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Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) I. Characterisation of systems

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ABSTRACT

Southeast Asian rice farmers often manage aquatic habitats and resources on their land to increase production of aquatic animals. We introduce the concept of 'farmer-managed aquatic systems' (FMAS) to capture the diversity of these resource systems at the interface of aquaculture and capture fisheries and characterize FMAS in contrasting agro-ecosystems of Cambodia, Thailand and Vietnam. Cambodian and Thai FMAS yielded primarily self-recruiting species (SRS) and were managed to allow or attract them, while Vietnamese FMAS were managed more intensively to produce mostly hatchery-reared species. More than 90% of rice farming households in the study areas of Cambodia and Thailand harvested aquatic animals from their land, and about 70% created aquatic habitats such as ponds in addition to rice fields in order to increase aquatic resource production. Cambodian households created and utilized a wide variety of man-made aquatic habitats, while Thai households created predominantly trap ponds. In contrast, less than half of Vietnamese farming households harvested SRS and very few undertook FMAS management specifically for them. Vietnamese FMAS were intensively stocked and managed as aquaculture systems, with SRS accounting for less than 30% of production. Nonetheless, SRS production per area of FMAS was comparable in the three countries. Contrasting FMAS characteristics in different study areas reflect underlying differences in agro-ecosystems, aquaculture technologies, farmer livelihoods and markets.

1. Introduction

Rice farming landscapes comprise extensive aquatic habitats that may be actively managed by farmers, at least in part, for aquatic animal production. We introduce the concept of 'farmer managed aquatic systems' (FMAS) to capture the diversity of these aquatic resource systems at the interface of aquaculture (the active rearing of aquatic animals held in private ownership) and capture fisheries (the harvesting of wild aquatic animals held in some form of common ownership). Our study aims to document and characterize the diversity of FMAS found in rice farming landscapes of mainland SE Asia. In a companion paper (Amilhat et al., companion paper II) we characterize the diversity of aquatic animals harvested from FMAS and the effects of FMAS management measures in on catch rates.

Rice farming systems and their aquatic ecosystems are among the oldest cultural landscapes, having evolved over 6000 years (Ruddle, 1982; Koohafkan and Furtado, 2004). Rice farming systems dominate land use in the lowland areas of tropical Asia, covering an area of 115 million hectares (over 50% of the continent's total wetland area of 204 million hectares; Finlayson and Spiers, 1999). About 57% of rice cultivation occurs in natural wetlands, while the remainder occurs on land that has been converted to retain rainfall and runoff (Hook, 1993). Based on their hydrology, rice fields are characterized as flood-prone (flooded from rivers and other open water bodies), rainfed (flooded by direct precipitation) or irrigated (flooded intentionally by human action).

Rainfed and flood-prone rice fields constitute temporary wetlands with many functional similarities to natural floodplains, and support diverse assemblages of wetland associated organisms (Heckman, 1979; Lawler, 2001). Rainfed and flood prone rice fields serve as important feeding and nursery areas for fish (Coche, 1967; Heckman, 1979; Little et al., 1996). Many fish species migrate into rice fields and surrounding wetland landscape during the wet season to feed and/or spawn, and return to permanent waterbodies as water levels decline (Coche, 1967; Fernando, 1993). Rice farming landscapes often support very productive fisheries, with intensive harvesting of wild fish being carried out in the rice fields, along drainage lines (the principal migratory pathways), and in natural streams and wetlands (Nguyen Khoa et al., 2005). In addition to capture fisheries, rice farming landscapes may support aquaculture systems of varying intensity such as capture-based culture of wild fish, rice–fish farming, and pond culture (Edwards et al., 1997; Halwart and Gupta, 2004; Lu and Li, 2006). In many rice farming

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landscapes, fisheries and aquaculture contribute significantly to the livelihoods of rural households (Tan et al., 1973; Garaway, 1999; Gregory and Guttman, 2002; Smith et al., 2005).

Rice farming households may engage in a diversity of linked aquatic resource management activities, ranging from aquaculture to capture fisheries with many intermediate forms. Aquatic resources research and extension however have remained fragmented along disciplinary lines between the aquaculture, fisheries, and agricultural sciences. Research on FMAS has focused on isolated, often qualitative studies of particular systems including aquaculture ponds (Edwards et al., 1997), rice–fish culture systems (Halwart and Gupta, 2004; Lu and Li, 2006), and trap ponds (Anegporn et al., 1998a,b; Pholwieng, 2001). Other studies have quantified fisheries production in rice farming landscapes without separating production from FMAS and OWB (Garaway, 2005; Nguyen Khoa et al., 2005). As a result, aquatic resource management in FMAS has generally been ignored in research on agro-ecosytems and in agricultural development policies. We aim to foster a more integrated and holistic approach to aquatic resources research in rice farming landscapes by introducing and applying the concept of 'farmer managed aquatic systems' (FMAS). FMAS are seasonal or permanent aquatic habitats such as rice fields or ponds, of which farm households have private ownership or exclusive access rights. FMAS, including farmed fish ponds, are usually, but not always situated on private farm land. By contrast, open water bodies (OWB) are those subject to public or communal ownership or access arrangements. Typically, FMAS are smaller and more intensively managed than OWB. The hydrological and ecological connectivity between FMAS and OWB varies among different landscapes, but it is often high. While aquatic animals that occur naturally in FMAS without regular stocking of hatchery-reared juveniles are referred here as 'self-recruiting-species' (SRS), animals that are regularly stocked are referred to as 'cultured species' (CS).

