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Restoration of Rice Ecosystem Services: 'Ecological Engineering for Pest Management' Incentives and Practices in the Mekong Delta Region of Vietnam

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Abstract: Ecological engineering is an agroecological approach to pest management that has been adopted by thousands of rice farmers in the Mekong Delta Region of Vietnam. Farmers adopted the intervention as part of a heuristic approach to developing the technology. This study assesses the knowledge, attitudes and practices related to ecological engineering among participating and non-participating farmers. Interviews with 315 farmers revealed a diversity of practices under the umbrella of ecological engineering, all of which were associated with the establishment of linear vegetation strips as habitat for natural enemies. As a restoring service from society to the rice ecosystem, ecological engineering incorporated significant positive-feedback loops, particularly regarding the production of supplementary foods (provisioning services) and the aesthetic value (cultural services) of planted rice bunds. Participating farmers reported fewer insecticide applications to their main rice crop; they applied insecticides at a later crop growth stage (protecting pest regulating services); and they reported higher rice yields. However, a high dependency on government support, the role of agrochemical extensionists in providing information, a tendency to apply pesticides to vegetation strips and little change in the appreciation of wildlife-related services all threaten the social sustainability of the intervention. We recommend greater attention to optimizing linear strips to not only support natural enemies but to also enhance supplementary farm incomes while reducing material and labor costs.

Keywords: diversification; ecosystem services; flower strips; insecticides; natural enemies; pesticides; rice–fish culture

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1. Introduction

Rice production landscapes constitute the principal terrestrial biome of much of Southeast Asia [1,2]. Since the Green Revolution, rice landscapes have transitioned from farmsteads producing traditional rice varieties on seasonally flooded land to intensified production systems with improved, high-yielding varieties under fuel-driven irrigation [3]. Intensified production systems are also recognized by relatively high inputs of inorganic fertilizers and pesticides [4–6]. Intensification has resulted in large increases in food production and is seen as a strategy to ensure food security for Asia's rapidly growing human population [3]. For example, rice yields in Vietnam are estimated to have increased from a national average of <2 tons ha^{-1} in 1980 to >5.5 tons ha^{-1} in 2015 [7]. Similar increases in rice production have been reported for several other Southeast Asian countries [8,9]. Increasing national rice productivity has been associated with improved rice varieties, increases in the use of nitrogenous fertilizers and the expansion of rice production areas [3–6]. In contrast, the contributions from pesticides to rice yield increases are far from clear. For example, rice production in Southeast Asia increased by <30% between 2000 and 2015, at a time when pesticide imports to the region had increased by over 300% [5]. Furthermore, certain regionwide pest problems, including frequent and sometimes devastating outbreaks of planthoppers and leafhoppers, are clearly associated with excessive pesticide use [10–16].

Evidence suggests that outbreaks of pests, such as planthoppers, in rice are at least partly due to insecticide-related reductions in the diversity, abundance and regulatory efficiency of natural enemies, including spiders, mirid bugs and parasitoid wasps [17–22]. Such outbreaks are a clear indicator of disruption to the regulating services provided by Asian rice ecosystems. Habitat diversification is proposed as a method to counter these outbreaks in rice by increasing rice ecosystem resilience against damaging pesticides and by restoring regulatory ecosystem services [23,24]. In particular, diversification by including flowering plants in rice ecosystems can provide supplementary food or refuges for natural enemies [25–28]. These functional plants can be conveniently deployed as linear strips on the bunds (levees) that transverse rice landscapes [24,25] (Figure 1). Because this approach is based on a sound knowledge of ecological interactions, it has been categorized as an ecological engineering approach to pest management [29,30]. The approach has been used with notable success in a range of other agricultural systems [31–33].

Figure 1. A rice bund planted with flowers as part of the ecological engineering approach to pest management in southern Vietnam. Image 'Ecological engineering' by CGIAR Climate licensed under CC BY-NC-SA 2.0.

A growing interest in ecological engineering for rice pest management is apparent through a number of recent case studies from across Asia [25,34–40]. Based on these studies, ecological engineering can be regarded as a primarily restorative practice because it responds to the 'state' of the rice ecosystem vis-á-vis the reduced effectiveness of natural enemies and consequent insect pest outbreaks [41]. Ecological restoration is one of a number of 'human services to ecosystems' as defined by Comberti et al. (2015) [42]. These services, which also include enhancing and protecting services, are frequently combined in community actions for biodiversity conservation under the influence of associated supporting services to ecosystems [42,43] (Figure 2). Supporting services to ecosystems include policies, legislation or directives around the sustainable management of the ecosystem, as well as community-held knowledge, beliefs and attitudes concerning components of the ecosystem or concerning the ecosystem as a whole. Horgan et al. (2021) [43] have indicated that cultural ecosystem services as defined during the Millennium Ecosystem Assessment (MEA [44]) are closely linked to supporting services to ecosystems and are largely determined by stakeholder interpretations of scientific knowledge and evolving beliefs with respect to the value of ecosystem components (Figure 2). The nature of these cultural ecosystem services (i.e., whether they are predominantly positive or negative) can determine whether supporting services to ecosystems ultimately facilitate or obstruct the enhancing, protecting or restoring services from human societies to ecosystems. Therefore, by exploring stakeholder appreciations of ecosystem services and their attitudes toward the implementation of conservation actions, assessments can be made regarding the sustainability and impact of restorative practices such as ecological engineering.

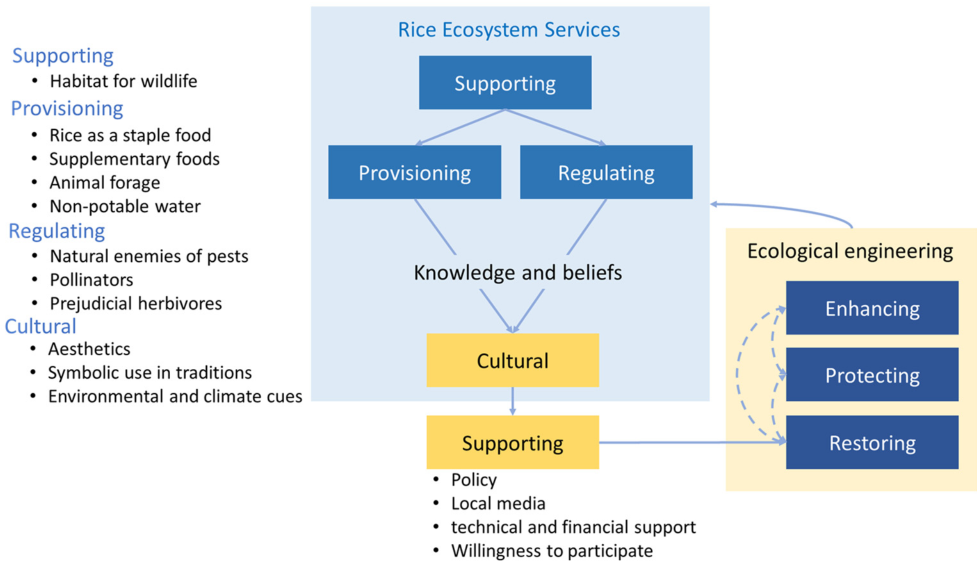

Figure 2. Linkage between the ecosystem services provided by tropical rice fields (indicated in the blue frame) and 'human services to the rice ecosystem' (indicated in the yellow frame) as mediated through policy, media and culture (supporting services to ecosystems (indicated by an orange rectangle)). The schematic presents the linkages as part of a positive-feedback system largely driven by farmers' appreciations of ecosystem services (knowledge and beliefs). Some of the supporting, provisioning, regulating and cultural services mentioned by farmers in this study are also listed.

