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RESEARCH PAPER

Wetlands and Ecosystem Services: Empirical Evidence for Incentivising Paddy Wetlands

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Abstract: Wetland paddy agro-ecosystems are recognized as important human-made wetland systems. Realizing that paddy lands are important ecological systems, the state of Kerala in southern India passed an act in 2008 preventing their conversion to other uses. The state provides subsidies and production bonuses to encourage paddy farmers and imposes penalties for non-compliance. However, the economic benefits associated with the conversion of paddy lands are considerably higher than the current subsidies and bonuses. As such, the conversion of paddy lands continues unabated despite the incentives and disincentives provided in the act. This study examines the ecological rationale for preventing paddy land conversion through a comparative assessment of the ecological health of paddy lands against that of lands with competing uses. Ecological health is assessed in terms of the amphibian population—specifically, frog abundance and diversity across different land uses, as frogs are considered bio-indicators of ecological health. The results reveal that the conversion of paddy lands adversely affects the survival of amphibians, especially frogs, thus emphasizing the role of paddy lands in maintaining the ecological health of a region. The study also provides empirical evidence for creating "Pigouvian subsidies" or ecological incentives for paddy farmers.

Keywords: Ecological health, Pigouvian subsidy, Amphibian diversity, Paddy wetlands, Kerala, India

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1. INTRODUCTION

Wetlands, both natural and human made, are a rich source of ecosystems services (Maltby and Acreman 2011; MEA 2005). They are critical natural resources that provide various socio-economic and environmental benefits to local communities (Dixon and Wood 2003). The role of wetlands in contributing to the Sustainable Development Goals (SDGs) has been well documented (Jaramillo *et al.* 2019). The SDG targets that have considerable relevance to wetlands are those related to "improving water quality", "sustainable food production", and "sustainable management of resources". Wetlands are a potentially valuable agricultural resource (McCartney and Houghton-Carr 2009). Wetland agriculture, if sustainably managed, could play a significant role in promoting food security and income (Dixon and Wood 2003). The maintenance of wetlands' ecosystem services depends on their ecological character. Any changes in the ecological character of wetlands alters the ecosystem service delivery, impacting human well-being (MEA 2005). Hence, the conservation of wetlands—both natural and human made—is essential to maintain the ecosystem services flow, which will contribute to achieving the SDGs.

The state of Kerala in southern India enacted The Kerala Conservation of Paddy Land and Wetland Act (KCPLW Act), 2008, with the twin objectives of promoting agricultural growth and preserving ecological systems (Chitra 2016). This act prohibits the conversion of wetlands and paddy lands for other land uses—agricultural or non-agricultural. The law directs the state to provide incentives to paddy farmers, and accordingly, the state extends special subsidies (US$15 per hectare [ha]) and production bonuses to the tune of US$67 per ha per season to paddy farmers, to encourage them to continue paddy cultivation. The penalty for non-compliance includes imprisonment for 6 to 11 months and a fine in the range of US$610 to US$1,220. But such a carrot-and-stick approach has been unsuccessful in preventing paddy lands from being converted to other lands, as the forgone benefit or opportunity cost of conservation is very high. From 1985–1986 to 2019–2020, an estimated 75% of the area that had been under paddy cultivation was converted for other land uses in Kerala (GoK 2021). The major competing crops in Kerala are banana and areca nut, both of which have high commercial value.[1]

[1] The sequence of conversion of paddy lands in Kerala is as follows: first it gets converted to banana, and after the cultivation of banana for more than five consecutive years, areca nut is planted. Conversion to banana is considered a reversible one, while conversion to areca nut, a plantation crop, is irreversible. Once paddy land gets converted to areca nut, it loses its wetland characteristics and can be easily put to non-agricultural uses.

Paddy wetlands are privately owned agro-ecosystems and often the only source of livelihood for most farmers. Any private land use choice by paddy farmers involves a trade-off between short-term profitability and long-term environmental sustainability. A study on the relative profitability of crops, carried out by the State Department of Agriculture, reveals that the average cost of cultivating[2] paddy is in the range of US$826[3] to US$907 per ha across the three cropping seasons in a year. The average costs of cultivating banana and areca nut are US$2,680 per ha and US$1,262 per ha, respectively.[4] The average net return per ha for paddy is in the range of US$418 to US$742, while for banana and areca nut, the returns are US$3,723 and US$1,918 per ha, respectively—six and three times higher than that of paddy (GoK 2022).

The production bonus and subsidy given by the government, which amounts to US$82 per ha of paddy land, neither compensates for the cost of cultivating paddy, nor bridges the huge profit gap between paddy and its competing crops. Thus, paddy remains an economically unviable option for farmers despite the state's focused support for paddy cultivation. Nevertheless, the KCPLW Act, 2008, mandates that paddy farmers continue paddy cultivation to sustain the ecological system of the state (a positive externality), which results in high private costs for the farmers. Given this background, the study compares the ecological health of wetland paddy vis-à-vis that of competing land uses and critically examines the rationale for conserving paddy lands to sustain the ecological system of the state. This assessment provides empirical evidence in support of the rationale behind offering ecological incentives to paddy farmers, who bear the costs of providing this social benefit.

1.2. Rationale for the Study

Environmentalists and ecologists worldwide have contrasting views on the utility of paddy wetlands. One section recognizes paddy lands as human-made wetlands that play a significant role in groundwater recharge, water regulation, flood and drought control, and conservation of biodiversity, in addition to their primary role in food production (Iwasaki *et al.* 2012; Blackwell and Pilgrim 2011; Shivakoti and Bastakoti 2010). They emphasize that paddy systems are landscapes that are not only integral to the food and livelihood security of people but are also a valuable source of ecosystem services. The habitat services and biodiversity conservation services offered

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[2] The cost presented here is Cost A, which includes all kind of expenses (paid out costs) actually incurred by the cultivators.

[3] US$1 = ₹82.

[4] Banana is an annual crop and areca nut is a perennial, while paddy is a 60- to 90-day crop.

by wetland paddy fields are well documented as are their regulating services in terms of eco–disaster risk reduction (Naoki *et al.* 2015; (Osawa. Nishida, and Oka 2020). Hence, wetland paddy is also increasingly being touted as valuable green infrastructure (Osawa, Nishida, and Oka 2022). However, a section of environmentalists' view paddy lands as contributing to greenhouse gas emissions and thereby to global warming (Singh *et al.* 2022; Bautista and Saito 2015; Wang *et al.* 2017).

In short, there exist conflicting views regarding the ecological/environmental utility of paddy wetlands, and land use decisions involve trade-offs between short-term profitability and long-term ecosystem sustainability. A key determinant of the ecosystem services potential of wetlands is their ecological health. An important ecosystem service of paddy fields is their role in facilitating biodiversity—both flora and fauna (Edirisinghe and Bambaradeniya 2006). The loss of paddy ecosystems is said to have a profound influence on biodiversity, inevitably disturbing the ecological balance (Luo, Fu, and Traore 2014). Hence, in studies comparing land use changes involving paddy, a key element of comparison is the gain/loss in useful biodiversity. The present study adopts a similar approach. Although paddy lands are home to various flora and fauna, our study quantifies the amphibian diversity, with a specific focus on frogs.