Understanding the ecology and management of FMAS is important because of their role in food production and income generation, as well as their potentially significant role in sustaining key ecosystem services and aquatic biodiversity in rice farming landscapes. Active management of FMAS for aquatic resources has the potential to enhance production of SRS and/or CS. Identifying management practices that are effective within particular types of FMAS therefore is an important topic for research and extension. Moreover, FMAS are intimately linked to the agricultural landscape and influenced by farming practices. Intensification of rice farming practices with irrigation and increased use of agrochemicals may be expected to interact with aquatic resource diversity and productivity in FMAS (Tilman et al., 2002; Lorenzen et al., 2007). Characterising FMAS, documenting their value, and exploring their linkages with the wider agroecosystem therefore is another research and extension priority.

Our study aimed to investigating the characteristics and importance of FMAS in selected areas of three Southeast Asian rice farming countries: southern Cambodia, northeast Thailand, and northern Vietnam. Using a consistent research framework in these contrasting regions, we derive an empirical typology of FMAS and elucidate how FMAS characterstics are influenced by their ecological and socio-economic context. Further details on FMAS management measures and their effectiveness are provided in a companion paper (Amilhat et al., Companion paper II).

2. Methodology

The research was designed as a nested observational study, covering over 500 farming households in eighteen villages, nested in six provinces within three countries. Surveys were carried out to quantify FMAS characteristics, management and aquatic animal production. Targeted selection of countries, provinces and villages was used so as to provide contrast in ecological, technological and socio-economic conditions.

2.1. Site selection and description

The study was carried out from May 2001 to May 2003 in rural areas of southern Cambodia, northeast Thailand and northern Vietnam (Table 1). In the study area, the climate is tropical with an average daily temperature of 27 °C and an average annual precipitation of 1500 mm, about 75% of which occurs in the monsoon season (May to October). Rice is the dominant agricultural crop. Cambodia has the lowest population density of the three countries, about half that of Thailand and less than a quarter that of Vietnam. Cambodia is also the poorest country in terms of per capita GDP and the proportion of the population that is undernourished. Thailand boasts by far the highest per capita GDP, but a greater proportion of undernourished people than Vietnam. The countries thus offer great contrast in terms of population density and development indicators. Rice farming dominates the landscapes of all study areas. The intensity of rice farming as indicated by yields and degree of irrigation development is lowest in Cambodia, intermediate in Thailand and very high on Vietnam.

Within the three countries, two provinces (or group of provinces for Thailand) each (one upland and one lowland) were selected for study (Table 1). The upland provinces consistently were characterized by a smaller area of perennial water bodies, and a lower occurrence of regular flooding than the lowland provinces in the same countries. Rice farming in the Cambodian and Thai study sites was predominantly rainfed (sometimes with small-scale supplementary irrigation), while farming in the Vietnamese sites was mostly

Table 1
Characteristics of study countries and regions.

	Cambodia		Thailand		Vietnam	
Area	181,035 km^2		514,000 km^2		331,000 km^2	
Total population in 2004	13.8 million		63.7 million		83.1 million	
Population density (no./km^2)	55.25		117.3		228.2	
Population living below the poverty line 1990–2003 (World Bank, 2006)	35.9%		13.1%		28.9%	
Gross domestic product (GDP) per capita in 2004 (in US$) (World Bank, 2006)	2423		8090		2745	
People undernourished (% of total population) 2001–2003 (World Bank, 2006)	33%		21%		17%	
Estimated indicative figures of inland capture fisheries (1000 tons) for 1999 (Coates, 2002)	290–430		350–800		600–800	
Average rice yield (t/ha) (IRRI 2002)	1.9		2.3		4.1	
Rice land irrigated (%) (IIRI 2002)	1		23		54	
Provinces	Svay Rieng	Takeo	Roi-Et/Yasothon	Sisaket	Hanoi	Phu Xuyen
Type of land	Low land	Up land	Low land	Up land	Low land	Up land
Irrigation development	Low	Low	Low	Low	High	High
Average perennial water body area in the study villages (ha)	128.6	7.7	164.6	36.5	10.5	2.9
Proportion of households reporting FMAS regularly flooded (%).	99	9	73	37	38[a]	3

[a] Limited to near river locations.

irrigated. Consequently, agricultural activities in the Cambodian and Thai sites were highly dependent on the monsoon cycle and only one rice crop was grown per year, while farmers in the Vietnamese sites tended to grow two or three crops per year.

