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Impacts of irrigation on fisheries in rain-fed rice-farming landscapes

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Summary

1. Expanding irrigation development threatens the productive and diverse fisheries of rain-fed rice-farming landscapes. Environmental management of irrigation can minimize negative impacts on fisheries, but its effectiveness is constrained by a lack of reliable information on the nature and magnitude of impacts.

2. To quantify the impacts of small- to medium-scale irrigation schemes on aquatic habitat availability, fish catches, species richness and ecological composition of fish assemblages in these landscapes, we conducted a field study in Laos. The observational study was replicated at irrigation scheme level, covering 10 weir and 10 dam irrigation schemes paired with non-impacted control sites.

3. Weir schemes had no significant impact on aquatic habitat, but caused a significant decline (–36%) in fish catches that was only partly explained by a reduction in fishing effort. Weirs had no effect on species richness, but were associated with a significant increase (+17%) in the relative abundance of omnivores.

4. Dam irrigation schemes significantly reduced riverine habitat area, and increased lacustrine and dry-season rice-field areas. Dams led to a marked redistribution of catch and fishing effort from non-reservoir habitats into reservoirs, but no overall change in catch or effort occurred. The redistribution reflected a response to fishing opportunities in the reservoir, rather than a loss of productivity in non-reservoir habitats. No significant impacts were detected on fish species richness or the relative abundance of functional feeding groups.

5. Overall impacts of irrigation on fisheries were related mostly to changes in fishing effort, rather than ecological effects on the resources. The unexpectedly moderate level of ecological impacts may reflect compensatory effects at the landscape level and the fact that rice fields, which dominated the wet-season habitat, continued to be managed as rain-fed deep-water systems even where dry-season irrigation had been developed.

6. *Synthesis and applications.* Small- to medium-scale irrigation schemes in rain-fed rice-farming landscapes have only moderate impacts on fisheries, which remain productive and diverse. Changes in agricultural practices in the wet season are likely to have greater effects on fisheries than dry-season irrigation.

Key-words: freshwater fisheries, impact assessment, irrigation impacts, Laos, rice agriculture

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Introduction

Freshwater ecosystems often support important subsistence, commercial and recreational fisheries (Arthington *et al.* 2004). Irrigated agriculture accounts for a large share of freshwater use by humans (de Fraiture *et al.*

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2001), and is widely regarded as a major cause of degradation of freshwater ecosystems and fisheries (Petr & Mitrofanov 1998; Dudgeon 2000; Lemly, Kingsford & Thompson 2000). Irrigation development may impact on their productivity and diversity through hydrological modifications (storage, abstraction and loss to evapotranspiration of river flows), modification of habitat connectivity by dams and canals, in-filling or drainage of wetlands in irrigated areas, and pollution of drainage water (Roggeri 1995; Petr & Mitrofanov 1998; Molden & Sakthivadivel 1999; Lemly, Kingsford & Thompson 2000). Freshwater fisheries are also impacted by irrigation indirectly as a consequence of changing local economic conditions and thus incentives for fishing (Smith, Lorenzen & Nguyen Khoa, in press).

The multitude and complexity of the above mechanisms make it difficult to predict overall impacts of irrigation and to identify effective mitigation or compensation measures. There is a dearth of rigorous and quantitative assessments to guide conservation, rehabilitation and compensation measures (Ormerod 2003; Pretty *et al*. 2003; Gillian *et al*. 2005; Lepori, Palm & Malmquist 2005; Palmer *et al*. 2005). Instream flow assessments (Bunn & Arthington 2003) are increasingly used to gauge impacts of abstractions, but they capture only part of the habitats that support aquatic ecosystems and fisheries (Lorenzen *et al*. 1998; Williams *et al*. 2003) and the processes impacting on them (Lemly, Kingsford & Thompson 2000). There is thus an urgent need for more integrated, landscape-level assessments to support conservation and management of aquatic ecosystems and fisheries within agricultural landscapes.

