Review article

Status and Issues in Ecological Engineering Techniques for Conserving Fish in the Paddy Field Areas of Japan

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Abstract Though land consolidation for paddy field areas has contributed to an increase in food supplies and an improvement in convenience, it has changed the physical structures and deteriorated paddy field ecosystems throughout Japan. Eco-friendly land consolidation in paddy field areas has been conducted based on the implication of ecosystem deterioration. Ecological engineering techniques, such as the placement of fish ladders between paddy fields and irrigation canals, were developed and applied to actual paddy fields to conserve fish. However, the techniques were not evaluated sufficiently. Therefore, I reviewed status and issues of ecological engineering techniques for conserving fish, which are often reported in Japan. This review showed the installation of fish ladders between paddy fields and drainage canals, as well as the construction of artificial ponds and wetlands, have contributed to providing fish with spawning and nursery areas in the paddy fields areas of Japan. On the other hand, the effects of ecological engineering techniques in canals, such as the construction of concrete block habitats, are not clear, although the techniques have already been applied to actual paddy field areas. Studies evaluating the effects of these techniques, which were applied for canals especially, should be conducted, and researchers and engineers should elucidate the most suitable structures, locations, scales and maintenance techniques for these constructions to best conserve fish in paddy field areas.

Keywords ecological engineering technique, paddy field ecosystem, fish, conservation, Japan

INTRODUCTION

Paddy fields have substituted for the back marshes of rivers, and play a role in the wetlands of low and flat-land areas (Moriyama, 1997; Natsuhara, 2013). They are not only food production areas, but also habitat, spawning, and nursery areas for aquatic organisms, such as fish, frogs, and aquatic insects.

Land consolidation in paddy field areas has contributed to an increase in food supplies and an improvement in convenience for farmers, and has exceeded 60 % of the paddy field areas in Japan. On the other hand, land consolidation has changed the physical structures of paddy fields, and deteriorated paddy field ecosystems in Japan (Lane and Fujioka, 1998; Hata, 2002a). For example, fish species that use paddy fields as spawning areas such as Japanese killifish (*Oryzias latipes* and *O. sakaizumii*) and mud loach (*Misgurnus anguillicaudatus*), cannot migrate from canals to paddy fields, because the creation of drainage canals create large drops between the paddy fields and themselves. Consequently, many endemic and/or dominant species in paddy field areas such as Japanese killifish and mud loach were designated as endangered species by the Ministry of the Environment and several prefectures of Japan.

Eco-friendly land consolidation in paddy field areas has been conducted based on the implications of ecosystem deterioration. A section of the "Land Improvement Act" of Japan was revised in 2001, and "consideration of harmony with the environment" was added a principle of the land improvement project.

Ecological engineering has been researched with the aim of designing sustainable ecosystems that integrate human society with its natural environment for the benefit of both humans and animals (Mitsch, 2012). Therefore, ecological engineering techniques in land consolidation projects are required to strike a balance between the increase in production and improvement in maintenance by farmers, and at the same time aid the conservation of aquatic organisms. The ecological engineering techniques, such as fish ladders between paddy fields and drainage canals, were adapted for paddy field areas where eco-friendly land consolidation was conducted. However, the techniques have been rarely evaluated.

OBJECTIVE

I have reviewed studies of ecological engineering techniques in the paddy field areas of Japan to discuss the status and issues with these techniques. In this paper, I have placed focus on the techniques for conserving fish in paddy field areas, because the development of these techniques has been adapted for actual paddy field areas in Japan frequently.

ISSUES OF PREVIOUS REVIEWS

Some researchers have reported studies on fish ecology and habitats in paddy field areas. Koizumi et al. (2012) showed that studies on fish lifecycles and ecology in the paddy field area have increased since 2000; however, the development of methods for estimating and predicting the fish populations and ecosystem of paddy field areas has been limited. Takemura et al. (2012) reviewed the methods of evaluating habitat quality, and the connectivity between the habitats and spatial arrangement of habitats for fish in paddy field areas, and discussed the issue of these methods. In addition, Nakano (2017) reviewed that previous studies have examined habitat preference of fish growth, spawning, wintering, migration, and dispersal of fish, in paddy field areas. These reviews did not focus on ecological engineering techniques.