Three villages in each province were selected based on the presence of water resources, the level of economic development and village population size. Districts were selected based on their physical geography. A transect line was then drawn on a map traversing the upland and lowland area of the district. Sets of villages were then identified from the three parts of the line, and the final selection made on the basis of the above criteria.

For simplicity, we refer to the study sites within countries by the respective country names. This is not meant to imply that the sites are representative of the respective countries as a whole. Indeed, all three countries cover a variety of different rice agro-ecosystems and our study covers only some of these. The aim was to explore FMAS under contrasting agro-ecological and socio-economic conditions rather than to provide a comprehensive survey.

2.2. Exploratory research

Exploratory research was conducted in all study areas in order to gain a preliminary understanding of FMAS and their local ecological and socio-economic context. This information was used in the design of quantitative surveys, ensuring that surveys captured all aspects relevant to characterising the diverse FMAS. The broad, qualitative understanding of FMAS and their context gained from exploratory research also aided the interpretation of quantitative survey results (e.g. in Section 4.1). Exploratory research was conducted between May and September 2001, using the framework of participatory rural appraisal (PRA) with specific tools including semi-structured interviews and various mapping and scoring techniques (Townsley, 1996).

2.3. Survey data collection

Data collection was carried out through two surveys: an initial baseline survey for FMAS system characterisation, and a subsequent one-year monitoring survey to estimate inputs and outputs of FMAS. The same standardised methods were used throughout all study sites. The surveys were designed and pre-tested by the project team, and all interviews were carried by local teams of native speakers.

During the baseline survey (September to December 2001), thirty households were surveyed per village. Information was collected on type and surface area of FMAS, on management practices, and on the presence of self-recruiting-species. To ensure adequate representation of all the types of FMAS, stratified sampling was used in villages where less than half of all households were considered to be engaged in aquaculture (defined to farmers as ‘the activity of stocking hatchery fish in their aquatic systems’). In such villages, 20 households were selected at random from the village list and 10 were chosen at random from a list of farmers engaged in aquaculture. If more than 50% of the households practiced aquaculture, all households were chosen randomly from the village list. Only the households selected at random from the village list were included in analyses of system characteristics and distribution. Households sampled specifically from the aquaculture stratum were used only in the analysis of aquaculture practices. The number of households selected at random represented between 10% and 40% of the total number of households in each village. A total of 529 households were surveyed during the baseline survey.

The monitoring survey was conducted in the same villages covered in the baseline survey, over a period of 13 months from February 2002 to April 2003. Nine households per village were selected for monitoring, from the sample of households covered on the baseline surveys. Targeted selection was employed to identify households for the monitoring survey to ensure representation of different system types, household socio-economic status, and leadership structures. As far as possible, the proportional distribution of FMAS types found in the random sample was maintained. In Vietnam, households with ponds were intentionally overrepresented in the sample, as most households only had rice fields and a random sample would have provided little information on households with other FMAS. This was accounted for in subsequent analyses. Data on farming, fishing, consumption, income and expenditure, and resource use were collected. Information on fishing (species, size, number, catch and effort data) were collected with a one-week recall. Visual aids such as sticks and bowls of different sizes were used to aid recall (Garaway, 1999). All monetary values were converted to US Dollars using average exchange rates during the monitoring period (when 1 US$ was equivalent to 3990 Cambodian Riel, 42 Thai Baht, and 15,300 Vietnamese Dong).

2.4. Statistical analysis

We used a nested general linear model (GLM) to reflect the natural clusters within the data set at three different hierarchical levels: country, province and village; and to determine which factors are important in determining the magnitude of the dependant variable (Crawley, 1993). The data were analysed using the SPSS package for windows, version 12. The distributions of total surface area for each system and of the household catch were positively skewed, therefore data were log-transformed before being analysed. The association between the villages and system-categories was explored for each country separately using Chi-square tests. To fulfil the test assumptions (less than 20% of the expected count <5) we had to combine the different types of ponds. Three villages responsible for low counts were removed from this particular analysis. Yangnoi (Thailand) and Svay Cheak (Cambodia) contained only farmers with ponds, whereas Hoang Nguyen (Vietnam) contained only farmers without ponds. To test whether removing the three villages influences the results, we ran a Fisher's exact test. All tests were regarded as statistically significant at $p<0.05$.

3. Results

3.1. Types of FMAS

Five different types of FMAS were identified: rice fields (RF) and 4 types of ponds characterized as household ponds (HP), ponds in rice fields (PRF), ponds in lakes (PL), and bid-rent ponds (BRP). This typology represents a consistent generalisation of traditional, local classifications, based on location, physical characteristics and primary purpose of FMAS. Access to aquatic animals in rice fields is often open to all, unless the household owning the rice fields has taken measures aimed at enhancing aquatic animal production within them (e.g. by constructing a linked pond). Access to animals in all other FMAS is always restricted.