Rain-fed rice-farming landscapes constitute major human-made wetlands, which dominate land use in the lowland areas of tropical Asia. Asian rice fields cover an area of 115 million ha, more than 50% of the continent's total wetland area (Finlayson & Spiers 1999; Koohafkan & Furtado 2004). About 57% of rice cultivation occurs within natural wetland areas, while the remainder occurs on land that has been converted to retain rainfall and runoff (Hook 1993). Rain-fed and flood-prone rice fields are temporary wetlands with many functional similarities to natural floodplains. They support diverse assemblages of wetland-associated organisms, and serve as important feeding and nursery areas for fish (Coche 1967; Heckman 1974, 1979; Little, Surintaraseree & Innes Taylor 1996; Lawler 2001). Many fish species migrate into rice fields at the beginning of the wet season and return to permanent waterbodies as water levels decline (Coche 1967; Fernando 1993; Meusch 1996). Rice-farming landscapes often support very productive fisheries in the rice fields, along drainage lines (the principal migratory pathways) and in natural streams and wetlands, contributing significantly to the livelihoods of rural households (Tan *et al*. 1973; Garaway 1999; Gregory & Guttmann 2002).

Rain-fed rice farming systems in monsoonal Asia are limited to a single wet season crop per year, which may be lost in very dry years. Irrigation development may allow a second crop of rice (or another field crop) or at least secure a single crop in dry years. Many irrigated rice systems are supplied by small- to medium-scale weir or dam schemes. Weirs are relatively low structures that divert water but do not create a storage reservoir. They are used mostly for supplemental irrigation in primarily rain-fed cropping systems. Abstracting water towards the end of the wet season tends to exacerbate the natural seasonality of river flows. Dam schemes create reservoirs and involve storage of wet-season flows for dry-season irrigation, thus tend to attenuate natural flow patterns, retaining a large share of peak flows while increasing dry-season flows through drainage returns and seepage. Significant modifications in river flow patterns inevitably affect fish ecology and fisheries within the impacted river (Bunn & Arthington 2003). In addition, availability of irrigation water may lead to changes in land and water use. By reducing the need to store water in the rice field itself, irrigation allows intensification, including use of higher yielding shallow-water rice varieties supported by increased inputs of fertilizers and pesticides. Such farming practices greatly reduce the suitability of rice fields as fish habitat (Ruddle 1982). Intensified farming practices may be adopted for the dry-season crop while maintaining a traditional rain-fed wet-season crop (as in the study area) or may be extended to both cropping seasons.

The aim of the present study was to assess overall impacts of irrigation on fisheries in rain-fed rice-farming landscapes, and to identify the key mechanisms by which these impacts arise. We conducted an observational study, designed as a comparison of aquatic habitat availability, fish catches, species richness and ecological composition of fish assemblages between irrigated and paired, non-impacted control sites.

Materials and methods

STUDY AREA

In Laos the climate is tropical, with an average daily maximum temperature of 31 °C and an average annual precipitation of 1500 mm, about 75% of which occurs in the monsoon season (May–October). Rice is the single most important crop, accounting for about 80% of the cultivated area. More than 85% of rice produced is of traditional deep-water varieties, and annual yields are in the range of 1·5–2·8 t ha^{-1} (SUAN 1989). Irrigation has expanded rapidly, from 3% of the rice-field area in the mid-1980s (SUAN 1989) to 18% in the late 1990s (FAO 2003). Field studies were carried out in three provinces of Southern Laos: Khammouane, Savannakhet and Champassak. The lowlands of these provinces are among the major rice-producing areas in Laos.

STUDY DESIGN AND SITE SELECTION

The impact assessment was designed as a paired observational study, replicated at irrigation scheme level, comparing irrigated sites with non-irrigated control sites selected to be as similar as possible (Eberhardt & Thomas 1991). Each site centred on a village and covered all aquatic habitat located within the land belonging to that village. Controls were located in the same watershed as the irrigated sites, on a stream or river of the same order, and were similar in terms of village population and agricultural land area. Irrigation impacts were measured as average differences between impacted and non-impacted sites in aquatic habitat areas, catch and fishing effort, species richness and ecological composition of fish assemblages. Preliminary investigations suggested that a 50% reduction in household fish catches would be sufficient to offset the net benefits of many irrigation schemes. Hence the survey was designed to detect a 50% reduction in household catch at a level of significance of $\alpha = 0{\cdot}1$ and power of $1 - \beta = 0{\cdot}9$. Based on estimates of within- and between-village variance in fish catches (Garaway 1999), power analysis suggested that 10 paired sites with samples of 10 households per site would be sufficient to meet the design criteria. Ten site pairs of weir and dam irrigation schemes were selected at random from lists provided by the provincial irrigation departments. Topographic maps and local knowledge of provincial and district agriculture and irrigation department staff were used to identify control sites.

