Material Balance and Ecological Functions of Paddy Farming in Japan

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Abstract

In Japan, the rapid decrease in the area of paddy fields is a major cause for concern in relation to the conservation of the land and the environment. Therefore, the beneficial ecological effects of the paddy fields on the environment have been studied and are summarized below.

"Physical effects" arise from the structure of the paddy fields such as the presence of ridges, plow sole and terraces. The water-storing capacity of the rice fields which is estimated by multiplying the area of paddy fields in Japan and the effective height of water storage (height of ridge−ordinary ponding depth) is estimated at 5.4 billion m^3, a value larger than that of flood regulation reservoirs. On the other hand, the plow sole regulates the water percolation for ponding and replenishing the groundwater resources and also preventing slope collapse through the avoidance of rapid water percolation. The terracing of the paddy fields reduces considerably soil erosion on sloping fields.

"Chemical effects" arise from water ponding. Since the soil in paddy fields under water-saturated conditions becomes reductive, the assimilation and nitrification of ammonium nitrogen by bacteria are limited and the ability of nitrogen fixation by algae in ponded water amounts to 25-40 kgN/ha/yr. As a result, a rice yield of 5 tons/ha can be obtained by limited nitrogen fertilization of less than 100 kgN/ha. Furthermore, under the reductive soil conditions, the denitrification process becomes active and plays a role in the purification of nitrate-rich water. The latter capacity is estimated at around 300 kgN/ha/yr.

Introduction

Approximately 70% of the national land is occupied by mountainous steep slopes which are mainly covered with forests. Agricultural areas, which are located in narrow plains, basins, valley floors and mountain foot slopes, occupying only 14% (5.1 million ha) of the total land, consist of 55% of paddy fields (2.76 million ha) and 45% of upland fields (2.32 million ha).

Under the rapid economical development in the past 30 years, 1 million ha of agricultural lands have been converted to non-agricultural uses in the periphery of urban areas and also due to abandonment mainly in mountainous regions. This rapid decline of paddy rice farming is causing national concern for the environmental conservation and for the prevention of natural disasters. Therefore, with a view to creating a national consensus for keeping a certain amount of paddy fields in our land, the beneficial ecological functions of the paddy fields

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have been studied in addition to the mechanism of sustainability of rice production.

The sustainability and the beneficial functions of the paddy fields will be outlined in the context of the irrigation water use and the physical and chemical soil characteristics related to flooding.

Ecological conditions of Japan

Japan consists of a chain of islands located on the eastern fringe of the Asian continent, under a monsoon climate and high tectonic activities. The annual precipitation averages 1,750 mm which is concentrated in summer with frequent heavy rains. A long range of high mountains runs down the center of the islands and plains are located on the edges of the mountains. As a result, the rivers flow down from mountains to the sea with a very high gradient. The runoff discharge fluctuates markedly within a short period causing a water shortage in case of dry year and severe flood by heavy rains. Therefore, the conservation of mountainous slopes with forest and the intensive use of controlled water in lowlands are the prerequisites of the life systems in Japan.

Water balance of paddy fields

In Japan, the total potential water resources (precipitation−evapotranspiration) are estimated at 430 billion m^3/year. At present, 91 billion m^3/y of water is consumed for various uses. Around 64% (58.6 billion m^3) of this amount is used for agriculture (Fig. 1) and 95%