Rice fields are shallow man-made wetlands used primarily for growing rice (Fig. 1a). Rice field area per household was much larger in Cambodia and Thailand than in Vietnam (GLM, $p<0.05$), and consistently larger in lowland as compared to upland areas (Table 2) (GLM, $p<0.05$). Rainfed and flood-prone rice fields are designed to retain sufficient water for a full cropping cycle, maintaining water levels of 20–50 cm over several months and thus offering good seasonal habitat for fish and other aquatic animals. Rice fields in irrigated areas often retain only low water levels (less than 10 cm, replenished by regular irrigation inflows) and provide less suitable habitat for truly aquatic organisms.

Household ponds (Fig. 1b and c) are closed or open ponds located near the main dwelling, and are commonly used for water supply and/or aquaculture. Within, our study areas, household ponds were found only in Cambodia and in Vietnam (but such ponds are known to exist in other areas of Thailand). Household ponds are usually perennial, with steep sides, so that their area does not vary much over the seasons. Cambodian household ponds served multiple purposes, were

Fig. 1. Farmer managed aquatic systems (FMAS): (a) rice fields, Vietnam; (b) household pond, Vietnam; (c) household pond (with latrine), Cambodia; (d) pond in rice field, Thailand; (e) ponds in lake, Cambodia; and (f) bid rent pond (with brush park), Vietnam. (Photos by E.J. Morales and E. Amilhat).

typically open to the wider aquatic environment and thus sustained or trapped wild aquatic animals. Cambodians distinguish between two types of household ponds: larger 'ponds' and small 'ditches'. Vietnamese household ponds were on average larger than those found in Cambodia (GLM, $p<0.05$), closed to the wider aquatic environment, and used intensively for aquaculture of CS.

Ponds in rice fields (Fig. 1d) tend to be open to the rice field and are used primarily for trapping wild fish ('trap ponds'), but may also be used for aquaculture with hatchery fish. Often these ponds have features designed to facilitate entry of fish from rice fields, such as connected ditches along the side if the field. Such ponds were found only in Cambodia and in Thailand.

Ponds in lakes (Fig. 1e) are situated in lakes, typically on public land. These ponds tend to be submerged in the lake during the monsoon season, but become distinct during the dry season. They serve as trap and/or culture ponds for fish. These ponds were found only in Cambodia. The right of local households to construct ponds at the fringe of public water bodies is based on traditional custom. The investment of building the pond is deemed to confer exclusive rights to the aquatic resources within it.

Table 2
Average area (with 95% CI) of different FMAS types, per household owning each type.

Country	Zone	Rice field (ha)	Household pond (ha)	Pond in rice field (ha)	Pond in the lake (ha)	Bid rent pond (ha)
Cambodia	L	1.63 [1.40–1.90]	Pond 0.0065[0.0053–0.0081] Ditch 0.0051 [0.0042–0.0061]	0.0052 [0.0030–0.0091]	0.0046 [0.0036–0.0058]	n/a
	U	0.64 [0.49–0.82]	0.0203 [0.0109–0.0378]	0.048 [0.028–0.84]	0.0090 [0.0047–0.0171]	n/a
Thailand	L	3.32 [2.79–3.94]	n/a	0.0099 [0.0064–0.015]	n/a	n/a
	U	1.86 [1.54–2.25]	n/a	0.0062 [0.0036–0.011]	n/a	n/a
Vietnam	L	0.27[0.22–0.32]	0.027 [0.022–0.033]	n/a	n/a	0.300
	U	0.15 [0.13–0.18]	0.0223 [0.013–0.038]	n/a	n/a	

Agroecological zones: U (upland), L (lowland).

Bid-rent ponds (BRP) are large ponds on public land (Fig. 1f) that can be rented by farmers or groups of farmers, and are used for aquaculture. These ponds were found only in Vietnam in our study, but are known to be present (if uncommon) in the other study countries. Access to aquatic resources in bed rent ponds is exclusive to the person or group renting the pond.

The average surface areas of different FMAS types are given in Table 2. Overall, rice fields dominated FMAS areas, except in households that have acquired large bid-rent ponds (Vietnamese lowland only). Virtually all FMAS were constructed with steep banks and flat bottoms so that water areas did not change continuously over the seasons but rather, the whole system tended to be either flooded or dry. Rainfed rice fields (found mostly in Cambodia and Thailand in our study) were under water during the wet season but dry for the rest of the year, while irrigated rice fields (found mostly in Vietnam) were under water for multiple crop cycles throughout the year with intermittent, short dry periods. Household ponds and ponds in rice fields typically held water year-round, but ponds in rice fields were often drained intentionally to harvest fish.