1.3. The Frog as a Bio-indicator for Ecosystem Health and Services

Among the faunal species found in paddy lands, frogs are common and representative of the health of the ecosystem (Sato and Azuma 2004). They are natural enemies of crop pests and are, therefore, good bio-control agents. Frogs are considered keystone species in food webs as they prey on arthropods, while they in turn are prey to snakes, birds, and even humans (Tsuji *et al.* 2011; Naito and Ikeda 2007). A decline in their population is bound to have a significant impact on other organisms in the food web. Several studies have established that frogs provide regulatory and supporting services in tropical ecosystems, playing a major role in nutrient recycling, bioturbation, seed dispersal, and biological control, in addition to being a source of medicine and food (Hocking and Babbitt 2014). Most importantly, frogs are used as bio-indicators of ecological health as they are highly sensitive to changes in ecosystems (Baharuddin, Ramli, and Othman 2015; Duré *et al.* 2008; Parmar, Rawtani, and Agrawal 2016; Samantha *et al.* 2015; Simon *et al.* 2011). The response of frogs to ecosystem changes has been used as an indicator in studies on the impacts of anthropogenic activities, habitat fragmentation, and general ecosystem stress (Beebee and Griffiths 2005; Cochard, Maneepitak, and Kumar 2014; Loumbourdis *et al.* 2007). Furthermore, among the faunal species observed in paddy lands, frogs are unique in that they need both aquatic (e.g., paddy) and terrestrial habitats (e.g., banana and areca nut) to complete their life cycle (Matsuno *et al.* 2006; Parmar, Rawtani, and Agrawal 2016). Thus, using frogs as an indicator of ecosystem health for a comparative analysis across land uses is justified.

The impact of land use changes and the effect of environmental management in paddy fields on frog species has been studied earlier by Naito *et al.* (2012) and Tsuji *et al.* (2011) in Japan. These studies showed a striking decline in frog distribution due to the conversion of paddy fields. Such studies linking land use changes to amphibian decline are scarce in India. In this context, our study establishes causality between land use changes and amphibian abundance and diversity. The results of this study show a strong association between paddy land conversion and decline in frog abundance and species diversity, thereby lending credence to the ecological argument in the KCPLW Act, 2008, for conserving paddy lands.

2. MATERIALS AND METHODS

This section describes the study area, methodology adopted, sampling framework, the data and details on the individual variables used in the study.

2.1. Study Area

This study was carried out in the Wayanad district[5] in the state of Kerala in southwest India, which is in the ecologically fragile Western Ghat region (Figure 1). The district covers 2,131 sq km and is divided into three taluks and four blocks. Each block is further divided into panchayats, and each panchayat into wards.[6]

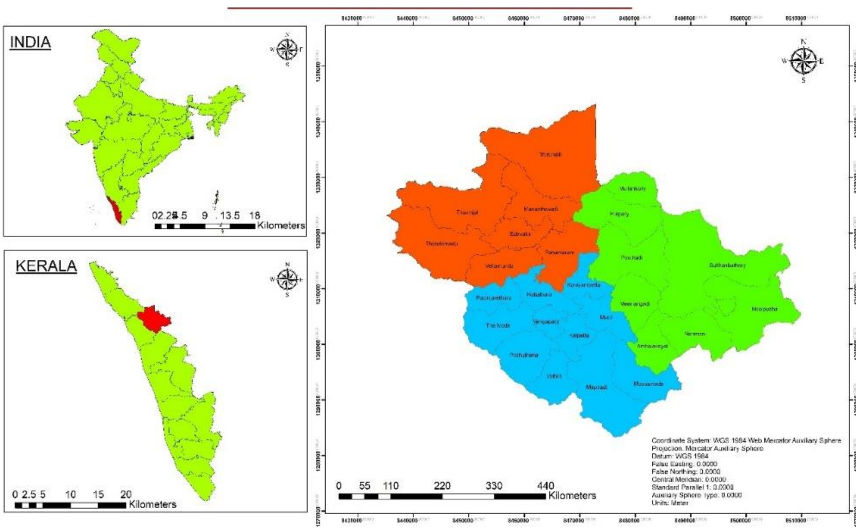
The district has undergone major land use changes since the mid-1980s, with the area under paddy cultivation declining by more than 75% between 1985–1986 and 2019–2020 (GoK 2022). Paddy farming in Wayanad, as in the rest of Kerala, is not remunerative, with net returns per ha from banana cultivation being three to four times that of paddy. However, several studies have shown that the conversion of paddy lands leads to adverse ecological outcomes like ground water depletion (Vinayachandran and Joji 2007), loss of diversity of wild edibles from paddy fields (Narayanan, Swapna, and Kumar 2004), and a loss of genetic diversity of rice (Kumar, Gopi, and

[5] A district is an administrative division within the state.

[6] Taluks and blocks are divisions within districts, and panchayats are local administrative divisions within blocks.

Prajeesh 2010) in the district. The Western Ghat region is rich in amphibian fauna and is home to almost 60% of the known amphibian species in India (117 out of 224). Of this, 89 species are endemic to the region (Daniels 1992; Myers *et al.* 2000).

Figure 1: Wayanad District Map



Source: Authors' creation based on Google Maps, accessed on 16 December 2022.

2.2. Methodology

The study adopted a functional form to estimate the ecosystem services gain/loss due to land use changes. The ecosystem services being measured are frog abundance and frog species diversity. The functional form is broadly denoted as ES = *f*(LU, Xn) + *u*, where

- ES is the ecological service measured in terms of frog abundance and species diversity
- LU is the land use (paddy, banana, and areca nut in this study)
- Xn are the other plot-level explanatory variables like (i) biophysical parameters, (ii) agronomic practices, (iii) boundary effect, (iv) plot history
- *u* is the error term.

Visual encounter surveys and male call recording methods were used to make plot-level measurements of frog abundance and species diversity across the different land uses. Measurements were taken between 7 and 11 pm on two occasions: (i) during peak monsoon (July–August) and (ii) when the monsoon was receding (September–October). Along with the number of frogs and the species diversity, plot-level biophysical variables like temperature, humidity, pH, and water levels in fields were measured. Apart from the ecological measurements, other plot-level details that are expected to have an influence on these measurements were collected using a survey schedule.

The outcome variables—frog abundance and frog species diversity—are non-negative count data. Hence, following Das (2011), a Poisson regression was used to estimate the impact of land use change and other plot-level explanatory variables on frog abundance and diversity. The details of the Poisson regression are given in Annexure A.