In southern Vietnam, government support has facilitated the adoption of ecological engineering for pest management by thousands of rice farmers [24,39,45]. Despite this, there is still little information on the evolving knowledge, attitudes and practices of rice farmers regarding ecological engineering and little understanding of the potential social sustainability of ecological engineering in Vietnam [39,46]. To bridge this knowledge gap, we assessed the impacts of ecological engineering in southern Vietnam. We conducted a survey of ecological engineering and conventional rice farmers from five provinces in the Mekong Delta Region. In particular, we wished to document the diversity of practices implemented by farmers under the umbrella of ecological engineering. We assessed farmer satisfaction with these practices and whether adoption of ecological engineering was associated with reductions in insecticide applications and/or increased yields as part of a strategy to enhance regulating and provisioning ecosystem services. We further assessed whether the adoption of ecological engineering was associated with a greater appreciation of 'nature' and/or 'ecological balance' or was associated with an appreciation of recent changes to the state (sensu Maxim et al. (2009) [41]) of the rice ecosystem as indicators of declining ecosystem services. We linked these appreciations to provisioning, regulating and cultural ecosystem services as defined during the MEA [46] and evaluated their role in ultimately determining the nature of support for the continued implementation of ecological engineering. We discuss our results in terms of the social sustainability of implementing ecological engineering and make recommendations to adjust ecological engineering research and practices for improved adoption among rice farmers.

2. Methods

2.1. Study Sites

Surveys were conducted in the Mekong Delta Region (MDR) of southern Vietnam during September 2015. The MDR of Vietnam has a population of over 17 million (20% of Vietnam's population) [39]. Most of the region's land is dedicated to agriculture, with rice as the principal crop [47]. Farmers in southern Vietnam were among the first to adopt large-scale ecological engineering for pest management in rice production systems [39,45]. The technology is locally known as 'công nghệ sinh thái'. The visually aesthetic flower strips associated with ecological engineering (Figure 1), as well as close collaboration between scientists and local radio and TV stations, has drawn considerable media attention to the intervention in the MDR, further promoting adoption by farmers [23,24,48]. Although farmers will sometimes adopt ecological engineering on an individual basis, varying levels of local government support together with cooperation from village leaders and a focus on community-based adoption has resulted in certain regions or villages having relatively high proportions of participating farmers [39].

We interviewed farmers at 19 villages distributed across five provinces (Figure 3). To facilitate in situ interviews, villages were identified as having relatively high numbers of farmers with experience of ecological engineering; however, most villages had a majority of conventional farmers. The villages were Tân Lý Tây (15 farmers interviewed), Tân Hội Đông (27 farmers) and Điềm Hy (9 farmers) in Châu Thành District (Tiền Giang Province); Tân Phú (15 farmers) in Cai Lậy District (Tiền Giang); Hiếu Nhơn (32 farmers), Trung Hiếu (17 farmers), Hieu Thanh (6 farmers), Vũng Liêm (2 farmers) and Trung Thành Đông (3 farmers) in Vũng Liêm District (Vinh Long Province); Vĩnh Khánh (22 farmers) and Vĩnh Trạch (3 farmers) in Thoại Sơn District (An Giang Province); Bình Hòa (22 farmers) and Vĩnh Thành (12 farmers) in Châu Thành District (An Giang); Vĩnh Hưng (16 farmers) and Châu Thới (14 farmers) in Vĩnh Lợi District (Bạc Liêu Province); Vĩnh Phú Đông (30 farmers) and Phước Thành (10 farmers) in Phước Long District (Bac Liêu); Thạnh Lộc (30 farmers) in Châu Thành District (Kiên Giang Province); and Thạnh Đông A (30 farmers) in Tân Hiệp District (Kiên Giang) (Figure 3). Collaborators at Provincial Plant Protection Departments coordinated with local village leaders at each of the selected villages to invite farmers to attend pre-established venues (usually the house of the leader of the farmers' association or a village hall). No information was given to either the village leaders or the farmers about the content of the questionnaire at any time prior to the surveys.