SURVEY METHODS

At each site, a site survey, a household fishing survey and a fish biodiversity survey were conducted. The household fishing and biodiversity surveys were carried out twice, in the dry season and during the period of receding water. All surveys were carried out by government livestock and fisheries officers with the active participation of local villagers, and with training and regular quality control by the research team.

The site survey was designed to provide general information on the village and to quantify aquatic habitat availability. Population data, rice field area and irrigated area were obtained from the village administration. Perennial and seasonal aquatic habitats were identified from topographic maps and through participatory mapping. Surveyors visited all identified habitats and measured area and depth in the wet and dry seasons. Overall aquatic habitat availability at each site was summarized as the area of riverine (flowing water, such as rivers and streams), lacustrine (standing water, such as reservoirs, natural lakes and ponds) and rice fields.

The household fishing survey covered 10 households selected at random from the village list. Surveyors collected data on fishing events (person fishing, time fished and catch in weight) with a 1-week recall. The interview method involved use of visual aids to recall (Garaway 1999). Household fishing effort was quantified as time spent fishing by all household members per week. Catch and effort data were recorded separately for reservoirs (where present) and for non-reservoir habitats.

For the fish biodiversity survey, large groups of villagers fished in all local aquatic habitats for a fixed period of about 2 h. All fish caught were preserved and identified to species level in the Department of Zoology, The Natural History Museum, London, UK. The number of specimens obtained differed between sampling locations, and species richness was positively correlated with the total number of specimens obtained. Effects of irrigation on species richness were estimated from the full samples, and from the average richness of computer-generated resamples of 30 fish (the lowest number of specimens obtained for a single site). To assess impacts of irrigation on ecological characteristics of fish communities, effects on composition of samples were quantified in terms of proportional abundance of functional feeding groups, and of proportion of rheophilic (flowing water-associated) fish. Classification of species by these characteristics was based on information from FishBase (Froese & Pauly 2004), Rainboth (1996) and Kottelat (2001).

DATA ANALYSIS

All survey data were stored in a relational database. Habitat data were aggregated at site level to provide average habitat areas per site in the wet and dry seasons. Household catch and fishing effort data were aggregated at site (village) level and expressed as site averages per household, and per unit aquatic habitat area (average of wet- and dry-season area). The fish biodiversity survey provided site-level data, which were pooled across seasons as no seasonal differences in composition were apparent.

The main impact assessment was based on differences between paired irrigated and non-irrigated sites in the various metrics. A non-parametric bootstrap (Efron & Tibshirani 1993) was used to generate confidence limits for effects. Results are reported as follows: for each variable, the mean value in non-impacted sites is given as a baseline, and the irrigation effect is shown as the mean and 90% confidence interval (CI) of differences between the paired, impacted and non-impacted sites (Tables 1 and 2).

Regression analysis of log-transformed variables was used to explore the role of fishing effort, habitat availability and irrigation impact in determining catch at village level. A regression model of the form:

$$\ln C + \alpha_0 + \sum \alpha_i \ln x_i + \beta_1 D \qquad \text{eqn 1}$$

was used, where C is the catch at village level, x_i are covariates (fishing effort, permanent and seasonal water area at village level), D is a dummy variable for impact (0, no irrigation; 1, irrigation), and α_i and β_i are the corresponding coefficients. Impacts of irrigation development on per-area fishery productivity of habitats were further explored using regression analysis of log-transformed catch (CPUA) and effort (EPUA) per unit area.

Table 1. Effects of irrigation on aquatic habitat areas at village level. Mean area at non-impacted (NI) sites is given as a baseline, and effects are shown as the mean difference in area between paired, impacted and non-impacted sites. Riverine habitat includes rivers, streams and canals; lacustrine habitat includes natural lakes and human-made reservoirs and ponds; rice field habitat includes all areas used for rice cultivation. Effects in bold are significant at $P < 0{\cdot}1$