2.3. Sampling Framework

The sampling framework is provided in Annexure B. Plots are the units of sampling. A stratified purposive sampling procedure was adopted to select the plots. The strata are (i) agro-climatic zones, (ii) panchayats, (iii) wards within the panchayat. The district has three agro-climatic zones, and one representative panchayat from each of the zones was selected. Following this, wards were ranked in descending order by acreage and extent of equitable distribution of the crops being studied. Two or three wards with the highest ranks were selected from each panchayat.

Contiguous plots of one acre and above under paddy, banana, and areca nut were included in the sample. GPS marking of the plots was done, and plot latitude and longitude coordinates, plot boundaries, and the distance from the next sample plot were recorded to ensure the required spatial distance between the sampled plots. Of the total sample of 178 plots, 62 were under paddy, 68 under banana, and 48 under areca nut cultivation. Ecological measurements like frog abundance and species diversity were recorded for the plots. Details regarding agronomic practices, plot history, and boundary details were also collected from the farmers working the plots.[7]

2.4. Data and Variables

Table 1 gives details regarding the variables, their nature, and their expected role in determining frog abundance and species diversity.

[7] If the land was on lease, details on agronomic practices were collected from the tenant farmers.

Table 1: List of Variables, Definitions, and Expected Role in Frog Abundance and Species Diversity

Name of Variable	Nature of Variable	Expected Role in Frog Abundance/Species Diversity
Outcome Variable		
Frog abundance (numbers)	Count data	
Frog species diversity (numbers)	Count data	
Explanatory Variables		
(i) Land use		
Paddy, banana, or areca nut (paddy = 1; banana = 2, and areca nut = 3)	Categorical	Shift from paddy is expected to exert a negative influence
(ii) Biophysical Parameters		
Temperature (°C)	Continuous	Negative/positive
Humidity (percentage)	Continuous	Negative/positive
pH (the degree of acidity or alkalinity of the soil in the plot) (numbers)	Continuous	Negative/positive
Water level (cm)	Continuous	Negative/positive
(iii) History and Boundary Effects		
History: Number of years that the plot has been under the particular land use	Continuous	Positive
Boundary effects		
Road as border to the plot (1 if yes, 0 otherwise)	Categorical	Negative
Fallow land as border to the plot (1 if yes, 0 otherwise)	Categorical	Negative/positive
Water body as border to the plot (1 if yes, 0 otherwise)	Categorical	Positive
(iv) Plot-level Agronomic Details		
Farmyard manure (1 if yes, 2 otherwise)	Categorical	Positive
Per-acre fertilizer use (kg)	Continuous	Negative
Per-acre pesticide use (litres)	Continuous	Negative
Per-acre man-days (numbers)	Continuous	Negative

Source: Analytical Framework Proposed in the Study by Authors

3. RESULTS

This section presents the summary statistics of the outcome and explanatory variables used in the analysis.

3.1. Frog Abundance and Diversity across Land Uses

Among the various plots, paddy fields had the highest abundance of frogs as well as species diversity (Table 2). The least abundance and species diversity was observed in banana plots. The coefficient of variation (CV) for frog abundance and species diversity was lowest for paddy and highest for banana plots. This indicates that paddy lands in Wayanad exhibit lesser variation in abundance and diversity across plots, compared to banana and areca nut plots. Frogs were observed to be "breeding", "calling", and "foraging" in paddy wetlands, while mostly "calling" and "foraging" in banana and areca nut plots.

Table 2: Summary Statistics of Outcome Variables

Outcome Variables	Land Use	Minimum	Maximum	Mean	CV
Frog abundance	Paddy	3.0	56.0	30.0	0.41
	Banana	0.0	18.0	4.0	0.81
	Areca nut	3.0	21.0	10.0	0.48
Frog species diversity#	Paddy	1.0	5.0	3.0	0.32
	Banana	0.0	3.0	1.0	0.54
	Areca nut	1.0	4.0	2.0	0.47

Source: Field-level ecological measurements.

Notes: Paddy (N = 62); banana (N = 68); areca nut (N = 48).

#Species diversity reported refers to the total number of species observed per plot across land uses and does not represent the actual number of different species observed across land uses.

3.2. Plot-level Biophysical Parameters

Not much variation was observed in temperature, humidity, and pH across land uses, with soils being generally acidic (Table 3). Variation in water depth was observed to be in the range of 4 to 11 centimetres (cm), with paddy reporting the greatest water depth.

3.3. Plot-level Input Intensiveness and Plot History

Input intensiveness and agronomic practices adopted have an impact on the floral and faunal diversity of plots. The intensive use of chemical inputs like synthetic fertilizers and pesticides and extravagant intercultural operations might negatively affect the abundance and diversity of faunal species (Cochard, Maneepitak, and Kumar 2014).

Manure is used extensively by both paddy and banana farmers, with a higher proportion of banana farmers reporting the application of manure. The per-acre manure use for paddy is in the range of 0.5–2 tonnes, while

Table 3: Plot-level Biophysical Parameters

Explanatory Variable	Land Use	Minimum	Maximum	Mean	CV
Temperature (°C)	Paddy	22.8	27.8	25.0	0.03
	Banana	23.5	28.1	25.0	0.04
	Areca nut	24.0	27.0	26.0	0.04
Humidity (percentage)	Paddy	62.0	85.0	73.0	0.09
	Banana	64.0	82.0	74.0	0.08
	Areca nut	64.0	88.0	75.0	0.08
Water depth (cm)	Paddy	1.0	24.0	10.5	0.50
	Banana	1.0	16.0	4.0	0.54
	Areca nut	2.0	8.0	4.3	0.37
pH (numbers)	Paddy	4.1	5.0	4.4	0.06
	Banana	3.9	5.3	4.7	0.07
	Areca nut	4.1	5.6	4.6	0.07

Source: Field-level ecological measurements and farming practice survey.
Note: Paddy (N = 62); banana (N = 68); areca nut (N = 48).

for banana, it is in the range of 1–8 tonnes. In the case of paddy, the manure mainly consists of cow dung, either from livestock at home or bought from the market. In the case of bananas, the manure is largely bought, and consists of cow dung, bone meal, and pig and poultry manure.

Fertilizer and pesticide use are also highest in banana plots (Table 4). The least amount of fertilizer and pesticide use is reported in paddy plots. On average, about five to six different fertilizers are used in banana plots, of which many are complex fertilizers.[8] In paddy plots, however, there is a predominant use of straight fertilizers[9] like urea and potash. The frequency of fertilizer application per season ranges from three to seven times for banana, while for paddy, fertilizer is applied only once or at most twice. Pesticide use is higher for banana, especially during fruit maturation. It has been observed that many farmers drench the banana bunches with

[8] Complex fertilizers or compound fertilizers have more than one primary nutrient. The primary nutrients are nitrogen, phosphorous, and potassium.
[9] Straight fertilizers have only one primary nutrient.

pesticides. In addition, they apply phorate to the soil to ward off rodents. Areca nut cultivation also involves high use of Bordeaux mixture, a fungicide. Paddy plots use the least quantity of pesticides.