Several researchers have reviewed conservation measures and ecological engineering techniques. Ogino and Ota (2007), Suzuki (2011), and Natuhara (2013) referred to the structure and installation method of fish ladders installed in paddy field areas of Japan; however, other techniques were not reported sufficiently. Mizutani (2011) and Minagawa (2015), and Mori (2017) presented some conservation measures for fish in paddy field areas; however, the status and issue of these measures and techniques were not discussed sufficiently. In addition, a large number of studies have been conducted with respect to ecological engineering techniques in the paddy field areas of Japan; however, it is difficult for people except those who speak Japanese to recognize these ecological engineering techniques, because many existing studies are published solely in Japanese.

Previous reviews in other countries have indicated the importance of paddy fields as habitats that are deteriorated by modern agricultural practices (Fernand, 1993; Herzon and Helenius, 2008; Luo et al., 2014). In addition, Chen et al. (2015) reported preliminary installation of fish ladders in the paddy field area of Taiwan. However, reviews and studies that focused on the ecological engineering techniques in the paddy fields have been rarely reported.

Sato (2014) conducted a questionnaire survey on the current status of ecosystem conservation in land consolidation projects to be carried out in the prefectures of Japan. He focused on ecological engineering techniques for fishes and frogs, because these measures have been conducted frequently based on their ecology and behavior, which has been revealed by previous studies (e.g., Saitoh et al., 1988). The techniques for fish in land consolidation projects in Japan shown by his questionnaire are summarized as follows (1-4 in Table 1). Although Sato's questionnaire survey did not report this fact, artificial wetlands and ponds were also constructed in land consolidation projects (Sugihara and Mizutani, 2006; Moriyama et al., 2010; Takemura et al., 2010; Nishida et al., 2014). Therefore, I have focused on and reviewed the below ecological engineering techniques for fish in land consolidation projects in Japan (1-5 in Table 1).

Table 1 Ecological engineering techniques for conserving fish in paddy field areas, which were often conducted in Japan

	Conservation measures	Ecological engineering techniques
1	Improvement of canal revetment	a) Construction of masonry and wooden revetment works (Takahashi et al., 2009). b) Construction of concrete block habitats.
2	Improvement of canal bed	a) Avoiding installation of concrete lining (Sato and Azuma, 2004). b) Installation of habitat pool section (Hiramatsu et al., 2010; Minagawa et al., 2015). c) Installation of spur dikes (Mukai et al., 2011) and blocks (Watabe et al., 2016).
3	Improvement of canal form	a) Construction of meandering section (Nishida et al., 2011). b) Construction of broaden section (Conservation Society-Japan, 1995; Nishida et al., 2011).
4	Installation of migration pathway	a) Installation of fish ladders between paddy fields and drainage canals (Hata, 2002b; Suzuki et al., 2004; Tanaka, 2006; Sato et al., 2008; Nakamura et al, 2009; 2012). b) Installation of fish ladders in canals (Moriyama et al., 2008).
5	Construction of calm waters	a) Construction of ponds (Sugihara and Mizutani, 2006; Takemura et al., 2010). b) Construction of wetlands (Nishida et al., 2014, 2015).

(a) Masonry revetment work (b) Wooden revetment work

Fig. 1 Example of (a) masonry and (b) wooden revetment works in canals
Riparian plants grow between the wooden stakes

IMPROVEMENT OF CANAL REVETMENT

Construction of Masonry Revetment Works

Stream and canal riparian structure influence the habitats of aquatic organisms (Pusey et al., 2003). The growth of riparian plants influences the habitation of fish and aquatic organisms (Kawaguchi, 2003). Masonry and wooden revetment works (Fig. 1), and similar structures, were traditional methods of canal improvement and repair. These structures have many spaces between materials, and it is considered that these spaces and the plants that grow in them provide habitats for fish (Katano, 1998). Takahashi et al. (2009) installed an experimental dummy of a wooden mattress dike, one of the traditional methods of revetment (shown in the middle right of Fig. 6), in a drainage canal to evaluate to the effects on fish habitation. They showed that this dike was frequently used by fish, such as crucian carp (*Carassius* spp.), in paddy field areas. However, other revetment works in canals were not investigated for their effects on fish habitats.