	Riverine habitat area (ha)		Lacustrine habitat area (ha)		Rice field habitat area (ha)	
	NI	Effect (90% CI)	NI	Effect (90% CI)	NI	Effect (90% CI)
Weirs						
Dry season	4·6	−1·7 (−4·6, 0·7)	7·5	−2·2 (−10·0, 4·4)	13·5	5·8 (−8·1, 17·2)
Wet season	9·3	−3·3 (−8·7, 3·1)	10·7	−4·8 (−16·4, 3·1)	59·6	−12·3 (−28·3, 3·4)
Dams						
Dry season	15·7	**−13·5 (−33·7, −1·6)**	4·5	**80·9 (14·4, 186·5)**	6·8	**47·1 (25·9, 72·7)**
Wet season	23·1	**−19·8 (−40·6, −5·6)**	5·9	**110·2 (28·7, 223·2)**	124·1	2·3 (−60·0 60·7)

Results

SITE CHARACTERISTICS

The study covered weir and dam irrigation schemes, with command (irrigated land) areas ranging from 17 to 515 ha (average 155 ha) and associated paddy areas varying from 3 to 346 ha (average 93 ha). Weirs had been in operation for an average of 12 years (range 3–35 years), and dams for an average of 7 years (range 3–13 years). As weir schemes and control sites tended to be located higher up in watersheds than dam sites and their controls, the area of irrigation command and overall aquatic habitat was smaller on average (Table 1). Village size was unrelated to irrigation type (weir/dam) or impact, varying between 15 and 256 households with an average of 102. Within all irrigation schemes, wet-season rice continued to be cultivated as a rain-fed, deep-water crop although supplemental irrigation was applied occasionally. Dry-season rice crops were cultivated with lower water levels and sometimes involved higher yielding varieties.

AQUATIC HABITAT AVAILABILITY

Aquatic habitats at all sites comprised a stretch of river (on which the weir or dam was located in the case of impacted sites), variable numbers and sizes of lacustrine waterbodies (natural lakes, wetland and human-made reservoirs and ponds) and rice fields. Total wet-season aquatic habitat in non-impacted sites averaged 79 ha in weir and 153 ha in dam control sites (Fig. 1). Dry-season areas were much smaller overall and more similar, at 25 ha and 27 ha in weir and dam controls, respectively. Temporary wetland area was two (weir controls) to four (dam controls) times greater than permanent water area, and was dominated by rice fields. Weir irrigation schemes had no significant impact on aquatic habitat areas (Table 1 and Fig. 1a). Dam irrigation schemes were associated with large and significant increases in lacustrine habitat area, and concomitant declines in riverine habitat area (Table 1 and Fig. 1b). Dam schemes also led to a significant expansion in dry-season rice field area.

HOUSEHOLD CATCH AND FISHING EFFORT

Eighty-three per cent of households participated in fishing during the survey period. In the non-impacted sites, average household fishing effort was consistently about 5 h week^{-1}, but household catches were lower in weir controls (0·77 kg week^{-1}) than in dam controls (2·07 kg week^{-1}). This difference in catch reflects the differences in location and habitat availability already outlined. On a per-area basis, fishing effort was much higher in weir than in dam controls (6·6 vs. 2·9 h ha^{-1} week^{-1}), while catches were similar. Average household catch and effort in all sites are shown in Fig. 2. Overall household catch and effort were far more variable among

Table 2. Paired comparisons of average household fishing effort (HH effort) and catch (HH catch), catch per unit of effort (CPUE), effort (EPUA) and catch (CPUA) per unit area, and species richness. Mean values for non-impacted (NI) sites are given as a baseline, and effects are shown as the mean difference between paired, impacted and non-impacted sites. Relative mean effects are also shown as a proportion of the NI value. Effects in bold are significant at $P < 0{\cdot}1$

	Weirs			Dams, all habitats			Dams, non-reservoir habitat		
	NI	Effect (90% CI)	Relative	NI	Effect (90% CI)	Relative	NI	Effect (90% CI)	Relative
HH catch (kg week^{-1})	0·77	**−0·28 (−0·50, −0·10)**	−36%	2·07	−0·36 (−1·18, 0·27)	−17%	1·80	**−0·91 (−1·89, −0·12)**	−51%
HH effort (h week^{-1})	4·84	−0·69 (−1·64, 0·21)	−14%	5·55	−0·72 (−1·91, 0·62)	−13%	4·48	**−2·58 (−4·04, −1·13)**	−58%
CPUE (kg h^{-1})	0·15	+0·01 (−0·04, 0·07)	+7%	0·38	0·29 (−0·05, 0·82)	+76%	0·37	−0·04 (−0·17, 0·10)	−11%
CPUA (kg ha^{-1} week^{-1})	1·01	**−0·63 (−1·73, −0·01)**	**−62%**				1·26	**−0·75 (−1·49, −0·13)**	**−69%**
EPUA (h ha^{-1} week^{-1})	6·62	−1·20 (−3·04, 0·39)	−18%				2·85	**−1·76 (−2·94, −0·66)**	**−61%**
Richness (raw)	12·9	−0·7 (−4·0, 2·7)	−5%	17·1	1·2 (−4·2, 5·8)	+7%			
Richness (standardized)	9·05	−0·50 (−1·80, 0·60)	−6%	8·94	+0·40 (−1·65, 2·21)	+4%			