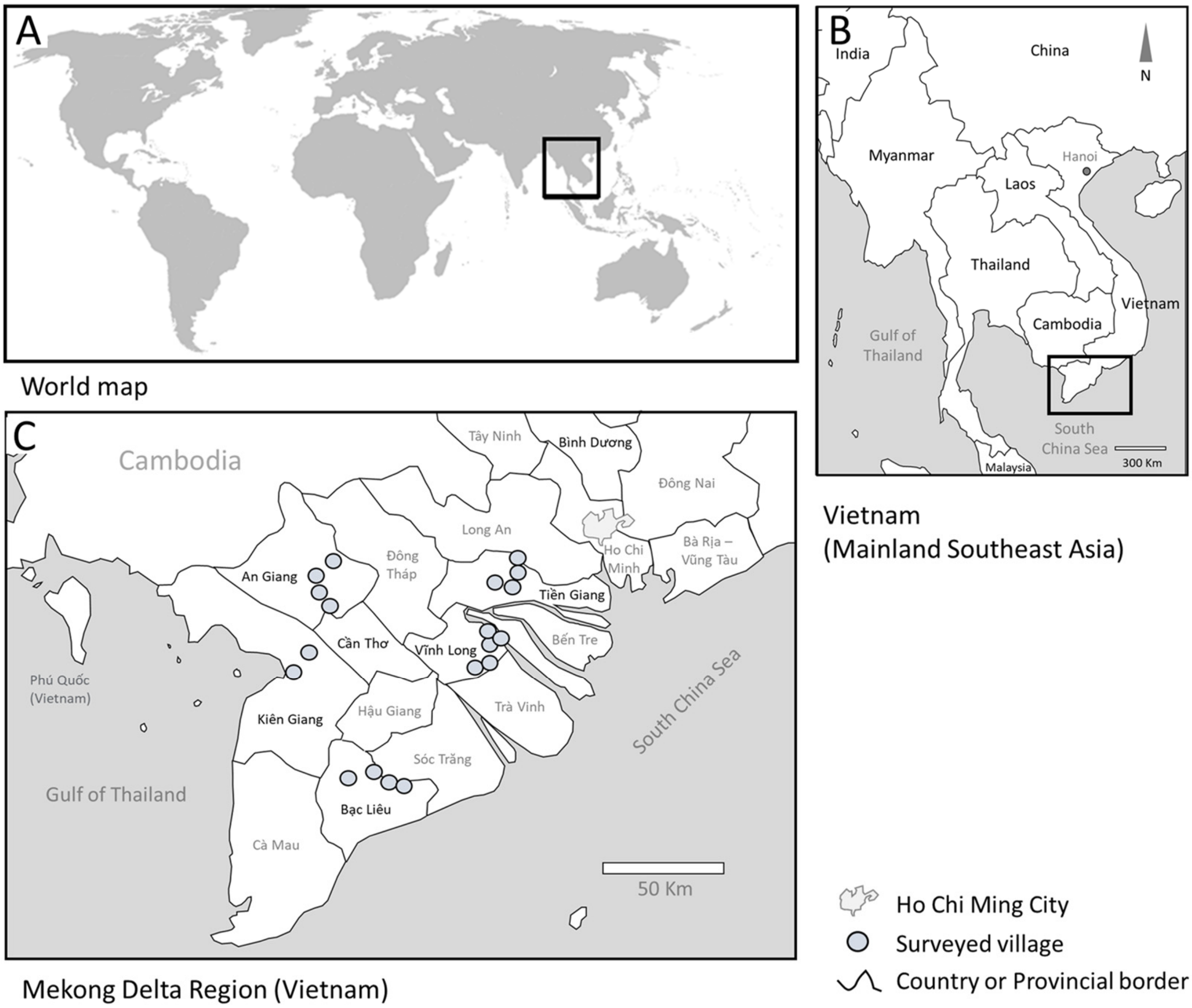

Figure 3. Map of study region. (**A**) indicates the location of mainland Southeast Asia, (**B**) indicates the location of the Mekong Delta Region (MDR) in Southeast Asia and (**C**) indicates 19 villages in rice-growing areas of the MDR that were surveyed in 2015.

2.2. Data Collection

Farmers were interviewed in Vietnamese by 20 trained interviewers. Using structured questionnaires, we elicited information from 315 rice farmers on their sources of information regarding pesticides and ecological engineering, on their farming practices and on their appreciations of the animal components of the rice ecosystem and the current state of the ecosystem. The questionnaire was developed according to the knowledge, attitudes and practices (KAP) survey technique [49]. This technique allows a relatively rapid appraisal of interventions in regions without pre-established researcher–community relations and has the advantage of being relatively resilient to varying interviewer techniques.

The survey consisted of four main parts: these were (1) farmers' profiles, (2) farmers' understandings of the concept of ecological engineering (using the term 'công hghệ sinh thái'), (3) farmers' pest management practices including practices related to ecological engineering and their sources of information regarding those practices and (4) farmers' appreciations of the state of the rice ecosystem and their interpretations of 'change impacts' related to that state. Part 4 consisted of a range of simple questions related to farmer perceptions of the abundances of different ecosystem components. For example, farmers were asked to indicate whether they perceived the abundance of birds, aquatic vertebrates (fish and frogs), snakes, butterflies and bees and rice pests as 'extinct', 'much declined',

'declined', 'no change', 'increased' or 'much increased' since they began rice farming. Farmers were also asked to indicate their perceptions of rice yields using the same scale (without 'extinct'). Farmers were then asked to indicate why they felt that birds, aquatic vertebrates (indicated as 'fish and frogs') and pest insects were each undergoing abundance changes. Finally, the farmers were asked to indicate the roles (ecosystem services) of birds, fish, frogs, snakes, bees and butterflies in the rice ecosystem.

The questionnaire was developed based on a focus group discussion (FGD) conducted in 2014 at Tân Lý Tây and was pre-tested, and amended where needed, in consultation with some of the interviewers and local farmers prior to conducting the survey proper. Based on the FGD and pre-testing, the predominant answers to questions were listed and coded on the questionnaire forms; furthermore, we incorporated triangulation into the survey to improve information quality and to cross-check responses [50,51]. Interviewers were also encouraged to record qualitative information during the interviews [52].

Interviewers conducted face-to-face interviews with the farmers that lasted approximately 12 min each. Prior to conducting the interviews, each farmer was informed about the objectives of the interview, how the data would be used and how the data would be stored (including that the farmers' names would not be recorded and that data would not be linked to individual farmers). Farmers were also advised that they were not obliged to answer any questions. Farmer responses to the KAP survey questions included unverified perceptions of measurable parameters (e.g., yields, pest damage, costs); because we mainly assessed attitudes and incentives for participation in ecological engineering, such perceptions constitute an influential component of supporting services to ecosystems and can sometimes be more influential than the real parameter values [43].

2.3. Data Analyses

Farmers were divided into three groups: (i) farmers who, at the time of the interviews, were participating in ecological engineering (henceforth 'current-EE' farmers); (ii) farmers who had participated in the past but had, by the time of the interviews, abandoned the intervention (henceforth 'former-EE' farmers); and (iii) standard practice farmers who had never implemented ecological engineering for pest management (henceforth 'conventional' farmers). Farmers had been asked to categorize their own farming methods; however, some farmers that described themselves as conventional had adopted practices that included characteristic interventions associated with ecological engineering (e.g., they planted flowers on their rice bunds). These farmers were therefore re-classified as participating in the ecological engineering movement (i.e., either current-EE or former-EE).

Where responses to questions were nominal or ordinal, we applied 2×2 contingency tables to test for associations with farmer category (conventional, current-EE, former-EE) and province. In cases where farmers listed multiple responses to questions (e.g., source of information = Department of Agriculture and universities and neighbors), we assumed that responses were largely independent of each other, and each answer was analyzed separately. Where province had no effect, we removed the factor from the analyses. To assess farmer responses to growing either vegetables or flowers on their bunds, we used individual bunds as subjects (i.e., all farmers were current-EE). At Bạc Liêu, a number of farmers produced fish or crabs in their rice fields. We examined aspects of fish production among these farmers and assessed associations between fish farming and rice pest management. Tests of homogeneity and of mutual and partial independence were conducted for all associations using χ^2 analyses.

Continuous dependent variables (e.g., reported chemical applications, reported species diversities, reported yields) were analyzed using univariate general linear models (GLM). The models examined the effects of farmer category, province and their interactions on farmer characteristics and practices. In all cases, province had no significant effect on farmer responses and was subsequently removed from the analyses. Where data were available for two seasons (e.g., yields or pesticide use associated with the previous February and June/July harvests), results were analyzed using repeated-measures GLMs. We used

Tukey post hoc tests to assess homogenous farmer categories. Residuals were examined after all parametric analyses and were normal and homogenous. Univariate GLMs and contingency table analyses were conducted using SPSS version 23.0 (IBM SPSS Statistics).

Three sets of appreciation variables were analyzed to understand the perceptions of farmers from each of the three categories concerning (a) trends in the abundance of rice-associated animal groups, as well as trends in the abundance of rice pests and yields; (b) farmer interpretations of the reasons behind these trends; and (c) the ecosystem services associated with a range of animals present in rice fields. Ecosystem services were categorized as regulating (e.g., natural enemies, pollinators, herbivores), provisioning (e.g., animals as food) and cultural (e.g., egrets as a sign of coming typhoons) (Figure 2). We further differentiated the services as positive services or negative disservices (e.g., herbivory is a regulating disservice). For analyses of farmers' interpretations of the reasons for changing animal abundances, we categorized impacts as 'hunting', 'pesticides', 'fertilizers', 'water/soil contamination', 'cropping intensity', 'climate', 'habitat change', 'insecticide resistance', 'natural enemies', 'rice management practices' or 'no knowledge'. In the case of birds and fish, farmers always referred to declining abundances. However, for pests, farmers referred to increasing or declining abundances; therefore, for pests we differentiated each impact as (a) responsible for increasing pest incidence or (b) responsible for declining incidences or for maintaining incidences without change.

