of reeds, Mekong Delta, Vietnam. *Geoderma* 97, 1–19. doi: 10.1016/S0016-7061(00)00016-1
- Ingalls, M. L., Diepart, J., Truong, N., Hayward, D., Neil, T., Phomphakdy, C., et al. (2018). *State of Land in the Mekong Region*. Bern; Vientiane: Lao PDR.
- IPES-Food (2016). *From Uniformity to Diversity: A Paradigm Shift From Industrial Agriculture to Diversified Agroecological Systems*. Brussels: International Panel of Experts on Sustainable Food Systems. Available online at: [https://cgispace.cgiar.org/bitstream/handle/10568/75659/UniformityToDiversity\\_FullReport.pdf?sequence=1&isAllowed=y](https://cgispace.cgiar.org/bitstream/handle/10568/75659/UniformityToDiversity_FullReport.pdf?sequence=1&isAllowed=y) (accessed 19 October 2020).
- Joffre, O., and Bosma, R. (2009). Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. *Agric. Ecosyst. Environ.* 132, 153–159. doi: 10.1016/j.agee.2009.03.010
- Joffre, O., Sheriff, N. (2011). *Studies and Reviews 2011–21*. Penang: The WorldFish Center. p. 46.
- Joffre, O. M., Klerkx, L., and Khoa, T. N. D. (2018). Aquaculture innovation system analysis of transition to sustainable intensification in shrimp farming. *Agron. Sustain. Dev.* 38:34. doi: 10.1007/s13593-018-0511-9
- Johnston, R., da Silva, S., and Try, T. (2014). “Investing in water management to improve productivity of rice-based farming systems in Cambodia,” in *A Policy Dialogue on Rice Futures: Rice-Based Farming Systems Research in the Mekong Region*. Proceedings No. 142, ed L. Robins (Phnom Penh: Australian Centre for International Agricultural Research), 116–119.
- Johnston, R., Hoanh, C. T., Lacombe, G., Noble, A., Smakhtin, V., Suhardiman, D., et al. (2019). *Scoping Study on Natural Resources and Climate Change in Southeast Asia with a Focus on Agriculture*. Vientiane
- Kam, S. P., Badjeck, M.-C., Teh, L., Teh, L., and Tran, N. (2012). *Autonomous Adaptation to Climate Change by Shrimp and Catfish Farmers in Vietnam’s Mekong River Delta*. Working Paper: 2012–24. Penang: Worldfish.
- Karim, M., Sarwer, R., Phillips, M., and Belton, B. (2014). Profitability and adoption of improved shrimp farming technologies in the aquatic agricultural systems of southwestern Bangladesh. *Aquaculture* 428–429, 61–70. doi: 10.1016/j.aquaculture.2014.02.029
- Kawarazuka, N., and Béné, C. (2011). The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. *Public Health Nutr.* 14, 1927–1938. doi: 10.1017/S1368980011000814
- Kim, M., Mam, K., Sean, V., Brooks, A., Thay, S., Hav, V., et al. (2019). *A Manual for Community Fish Refuge-Rice Field Fisheries System Management in Cambodia*. Phnom Penh: Fisheries Administration and WorldFish Cambodia.
- Koohafkan, P., and Furtado, J. (2004). “Traditional rice fish systems and globally indigenous agricultural heritage systems,” in *FAO Rice Conference*. Available online at: <http://www.fao.org/3/y5682e/y5682e0b.htm>
- Liu, Y., Duan, M., and Yu, Z. (2013). Agricultural landscapes and biodiversity in China. *Agric. Ecosyst. Environ.* 166, 46–54. doi: 10.1016/j.agee.2011.05.009
- Lu, J., and Li, X. (2006). Review of rice-fish-farming systems in China - one of the globally important ingenious agricultural heritage systems (GIAHS). *Aquaculture* 260, 106–113. doi: 10.1016/j.aquaculture.2006.05.059



- MAFF (2014). *Cambodia Climate Change Priorities Action Plan for Agriculture, Forestry and Fisheries Sector 2014–2018*. Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.
- MAFF (2017). *Annual Report of Agriculture, Forestry and Fisheries 2016–2017 and Directions 2017–2018*. Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.
- MAFF (2018). *Annual Report 2017–18 and Directions for 2018–19*. Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.