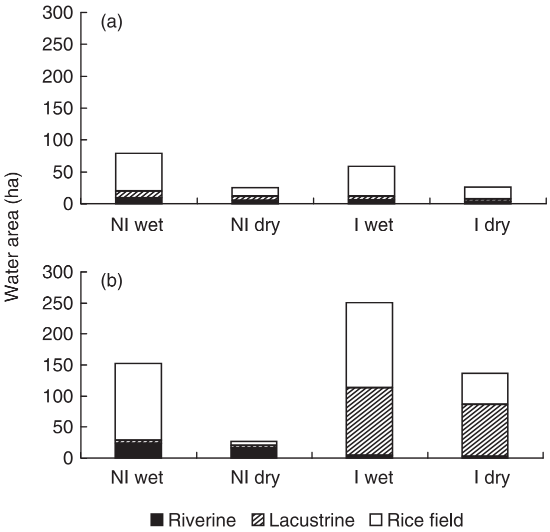

Fig. 1. Mean aquatic habitat areas at village level in the weir (a) and dam (b) sites. Non-impacted (NI) control and impacted (I) sites in the wet and dry seasons. Habitats are classified as riverine (rivers, streams and canals), lacustrine (reservoirs, lakes, and ponds) and rice fields.

than within pairs, suggesting that the paired design had effectively controlled for environmental variation between watersheds.

Weir schemes were associated with a significant, 36%, decline in household catch and a smaller, non-significant, decline of 14% in household effort (Table 2). Overall this indicated a moderately negative effect of weir irrigation schemes on fish catches, partly but not fully explained by a decline in fishing effort. No significant overall impacts were detected for dam schemes, although a tendency towards reduced household catch and effort was noticeable (–17% and –13%, respectively). However, very substantial changes emerged when analysing the data separately between the newly created reservoirs and non-reservoir habitat. Dam schemes were associated with drastic and statistically significant reductions in non-reservoir catch (–51%) and effort (–58%) on a household and per unit area basis. Reservoir catch and effort partially compensated for the reduction in non-reservoir fishing, so that net effects were smaller and not significant.

There were no statistically significant seasonal differences in catch and effort, but average household catches were consistently lower, and the level of effort expended consistently higher, in the dry than in the wet season in all but the dam impacted sites. Catch per unit effort (CPUE) was significantly higher in the wet season than in the dry season in all but the dam-impacted sites, where no seasonal effect on CPUE was detectable. Dam schemes thus reduced the normal, seasonal variation in aquatic resource availability.

SPECIES RICHNESS AND ECOLOGICAL COMPOSITION OF ASSEMBLAGES

Participatory test fishing yielded between 30 and 353 (average 101) specimens site^{-1}, representing a total of 124 fish species. Numerically the most common species were the flying barb *Esomus metallicus* Ahl, the climbing perch *Anabas testudineus* Bloch and the snakehead *Channa striata* Bloch, which together accounted for about 40% of the samples. The latter two species are able to migrate across dry land, and are thus well adapted to colonizing rain-fed rice fields (Rainboth 1996). Average species richness in the full samples was 12·9 in weir and