Each of the three sets of appreciation variables were analyzed separately using permutation-based univariate or multivariate analysis of variance (PERMANOVA) routines [53]. 'Farmer category' was treated as a fixed factor with three levels: conventional, current-EE and former-EE. PERMANOVA pair-wise tests were used to check for differences between levels. PERMANOVA analyses were based on Bray–Curtis similarity resemblance matrices with each analysis permutated 9999 times. The similarity percentages routine (SIMPER) was applied to each of the three sets of variables to understand which variables contributed most to generate dissimilarities between pairs of groups [54]. Only variables contributing at least 5% to the dissimilarity were included in the SIMPER analyses. PERMANOVA and SIMPER routines were performed using PRIMER (v. 6.1.16) and the PERMANOVA + extension (v. 1.0.6).

3. Results

3.1. Farmer Profiles

Farmer profiles are presented in Table S1. The farmers associated with each of the three farming categories had largely similar profiles (Table S1). Apart from rice, a large proportion of farmers also grew horticultural or fruit crops on their land, irrespective of farming category (21.9%: $\chi^2 = 2.274$, $p = 0.685$); horticultural crops included chilies, *Capsicum* spp., cucumbers, *Cucumis sativus* L., luffa, *Luffa* spp., and gourds, *Lagenaria* spp., among other vegetables. The only significant difference between farmers in the three categories was that the former-EE farmers tended to have larger farms (2.48 $\pm$ 0.60 ha) than farmers in the other two groups (conventional = 1.53 $\pm$ 0.12 ha; current-EE = 1.84 $\pm$ 0.17 ha: Table S1).

3.2. Knowledge of Ecological Engineering

Most of the farmers (80.5%) that we surveyed had heard of ecological engineering (i.e., công nghệ sinh thái); however, fewer of the conventional farmers were familiar with the term compared to farmers from the other two groups (Table 1). A small number of farmers (<6%), whose farm practices included planting flowers or vegetables on their bunds in response to government or other incentives, were unfamiliar with the term or concepts around ecological engineering (Table 1).

Table 1. Farmer exposure to information concerning ecological engineering for pest management and their responses to various objectives of the intervention.

Responses	Conventional [1]	Current-EE [1]	Former-EE [1]	L-R χ^2 -Statistic [2]
Heard of ecological engineering [3]	48.3 ^{a}	95.5 ^{b}	89.7 ^{b}	8.482 ***
Understanding of ecological engineering				
(i) Grow flowers on bunds	60.9	90.6	77.1	5.006 ^{ns}
(ii) Reduce or stop using pesticides	13.0 ^{a}	33.9 ^{b}	17.1 ^{a}	11.693 ***
(iii) Conserve natural enemies	11.6 ^{a}	23.6 ^{b}	5.7 ^{a}	8.395 **
(iv) Grow vegetables on bunds	4.3	12.6	11.4	3.494 ^{ns}
(v) Other management-related interventions	2.9	6.3	8.6	1.647 ^{ns}
(vi) Protect the environment	4.3	7.1	0.0	2.941 ^{ns}
Who recommended ecological engineering				
(i) Department of Agriculture	11.6 ^{a}	56.7 ^{b}	42.9 ^{b}	37.829 ***
(ii) Extension technicians	17.4 ^{a}	43.3 ^{b}	31.4 ^{b}	13.527 ***
(iii) TV/radio	52.2 ^{b}	18.9 ^{a}	14.3 ^{a}	28.398 ***
(iv) University personnel	5.8 ^{a}	18.1 ^{b}	11.4 ^{ab}	5.975 *
(v) Neighboring farmers	14.5 ^{b}	2.4 ^{a}	2.9 ^{a}	12.299 ***
(vi) Village leaders	0.0 ^{a}	11.8 ^{b}	5.7 ^{ab}	9.312 **
(vii) Agrochemical companies	0.0 ^{a}	10.2 ^{b}	5.7 ^{ab}	7.757 *
Why ecological engineering was recommended				
(i) To protect/enhance natural enemies	37.7 ^{a}	70.9 ^{b}	21.2 ^{a}	21.718 ***
(ii) To reduce pesticide use	59.4 ^{b}	48.0 ^{ab}	34.3 ^{a}	6.065 *
(iii) To reduce input costs	26.1 ^{a}	42.5 ^{b}	22.9 ^{a}	7.859 *
(iv) To restore ecological balance	5.8 ^{a}	33.1 ^{b}	28.6 ^{b}	18.530 ***
(v) To improve farmer health	17.4	25.2	28.6	2.142 ^{ns}
(vi) To protect the environment	11.6 ^{a}	27.6 ^{b}	22.9 ^{b}	6.638 *
(vii) To beautify the landscape	14.5	18.9	11.4	1.388 ^{ns}
Why convinced to practice ecological engineering				
(i) Government support		51.9	38.5	2.173 ^{ns}
(ii) Simple to adopt		30.1	30.8	0.007 ^{ns}
(iii) To increase farm profits		26.3	12.8	3.077 ^{ns}
(iv) Advice from peers		16.5	10.3	0.928 ^{ns}
(v) To use plants grown on bunds		6.8	15.4	2.813 ^{ns}
(vi) To conserve natural enemies		6.8	5.1	0.135 ^{ns}
(vii) To reduce weeds on bunds		7.5	2.6	1.237 ^{ns}
(viii) Because insecticides had failed		0.0	7.7	10.412 ***
(ix) To reduce pests in rice		1.5	2.6	0.198 ^{ns}
(x) To reduce pesticide use		3.8	0.0	1.510 ^{ns}

[1]: means with the same letters indicate homogenous groups; [2]: ^{ns} = $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$; χ^2 degrees of freedom = 2; [3]: n = 133, 134 and 39 for conventional, current-EE and former-EE farmers, respectively, when considering the frequencies of farmers having heard of the intervention; otherwise, n = 69, 127 and 35 for conventional, current-EE and former-EE farmers, respectively.

Among farmers familiar with the term ecological engineering, the majority (79.7%) described it as ‘growing flowers on rice bunds’, and 9.9% described it as ‘growing vegetables on rice bunds’. Relatively few farmers (17.3%) mentioned that the intervention was to protect or encourage natural enemies, although 25.1% mentioned that it was to reduce (farmers mainly said ‘to stop’) pesticide applications. In both cases, a higher percentage of current-EE farmers mentioned the reduction of pesticide use and the promotion of natural enemies as objectives (Table 1).

Farmers with experience of ecological engineering mainly received their information from extension technicians and agents related to the Department of Agriculture (Table 1). A larger proportion of the conventional farmers obtained their information about the intervention from the TV or radio and from neighboring farmers (Table 1). Farmers in Vinh

Long in particular more frequently mentioned village leaders and agrochemical companies (31.1%) as recommending the intervention compared to farmers from the other provinces (village leaders: $\chi^2 = 48.920$, $p < 0.001$; agrochemical companies: $\chi^2 = 55.981$, $p < 0.001$).