- Magrini, M.-B., Anton, M., Chardigny, J.-M., Duc, G., Duru, M., Jeuffroy, M.-H., et al. (2018). Pulses for sustainability: breaking agriculture and food sectors out of lock-in. *Front. Sustain. Food Syst.* 2, 1–17. doi: 10.3389/fsufs.2018.00064
- McCartney, M. P., Whiting, L., Makin, I., Lankford, B. A., and Ringler, C. (2019). Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries. *Mar. Freshw. Res.* 70, 1265–1273. doi: 10.1071/MF19161
- Meynard, J. M., Charrier, F., Fares, M., Le Bail, M., Magrini, M. B., Charlier, A., et al. (2018). Socio-technical lock-in hinders crop diversification in France. *Agron. Sustain. Dev.* 38:54. doi: 10.1007/s13593-018-0535-1
- Miao, W. (2010). “Recent developments in rice-fish culture in China: a holistic approach for livelihood improvement in rural areas,” in *Success stories in Asian aquaculture*, eds S. S. De Silva and F. B. Davy (Dordrecht: Springer), 15–40. doi: 10.1007/978-90-481-3087-0\_2
- Miao, W. (2016). Highlights of regional initiative for blue growth in Asia-Pacific. *FAO Aquac. Newslett.* 54, 20–21. Rome: Food and agriculture organisation of the United Nations.
- Minderhoud, P., Erkens, G., Pham, V., Bui, V., Erban, L., Kooi, H., et al. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong Delta, Vietnam. *Environ. Res. Lett.* 12:064006. doi: 10.1088/1748-9326/aa7146
- Mukherji, A., Facon, T., Burke, J., de Fraiture, C., Faurès, J., Füleki, B., et al. (2009). *Revitalizing Asia's Irrigation: To Sustainably Meet Tomorrow's Food Needs*. Colombo: International Water Management Institute; Rome: Food and Agriculture Organization of the United Nations.
- Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., et al. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health* 38, 259–277. doi: 10.1146/annurev-publhealth-031816-044356
- Nasielski, J., Kc, K. B., Johnstone, G., and Baran, E. (2016). When is a fisher (not) a fisher? Factors that influence the decision to report fishing as an occupation in rural Cambodia. *Fish. Manag. Ecol.* 23, 478–488. doi: 10.1111/fme.12187
- Nguyen Khoa, S., Lorenzen, K., Garaway, C., Chamsinhg, B., Siebert, D., and Randone, M. (2005). Impacts of irrigation on fisheries in rain-fed rice-farming landscapes. *J. Appl. Ecol.* 42, 892–900. doi: 10.1111/j.1365-2664.2005.01062.x
- Nguyen, V. K., Dumaresq, D., and Pittock, J. (2018). Impacts of rice intensification on rural households in the Mekong Delta: emerging relationships between agricultural production, wild food supply and food consumption. *Food Secur.* 10, 1615–1629. doi: 10.1007/s12571-018-0848-6
- Nguyen, V. K., Nguyen, H. H., and Cramb, R. (2020). “Trends in rice-based farming systems in the Mekong delta,” in *White Gold: The Commercialization of Rice Farming in Lower Mekong Basin*, ed R. Cramb (Singapore: Palgrave Macmillan), 347–373.
- Nhan, D. K., Trung, N. H., and Van Sanh, N. (2011). “The impact of weather variability on rice and aquaculture production in the mekong delta,” in *Environmental Change and Agricultural Sustainability in the Mekong Delta. Advances in Global Change Research*, Vol. 45, eds M. Stewart, and P. Coclanis (Dordrecht: Springer). doi: 10.1007/978-94-007-0934-8\_24
- Oo, A. T., Huylenbroeck, G., Van Huylenbroeck, G., and Speelman, S. (2018). Assessment of climate change vulnerability of farm households in Pyapon District, a delta region in Myanmar. *Int. J. Disaster Risk Reduct.* 28, 10–21. doi: 10.1016/j.ijdrr.2018.02.012
- Oo, S. M., and Mackay, K. T. (2018). Small-scale aquaculture of wild fish in Myanmar: a preliminary report from the Bago region. *Aquac. Asia Magazine* 22, 19–26.
- Pingali, P. L. (2012). Green revolution: impacts, limits, and the path ahead. *Proc. Natl. Acad. Sci. U.S.A.* 109, 12302–12308. doi: 10.1073/pnas.0912953109
- Ponte, S., Kelling, I., Jespersen, K. S., and Kruijssen, F. (2014). The blue revolution in asia: upgrading and governance in aquaculture value chains. *World Dev.* 64, 52–64. doi: 10.1016/j.worlddev.2014.05.022
- Rahman, A., Quddus, A., Pokrant, B., and Ali, M. (2006). *Shrimp Farming and Industry: Sustainability, Trade and Livelihoods*. Dhaka: Bangladesh Center for Advanced Studies and the University Press Limited.