Construction of Concrete Block Habitats

Concrete block habitats (Fig. 2) were often installed for canal revetments to enable fish to use canal improvements as habitats in Japan (Sato, 2014; Japanese Society of Irrigation, Drainage and Rural Engineering, 2016). These blocks have cavities inside in the expectation that fish may use them as habitats. However, no study has evaluated the exact effects of these concrete block habitats on fish and other aquatic organisms in irrigation canals. In addition, there is no knowledge on which species and growth stages of fish can use these concrete blocks as habitats.

Fig. 2 Example of a concrete block habitat installed in a drainage canal

IMPROVEMENT OF CANAL BED

Avoiding the Installation of Concrete Lining

Concrete lining was usually installed in canals during conventional canal improvements. However, the number of fish species and individuals was reported to drastically decrease because fish habitats were often removed by the improvements (Kihira, 1983; Tsubokawa, 1985). Therefore, the installation of concrete lining was partially avoided as much as possible to allow eco-friendly canal improvements. Sato and Azuma (2004) investigated the difference in fish habitation among construction methods after canal improvements. Some canal sections improved by eco-friendly construction methods such as concrete revetment works with concrete block habitats, and concrete canal beds were not installed in these sections to enable fish to inhabit (Fig. 3).

(a) Straight section (b) Meandering section

Fig. 3 Example of (a) straight and (b) meandering sections of the drainage canal
These photographs were taken five years after canal improvement was undertaken

Numbers of fish species and individuals, and diversity indices in conventional concrete lining canal sections were significantly smallest than those in other sections. On the other hand, these values in concrete revetment canal sections were not significantly different from those in earth canal sections. These observations indicated that avoiding the installation of concrete lining is the key to conserving fish in paddy field areas.

Installation of a Habitat Pool Section

Sato (2014) indicated that habitat pools (Fig. 4) were often installed during land consolidation projects in Japan. Hiramatsu et al. (2010) and Minagawa et al. (2015) investigated fish assemblages and physical environments in pools that were installed by canal improvement projects. These pool beds were concrete and 0.30-0.50 m deeper than other canal sections. Their findings indicated that these pools were important for fish to winter in. On the other hand, Minagawa et al. (2015) also reported that sand and silt had accumulated excessively, and the water depth was lower in some pools. Further studies are needed to elucidate how to wash away or remove these sand and silt accumulations to maintain a water depth that is inhabitable by fish.

Fig. 4 Example of a habitat pool installed in a drainage canal

This pool bed was dug 0.3 m deeper than the normal canal section.
Sand and silt were accumulating, and the water depth had been reducing gradually

Installation of Spur Dikes and Blocks

Mukai et al. (2011) experimentally installed spur dikes with notches on the canal bed crossing the canal to form sand bars, riffles, and pools for aquatic organisms. They investigated the temporal change in the formation of sand bars and invertebrate assemblage before and after the installation. The formation of sand bars was observed by investigation after one year of the installation of the dike. Riparian plants were formed on the sand bars six months after the sand bar formation. The number of invertebrate individuals increased after the formation of sand bars and riparian plant zones, indicating these formations created invertebrate habitats. These methods might provide fish habitats, as well as help to explain the findings of Nishida et al. (2011) described below. However, the effect on fish habitation was not investigated.

Fig. 5 Example of concrete blocks on the concrete lined canal bed

These blocks captured sediments and created sand bars and/or small riparian plant zones

Watabe et al. (2016) also installed concrete blocks, such as the one seen in Fig. 5, on the concrete lining of a canal bed, and investigated the fish assemblage and canal environment before and after the installation. They arranged the long sides of the rectangular concrete blocks perpendicular to the water direction in the canal. Their observation showed that the blocks created calm water and sand sediment zones in the canal. However, the change in the number of fish individuals before and after the installation was small. There is no sufficient evidence that these concrete blocks create suitable fish habitats.

IMPROVEMENT OF THE CANAL FORM

Construction of Meandering Sections

Nishida et al. (2011) investigated the temporal change in fish assemblages and physical environments of drainage canals before and after canal improvements by eco-friendly construction methods. In particular, they focused on the differences in temporal changes between meandering and straight sections where revetments were installed (Fig. 3). Sand bars did not form, riparian plants did not grow, only mud loach were dominant, and the number of species and diversity indices had declined in the straight sections five years after the canal improvement. On the other hand, sand bars formed, riparian plants grew, and a number of fish species and diversity indices did not change before and after canal improvements in the meandering sections. These differences between straight and meandering sections may be due to the presence or absence of calm waters made by sand bars and riparian plants, which create natural hiding spots for fish. Further studies are needed to elucidate how canal form and structure can form sand bars and riparian plant zones.