When asked why ecological engineering had been recommended, 53.5% of farmers mentioned that it was to protect natural enemies or enhance their abundance. However, this objective was mentioned more frequently by currently participating farmers (70.9%) than by farmers from the other two groups (Table 1). Current-EE farmers also more frequently recalled objectives related to reducing input costs and, together with former-EE farmers, they also recalled objectives related to a restoration of ecological balance or protecting the environment. Conventional farmers mainly recalled recommendations related to reducing pesticide use (Table 1). Nevertheless, among current-EE and former-EE farmers, the ultimate reasons for adopting the practice were generally similar, with most mentioning government support and few mentioning objectives related to the restoration of ecosystem services (Table 1).

Among 32 farmers who gave reasons for abandoning ecological engineering, 84.4% mentioned that it was either impractical (59.4%: i.e., bunds too narrow, issues with water) or too labor or time consuming (40.6%). Other reasons for abandoning the practice included theft (6.2%), issues with rats (6.2%), poor access to materials (6.2%), problems with herbicide drift from neighboring farms (3.1%) and the need to graze livestock on the bunds (3.1%).

3.3. Ecological Engineering Practices

Information on bund management is presented in Tables S2 and S3. Similar percentages (62.2%) of conventional and ecological engineering farmers removed weeds from their rice bunds, with 38.4% of farmers using herbicides on the bunds (Table S2). More farmers from An Giang (61%), Bạc Liêu (70%) and Kiên Giang (40%) used herbicides on their bunds compared to the other two provinces (<14%: $\chi^2 = 87.77$, $p < 0.001$). Among farmers with current or past experience of ecological engineering, 47.8% planted flowers only, 17.5% planted vegetables only and 36.5% planted both flowers and vegetables on the bunds. The total richness of planted species and richness of vegetable or flower species were similar between current-EE farmers (2.83 ± 0.14) and former-EE farmers (2.13 ± 0.19) (Table S2). Fourteen vegetables and ten ornamentals were mentioned by farmers as species planted on bunds. A small number of farmers also mentioned weeds or tree species as part of their ecological engineering designs (Table S3).

Current-EE farmers were more likely than former-EE farmers to mention increased farm profits or provision of supplementary foods and materials as reasons for their choice of plants ($\chi^2 = 27.463$, $p < 0.001$: Table S2). Farmers that planted vegetables (64.5%) or both vegetables and flowers (46.6%) on their bunds were more likely to mention profits as a motivation than farmers who planted flowers (14.5%); more farmers that planted flowers indicated landscape (flowers = 59.0%, vegetables = 22.6%, both = 25.9%) and recommendations (flowers = 16.9%, vegetables = 0.0%, both = 5.2%) as their principal reasons behind plant choice ($\chi^2 = 48.429$, df = 6, $p < 0.001$). More current-EE farmers indicated that their activities were coordinated at a community level (particularly farmers from Vinh Long: 73.6% of 29 farmers) compared to former-EE farmers (i.e., 45.5% made decisions alone: Table S2).

Farmers mainly acquired vegetable seeds at agricultural supply stores, whereas flower seeds were mainly received from the government (Table 2). Many farmers also collected flower seeds from 'wild' areas; these were mainly *Lantana camara* L. seeds collected by farmers in Vinh Long. The management of vegetables and flowers on bunds was largely similar; however, more flower bunds than vegetable bunds were planted or transplanted before the rice crop, and more insecticide was applied to bunds with vegetables than with flowers (Table 2). The vegetables produced on bunds were mainly used as supplementary foods for farming households and/or gifted to relatives and neighbors. Flowers were often sold at local markets, particularly in Vinh Long Province (Table 2). Farmers did not indicate flower growing as profitable; although, a large proportion indicated that they could sell their flowers. In total, 32% of farmers that grew vegetables on the bunds indicated that the practice was profitable. Over 60% of farmers who found vegetable production profitable applied insecticides to their bund vegetables (χ^2 = 10.915, df = 1, p = 0.001).

Table 2. Management of flowers and vegetables grown on rice bunds as part of ecological engineering for pest management. Note that these farmers were all currently participating in ecological engineering (current-EE). For comparisons between conventional, current-EE and former-EE see Table S2, and for a list of vegetable and flower species planted on bunds see Table S3.

Responses	Vegetables	Flowers	L-R χ^2 -Statistic [1]
Use a frame (%)	12.5	0.0	17.751 ***
Remove weeds (%)	65.9	72.6	1.132 ns
Apply herbicide (%)	36.4	38.5	0.105 ns
Apply insecticide (%)	23.9	3.0	23.38 ***
Seed source (%)			
(i) Department of Agriculture	9.1	42.2	162.57 ***
(ii) Neighboring farmers	3.4	16.3	
(iii) Collected wild	1.1	38.5	
(iv) Store bought	86.4	3.0	
Sow or plant before rice (%)	30.7	45.9	5.162 *
Time before rice of sowing/planting to bunds (%)			
(i) >1 week before	19.3	27.4	6.050 ns
(ii) <1 week before	11.4	18.5	
(iii) <1 week after	52.3	37.0	
(iv) >1 week after	17.0	17.0	
Use of produce			
(i) Home use	59.1	35.6	12.185 ***
(ii) No use	4.5	5.2	
(iii) Sell to market/traders	36.4	59.2	

[1]: ns = $p > 0.05$, * $p < 0.01$, *** = $p < 0.001$.

When asked about their satisfaction with planting on bunds, 61.7% of current-EE farmers were 'satisfied' with their practices, and a further 32.5% were 'somewhat satisfied'. This was significantly more than among former-EE farmers (45.2%: χ^2 = 37.448, p < 0.001: Table S4). As their main reasons for satisfaction, farmers mentioned reduced pest, disease and weed damage (49.6%), an improved environment, including a more aesthetically pleasing landscape (47.8%) and reduced input costs (43.5%). More current-EE farmers (47.1%) mentioned reduced costs, compared to former-EE farmers (15.4%, χ^2 = 5.25, p = 0.022). Other reasons for satisfaction included increased farm profits (including supplementary goods) (30.4%) and improved wellbeing (including a sense of joy/happiness, improved health and fewer worries about crop/pest management) (23.5%) (Table S4). Current-EE and former-EE farmers had similar reasons for dissatisfaction with the method including issues around drudgery, costs and consequences for other aspects of crop management (i.e., rodents, herbicide drift, drainage) (Table S4).

3.4. Fish–Rice Culture

Among farmers surveyed in Bạc Liêu, 27% (19 farmers) produced fish in their rice paddies. Fish production was significantly associated with ecological engineering (Table 3). The main species produced were catfish, *Pangasianodon* sp., tilapia, *Oreochromis* spp., and mud crabs, *Scylla* sp., all of which were sourced locally. Eight of the farmers produced fish simultaneously with rice; the remaining farmers rotated fish with rice by producing fish during the high-water season. In total, 73.7% of farmers that produced fish or crabs indicated that their production was to supplement farm incomes. The remaining farmers produced fish for home consumption; these latter were all farmers that produced fish among their rice plants (i.e., rice–fish coculture).

Table 3. Details of fish production in paddy landscapes at Bạc Liêu.

Responses	Conventional [1]	Ecological Engineering	L-R χ^2 -Statistic [2]
Farmers producing fish or crabs (%) [3]	17.9	45.8	6.423 **
Practice rice–fish coculture (%) [4]	37.5	45.5	0.121 ns
Apply chemicals to fish ponds (%) [4,5]	50.0	36.4	0.353 ns
Fish production for profit (%) [4]	75.0	72.7	0.012 ns
Fish regarded as natural enemies (%) [4]	37.5	100.0	6.386 **

[1]: former-EE farmers are included with the conventional farmers; [2]: ns = $p > 0.05$, ** $p < 0.01$; [3]: total of 70 farmers; [4]: total of 19 farmers; [5]: mainly applied hydrated lime to increase hardness and raise pH of the ponds.