3.2. FMAS combinations

Many farmers had access to more than one FMAS, and the combinations of FMAS varied greatly among countries. To examine these combinations (Table 3), farmers were allocated to one of the following categories: rice fields only (RF), rice fields and household ponds (RF + HP), rice fields and ponds in rice fields (RF + PRF), rice fields and other ponds (RF + OP), or rice fields, household ponds and other ponds (RF + HP + OP). The term ‘other ponds’ is used here for any ponds other than household ponds in Cambodia, and for bid-rent ponds in Vietnam.

Cambodia showed by far the greatest diversity of FMAS combinations, and distribution of combinations differed significantly (χ^2, $p<0.01$) between the upland and lowland provinces. A combination of rice field, household pond and another pond (RF + HP + OP) was the most prevalent in lowland Cambodia, followed by rice field and household pond only (RF + HP). In upland Cambodia, rice field only was the most common category, followed by rice field and other pond (mostly, pond in the lake). In Thailand, most farmers had combined rice fields and trap ponds (RF + PRF), but some had rice fields only. In Vietnam, most farmers had only rice fields but some also had a household pond. FMAS combinations did not differ significantly between upland and lowland provinces in either Thailand or Vietnam (χ^2, $p>0.05$).

3.3. FMAS management and the role of self-recruiting species

While all types of FMAS contributed to aquatic animal harvest, active management to enhance aquatic animal production was carried out only in ponds but not in rice fields. Active management measures included modifications of pond depth and construction of dikes; water management; screening on the pond to keep animals in or out; feeding, fertilisation, stocking of hatchery-bred fish; pond preparation (draining and application of lime and/or piscicides); clearing macrophytes and treatment of fish diseases. Between 53 and 92% of the farmers with ponds practiced at least one activity to enhance aquatic animal production. The particular management measures used at different locations reflect local agro-ecological and socio-economic conditions and the farmer's attitude towards self-recruiting (SRS) and stocked hatchery (CS) aquatic animals. Further details of management measures and their effectiveness are provided in Amilhat et al. (companion paper II).

Attitudes towards SRS in FMAS fall within three broad categories. Some farmers took positive measures to allow or attract SRS into their FMAS. Others sought to prevent access for SRS, or actively eliminated them. Finally, some farmers did not manage SRS at all. In Cambodia and in Thailand the majority (more than 80%) of farmers allowed and attracted SRS in their FMAS (Fig. 2). In Vietnam on the other hand, only 25% of farmers did so while 38% excluded or eliminate SRS. This reflects a focus of Vietnamese farmers on aquaculture using CS. In Cambodia and Thailand, farmers saw management for SRS and more intensive aquaculture practices including use of CS as a continuum rather than a dichotomy, and often ‘mixed and matched’ management measures according to the local conditions prevailing at the time.

Less than 30% of Cambodian and 40% of Thai households stocked CS in their ponds. By contrast, all Vietnamese farmers with ponds did stock CS. The main species stocked in Cambodia were Pangasiid catfish (*Pangasius* spp.) and Nile tilapia (*Oreochromis niloticus*). In northeast Thailand, silver barb *Barbonymus gonionotus*, Nile tilapia *O. niloticus*, the African walking catfish *Clarias gariepinus* and common carp *Cyprinus carpio* were the most commonly stocked species. In the study sites in Vietnam, polyculture of major carps was the dominant

Table 3
Proportion of different FMAS combinations found in the study villages.

Country	Province	Village	Perennial water bodies area (ha)	FMAS combinations (%)					
				RF	RF + HP	RF + PRF	RF + OP	RF + HP + OP	At least one pond
Cambodia	Svay Rieng	Prey Sokrum	0.09	3	7	14	0	76	97
	(L)	Sv Cheak	252.67	0	33	0	10	57	100
		Thom	15.81	4	32	0	8	56	96
		Trapieng D	245.99	4	33	0	0	63	96
	Takeo	Angtason	15.11	15	54	7	4	32	46
	(U)	Prey Tadok	0.26	12	48	24	0	28	52
Thailand	Yasothon/	Kudlod	11.50	20	0	80	0	0	80
	Roi Et	Siangam	476.72	53	0	47	0	0	47
	(L)	Yang Noi	5.44	0	0	100	0	0	100
	Sisaket	Samoe chai	0.86	33	0	67	0	0	67
	(U)	Lumpoo	93.33	25	0	75	0	0	75
		Nong Weang	15.40	44	0	56	0	0	56
Vietnam	Hanoi	Cong Hoa	14.20	65	35	0	0	0	35
	(L)	Phu Cuong	14.72	65	35	0	0	0	35
		Yen Tang	2.52	81	19	0	0	0	19
	Phu Xuyen	Hoang Nguyen	0.94	100	0	0	0	0	0
	(U)	Trai	0.47	89	6	0	6	0	11
		Cham Ha	7.29	65	30	0	5	0	35

RF = rice field, HP = household pond, PRF = pond in the rice field, OP = pond in the rice field, in the lake or both in Cambodia and OP = bid rent pond in Vietnam. Provinces are characterised as lowland (L) or upland (U) topography.