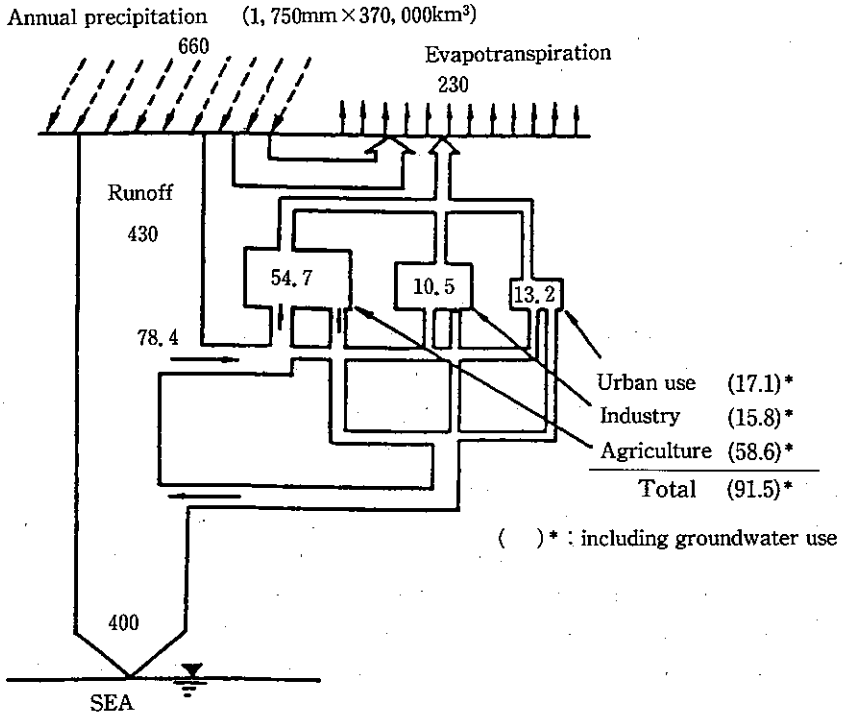

Fig. 1 Water balance in Japan (billion m^3)

(55.9 billion m^3) of the water taken for agriculture was used for the paddy fields. The evapotranspiration and rainfall on the paddy rice fields amount to about 500 mm and 400 mm, respectively for an irrigation period of 100 days. Therefore, almost an equal amount of the water irrigated for the paddy fields returns to rivers and percolates into groundwater. The ecological functions of paddy fields are related to the water inflow to, storage capacity of and outflow from paddy fields as well as irrigation facilities such as dams, small reservoirs and canals.

Physical functions

1 Flood prevention functions

Due to the presence of surrounding ridges and plow soles with a low permeability, paddy fields can temporarily receive and store a considerable amount of rain water and then release it gradually into rivers. Especially, in case of heavy rain, the remarkable increases in river flow peak can be eased and the flood damage in surrounding areas and downstream can be prevented or mitigated. Moreover, most of the paddy fields are located in an area which was originally a floodplain where the zonal water storage capacities acting as flood prevention reservoirs are larger than those estimated by the height of surrounding ridges. Recently, this function has been recognized by urban communities which subsidize the farmers to maintain their lands in neighboring urban areas as paddy fields.

The temporary water storage capacity of paddy fields can be estimated by a simple equation,

"Temporary water storage capacity" = {Average height of ridge − ordinary ponded water depth} × {Total area of paddy fields}.

In Japan, the temporary water storage capacity amounts to 5.38 billion m^3.

5.381 billion $m^3 = (0.236\ m - 0.03\ m) \times 261$ million ha

Average height of ridges : 23.6 cm

Average normal ponded depth : 3 cm

Total area of paddy fields : 261 million ha

The temporary water storage capacity of each land use is shown in Table 1.

The forests which are located on mountainous areas account for the largest water storage capacity in Japan. Although the water storage of the paddy fields and of small reservoirs for irrigation is one-fourth of that of forests, it plays a very important role in the prevention of flood damage. Since the paddy fields are mainly located on a floodplain where main buildings and infrastructures are constructed, the storage capacity of paddy fields is almost two times larger than that of dams and reservoirs.

Besides, many other ecological functions such as water seepage to the groundwater reservoirs, stabilization of river flow, mitigation of high air temperature, scenery, and wild life habitat are related to water ponding in paddy fields.

2 Slope conservation and rice terraces

Agricultural land had been scarce during Japanese history until quite recently. Therefore rice terraces were constructed on slopes even steeper than 15° where a small amount of

Table 1 Water storage capacity in each land use

Land use	W. S. capacity (mm)	×	area (million ha)		Volume of water (billion m^3)
Forest:	176	×	25.20	=	44.4
Paddy fields:	206	×	2.58	=	5.4
Upland fields:	37	×	2.40	=	0.46
Grasslands:	22	×	0.66	=	0.15
Orchards:	106	×	0.41	=	0.43
Waste lands:	15	×	0.40	=	0.06
Dams:					2.7
Small reservoir:					4.8
Total temporary water storage capacity (≒ Flood prevention capacity)					56.4

Table 2 Change in basic intake rate at leveled surface of rice terrace with years after the abandonment

Rice terrace	Soil moisture reqime	
	ill-drained mm/h	drained mm/h
Under rice cultivation	0.1	0.1
12years after abandonment	0.1	8.0
20years after abandonment	2.3	147.5

Source: Ota *et al.*, 1966.

water for irrigation could be obtained. The area of rice terraces on slopes steeper than 3° covers 220 thousand ha (around 10% of total area of rice fields) and the terraces have played an important role in the remote rural communities.