Farmers that produced fish made fewer insecticide applications to their rice fields (fish = 2.63 ± 0.34, no fish = 3.65 ± 0.21; $F_{1,66} = 6.404$, $p = 0.028$), irrespective of farming method (conventional or ecological engineering). Similar percentages of fish producers used chemicals as part of fish production (Table 3); however, this mainly referred to the application of lime to their fish ponds. When asked whether fish provide services other than food production to their paddy fields, farmers mentioned that the fish 'clean the water' or 'consume decaying vegetation', but no farmers mentioned a possible role for fish in crop pest management. However, when asked what role 'fish' (in general) play in the environment (see below), fish producers that also practiced ecological engineering were more likely to mention fish as natural enemies (Table 3).

3.5. Insecticide Use in Rice Fields

Only six (four current-EE and two conventional) of the farmers we surveyed had not used insecticides during the year of sampling. Farmers made up to 8 applications in a growing season; however, on average, farmers applied insecticides < 3 times (Table 4). Current-EE farmers made fewer applications than conventional and former-EE farmers and began their applications later (Table 4). The principal targets of applications were leaffolders, *Cnaphalocrocis medinalis* (Guenée) (mainly among current-EE and former-EE farmers) and panicle mites, *Steneotarsonemus spinki* Smiley (mainly among conventional farmers). Farmers received information on insecticides from a range of sources (Table 4). There was no relation between the source of information about insecticides and the numbers of applications farmers made in either season. Rice yields were higher in the first season (February harvest), and current-EE farmers reported higher rice yields than conventional farmers in both seasons (Table 4).

Table 4. Information from farmer surveys related to insecticide applications to rice crops and reported grain yields.

Responses	Conventional	Current-EE	Former-EE	Test Statistic-Season [1]	Test Statistic -Method [1]
Insecticide applications (number)					
2015 1st season	2.57 ± 0.12 [b]	2.01 ± 0.11 [a]	2.56 ± 0.22 [b]	4.848 *	7.809 ***
2015 2nd season	2.45 ± 0.12	1.82 ± 0.12	2.56 ± 0.23		
Time of first application (DAS/DAT)					
2015 1st season	31.59 ± 0.95 [a]	35.86 ± 1.10 [b]	29.53 ± 1.98 [a]	0.010 ns	7.958 ***
2015 2nd season	31.13 ± 1.06	36.61 ± 1.10	28.67 ± 1.91		

Table 4. *Cont.*

Responses	Conventional	Current-EE	Former-EE	Test Statistic-Season [1]	Test Statistic -Method [1]
Priority pests					
(i) No pests	15.4	9.0	12.8		41.374 ***
(ii) Leaffolders	39.2	51.1	53.8		
(iii) Panicle mites	30.1	14.3	0.0		
(iv) Planthoppers	12.6	16.5	17.9		
(v) Case worms	2.8	9.0	12.8		
(vi) Stemborers	0.0	0.0	2.6		
Information sources					
(i) Chemical industry	44.0	54.9	53.8		3.555 ^{ns}
(ii) Self-taught	31.9	38.3	48.7		3.915 ^{ns}
(iii) Farm neighbors	20.6 ^{b}	8.3 ^{a}	5.1 ^{a}		11.852 ***
(iv) Department of Agriculture	7.1	12.0	12.8		2.351 ^{ns}
(v) TV or radio	5.7	9.0	10.3		1.506 ^{ns}
Reported yield (tons/ha)					
2015 1st season	7.01 ± 0.09 ^{a}	7.40 ± 0.11 ^{b}	7.35 ± 0.12 ^{ab}	347.574 ***	5.929 ***
2015 2nd season	5.73 ± 0.07	6.06 ± 0.10	5.98 ± 0.12		

[1]: test statistics are F-values for pesticide applications, time of application and yields; L-R χ^2 for all other variables; ^{ns} = $p > 0.05$, * $p \leq 0.01$, *** = $p \leq 0.001$; lowercase letters indicate homogenous groups; interactions had no significant effects.

3.6. Farmer Appreciation of Conservation and Ecosystem Services

PERMANOVA results indicated that rice management had a significant effect on how farmers perceive the ecosystem services provided by biodiversity (Pseudo-F = 2.329, $p = 0.031$). Pair-wise tests indicated significant differences between current-EE and former-EE farmers (t = 1.914, $p = 0.015$) but not between any other pair of groups ($p > 0.05$) (Figure 4). SIMPER analysis showed that, compared to the current-EE group, a higher proportion of former-EE farmers perceived butterflies and fish as providers of regulating services; frogs and fish as providers of provisioning services (i.e., food); and also butterflies as providers of regulating disservices (i.e., rice pests). Moreover, a higher proportion of current-EE farmers perceived fish as providers of regulating services (Figure 4).

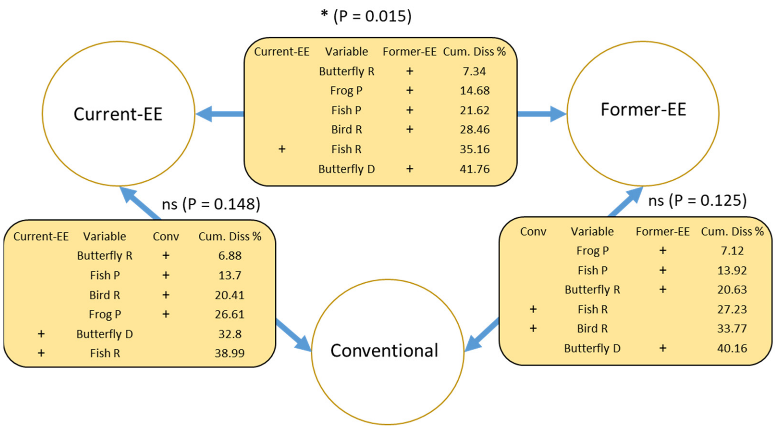

Figure 4. Differences between farmers' appreciations of biodiversity based on rice management (in circles). Results of PERMANOVA pair-wise analyses are shown. SIMPER analyses (in orange boxes) show the variables (an animal and an observed ecosystem service: 'R' for regulating services, 'P' for provisioning services, 'D' for regulating disservices) contributing most to the dissimilarity between each pair of groups. The '+' symbols indicate the group in which each variable is more prevalent. 'Cum. Diss %' = cumulative dissimilarity between pairs, expressed as a percentage.

PERMANOVA results showed no significant differences in group-related perceptions of trends in animal abundance and rice yields (Pseudo-F = 1.114, $p = 0.363$) or of the reasons underlying changing animal abundances (Pseudo-F = 1.915, $p = 0.067$). However, compared with the other groups, higher numbers of conventional farmers perceived increasing trends in both rice pests and yields (Figure S1). Farmers from all three categories shared a common perception about the two main reasons for declines in biodiversity, which they indicated as hunting and pesticide use (Figure S2).