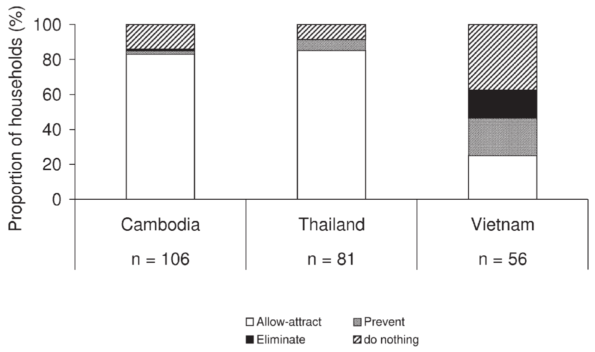

Fig. 2. Attitude and management actions towards SRS of farmers with ponds. *n* is the number of random households interviewed.

form of pond culture, based primarily on mud carp *Cirrhinus molitorella*, silver carp *Hypophthalmus molitrix*, grass carp *Ctenopharyngodon idella*, and common carp *C. carpio*.

3.4. Aquatic animal harvest from FMAS

Participation in aquatic animal harvest was near-ubiquitous in Cambodia (98% of households), Thailand (100%) and Vietnam (85%). A wide range of harvesting methods were employed including cast and lift nets, draining, collection by hand, baited hooks, gill nets, traps and harpoons. Catches of SRS and CS in FMAS, and of wild fish in open water bodies are shown in Fig. 3. Catches of aquatic animals varied among countries and provinces in both, overall magnitude and source. Catches were dominated by wild aquatic animals (SRS from FMAS and wild animals from OWB) in Cambodia and Thailand (GLM, $p<0.05$), and higher on average in the lowlands than in the uplands (though the difference was significant only in Cambodia: GLM, $p<0.05$). Catches in Vietnam were strongly dominated by cultured fish from FMAS, and higher in the upland than in the lowland area (GLM, $p<0.05$). In all three locations, catches of wild aquatic animals were significantly higher in FMAS than in open waters (GLM, $p<0.05$).

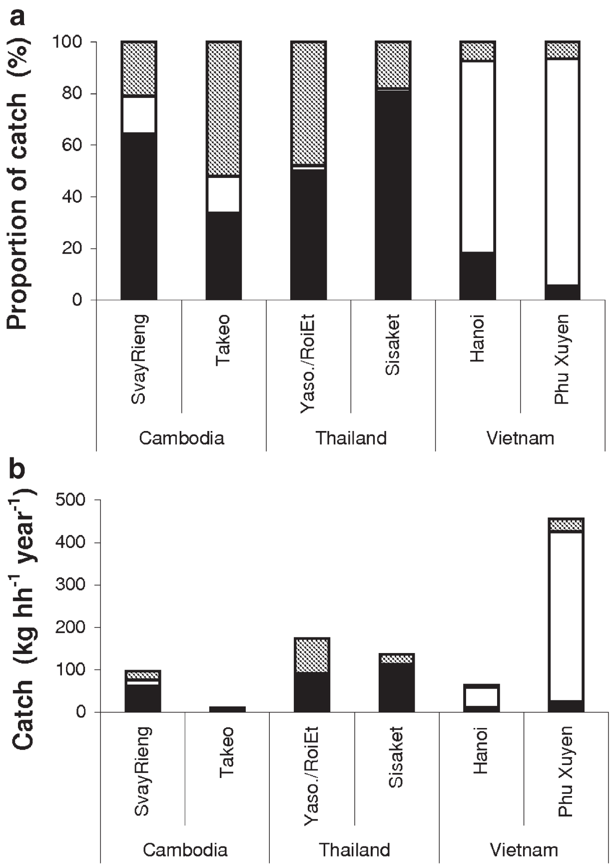

Fig. 3. Average catch per household per year showing proportions (a) and absolute weight (b) of SRS (black) and stocked species (white) from FMAS, as well as wild fish caught in open waters (grey).

3.5. Use of the catch

Most of the households in Cambodia and Thailand retained their aquatic animal catch for home consumption. When catches exceeded own consumption, Cambodian households tended to sell the surplus while Thai households tended to preserve the catch for later consumption or make gifts. In Vietnam, selling of aquatic animals was more common and households with aquaculture ponds in particular sold a large share of their catch.

3.6. Economic value and per-area productivity of SRS from FMAS

SRS production from FMAS is the least well documented and valued aspect of aquatic resource management in rice farming landscapes. In order to explore the economic importance of SRS production, the average value of SRS catch was compared to the average value of rice production on a per-household basis (Table 4). The average net income from rice cultivation was estimated by the farmers monitored to be 88 USD and 194 USD in Takeo and Svay Rieng Provinces of Cambodia respectively, 660 USD in Thailand, and 260 USD in Vietnam. The average market value of aquatic animals was 0.6 USD/kg in Thailand, 0.4 USD/kg in Vietnam and 0.7 USD/kg in Cambodia. SRS represent on average about 10% of the value of the rice crop for households in Cambodia and Thailand, but only about 3% in Vietnam. The per-area productivity of SRS from FMAS ranged from 5 to 151 kg $ha^{-1}year^{-1}$ with an overall average of 56 kg $ha^{-1}year^{-1}$. While Vietnamese FMAS produce comparatively low SRS catches on a per-household basis, this reflects small landholdings rather than low per-area SRS productivity of FMAS.