Table 4: Input Use and Plot History

Crop	Minimum	Maximum	Mean	CV	Total
Per-acre Fertilizer Use (Kg)					
Paddy	0.0	300.0	78.0	0.93	62.0
Banana	200.0	3,600.0	1,203.0	0.49	68.0
Areca nut	0.0	900.0	94.0	1.90	48.0
Per-acre Pesticide Use (Litres)					
Paddy	0.0	30.0	0.7	5.7	62.0
Banana	0.0	210.0	8.1	3.6	68.0
Areca nut	0.0	67.4	6.0	2.0	48.0
Per-acre Labour Man-days (Numbers)					
Paddy	0.0	140.0	51.0	0.54	62.0
Banana	5.0	221.0	90.0	0.56	68.0
Areca nut	0.0	126.0	42.0	0.91	48.0
History of the Plot (Years)					
Paddy	15.0	66.0	51.0	0.19	62.0
Banana	2.0	42.0	17.0	0.48	68.0
Areca nut	10.0	35.0	23.0	0.27	48.0

Source: Plot-level farming practice survey.

Bananas require the highest number of man-days—the labour includes making drainage channels, applying fertilizer, applying pesticide, protecting the crop from the wind, and harvesting. Unlike in the case of paddy, those employed in banana cultivation are mostly male. Paddy cultivation creates employment for local women, as key operations like transplanting and harvesting are done by them.

3.4. Plot History and Boundary Effects

The number of years that the land has been under a particular land use, and the type of land use within the boundary of the plot, is said to influence the ecological measurements of the plot. The number of years a plot has been constantly under a particular crop (plot history) range from 2 years for banana to 66 years for paddy. Note that prior to banana and areca nut cultivation, the plots were invariably under paddy (Table 4).

The commonly observed boundaries for plots are roads, water bodies (streams, rivers, or canals), vacant/fallow plots, and other cropped fields (Table 5). Having a road as a boundary is expected to have a negative influence on the abundance of frogs, as there are chances of them being crushed to death by passing vehicles (Dhanukar and Padhye 2005). The presence of a water body is expected to positively influence the abundance and diversity of frogs.

Table 5: Border Effect (Number of Plots)

Crop	Road	Water Bodies	Fallow Land	Other Crops	Total
Paddy	8.0	16.0	23.0	15.0	62.0
Banana	35.0	11.0	6.0	16.0	68.0
Areca nut	13.0	6.0	5.0	24.0	48.0

Source: Plot-level farming practice survey.

Of the 62 paddy plots, 8 had roads as boundaries, 16 had water bodies, and 23 had fallow lands. In the case of banana, 35 plots had roads on at least one or all sides, 11 had water bodies, and 6 had fallow land. Six areca nut plots had water bodies, 13 had roads, and 5 had fallow land as borders.

3.5. Regression Results

Sections 3.6 to 3.10 present the results from the Poisson regression analysis. To effectively tease out the impact of land use change on frog abundance and species diversity, a stepwise Poisson regression was run with a new variable added at each step. Altogether, five regression models were run. The results are presented in the subsequent sections.

3.6. Frog Abundance

Table 6 gives the Poisson coefficients for the explanatory variables on frog abundance. Sequential building of the Poisson regression with explanatory variables resulted in five Poisson regression outputs. Paddy is the reference land use category in the Poisson outputs.

Banana and areca nut plots negatively influence the abundance of frogs, unlike paddy plots. This result is consistent across the five models and is significant at the 1% level. Plot water levels are observed to influence frog abundance positively and significantly across the models.

Table 6: Poisson Coefficients—Results of the Poisson Regression on Frog Abundance

Outcome Variable (Frog Abundance)	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
		Explanatory Variables			
Banana (2)	−2.124*** (0.116)	−1.565*** (0.131)	−1.242*** (0.141)	−1.311*** (0.201)	−1.394*** (0.237)
Areca nut (3) (Paddy is the reference land use category)	−1.141*** (0.084)	−0.600*** (0.103)	−0.501*** (0.101)	−0.588*** (0.162)	−0.577*** (0.166)
Temperature (ºC)		0.045 (0.035)	−0.022 (0.033)	−0.022 (0.031)	−0.020 (0.031)
Humidity (%)		−0.017*** (0.006)	−0.011** (0.005)	−0.008 (0.006)	−0.008 (0.006)
Water level (cm)		0.061*** (0.009)	0.055*** (0.010)	0.052*** (0.011)	0.052*** (0.011)
pH (numbers)		−0.468*** (0.140)	−0.560*** (0.137)	−0.507*** (0.141)	−0.507*** (0.139)
Frog species diversity			0.198*** (0.038)	0.212*** (0.037)	0.209*** (0.038)
Years under the crop (numbers)				−0.001 (0.004)	−0.001 (0.004)
Road as border (1 if yes, 0 otherwise)				−0.038 (0.082)	−0.038 (0.085)
Water body as border (1 if yes, 0 otherwise)				0.021 (0.080)	0.027 (0.079)
Fallow land as border (1 if yes, 0 otherwise)				−0.170** (0.086)	−0.166* (0.088)
Farmyard manure (1 if applied, 2 otherwise)					(0.083) 0.000
Per-acre fertilizer quantity (kg)					(0.000) −0.001
Per-acre pesticide quantity (litres)					(0.002) −0.000
Per-acre man-days (numbers)					(0.001)
Constant	3.414*** (0.061)	4.889*** (1.126)	5.984*** (1.051)	5.667*** (1.083)	5.618*** (1.082)
Pseudo R^2	0.54	0.64	0.66	0.66	0.66
Observations	178	178	178	178	178

Source: Based on analysis of primary data collected in the project
Note: Robust standard errors are in parentheses.
***p<0.01; **p<0.05; *p<0.1.

This result is also significant at the 1% level. Biophysical variables like soil pH have a negative influence on frog abundance, and the effect is significant at the 1% level across the models. Humidity also has a negative effect on frog abundance, but this variable is significant only in two of the Poisson regression models. Humidity is significant at the 1% level in one model, while it is significant at the 5% level in the other.

The other explanatory variable—namely, frog species diversity—is positive and significant at the 1% level across models, wherever included. However, having a fallow border is observed to negatively influence frog abundance, and the effect is significant at the 1% level. Input intensiveness—captured through the variables per-acre use of fertilizer, pesticide, labour, and farmyard manure—is observed to have no effect on frog abundance across the models.

3.7. Frog Species Diversity

Table 7 has the Poisson regression results for frog species diversity. Here, again, paddy is the reference land use category. It can be observed that a shift from paddy to banana has a negative impact on frog species diversity across all the models, and the effect is significant at the 1% level. A shift from paddy to areca nut significantly and negatively affects frog species diversity only in Model 1. This is the model that has land use as the only explanatory variable. Once we add other explanatory variables, the impact of the shift to areca nut from paddy on frog species diversity is statistically insignificant.