However, recently, these rice terraces especially on steep slopes in remote areas are being abandoned due to the steepness, small lots, unsuitability for machinery use and instability in water supply. On abandoned terraces, soil erosion and slope collapses occur due to runoff of water from abandoned canals and the terraces are not being rehabilitated, resulting in hazards such as landslide and flood.

The basic constituents of the rice terraces consisting of leveled surfaces for ponding, embanked slopes, canals and small reservoirs which effectively conserve slope and water, have been maintained by farmers. The soil movement on terraced steep slopes occurring under rice cultivation was estimated at 20 tons/ha/year based on the labor hours used for terrace repairs in Shikoku district (Osozawa, 1997). Moreover, most of the embanked slopes are too steep and too high beyond the stable range of soil embankment as shown in Fig. 2. The slopes soon after abandonment experience collapse and slopes with established tree vegetation of old abandoned terraces are also gradually collapsing even 20 years after the abandonment.

The impermeable plow sole of terraces resulting from careful puddling and strong compaction contributes to the ponding of water with minimum loss and also to the prevention of slope collapse by avoiding rapid water percolation into subsoils (Table 2). However due to the decline in rice production, the presence of strongly impermeable layers becomes an obstacle for use for the cultivation of upland crops and fruit trees. Also the presence of plow sole prevents the intrusion of tree vegetation on leveled parts of terraces, in extreme cases even 20 years after the abandonment.

The structures of the terraces constructed for rice cultivation which contribute to the conservation of soil and water under rice cultivation, hamper conversion to other land uses. As a result the slopes collapse in the absence of rice cultivation.

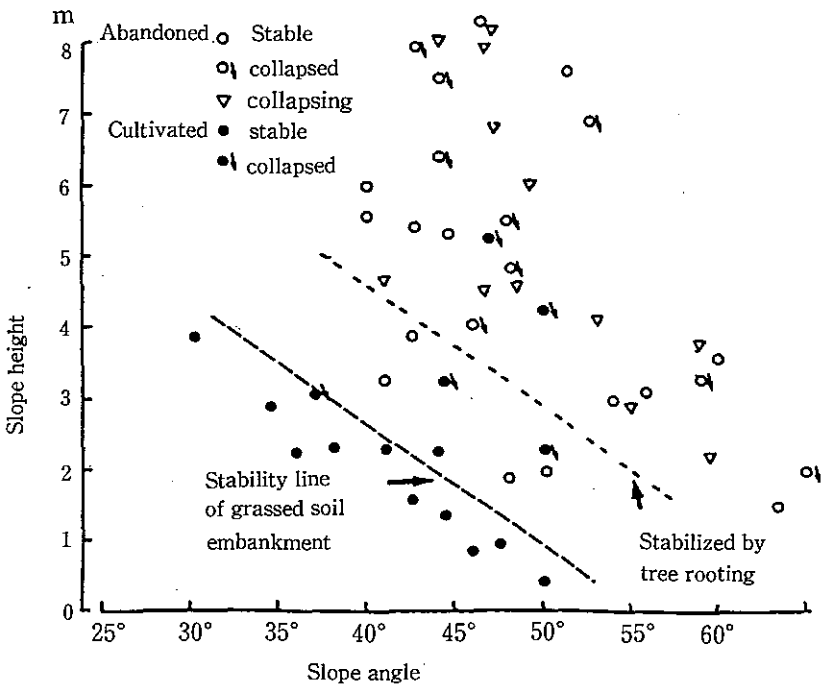

Fig. 2 Stability of soil embankment slopes of terraces
Source: (Iwama *et al.*, 1997)