Construction of Broadened Sections

Ecosystem Conservation Society-Japan (1995) reported that the number of fish species increased in a broadened section of a canal after canal improvements (Fig. 6). The construction of broadened sections probably provided calm water areas in the canal. However, which factor increased the number of fish species was not clear. In addition, studies that elucidate the effect of construction of broadened canal sections on fish assemblage are limited.

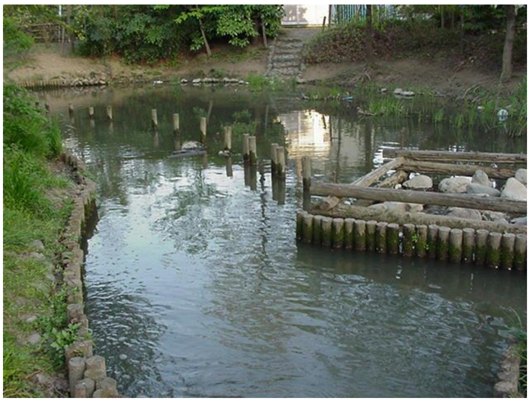

Fig. 6 Example of a broadened section in a canal
The previous canal width before improvement was between the left bank and stakes located in the center of this photograph

Some meandering sections that Nishida et al. (2011) investigated were also broadened by the eco-friendly canal improvements. Large sand bars formed and riparian plants thrived in these broadened sections. This increased plant growth perhaps increased the management efforts of farmers and prevented drainage water flow. Research into construction methods that strike a balance between improving the convenient management of canals and conservation of aquatic organisms is required.

INSTALLATION OF A MIGRATION PATHWAY

Fish Ladder between Paddy Fields and Drainage Canals

Endemic and/or dominant fish in paddy field areas such as mud loach and Japanese killifish migrate from canals and spawn in paddy fields (e.g., Saitoh et al., 1988). However, these fish species often cannot migrate to paddy fields after a land consolidation project, because drainage canals are dug to improve the draining ability of paddy fields (Hata, 2002b). This digging creates a large drop between the paddy field and drainage canal.

Japanese researchers have tried to develop fish ladders to enable these fish species to migrate from drainage canals to paddy fields (Hata, 2002b; Suzuki et al., 2001; Tanaka, 2006; Sato et al., 2008). These fish ladders were classified into two types, and were installed in paddy field areas as follows.

1) Paddy field outlet ladder (Fig. 7a): This ladder type was installed at each outlet of paddy fields in order to allow fish migration from drainage canals. Fish ladders of variable structures were developed, and they were installed in every region of Japan by farmers and/or local governments.

2) Up-dam ladder (Fig. 7b): This fish ladder type was installed at drainage canals and dams with a higher water level at the upper section of drainage canal from this ladder. This improvement enables fish to migrate from downstream of the ladder to the paddy field because the water level between the drainage canal and the paddy fields is lower. This fish ladder type has been utilized in paddy field areas around Lake Biwa.

(a) Paddy field outlet ladder (b) Up-dam ladder

Fig. 7 Example of the two type of fish ladders in use

(a) paddy field outlet ladder and (b) up-dam ladder between paddy fields and the drainage canal

The effects of the fish ladders have been investigated by some researchers. Suzuki et al. (2004) investigated the effects of fish ladders between drainage canals and paddy fields. They indicated that mud loach and crucian carp migrated from drainage canals to paddy fields through fish ladders, and spawned in the paddy fields. After hatching, their larvae probably grew in the paddy fields and then migrated to the drainage canals. As a result, increases in fish wet weights in paddy fields after land improvement projects were equal to or larger than those before them.

Nakamura et al. (2009, 2012) reported that the drainage of water from paddy fields through fish ladders was greater than that from the outlets of paddy fields in which the fish ladder was not installed. This finding indicated that irrigation water is required in the paddy fields that fish ladders are installed. Therefore, new water management practices are crucial to enable fish to migrate through the fish ladder and spawn in the paddy fields.