Biophysical variables like plot-level temperature, humidity, and water level have a significant influence on species diversity across all the models in which they are included. Plot-level temperature has a positive and significant impact on species diversity across models. This effect is significant at the 1% level across all models. Humidity has a negative impact on species diversity, and the effect is significant at the 1% level across the models.

Water level in the plot and the consecutive number of years that a plot is under a particular land use (plot history) has a positive and significant influence on frog species diversity. The influence of water level is significant at the 5% level, while the number of years under the land use is significant at the 1% level across the models. Farmyard manure application has a negative influence on species diversity in the two models where it is included as an explanatory variable. The effect is significant at 5% in one model and 10% in the second model.

3.8. Marginal Effects: Frog Abundance and Species Diversity

The Poisson coefficients reflect the nature of influence of the explanatory variables on the outcome variables, namely, abundance and species diversity. The coefficients of the variables cannot be directly interpreted as the magnitude of the effect. Hence, marginal effects are estimated to capture the magnitude of impact of the explanatory variables on the outcome variables. Table 8 lists the marginal effects of the explanatory variables on frog abundance and species diversity.

3.9. Marginal Effects: Frog Abundance

A shift to banana from paddy results in a reduction in frog abundance by 16%, while a shift to areca nut results in a reduction in frog abundance by 9%. A one-unit increase in water level increases the number of frogs in the plot by 0.8%. If the adjoining plot is fallow, it reduces frog abundance by 3%. A one-unit increase in soil pH reduces frog abundance by 7%, whereas a one-unit increase in frog species diversity increases frog abundance by 3%.

3.10. Marginal Effects: Frog Species Diversity

Shifting from paddy to banana would reduce the species diversity by 0.7%. A one-unit increase in temperature and water level in the plot would increase frog species diversity by 0.3% and 0.04%, respectively. However, a one-unit increase in humidity would reduce abundance by 0.02%. One more consecutive year under the same land use (plot history) would increase species diversity by 0.02%. Farmyard manure application would reduce species diversity by 0.3%.

4. DISCUSSION

From the Poisson regression results, it follows that shifting from paddy to banana or areca nut has adverse effects on both frog abundance and species diversity. Frog abundance is negatively impacted by shifting away from paddy to either banana or areca nut, while the impact on species diversity is more robust for a shift to banana when compared to a shift to areca nut. Paddy lands are not only important as breeding sites due to the presence of standing water but also as foraging sites (ecological data sheets). Cultivated paddy lands, compared to banana and areca nut lands, offer an advantage to frogs in terms of foraging, as insects and microorganisms thrive on them. This can also be attributed to the fact that of the three crops, paddy is associated with the lowest pesticide use, thus providing a conducive environment for the sustenance of faunal biodiversity in general. Furthermore, even the terrestrial frogs found in banana and areca nut plots need water bodies for their sustenance. Thus, the presence of cultivated

Table 7: Poisson Coefficients (Poisson Regression Results)- Frog Species Diversity

Outcome Variable: Species Diversity	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
		Explanatory Variables			
Banana (2)	–0.848***	–0.763***	–0.474***	–0.393**	–0.383**
	(0.077)	(0.089)	(0.163)	(0.180)	(0.178)
Areca nut (3)	–0.209***	–0.134	0.112	0.123	0.125
(Paddy -reference category)	(0.106)	(0.155)	(0.251)	(0.261)	(0.259)
Temperature (ºC)		0.117***	0.109***	0.113***	0.118***
		(0.035)	(0.033)	(0.031)	(0.030)
Humidity (%)		–0.010*	–0.012**	–0.010*	–0.010*
		(0.005)	(0.006)	(0.006)	(0.006)
Water level (cm)		0.015**	0.016**	0.017**	0.017**
		(0.007)	(0.008)	(0.008)	(0.008)
pH (numbers)		–0.050	–0.058	–0.064	–0.065
		(0.104)	(0.110)	(0.121)	(0.124)
Years under the crop			0.009***	0.009***	0.009***
(numbers)			(0.003)	(0.003)	(0.003)
Road as border (1 if			0.079	0.064	0.070
yes, 0 otherwise)			(0.078)	(0.076)	(0.079)
Water body as border (1 if yes, 0 otherwise)			–0.061 (0.078)	–0.057 (0.082)	–0.067 (0.079)
Fallow land as border (1 if yes, 0 otherwise)			0.005 (0.069)	0.003 (0.074)	0.007 (0.075)
Farmyard manure (1 if applied, 2 otherwise)				–0.140** (0.071)	–0.137* (0.072)
Per-acre fertilizer quantity (kg)					–0.000 (0.000)
Per-acre pesticide quantity (litres)					–0.000 (0.001)
Per-acre man-days (numbers)					–0.001 (0.001)
Constant	1.082***	–1.096	–1.124	–1.128	–1.287
	(0.041)	(1.120)	(1.090)	(1.128)	(1.139)
Pseudo R^2	0.08	0.10	0.10	0.10	0.11
Observations	178	178	178	178	178

Source: Based on analysis of primary data collected in the project

Note: Robust standard errors are in parentheses.

***p<0.01; **p<0.05; *p<0.1.

paddy fields with standing water for a large part of the year helps with the multiplication and sustenance of the amphibian population and promotes diversity within the agro-ecosystem. This is further corroborated by the fact that the level of water in the observation plots positively influenced frog abundance and species diversity across all regression models.

Table 8: Marginal Effects of the Explanatory Variables

Explanatory Variable	Frog Abundance	Frog Species Diversity
Banana (2)	–15.81***	–0.73*
	(2.56)	(0.34)
Areca nut (3)	–9.26***	0.31
	(2.65)	(0.36)
Temperature (ºC)	–0.35	0.25***
	(0.47)	(0.07)
Humidity (%)	–0.09	–0.022*
	(0.08)	(0.012)
Water level (cm)	0.76***	0.037*
	(0.16)	(0.16)
pH (numbers)	–6.78**	–0.140
	(0.59)	(0.27)
Frog species diversity	3.07***	
	(0.57)	
Years under the crop (numbers)	–0.007	0.019**
	(0.06)	(0.06)
Road as border (1 if yes, 0 otherwise)	–0.97	0.15
	(1.20)	(0.18)
Water body as border (1 if yes, 0 otherwise)	0.72	–0.14
	(1.13)	(0.16)
Fallow land as border (1 if yes, 0 otherwise)	–2.58*	0.015
	(1.18)	(0.16)
Farmyard manure (1 if applied, 2 otherwise)	–0.49	–0.30*
	(1.19)	(0.16)
Per-acre fertilizer quantity (kg)	0.002	–0.00
	(0.002)	(0.00)
Per-acre pesticide quantity (litres)	–0.016	–0.00
	(0.028)	(0.002)
Per-acre man-days (numbers)	–0.008	–0.003
	(0.02)	(0.002)

Source: Based on analysis of primary data collected in the project
Notes: Standard errors are in parentheses.
***p<0.01; **p<0.05; *p<0.1.
Paddy is used as the reference land use category.