4. Discussion

Ecological engineering for pest management was adopted by thousands of Vietnamese farmers as a heuristic approach [55,56], often without accurate knowledge to support interventions. However, this case of participatory research has been highly effective in generating a large amount of information related to flower or vegetable strips and their effects on pest insects [25] and, according to our results, has received generally favorable reviews from participating farmers. However, our results also indicate that the heuristic approach carries with it an inherent risk of generating apathy or dissatisfaction as communities of farmers iterate on methods and practices. We discuss our results by highlighting some of the strengths and limitations of the ecological engineering movement in the MDR.

4.1. Strengths

In the MDR of Vietnam, ecological engineering for pest management has had tremendous support from regional and local governments (supporting services to ecosystems: Figure 2). This included policy at provincial levels to encourage farmers and villages to adopt the intervention. Government support was available for farmers to source flower seeds and to advise farmers on aspects of implementation (Table 1). Researchers and technicians at regional research centers such as the Southern Regional Plant Protection Center were also supported to conduct research aimed at assessing the effects of flower and vegetable strips on natural enemy and pest abundance, thereby responding to knowledge gaps associated with the intervention [25]. This research highlighted several benefits derived from flower strips including the suppression of key rice pests [25].

Government support had a major impact on farmer willingness to participate in ecological engineering. Current-EE farmers were more likely to mention government support (>56.7%) than former-EE farmers as a reason for participating in the movement. Furthermore, 51.9% of current-EE farmers mentioned government-provisioned resources (mainly flower seeds) as a major incentive for their participation (Figure 5). Government support and the movement's momentum may have influenced other stakeholders to also promote the intervention. For example, significantly more current-EE farmers (10.2%) than farmers in the other groups indicated that they received recommendations from agrochemical dealers to participate in ecological engineering (Figure 5). Finally, media attention, sometimes promoted through financial and technical support from national and international development projects [23,48], was widely acknowledged by farmers as a further source of recommendations (Figure 5).

Our results indicate that ecological engineering generated a series of positive feedback loops to further support participation (Figure 5). For example, significantly more current-EE farmers (40.6%) than former-EE farmers indicated that they perceived ecological engineering as improving their farm economies by increasing rice yields, providing supplementary goods such as fruits and vegetables for home consumption, producing flowers that they could sell at local markets and producing forage for animals or materials for construction (Figure 5). Furthermore, significantly more current-EE farmers (47.1%) than former-EE farmers perceived more favorable cost/benefit ratios associated with rice farming (Figure 5). Possibilities for the provisioning of supplementary goods through ecological engineering have been observed in previous studies [12,36,37]. Indeed, a recognition of the provisioning services provided by flower and vegetable strips distinguished current-EE farmers from former-EE farmers in our study, thereby highlighting the role of this feedback in sustaining the practice. Farmers did not report landscape aesthetics as governing their decisions to participate in the ecological engineering movement. However, a large number of farmers (42.9%) mentioned that their planted bunds were aesthetically pleasing (Figure 5), thereby constituting a further feedback loop that promotes the social sustainability of the intervention.

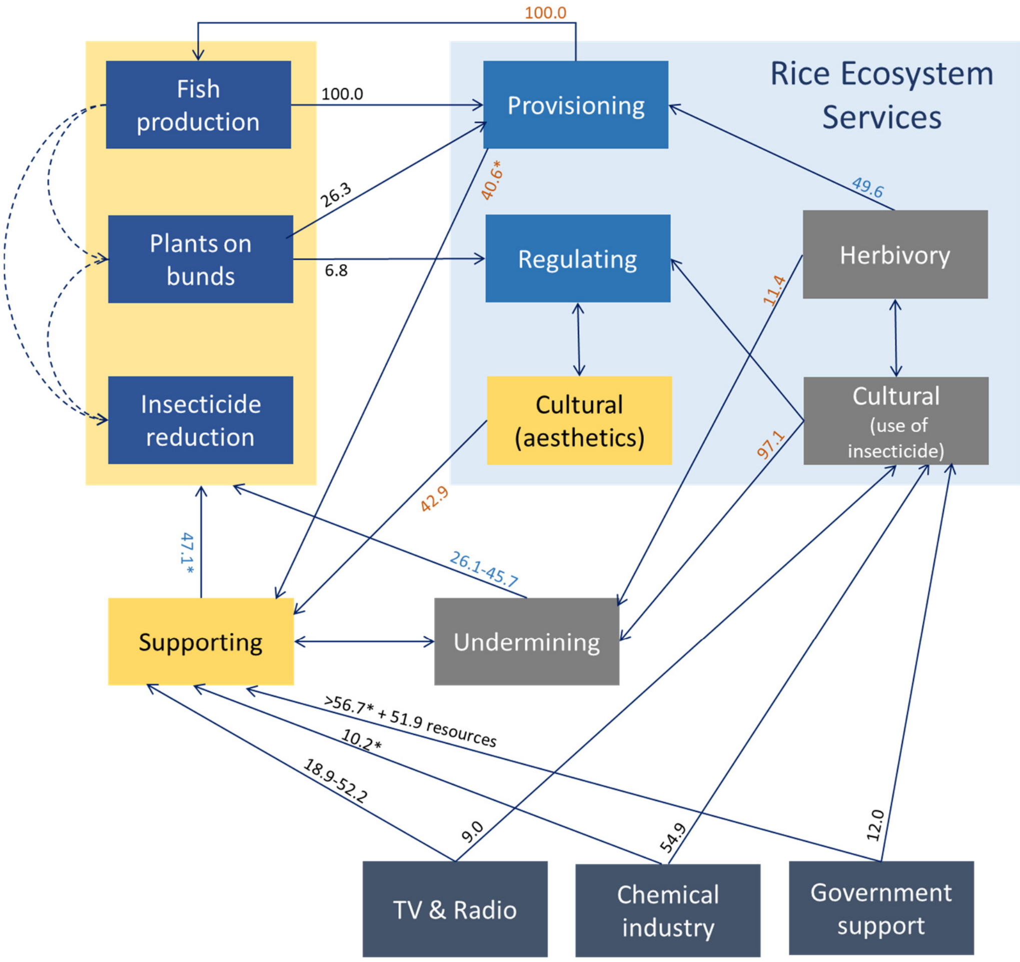

Figure 5. Summary of incentives and disincentives for farmers to adopt ecological engineering in rice ecosystems based on surveys from south Vietnam. Provisioning, regulating and cultural services are indicated with regulating disservices (herbivory) and cultural disservices (belief that insects reduce yields and insecticides are necessary) associated with the rice ecosystem. Restoring services from human society to the rice ecosystem are indicated as plants on bunds, insecticide reduction and rice–fish systems. The underlying supporting services and disservices (undermining) are linked to the restoration services. Services are indicated by blue rectangles and disservices by grey rectangles (see also Figure 2). The main external influencers are indicated by dark blue rectangles, such as 'TV & Radio', 'Chemical industry' and 'Government Support'. Numbers in black indicate percentages of farmers mentioning the associated linkages (indicated by arrows) (Table 1). Numbers in brown indicate farmers' motivations for choosing specific plants based on Table S2 as well as their satisfaction or dissatisfaction with planted bunds or insecticides. Numbers in blue indicate farmers' expressed satisfaction or dissatisfaction with ecological engineering based on Table S4. Numbers with asterisks are significantly different between conventional and ecological engineering farmers (including former-EE farmers).