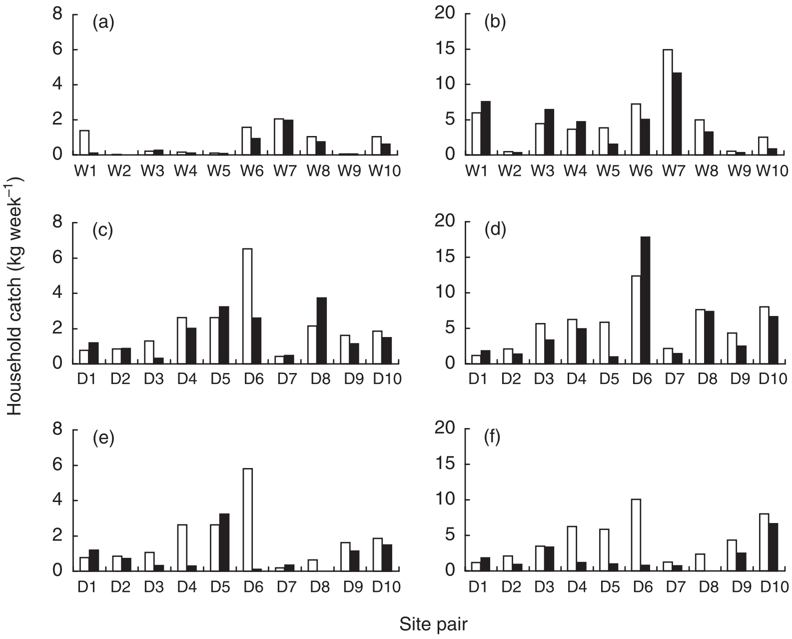

Fig. 2. Average household catch and fishing effort in the paired weir (a, b) and dam (c–f) sites. Open bars denote the non-impacted control, solid bars the impacted site of each pair. For dam sites, catch and effort are shown for all aquatic habitats (c, d) and for non-reservoir habitats only (e, f).

Table 3. Parameter estimates (with standard error in parentheses) for the regression models of village-level catch (equation 1). Coefficients in bold are significant at $P < 0{\cdot}1$

	Effect	Weirs	Dams, all habitats	Dams, non-reservoir habitats
Constant	α_0	−1·69 (1·03)	**−3·07 (1·74)**	**−4·75 (1·36)**
Effort	α_1	**0·48 (0·25)**	**1·06 (0·22)**	**1·21 (0·22)**
Dry season area	α_2	0·15 (0·14)	−0·16 (0·19)	0·00 (0·15)
Temporary area	α_3	**0·61 (0·20)**	**0·46 (0·23)**	**0·54 (0·23)**
Irrigation	α_1	−0·44 (0·45)	0·17 (0·39)	0·00 (0·41)

17·1 in dam controls. In the samples standardized to 30 specimens through computer-generated resampling, species richness was equal at 9 in both weir and dam controls (Table 2). No impacts of irrigation on average fish species richness were evident, regardless of whether effects were estimated from full or standardized samples. Confidence limits on impacts were fairly narrow, with all 90% confidence limits within 33% of the mean.

The proportional representation of functional feeding groups was similar in weir and dam control sites, with 27% carnivores, 20% omnivores, 45% planktivores and 8% insectivores. Weir-impacted sites were associated with a significant increase in omnivores (+17%), and concomitant reductions in planktivores (–10%) and insectivores (–6%). No significant changes in the relative abundance of feeding groups were detected in dam-impacted sites. The proportion of rheophilic individuals was higher in weir control sites (25%) than in dam controls (13%). There was no significant impact of either weir or dam schemes on the proportional abundance of rheophilic fish.

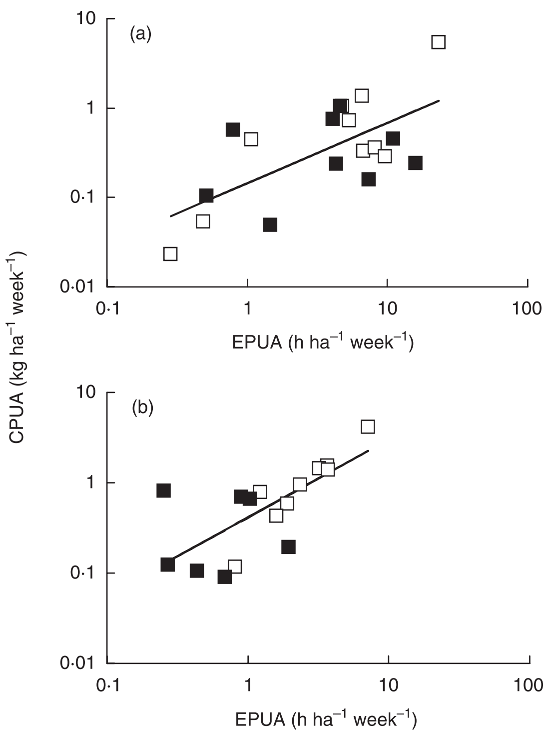

Fig. 3. Relationships between fishing effort and catch per unit area (EPUA and CPUA) in weir (a) and dam (b) sites. Non-impacted controls (open squares) and impacted sites (solid squares).