- Raihan, M. L., Onitsuka, K., Basu, M., Shimizu, N., and Hoshino, S. (2020). Rapid emergence and increasing risks of hailstorms: A potential threat to sustainable agriculture in Northern Bangladesh. *Sustain.* 12:5011. doi: 10.3390/su12125011
- Raitzer, D., Wong, L., and Samson, J. (2015). Myanmar's agriculture sector: unlocking the potential for inclusive growth. *Asian Development Bank Economics Working Paper Series No. 470*. Available online at: <https://ssrn.com/abstract=2709353>
- Ratner, B. D., and Allison, E. H. (2012). Wealth, rights, and resilience: an agenda for governance reform in small-scale fisheries. *Dev. Policy Rev.* 30, 371–398. doi: 10.1111/j.1467-7679.2012.00581.x
- Reardon, T., and Timmer, C. P. (2014). Five inter-linked transformations in the Asian agrifood economy: food security implications. *Glob. Food Sec.* 3, 108–117. doi: 10.1016/j.gfs.2014.02.001
- RGC (2008). *Rectangular Strategy for Growth, Employment, Equity, and Efficiency*. Phnom Penh.
- Robertson, B., Young, P., Kristensen, J., Cho, K. M., Thwe, H. M., Pannchi, M., et al. (2018). *Strategic Review of Food and Nutrition Security in Myanmar: “In Support of Sustainable Development Goal (SDG) 2-Roadmap to 2030”*. Nay Pyi Taw: Myanmar Institute for Integrated Development. Available online at: <https://docs.wfp.org/api/documents/WFP-0000073885/download/> (accessed October 19, 2020).
- Ruddle, K. (1982). Traditional integrated farming systems and rural development: the example of ricefield fisheries in Southeast Asia. *Agric. Adm.* 10, 1–11. doi: 10.1016/0309-586X(82)90036-X
- Schipanski, M. E., MacDonald, G. K., Rosenzweig, S., Chappell, M. J., Bennett, E. M., Kerr, R. B., et al. (2016). Realizing resilient food systems. *Bioscience* 66, 600–610. doi: 10.1093/biosci/biw052
- Shankar, B., Halls, A., and Barr, J. (2005). The effects of surface water abstraction for rice irrigation on floodplain fish production in Bangladesh. *Int. J. Water* 3, 61–83. doi: 10.1504/IJW.2005.007159
- Sheriff, N., Joffre, O., Hong, M., Barman, B., Haque, A., Rahman, F., et al. (2010). *Community-Based Fish Culture in Seasonal Floodplains and Irrigations Systems. Challenge Programme on Water and Food (CPWF)*. Project Report, Project Number CP35, 120. Available online at: <https://www.worldfishcenter.org/content/community-based-fish-culture-seasonal-floodplains-and-irrigation-systems-0> (accessed October 19, 2020).
- Sinclair, F., and Coe, R. I. C. (2019). The options by context approach: a paradigm shift in agronomy. *Exp. Agric.* 55, 1–13. doi: 10.1017/S0014479719000139
- Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., and Harrison, R. (2019). *The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture*. Background Paper. Rotterdam; Washington, DC: Global Commission on Adaptation. Available online at: <https://cdn.gca.org/assets/2019-12/TheContributionsOfAgroecologicalApproaches.pdf> (accessed October 19, 2020).
- South China Morning Post (2020). *Drought drives Vietnam's Mekong Delta to Declare State of Emergency*. Available online at: <https://www.scmp.com/news/asia/southeast-asia/article/3074064/drought-drives-vietnams-mekong-delta-declare-state> (accessed October 19, 2020).
- Stür, W., Gray, G. D. (2015). “Livestock in smallholder farming systems of mainland Southeast Asia,” in *Trajectories of Rice-Based Farming Systems in Mainland Southeast Asia*, ed R. Cramb (Canberra, ACT: Australian Centre for International Agricultural Research), 139–188.
- Taki, Y. (1975). Fish Fauna and Inland Fisheries of the Mekong Delta. *South East Asian Stud.* 13, 146–160.
- Tezzo, X., Belton, B., Johnstone, G., and Callow, M. (2018). Myanmar's fisheries in transition: current status and opportunities for policy reform. *Mar. Policy* 97, 91–100. doi: 10.1016/j.marpol.2018.08.031
- Tezzo, X., Bush, S. R., Oosterveer, P., and Belton, B. (2020). Food system perspective on fisheries and aquaculture development in Asia. *Agric. Human Values*. doi: 10.1007/s10460-020-10037-5
- Thang, T. (2017). *Current Status of Vietnam Rice Export Quality*. Taipei: FFTC Agricultural Policy Platform. Available online at: <https://ap.fttc.org.tw/article/1204> (accessed October 19, 2020).
- Thangrak, V., Somboonsuke, B., Sdoodee, S., Darnsawasdi, R., and Voe, P. (2020). The smallholder farmers' perceptions of climate variability impact on rice



- production and the case of adaptation strategies in Banteay Meanchey, (BMC), Cambodia. *Int. J. Agric. Technol.* 16, 505–516.