4. Discussion and conclusions

4.1. Characteristics of FMAS in the study region

Our study provides the first broad-based, systematic documentation and characterisation of FMAS and aquatic resource production within them in Southeast Asian rice farming landscapes. We now synthesize information reported here and in our companion paper (Amilhat et al., companion paper II), together with contextual information obtained from our exploratory research, to characterise different FMAS within their local and national context. In doing so we consider the role of physical habitat, wild aquatic animal species and their biology, aquaculture technology, market attributes, and farmer livelihood strategies within an integrative systems perspective (Edwards et al., 1997; Lorenzen, 2008).

Cambodia boasted the greatest diversity of FMAS in terms of physical characteristics and the combinations of systems on a household basis. The systems were geared towards the production of SRS as well as CS and combined both traditional and modified elements (cf. Edwards et al., 1997). Management actions were diverse, including drying and deepening the pond, construction of brush parks, stocking of CS, and feeding, but only construction of brush parks was found to increase catch rates significantly (Amilhat et al., companion paper II). The Cambodian FMAS operated in a context of low population density and largely rainfed, low external input rice farming systems. Access to markets and off-farm employment was limited. Cambodian FMAS

Table 4
Mean SRS catch per household and per area of FMAS and its market value.

Countries	Provinces	Mean SRS catch per household (kg hh^{-1} $year^{-1}$)	Value of SRS catch (USD hh^{-1} $year^{-1}$)	Value of SRS compared to rice crop (%)	Mean FMAS area (ha)	Mean SRS catch per FMAS area (kg ha^{-1} $year^{-1}$)
Cambodia	Svay Rieng (L)	64.7 [46.2–90.5]	45.29	23	1.62	40
	Takeo (U)	3.1 [1.0–7.2]	2.17	2	0.66	5
Thailand	Yasothon (L)	80.1 [43.7–146.4]	48.06	7	3.13	26
	Sisaket (U)	114.5 [71.9–182.0]	68.7	10	1.75	65
Vietnam	Hanoi (L)	14.2 [5.4–35.6]	5.68	2	0.27	52
	Phu Xuyen (U)	24.2 [7.9–95.7]	11.36	4	0.16	151

formed a flexible part of diversified semi-subsistence livelihoods geared towards making the best use of local resources and household assets (cf. Smith et al., 2005).

In the Thai study area, FMAS diversity was low and dominated by the rice field–trap pond combination. The ricefield–trap pond system is a traditional form of SRS aquaculture that has equivalents on a larger scale in many river–floodplain fisheries (Welcomme, 1985; Edwards et al., 1997). Thai FMAS were carefully designed exploit ecology and movement behaviour of key SRS, particularly the snakehead *Channa striata* (Amilhat and Lorenzen, 2005). CS were sometimes stocked, but account for only a very small proportion of the catch. The diversity of management actions practised in this system was low, involving primarily the construction of brush parks, fertilisation and some feeding. Only fertilisation was found to have a significant effect on aquatic animal catch rates (Amilhat et al., companion paper II). FMAS in the Thai study area operated in the context of marginal, rainfed rice farming within an advanced economy where off-farm employment was widely available and FMAS management was geared towards providing high returns to low investment of labour and caopital. In addition, wild fish were preferred to cultured fish in Thailand and achieved better prices when sold. In socio-economic terms, the Thai FMAS form a fairly well-defined part of diversified accumulation livelihoods (cf. Smith et al., 2005).

In the study area in Vietnam, FMAS were limited to rice fields or intensive aquaculture ponds. Rice fields were mostly irrigated and farmed with high levels of external inputs. Pond management involved stocking of CS, feeding, fertilisation and pond preparation methods aimed *inter alia* at eliminating wild fish. Aquatic animal harvests were dominated by CS and FMAS management was focused on integrated polyculture of major carps (Edwards et al., 1997; Michielsens et al., 2002). Despite this, Vietnamese FMAS supported per-area levels of SRS production even higher than those found in Cambodia or Thailand. However, due to the small land holdings and high levels of agricultural and aquaculture production, SRS made only a marginal contribution to average household income. High population density has forced intensification of both agriculture and aquaculture to generate high levels of production from small holdings of land and FMAS. Vietnamese FMAS formed part of specialised, rural accumulation livelihoods (cf. Smith et al., 2005).