DETERMINANTS OF CATCH

Regression analysis of village-level fish catch consistently identified fishing effort (total time spent fishing by all households) and temporary wetland area as key determinants of total catch (Table 3). The estimated values of coefficient α_3 (0·46–0·61) indicated that a 1% reduction in temporary wetland area caused a 0·4–0·6% reduction in village level catch. The coefficient of irrigation impact α_1 was not significant, confirming that effects observed in the paired comparisons were the result of differences in fishing effort and habitat area, rather than a reduction in per-area fisheries productivity of habitats. The same was evident from the relationships between CPUA and EPUA, which showed no systematic differences between non-impacted control and impacted sites (Fig. 3).

Discussion

METHODOLOGICAL CRITIQUE

Observational studies replicated at the irrigation scheme level are an efficient way of assessing irrigation development impacts on aquatic resources in a rigorous manner and at relevant spatial scales. They are, of course, more susceptible to biases than experiments (where treatments are allocated randomly to experimental units) or survey sampling (where observational units are selected without reference to impact status) because of the subjectivity involved in selecting control sites (Eberhardt & Thomas 1991). However, fully designed experiments with large-scale disturbances are rarely possible (or ethically desirable) and survey approaches tend to require far larger sample sizes to achieve a power similar to that of targeted observational studies. The close correlation of catch and fishing effort between impacted and paired control sites (Fig. 2) suggests that the selection of controls within the same watershed and with similar village characteristics has successfully reduced environmental variation and increased the statistical power of the impact study. Overall impacts were moderate but consistent. Although the possibility of an inadvertent bias can not be ruled out completely, neither the location of irrigation schemes nor the selection of control sites was in any way influenced by prior knowledge on the productivity or diversity of fisheries. A more important factor likely to contribute to the moderate level of impacts detected is the fact that impacted sites were embedded within largely intact river systems. This configuration allowed us to adopt a rigorous comparative methodology in the first place, but it also meant that colonization of irrigated sites from the surrounding area could raise local productivity and diversity. Cumulative and synergistic impacts are likely to occur as a result of increasing density of small- to medium-scale schemes, and repeated interruptions of longitudinal connectivity in rivers and streams. Further studies on such effects are warranted, and could be carried out in the study area once irrigation development has expanded.

FISHERIES IN RAIN-FED RICE-FARMING LANDSCAPES

The rain-fed rice-farming landscapes of southern Laos support diverse fish assemblages (at least 124 species, about 10% of the total estimated for the Mekong basin; Coates *et al*. 2003) and productive fisheries (with annual average yields of 60 kg ha^{-1} of wet-season water area). These yield figures are broadly similar to those estimated for flood-prone rice systems in Bangladesh (Halls, Hoggarth & Debnath 1999) and natural floodplains (Bayley 1988). Hence rain-fed rice-farming landscapes in the study area may be regarded as broadly intact floodplain-like ecosystems. The importance of fisheries to rural livelihoods is apparent from the fact that 85% of households participated in fishing during the study, and achieved an average catch of 60 kg $household^{-1}$ $year^{-1}$. Using market prices and exchange rates of 1999, the fish catch has been valued at approximately 90 US\$ $household^{-1}$ $year^{-1}$ (60 kg at a market value of 1·5 US\$ kg^{-1}), compared with the value of the rain-fed rice crop of 150 US\$ $household^{-1}$ $year^{-1}$ (1·5 t at a market value of 0·1 US\$ kg^{-1}).

IMPACTS OF IRRIGATION DEVELOPMENT

Weir irrigation schemes had no significant effect on aquatic habitat areas, but were associated with a significant decline in household fish catches. This catch decline was partially, but not fully, explained by reduced fishing effort. Weirs had no effect on fish species richness, but were associated with a moderate, statistically significant increase in the relative abundance of omnivores and concomitant reductions in planktivores and insectivores.

Dam irrigation schemes significantly reduced riverine habitat area, and increased lacustrine habitat and dry-season rice field area. Dam schemes led to a redistribution of fishing effort towards reservoir habitats in response to new opportunities. Dam schemes also significantly reduced seasonality in both aquatic habitat and resource availability. No significant impacts of dams were detected on fish species richness or the relative abundance of functional feeding groups.