- The World Bank (2017a). *Cambodia - Sustaining Strong Growth for the Benefit of All*. Available online at: <https://openknowledge.worldbank.org/handle/10986/27149#> (accessed October 19, 2020). doi: 10.1596/27149
- The World Bank, (2017b). *World Development Indicators Database*. Available online at: <https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD> (accessed October 19, 2020).
- Therond, O., Duru, M., Roger-Estrade, J., and Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. *A review. Agron. Sustain. Dev.* 37:21. doi: 10.1007/s13593-017-0429-7
- Thilsted, S. H., Thorne-Lyman, A., Webb, P., Bogard, J. R., Subasinghe, R., Phillips, M. J., et al. (2016). Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* 61, 126–131. doi: 10.1016/j.foodpol.2016.02.005
- Tilman, D. (1998). The greening of the green revolution. *Nature* 396, 211–212. doi: 10.1038/24254
- Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. doi: 10.1038/nature01014
- Tirol-Padre, A., Minamikawa, K., Tokida, T., Wassmann, R., and Yagi, K. (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis. *Soil Sci. Plant Nutr.* 64, 2–13. doi: 10.1080/00380768.2017.1409602
- Tong, Y. D. (2017). Rice intensive cropping and balanced cropping in the Mekong Delta, Vietnam — economic and ecological considerations. *Ecol. Econ.* 132, 205–212. doi: 10.1016/j.ecolecon.2016.10.013
- Toufique, K. A., and Gregory, R. (2008). Common waters and private lands: distributional impacts of floodplain aquaculture in Bangladesh. *Food Policy* 33, 587–594. doi: 10.1016/j.foodpol.2008.04.001
- Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., et al. (2014). Does aquaculture add resilience to the global food system? *Proc. Natl. Acad. Sci. U.S.A.* 111, 13257–13263. doi: 10.1073/pnas.1404067111
- UNDP (2020). *Human Development Data*. Available online at: <http://hdr.undp.org/en/data#> (accessed October 19, 2020).
- Vo, X. (1975). Rice cultivation in the Mekong Delta present situation and potentials for increased production. *Southeast Asian Stud.* 13, 88–111.
- Vu, H. (2012). *Moral Economy Meets Global Economy: Negotiating Risk, Vulnerability and Sustainable Livelihood among Shrimp Farming Households in Vietnam's Mekong Delta*. Available online at: [https://surface.syr.edu/ant\\_etd/98](https://surface.syr.edu/ant_etd/98) (accessed October 19, 2020).
- Vyas, S., Kov, P., Smets, S., and Spears, D. (2016). Disease externalities and net nutrition: evidence from changes in sanitation and child height in Cambodia, 2005–2010. *Econ. Hum. Biol.* 23, 235–245. doi: 10.1016/j.ehb.2016.10.002
- Welcomme, R., and Bartley, D. (1998). Current approaches to the enhancement of fisheries. *Fish. Manag. Ecol.* 5, 351–382. doi: 10.1046/j.1365-2400.1998.550351.x
- WHO (2016). *Global Health Observatory Data Repository/World Health Statistics*. World Bank; World Health Organization. Available online at: <https://data.worldbank.org/indicator/SH.PRG.ANEM>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4
- Wilson, S., and Wai, N. (2013). *Food and Nutrition security in Myanmar*. East Lansing: Michigan State University; Yangon: Myanmar Development Resource Institute, Centre for Economic and Social Development (MDRI-CESD).
- World Bank (2018). *Navigating Risks. Myanmar Economic Monitor*. Washington, DC: World Bank. Available online at: <http://documents1.worldbank.org/curated/en/98646154454263353/pdf/132847-REVISED-MEM-Final.pdf> (accessed October 19, 2020).
- World Bank Group (2015). *Bangladesh: More and Better Jobs to Accelerate Shared Growth and End Extreme Poverty. Systematic Country Diagnostic*. World Bank, Washington, DC. Available online at: <https://openknowledge.worldbank.org/handle/10986/23101> (accessed 19 October 2020).
- Xie, J., Hu, L., Tang, J., Wu, X., Li, N., Yuan, Y., et al. (2011). Ecological mechanisms underlying the sustainability of the agricultural heritage rice-fish coculture system. *Proc. Natl. Acad. Sci. U.S.A.* 108, E1381–E1387. doi: 10.1073/pnas.1111043108
- Zhang, D., Min, Q., Liu, M., and Cheng, S. (2012). Ecosystem service tradeoff between traditional and modern agriculture: a case study in Congjiang County, Guizhou province, China. *Front. Environ. Sci. Eng. China* 6, 743–752. doi: 10.1007/s11783-011-0385-4

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