The limited spatial coverage of our surveys within countries, combined with a poor information base on inland fisheries statistics in general, make it difficult estimate the contribution of FMAS to national fisheries production. However, we note that participation in aquatic animal harvesting was very common among the households surveyed and that FMAS were the source of 50–90% of household catches. This suggests a major role of FMAS in the supply of aquatic animal protein to rural households throughout the inland areas of the region.

4.2. Utility of the FMAS concept for bridging the gap between aquaculture and fisheries

Farming households throughout the study area engaged in a wide range of aquatic resource management activities including various forms of aquaculture (active husbandry of stocks held in private ownership) and capture fisheries (harvesting of stocks held in public or communal ownership). Active management of FMAS for aquatic resource production constitutes aquaculture because it involves both active husbandry and private ownership which is traditionally accorded to owners who undertake active aquatic animal husbandry in FMAS. Such active management involved stocking of hatchery-produced fish seed, stocking of wild caught fish seed (e.g. of Pangasiid catfish in Cambodia, Poulsen et al., 2008), and husbandry of self-recruiting species. Where FMAS were not actively managed for aquatic animal production, access to resources within them was regarded as open and harvests of such animals therefore constitutes a form of capture fisheries (Nguyen Khoa et al., 2005). Many farming households also engaged in capture and culture-based fisheries in open water bodies (Lorenzen et al., 1998a,b; Nguyen Khoa et al., 2005). In rural SE Asia, aquaculture and capture fisheries are not dichotomous but form a continuum in which a diversity of pure and intermediate forms are practiced in a locally adapted and flexible manner. As out study shows, FMAS play a key role in aquatic resource production and, being under the control of individual households, offer excellent opportunities for active management. Using the holistic FMAS concept to frame our study has helped to capture the full diversity of farmer managed systems, characterize previously overlooked aspects such as the widespread active management of SRS, and identify effective management measures for different FMAS types (Amilhat et al., companion paper II). We suggest that the FMAS concept provides a suitable framework for aquatic resources research and extension in rice farming landscapes, helping to bridge the disciplinary gap between aquaculture and fisheries science.

4.3. FMAS in rice agro-ecosystems

Throughout the study areas, FMAS were closely integrated within the local rice agro-ecosystems. Rice fields themselves were the largest FMAS by area, with rainfed and flood-prone rice fields being deep flooded and supporting a high level of natural aquatic animal production during the monsoon. Construction of ponds in rice fields serves to concentrate aquatic animals within them and extend their availability into the dry season. Recruitment of SRS into rice fields and associated ponds may be partly autochthonous (based on animals retained in ponds or surviving in mud during the dry season), but in most cases is likely to rely strongly on immigration of animals from permanent water bodies during the monsoon. The aquatic resource ecology of rainfed and flood-prone rice fields and associated ponds is thus closely linked to the monsoon cycle. Household ponds serve water storage and/or culture of hatchery-bred fish, and are more separate from the rice agro-ecosystem. However, such ponds may still receive substantial recruitment of SRS during the monsoon when the landscape is dominated by aquatic habitats. Similar levels of per-area SRS production (5 to 151 kg ha^{-1} $year^{-1}$ with an overall average of 56 kg ha^{-1} $year^{-1}$) were achieved in FMAS managed at very different levels of overall intensity. A very similar average level of wild fish production (60 kg ha^{-1} $year^{-1}$) has been reported from Lao rice farming landscapes where there was no active management of FMAS for aquatic animals (Nguyen Khoa et al., 2005). This suggests a fairly consistent base level of wild aquatic animal production in rice farming landscapes, which is strongly reliant on natural processes but may be influenced by active management practices (Amilhat et al., companion paper II). The high level of SRS production found in Vietnamese FMAS, despite intensive shallow-water rice production and pond management measures designed to exclude and eliminate SRS, may reflect a high contribution of non-fish SRS (see Amilhat et al., companion paper II), almost year-round water availability in rice fields and high external inputs that raise overall productivity and also benefit SRS. The overall picture thus suggests that SRS production may be fairly resilient to changes in aquaculture or agricultural practices within rice agroecosystems.

Our study shows that active management of FMAS for aquatic animals through traditional and modified practices is an integrated part of many rice agro-ecosystems. Aquatic animal production from FMAS can play an important role in the livelihoods of rice farming households, contributing to nutrition, cash income, and social networking. SRS production from FMAS was valued at between 2% and 23% of the value of the rice crop. Higher values may be realized where production is intensified, including the stocking of CS, but this also tends to raise production costs. In addition to their direct use value, aquatic animals in FMAS are likely to provide valuable ecosystem services, particularly with respect to pest control (Frei and Becker, 2005). Finally, FMAS may support aquatic biodiversity conservation at the landscape level by increasing overall habitat area and providing a high-quality matrix that permits movement of organisms between natural water bodies (Rosenzweig, 2003; Perfecto and Vandermeer, 2008). FMAS should receive greater attention in the science and practical application of agroecology, which has traditionally focused almost exclusively on terrestrial components of agroecosystems (Altieri, 2002).

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