Other biophysical variables like soil pH negatively influenced the abundance, but pH had no significant influence on species diversity. Paddy lands had the lowest mean soil pH, which could partly explain the decline in abundance that would be triggered by a shift away from paddy. However, the humidity of the microenvironment had a significant negative influence on species diversity, but its impact on abundance was not significant in models that included other explanatory variables such as plot history, boundaries, and agronomic details. Paddy lands reported the lowest mean humidity compared to banana and areca nut plots, thereby providing a conducive microenvironment for amphibians like frogs.

Soil temperature had a positive and significant influence on species diversity. Areca nut plots had the highest mean soil temperature. This could explain to some extent the lack of significant impact of a shift away from paddy to areca nut on frog species diversity once soil temperature was included as an explanatory variable in the relevant Poisson regression models. The positive influence of temperature on species diversity is also corroborated by the number of species reported from areca nut plots in the sample. Descriptive statistics reveal that after paddy lands, areca nut plots had the largest number of species (Table 3). This could be because the soil temperature of areca nut plots is conducive to sustaining the life cycles of different species of frogs. Nevertheless, the number of individuals reported per species in areca nut plots was much lower compared to that in paddy plots. The fact that the number of individuals per species was highest in wetland paddy ecosystems is significant evidence of the role of paddy lands in maintaining the amphibian population density and species diversity, which was not seen with banana and areca nut.

The positive, significant, and consistent influence of the explanatory variable "years under the crop"—which is reflective of plot history—on species diversity explains to some extent the reason for observing the highest diversity of species in paddy lands, followed by areca nut. Paddy lands had been used for the highest average number of consecutive years (51 years) without any change in land use, followed by areca nut (23 years). An interesting result is the negative influence of "presence of a fallow plot" adjacent to the observation plot on frog abundance. Fallow lands are mostly overgrown with weeds and shrubs and have poorly maintained bunds. Thus, they do not have adequate standing water for calling and breeding.

To sum up, our empirical results suggest that paddy lands play a significant role in supporting frog abundance and diversity. Amphibian conservation through the conservation of paddy wetlands gains significance in Wayanad—the study area—as this district in Kerala is situated within the Western Ghats, a highly ecologically sensitive region and one of the eight "hottest hotspots" of biodiversity (GoI 2011; Myers *et al.* 2000) in the world. Conservation of frogs, a key bio-indicator and keystone species in the food web, will help conserve the macro- and micro-biodiversity within the Western Ghat agro-ecosystems. The study results conform with those of Naito *et al.* (2012) and Tsuji *et al.* (2011), which showed a decline in frog abundance due to the conversion of paddy lands. The result provides strong empirical evidence for the role of paddy lands in sustaining ecosystem health and providing ecosystem services. Furthermore, paddy lands being human-made wetlands with all the characteristics of natural wetlands offer valuable ecological and environmental benefits to society (Iwasaki *et al.* 2012; Blackwell and Pilgrim 2011). The results of the study lend credence to the legislation in Kerala that regulates the conversion of paddy lands on grounds of ecological sustenance.

Still, paddy farmers across Kerala incur significant personal losses by continuing with paddy cultivation, as is reflected in the benefits forgone due to conservation. The regulatory mechanism restricting paddy land conversion in the state of Kerala penalizes paddy farmers without adequately compensating them for private economic losses. In light of the results of the study, we argue that the current regulatory mechanism needs to be complemented by market-based policy instruments over and above the prevailing subsidy and production bonus to incentivize conservation efforts. This recommendation is in line with suggestions that call for the payment of an "ecological incentive" to paddy farmers, which were put forth in the draft Kerala State Agricultural Development Plan of 2013, and the Gadgil Committee recommendation to pay a "conservation service charge" to farmers who adopt environmentally sustainable farming practices in the Western Ghat region. The market-based policy instrument could be a "Pigouvian subsidy" or an "ecological incentive" that is at least equivalent to the opportunity cost of conservation, which is the "economic rent" forgone by paddy farmers who do not shift to banana—the first stage of conversion, which is still reversible. A shift to areca nut is considered a permanent conversion as paddy lands brought under areca nut lose their wetland characteristics, making it impossible to bring the land under paddy again. Hence, it is important to stop conversion when it is still reversible. Having said this, it is also important to acknowledge that an appropriate value for the Pigouvian subsidy or ecological incentive can only be arrived at through an economic valuation of the non-market ecosystem services provided by wetland paddy.

5. CONCLUSION

This study investigated the ecological rationale behind the restrictive regulations on paddy land conversion in Kerala, India. To accomplish this, a comparative analysis of the ecological health of paddy wetlands and its competing land uses—banana and areca nut—was done. Frog abundance and diversity were used as proxies to assess the ecological health of plots with alternate land uses because frogs are bio-indicators of ecological health. The study results establish that a shift away from paddy to banana and areca nut can have adverse effects on frog abundance and diversity.

The role of paddy lands in sustaining frog populations goes beyond its provisioning services, such as food and feed. The ability of paddy lands to support frogs is reflective of their capacity to bolster ecological health. The results of the study provide evidence of the significance of paddy agro-ecosystems in sustaining ecological health, which has larger societal benefits.

However, paddy farming is estimated to be less economically viable, and paddy farmers, who supply valuable non-market ecosystems services, as also evidenced in this study, need to be compensated for their private losses if a socially desirable and environmentally responsible land use system is to thrive. The state, in addition to promulgating legislations controlling land use, should pitch in with a Pigouvian subsidy (ecological incentives) to encourage paddy farmers to continue to cultivate paddy, at the risk of personal economic losses, for larger societal benefit. This Pigouvian subsidy should be in addition to the existing production bonuses and subsidies for paddy farmers in Kerala. It should at least match the opportunity cost of conserving paddy lands and provide the "economic rent" forgone by not shifting to banana. As indicated earlier, a shift to banana is considered an intermediary conversion as it is still reversible. The aim of the Pigouvian subsidy would be to arrest the intermediary conversion. This suggestion is also in line with the idea of ecological/conservation incentives referred to in previous state policy documents. As indicated earlier, estimating the Pigouvian subsidy is an area of future research and necessitates an economic valuation of ecosystem services from paddy wetlands.

Ethics Statement: I hereby confirm that this study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Data Availability statement: The data used in this paper is available on request under condition that it will not be used for research or commercial purposes without the knowledge or prior consent from the authors.

Conflict of Interest Statement: No potential conflict of interest was reported by the author.