The overall impacts of irrigation development on fisheries in the rain-fed rice-farming landscapes of Laos have been fairly limited. This result is consistent with the perceptions of local villagers, as expressed in meetings both before and after the quantitative assessment. Changes in catch were explained largely by changes in fishing effort, i.e. arose through socio-economic rather than ecological mechanisms. Changes in overall effort levels and the redistribution of effort into the reservoir in dam schemes most probably reflect the new economic opportunities provided by irrigated agriculture and reservoir fishing, which have increased the opportunity costs of fishing overall and in non-reservoir habitats (Smith, Lorenzen & Nguyen Khoa, in press). Neither the moderate overall reduction in catches, nor the more dramatic shift of fishing activities into reservoirs, indicate reduced productivity in traditional habitats, as per-area catch–effort relationships in habitats outside the reservoir have been maintained. The strongest indication of ecological impacts was found in weir schemes, where the decline in catches was not fully explained by a concomitant reduction in effort, and a moderate shift was detected in the representation of functional feeding groups. No such ecological effects were evident in dam schemes, despite their far greater effects on river flows and longitudinal connectivity of river habitats (Jackson & Marmulla 2001; Welcomme 2001). This suggests that at the landscape level (i.e. integrating across the various habitats present within sites), the creation of reservoir habitat and increase in dry-season water availability have compensated for reductions in wet-season river flow and connectivity of riverine habitat. This broad compensation does not, of course, preclude the possibility that certain vulnerable species may be adversely affected. A factor likely to contribute to the moderate level of ecological impacts in both weir and dam schemes is the dominance of rain-fed rice fields within wet-season aquatic habitat. The hydrology of rain-fed rice fields is driven by runoff and direct precipitation, and thus is insensitive to modifications of river flow. The fishery productivity of rain-fed rice fields is likely to be maintained as long as ecological connectivity with perennial habitats is sufficient to allow colonization by fish.

The greatest threat to the fisheries' productivity of rain-fed rice-farming landscapes is not the infrastructure (weirs and dams) created for dry-season or supplemental irrigation, but a possible reduction in rice field water storage during the wet season, which would drastically affect the extent of temporary wetland area suitable as fish habitat. Whereas in the study area the wet-season crop was cultivated in the traditional rain-fed way, even in irrigated sites availability of irrigation water can facilitate the intensification of wet-season rice production with a concomitant reduction in rice field water storage. Given the strong effect of seasonal wetland area on catches, modifications in wet-season farming practices may have a more dramatic impact in fishery production than the development of dry-season irrigation.

The results obtained here for irrigation development in rain-fed rice-farming landscapes are remarkably similar to those obtained for flood control and irrigation schemes in the flood-prone rice-farming landscapes of Bangladesh. Flood-prone rice-farming systems can continue to support productive fisheries within flood control schemes (Sultana & Thompson 1997; Halls, Hoggarth & Debnath 1999). Small adjustments in the design and operation of flood control structures and creation of perennial aquatic habitat within flood control schemes can dramatically improve production. In a different tropical system, Dudgeon (2003) shows that even highly modified streams in Hong Kong can maintain substantial biological diversity. Hence there is increasing evidence to suggest that even highly modified landscapes can support productive and diverse aquatic ecosystems and fisheries, and that conservation and restoration measures in such systems need not be in vain.

MANAGEMENT IMPLICATIONS

There are several important implications of these results for the management of irrigation development impacts on fisheries. First, ecological attributes of rain-fed rice-farming landscapes are such that they may support diverse and productive fisheries even within irrigated areas. The value of these fisheries to livelihoods and biodiversity conservation should be assessed and considered in agricultural and water management decisions. Secondly, irrigation water management and farming practices within irrigated rice farming systems may have a greater impact on fisheries productivity than irrigation infrastructures such as weirs and dams. Management practices that conserve and enhance natural aquatic resource productivity should be maintained and developed where feasible, and may yield ecological and social benefits. Thirdly, cumulative and synergistic impacts of irrigation schemes should be considered even where the individual schemes appear to have only limited impacts. Our study also demonstrates the value of rigorous empirical assessments of irrigation impacts on fisheries to the development of management and policy guidance. In the face of increasing pressure on water resources, such studies will make an important contribution to the conservation of inland aquatic resources in the tropics.

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