Installation of Fish Ladders in Canals

Fish ladders were also installed at drop structures and outlets of the canals (Fig. 8). Pool and canal types of fish ladder that were developed by river engineering researchers were installed at the drop structures. Moriyama et al. (2006) reported new fish species were detected in the irrigation canals after the installation of fish ladders on outlets, suggesting that these fish ladders enabled fish to migrate from lower water areas. On the other hand, the fish ladders may also allow alien fish species to invade the irrigation canals.

(a) Fish ladder at a drop structure in a canal

(b) Fish ladder at an outlet of a canal

Fig. 8 Examples of fish ladders installed (a) at a drop structure and (b) outlet of a canal

CONSTRUCTION OF CALM WATERS

Construction of Ponds and Wetlands

Sugihara and Mizutani (2006) investigated fish habitation in an artificial pond (Fig. 9), and the migration between an artificial pond and the adjacent water areas, in paddy field areas. A large number of age-0 pale chub (*Opsariichthys platypus*) as well as crucian carp and Japanese killifish were captured in the artificial ponds in winter, indicating that these fish species wintered there. In addition, for fish that spawn in paddy fields, such as the field gudgeon (*Gnathopogon elongatus elongatus*), adults ascended from connected drainage streams to the pond, and oppositely, juveniles and sub-adults descended from the pond to the drainage streams. These findings indicated that these fish species probably used the pond as a spawning and nursery areas, as well as paddy fields.

(a) Artificial pond

(b) Artificial wetland

Fig. 9 Examples of an (a) artificial pond and (b) artificial wetland constructed in a paddy field area

Takemura et al. (2010) reported that ninespine stickleback (*Pungititus* sp. 2) made nests on aquatic plants in artificial ponds. On the other hand, they also suggested that artificial ponds will become unsuitable for nesting by ninespine stickleback if aquatic plant mowing is abandoned and plant cover is increased throughout the pond, because ninespine sticklebacks often made nests on the edge of each plant zone, but did not make nests in the center of the plant zone. On the other hand, intense mowing may remove all nest substrate for ninespine sticklebacks. In addition, in these shallow and calm waters, sand and silt accumulates and aquatic plants grow easily. Therefore, maintenance of these water areas may be crucial to conserve fish habitats. Further studies are needed to elucidate how to suitably maintain these water areas.

Nishida et al. (2014) investigated fish habitation in an artificial wetland (Fig. 9), and migration between an artificial wetland and connected stream, and the migration of the mature mud loach and eight-barbell loach (*Lefua echigonia*) was detected between late winter and spring. Juveniles and sub-adults of these two loach species migrated from the wetland between summer and winter. These results confirmed that wetlands act as spawning and nursery habitats for these two species of loach. On the other hand, fish species other than the mud loach and eight-barbell loach, frogs, and aquatic insects that were found in the adjacent paddy fields, were rarely detected (Nishida et al., 2015). The unique characteristics of artificial wetlands that are frequently used by many aquatic organisms are not known yet.

CONCLUSION

This review showed that the installation of the fish ladders, which were developed by Japanese researchers and engineers, between canals and paddy fields provides fish, such as mud loach and crucian carp, with spawning and nursery areas . Similarly, artificial ponds and wetlands constructed in a paddy fields area were sufficiently used by fish as spawning and nursery areas especially. On the other hand, the effects of ecological engineering techniques on canals where fish spent most of their life cycles are not clear, although the techniques have already been applied to actual paddy field areas. Studies evaluating the effects of these techniques in canals should be conducted, and researchers and engineers should elucidate the most suitable structures, locations, scales, and maintenance techniques for these constructions to best conserve fish in paddy field areas.

Middle- or long-term monitoring is required to evaluate these techniques, because ecosystems and physical environments often fluctuate, and previous studies have indicated it can take a long time until they stabilize after disturbance. However, this monitoring is rarely conducted in Japan; the development of monitoring methods and mechanisms are needed.

In Japan, many studies evaluating the effects of these techniques are published in Japanese, because the local language is useful to easily show the effects to the Japanese and local governments, as well as domestic engineers. On the other hand, studies published in English are needed to provide knowledge of these ecological engineering techniques to people globally. This knowledge may be useful in Southeast Asia especially, because paddy fields in this area could be improved to increase future agricultural production and convenience.

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