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REFERENCES

Anil Kumar, Nadesapanicker, Girigan Gopi, and Parameswaran Prajeesh. 2010. "Genetic Erosion and Degradation of Ecosystem Services of Wetland Rice Fields: A Case Study from Western Ghats, India." In *Agriculture, Biodiversity and Market*: *Livelihoods and Agroecology in Comparative Perspective*, edited by Stewart Lockie and David Carpenter, 137–153. Devon, UK: Earthscan Publishers.

Baharuddin, Zainul Mukrim, Lukman Ramli, and Rashidi Othman. 2015. "The Diversity of Amphibian Species in Urban Lake as Ecological Indicator for Healthy Aquatic Environment." *Universiti Putra Malaysia* 8 (1): 70–76.

Bautista, Elmer G, and Masanori Saito. 2015. "Greenhouse Gas Emissions from Rice Production in the Philippines Based on Life-cycle Inventory Analysis." *Journal of Food, Agriculture and Environment* 13 (1): 139–144.

Beebee, Trevor J C, and Richard A Griffiths. 2005. "The Amphibian Decline Crisis: A Watershed for Conservation Biology?" *Biological Conservation* 125 (3): 271–285. https://doi.org/10.1016/j.biocon.2005.04.009

Blackwell, Martin S A, and Emma S Pilgrim. 2011. "Ecosystem Services Delivered by Small-scale Wetlands." *Hydrological Sciences Journal* 56 (8): 1467–1484. https://doi.org/10.1080/02626667.2011.630317

Chitra, K P. 2016. "How Kerala Is Destroying Its Wetlands: Amendments to Kerala Conservation of Paddy Land and Wetland Act 2008." *Economic & Political Weekly* 51 (22): 1–6.

Cochard, Roland, Suthamma Maneepitak, and Prabhat Kumar. 2014. "Aquatic Faunal Abundance and Diversity in Relation to Synthetic and Natural Pesticide Applications in Rice Fields of Central Thailand." *International Journal of Biodiversity Science, Ecosystem Services and Management* 10 (2): 157–173. https://doi.org/10.1080/21513732.2014.892029

Daniels, R J Ranjit. 1992. "Geographical Distribution Pattern of Amphibians in the Western Ghats in India." *Journal of Biogeography* 19 (5): 521–529. https://doi.org/10.2307/2845771

Das, Saudamini. 2011. "Sustaining Mangrove Forests to Reduce Vulnerability of Coastal Villages from Climate Change." In *Proceedings of Conference on Sustaining Commons: Sustaining Our Future, 13th Biennial Conference of the International Association for the Study of the Commons*, *Hyderabad, India, January 10–14*. http://hdl.handle.net/10535/7110

Dhanukar, Neelesh, and Anand Padhye. 2005. "Amphibian Diversity and Distribution in Tamhini, Northern Western Ghats, India." *Current Science* 88 (9): 1496–1501.

Dixon, Alan B, and Adrian P Wood. 2003. "Wetland Cultivation and Hydrological Management in Eastern Africa: Matching Community and Hydrological Needs through Sustainable Wetland Use." *Natural Resources Forum* 27 (2): 117–129. http://dx.doi.org/10.1111/1477-8947.00047

Duré, Marta I, Arturo I Kehr, Eduardo F Schaefer, and Federico Marangoni. 2008. "Diversity of Amphibians in Rice Fields from Northeastern Argentina." *Interciencia* 33 (7): 528–531.

Edirisinghe, Jayanthi P, and Channa N Bambaradeniya. 2006. "Rice Fields: An Ecosystem Rich in Biodiversity." *Journal of National Science Foundation of Sri Lanka* 34 (2): 57–59.

Government of India. 2011. *Report of the Western Ghats Ecology Expert Panel*. New Delhi, India: Ministry of Environment, Forest and Climate Change, Government of India.

Government of Kerala. 2021. *First Advance Estimates of Area, Production and Yield of Crops in Respect of Kerala State*. Thiruvanthapuram, India: Department of Economics and Statistics, Government of Kerala.

———. 2022. *Agricultural Statistics*. Thiruvanthapuram, India: Department of Economics and Statistics, Government of Kerala.

Hocking, Daniel J, and Kimberly J Babbitt. 2014. "Amphibian Contributions to Ecosystem Services." *Herpetological Conservation and Biology* 9 (1): 1–17.

Iwasaki, Yumi, Masashi Ozaki, Kimihito Nakamura, Haruhiko Horino, and Shigeto Kawashima. 2012. "Relationship between Increment of Groundwater Level at the Beginning of the Irrigation Period and Paddy Field Area in the Tedori River Alluvial Fan Area, Japan." *Paddy Water Environment* 11 (1–4): 551–558. http://dx.doi.org/10.1007/s10333-012-0348-9

Jaramillo, Fernando, Amanda Desormeaux, Johanna Hedlund, James W Jawitz, Nicola Clerici, Luigi Piemontese, Jenny Alexandra Rodríguez-Rodriguez, *et al.* 2019. "Priorities and Interactions of Sustainable Development Goals (SDGs) with Focus on Wetlands." *Water* 11 (3): 619. https://doi.org/10.3390/w11030619

Loumbourdis, Nikolaos S, Lason Kostaropoulos, Basiliki Theodoropoulou, and Dimitra Kalmanti. 2007. "Heavy Metal Accumulation and Metallothionein Concentration in the Frog Rana Ridibunda after Exposure to Chromium or a Mixture of Chromium and Cadmium." *Environmental Pollution* 145 (3): 787–792.

Luo, Yufeng, Haolong Fu, and Seydou Traore. 2014. "Biodiversity Conservation in Rice Paddies in China: Toward Ecological Sustainability." *Sustainability* 6 (9): 6107–6124. https://doi.org/10.3390/su6096107

Maltby, Edward, and Mike C Acreman. 2011. "Ecosystem Services of Wetlands: Pathfinder for a New Paradigm." *Hydrological Sciences Journal* 56 (8): 1341–1359. https://doi.org/10.1080/02626667.2011.631014

Matsuno, Yutaka, Kimihito Nakamura, Takao Masumoto, H Matsui, T Kato, and Y Sato. 2006. "Prospects for Multifunctionality of Paddy Rice Cultivation in Japan and Other Countries in Monsoon Asia." *Paddy Water Environment* 4 (4): 189–197. http://dx.doi.org/10.1007/s10333-006-0048-4

McCartney, Mathew P, and Helen A Houghton-Carr. 2009. "Working Wetland Potential: An Index to Guide the Sustainable Development of African Wetlands." *Natural Resources Forum* 33 (2): 99–110. http://dx.doi.org/10.1111/j.1477-8947.2009.01214.x

Millennium Ecosystem and Assessment Board. 2005. *Ecosystems and Human Well-being: Wetlands and Water Synthesis*. Washington, DC: Island Press.

Myers, Norman, Russell A Mittermeier, Cristina G Mittermeier, Gustavo A B Da Fonseca, and Jennifer Kent. 2000. "Biodiversity Hotspots for Conservation Priorities." *Nature* 403 (6772): 853–858. https://doi.org/10.1038/35002501

Naito, Kazuaki, and Hiroshi Ikeda. 2007. "Habitat Restoration for the Reintroduction of Oriental White Storks." *Global Environmental Research* 11 (2): 217–221.