Although the main purpose of ecological engineering is to promote herbivore regulation services by natural enemies in rice ecosystems, this service was rarely mentioned by farmers (only 6.8%: Figure 5) as a factor to stimulate their participation and was not mentioned as an outcome of establishing flower or vegetable strips. Nevertheless, 49.6% of current-EE farmers perceived lower pest, disease and/or weed damage to their rice crops (Figure 5). This perception that declining pest damage is linked to planted bunds reveals an understanding by farmers of pest–natural enemy interactions through the visible consequences of those interactions. This specific response by farmers during the listing of ecological engineering outcomes suggests that the farmers largely based their perceptions on direct observations and were not simply repeating concepts they learned during training/extension.

Finally, the observation that current-EE farmers reported fewer insecticide applications to their rice fields than both conventional and former-EE farmers, and that their reduction in insecticide use was related to fewer applications during early crop stages (Table 4), strongly suggests that current-EE farmers see the intervention as an effective pest management option. Furthermore, current-EE farmers reported higher yields than the conventional farmers (Table 4). We did not verify these reports of higher yields; however, Vo et al. (2015) [39] have indicated that ecological engineering in An Giang reduced pesticide inputs while delivering similar or higher rice yields. Gurr et al. (2016) [25] also reported that ecological engineering reduced pesticide inputs at sites in the MDR while delivering higher rice yields.

4.2. Limitations

The adoption of ecological engineering in the MDR has occurred despite relatively poor knowledge of the interactions between flower or vegetable strips, insect herbivores and natural enemies. This may have affected the efficacy of the intervention. For example, many of the flower species that farmers planted on their bunds do not have any documented association with natural enemies [26,28,57]. Most of the species were non-native plants, and some, such as lantana and *Macroptilium lathyroides* (L.) Urb. (wild pea), are recognized invasive species in Southeast Asia [58,59] (Table S3). Indeed, many of the weeds that the farmers had cleared from the bunds might be superior as forage or refuge plants for natural enemies than some of the ornamental flowers that were subsequently planted [60]. Furthermore, many of the farmers indicated that it was difficult to grow plants on the bunds, particularly during dryer months (Table S4). Although a large number of farmers reported that they sold flowers to local markets, this was not regarded as a profitable activity, and the demand for bund-grown flowers is probably much lower than the supply.

Among the current-EE and former-EE farmers, 48.5% had planted vegetables on their rice bunds, with more than half of these farmers also growing flowers. Vegetable species included ladyfinger, sesame, mung bean and cucumbers (Table S3), all of which are associated with natural enemy abundance in rice production systems [26,28,61]. In many cases, vegetable plants, such as sesame, may be superior to ornamental flowers for sustaining natural enemy populations [26,28]. Nevertheless, our results indicate that vegetable growers were less compliant with recommended ecological engineering practices. For example, compared to flower growers, farmers planted bund vegetables later (69.3% planted too late for the plants to have any effect on early-stage rice pests: see Settle et al. (1996) [62]), and 23.9% of current-EE farmers applied insecticides to their planted bunds (Table 2). Indeed, there was a significant association between insecticide applications to bund vegetables by farmers and the declared profitability of supplementary crops. By advising farmers to only plant selected, tolerant vegetables [30,61], a trajectory toward chemical-dependent intensification of bund production might be avoided.

As indicated in Figure 5, farmers were almost unanimous in their beliefs that insecticides are effective in reducing pest damage and thereby contribute to higher yields. This represents a significant undermining service (i.e., supporting disservice) to the restoration of rice ecosystems, particularly since there were indications that insecticides may already have had a negative impact on rice production in some of the farmers' fields. For example, farmers that were 'somewhat satisfied' with insecticides, or were 'not satisfied', tended to make multiple insecticide applications (>5) per season. Furthermore, panicle mites were among the greatest of concerns for conventional farmers and were significantly more problematic than for current-EE or former-EE farmers (Table 4). Insecticide-induced outbreaks of mites have been reported across a range of agricultural systems, particularly in response to pyrethroid insecticides [63].

Among the ecological engineering farmers we interviewed, 23.8% had abandoned the intervention. A large proportion of these farmers indicated that the practice was difficult (because of narrow bunds, a lack of experience in growing plants on bunds and problems with synchronization) and that the practice was costly or labor-intensive. This dissatisfaction with ecological engineering indicates an underlying risk associated with the strong incentives from the government for farmers to participate in the movement without considering the possible consequences of related drudgery. Because most of the species that farmers planted on the bunds were annual plants, any relaxing of the government incentives might result in further declines in farmer participation. In contrast, although only 19 of the farmers we interviewed also produced fish or crabs, information from these farmers (Table 4) suggests that, by promoting rice–fish systems, farmers might be further encouraged to avoid insecticides (see also Berg (2001) [64]) and to adopt ecological engineering practices.

4.3. Recommendations

Based on our analyses, we believe that ecological engineering in the MDR requires further research to optimize practices. The heuristic approach to developing ecological engineering for rice ecosystems has been tremendously successful in promoting the technology among farmers; however, without further attention to the ecology of the system and basic research regarding the best ornamental or vegetable species to plant on bunds, the experience could represent a significant loss of opportunity. Worrisome indicators of farmer dissatisfaction with the intervention due to labor and material costs, and a shift toward insecticide use on the planted bunds, suggest that simpler and more insect-resilient ecological engineering practices are urgently required. Issues around the social sustainability of the intervention also need to be addressed. At the time of our interviews, farmers relied heavily on government support to transition toward ecological engineering. Because the nature and extent of government support is subject to changing policies, positive feedback derived from provisioning, regulating or cultural services should be encouraged to enhance the social supporting services associated with ecological engineering (Figure 5).

5. Conclusions

Ecological engineering has evolved into a diversity of practices among farmers in the MDR of Vietnam. This includes the planting of various ornamental flowers and vegetables on rice bunds and the incorporation of fish into ecologically engineered paddy fields. To further enhance the provisioning services of the rice ecosystem, many farmers have opted to grow vegetables on their rice bunds. This practice can augment farm profitability and represents a sustainable feedback loop to further support continued restoration actions. However, a strong dependency on government support, widespread satisfaction with insecticides and a significant presence of agrochemical agents in rice-producing areas risks depleting the restoration value of ecological engineering practices and threatens the social sustainability of the ecological engineering movement. Nevertheless, at the time of our study, farmers were still largely satisfied with the intervention, and participating farmers indicated that they made significantly fewer insecticide applications to their rice fields, that they applied insecticides later to the crop and that they attained higher yields than conventional farmers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12051042/s1. Table S1: Profiles of participating farmers from southern Vietnam. Table S2: Management of bund vegetation by farmers in south Vietnam and motivations for choice of bund plant. Table S3: Flowering plants used as part of ecological engineering for pest management in southern Vietnam. Table S4: Farmer responses to questions about their satisfaction with ecological engineering. Figure S1: Differences between farmers' perception about the trends of biodiversity, rice pests and yields, based on rice management. Figure S2: Differences between farmers' perception about the declining trends of biodiversity, based on rice management.

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Data Availability Statement: The data presented in this study are available on reasonable request to the corresponding author.

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