Naito, Risa, Michimasa Yamasaki, Ayumi Lmanishi, Yosihiro Natuhara, and Yukihiro Morimoto. 2012. "Effects of Water Management, Connectivity, and Surrounding Land Use on Habitat Use by Frogs in Rice Paddies in Japan." *Zoological Science* 29 (9): 577–584. https://doi.org/10.2108/zsj.29.577

Naoki Katayama, Yuki G Baba, Yoshinobu Kusumoto, and Koichi Tanaka. 2015. "A Review of Post-war Changes in Rice Farming and Biodiversity in Japan." *Agricultural Systems* 132: 73–84. https://doi.org/10.1016/j.agsy.2014.09.001

Narayanan, Ratheesh M K, M P Swapna, and Anil N Kumar. 2004. *Gender Dimensions of Wild Food Management in Wayanad, Kerala*. Chennai, India: M S Swaminathan Research Foundation.

Osawa, Takeshi, Takaaki Nishida, and Takashi Oka. 2020. "Paddy Fields Located in Water Storage Zones Could Take Over the Wetland Plant Community." *Scientific Reports* 10 (14806): 1–8. https://doi.org/10.1038/s41598-020-71958-z

———. 2022. "Paddy Fields as Green Infrastructure: Their Ecosystem Services and Threatening Drivers." In *Green Infrastructure and Climate Change Adaptation: Function, Implementation and Governance*, edited by Futoshi Nakamura, 175–185. Singapore: Springer. https://doi.org/10.1007/978-981-16-6791-6_11

Parmar, Trishala K, Deepak Rawtani, and Y K Agrawal. 2016. "Bioindicators: The Natural Indicator of Environmental Pollution." *Frontiers in Life Science* 9 (2): 110–118. https://doi.org/10.1080/21553769.2016.1162753

Samantha, Trocchia, Sofiane Labar, Fagr K Abdel Gawad, Rabbito Dea, Gaetano Ciarcia, and Giulia Guerriero. 2015. "Frog Gonad as Bio-indicator of Sarno River Health." *International Journal of Scientific and Engineering Research* 6 (1): 449–456.

Sato, Taro, and Atsuki Azuma. 2004. "Frogs Abundance and Environments of Levees Relationships around Paddy Fields in Alluvial Fan." *Journal of the Japanese Institute of Landscape Architecture* 67 (5): 519–522. https://doi.org/10.5632/jila.67.519

Shivakoti, Ganesh P, and Ram C Bastakoti. 2010. *Multi-functionality of Paddy Fields over the Lower Mekong Basin*. Mekong River Commission Technical Paper No. 26. Vientiane, Lao PDR: Mekong River Commission.

Simon, Edina, Miklós Puky, Mihály Braun, and Béla Tóthmérész. 2011. "Frogs and Toads as Biological Indicators in Environmental Assessment." In *Frogs: Biology,* *Ecology and Uses*, edited by James L Murray, 141–150. Hauppauge, NY: Nova Science Publishers Inc.

Singh, Abhishek, Anil K Singh, Sapna Rawat, Neeraj Pal, Vishnu D Rajput, Tatiana Minkina, Ragini Sharma, Narendra P Singh, and Jayant N Tripathi. 2022. "Satellite-based Quantification of Methane Emissions from Wetlands and Rice Paddies Ecosystems in North and Northeast India." *Hydrology* 1 (3): 317–330. https://doi.org/10.3390/hydrobiology1030023

Tsuji, Marina, Atushi Ushimaru, Takeshi Osawa, and Hiromune Mitsuhashi. 2011. "Paddy-associated Frog Declines via Urbanization: A Test of the Dispersal–Dependent–Decline Hypothesis." *Landscape and Urban Planning* 103 (3–4): 318–325. https://doi.org/10.1016/j.landurbplan.2011.08.005

Vinayachandran, N, and V S Joji. 2007. *Ground Water Information Booklet of Wayanad District, Kerala State*. Bandlaguda, India: Central Ground Water Board, Ministry of Water Resources, Government of India.

Wang, Chun, Derrick Y F Lai., Jordi Sardans, Weiqi Wang, Congsheng Zeng, and Josep Peñuelas. 2017. "Factors Related with CH_4 and N_2O Emissions from a Paddy Field: Clues for Management Implications." *PLoS ONE* 12 (1): 1–23. https://doi.org/10.1371/journal.pone.0169254

ANNEXURES

Annexure A: Poisson Regression Function Equations

The probability density function of a Poisson distribution is given by

$$P(Y_i = y_i) = \frac{e^{-\lambda i}\, \lambda_i^{yi}}{y_i!}, y_i = 0,1,2, \ldots \ldots$$

where $P(Y_i = y_i)$ is the probability that the variable Y_i takes a non-negative integer value y_i, and λ_i is the mean (and the variance) of the variable y_i, which is assumed to have a Poisson distribution.

The marginal effect of variables on the probability of non-zero abundance/diversity can be estimated using the following equation:

$$\frac{\partial P(Y_J > 0)}{\partial x_J} = \frac{\partial [1 - e^{-\lambda_i}]}{\partial x_J} = -\frac{\partial \exp(-\hat{\lambda_i})}{\partial x_J} = \exp(-\hat{\lambda_i}) \frac{\partial \hat{\lambda_i}}{\partial x_J},$$

where $\frac{\partial \hat{\lambda_i}}{\partial x_J}$ is the marginal effect of the *j*th variable on the expected abundance and species diversity of the *i*th plot. The marginal effects measure the expected change in probability of the outcome variables—frog abundance and species diversity—with respect to unit change in the explanatory variables.

Table A1: Stepwise Poisson Regression Model Used in the Study – Variables Added in Each Model

Outcome Variables Frog Abundance and Frog Species Diversity	
Models	**Explanatory Variables**
1	Land use
2	Land use, biophysical parameters
3	Land use, biophysical parameters, plot history, boundary effect
4	Land use, biophysical parameters, plot history, boundary effect, manure use
5	Land use, biophysical parameters, plot history, boundary effect, manure use, per-acre fertilizer use, per-acre pesticide use, and per-acre labour use

Source: Analytical framework proposed in the study by the authors

Annexure B: Sampling Framework

Table A2: Sampling Framework

No.	**Agro-climatic Zone**	**Representative Panchayat**	**Ward Numbers**
1	AES 1 (drought area)	Nenmeni (block: Sulthan Bathery)	18, 19, and 23
2	AES 2 (valley paddy area)	Kaniyambatta (block: Mananthavady)	9 and 14
3	AES 3 (humid, high-altitude area)	Pozhuthana (block: Kalpetta)	1, 2, 4, and 5

Source: Wayanad district data, Government of Kerala.