Chemical functions

Irrigated paddy rice fields are chemically characterized by nutrient transportation with irrigation water in horizontal and vertical directions and also by the peculiar metabolic systems developed on the soil surface and in the soil layers. The ecological functions and the sustainability of paddy fields are based on the presence of these chemical systems and water movement. The main chemical functions of paddy field are summarized as follows,

(1) Nutrient supply with irrigation water supply
(2) Suppression of decomposition of soil organic matter
(3) High efficiency of NH_4-N fertilizers
(4) Nitrogen fixation in ponded water
(5) High availability of soil-P under soil reductive conditions

(6) Vertical leaching of excessive nutrients and harmful metabolites
(7) Nitrification on interface of soil and flooded water
(8) Denitrification of nitrate in reduced soil layers

The disadvantages of paddy soils include nitrogen loss by denitrification, methane emission, production of hydrogen sulfide and organic acids and leaching of nutrients and iron oxides. However, these shortcomings can be alleviated by soil and water management.

In this part, nitrogen metabolism will be mainly considered.

1 Maintenance of soil organic matter level

The maintenance of the soil organic carbon content in agricultural fields is essential for sustainable nitrogen fertility. Fig. 3 shows that the content of soil organic carbon of paddy soils is higher than that of upland soils. It is assumed that the difference in organic carbon content is caused by the difference in land use for a long period of time from the same soils (Mitsuchi, 1974).

The soil carbon balance in fields at Tsukuba was determined by Koizumi (1994). Although the experiments were carried out without return of rice straw to the fields, the soil carbon balance of paddy fields showed a slightly negative value, -22.3 gC/m^2 per year which was considerably lower than that recorded in corn and wheat fields (Table 3). In paddy fields, the decomposition rate of soil organic matter in the summer season was one-third of that in upland fields.

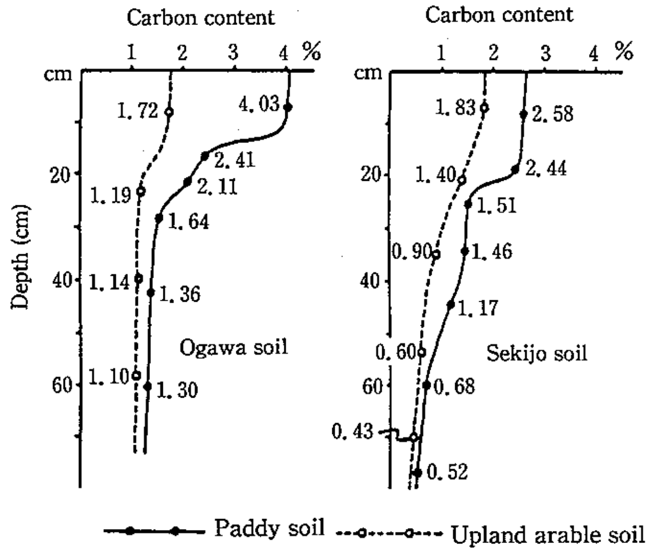

Fig. 3 Changes in humic carbon content of Lowland soils under different land uses
— Brown Lowland soils —
Source: (Mitsuchi, 1974)

Table 3 **Annual Carbon budget in Paddy fields and upland crop fields**
(Koizumi. H. *et al.*, 1994)

	Paddy field			Upland crops	
	Fallow p. (gC/m^2)	Irrigat. p. (gC/m^2)	Total (gC/m^2)	Dry rice (gC/m^2)	Corn (gC/m^2)
I. C fixed by plants	61.4	1,311.0	1,372.4	436.1	548.1
(a) total fixed C	61.4	1,311.0	1,372.4	436.1	548.1
(b) net fixed C	36.1	713.7	749.7	259.1	381.7
i) left C as products	0	543.4	543.4	114.8	179.9
ii) C returned to soil	36.1	170.3	206.4	144.3	201.8
(c) respired C	25.3	597.4	622.7	177.0	166.5
I'. C fixed by algae					
(a) total fixed C	0	36.8	36.8	0	0
(b) net fixed C		25.7	25.7		
(c) respired C		11.1	11.1		
II. C in soil					
(a) crop residues+algae	36.1	196.0	232.1	144.3	201.8
(b) decomposition	106.3	131.9	238.2	459.9	468.7
III. C balance in soil*	−69.0	46.7	−22.3	−315.6	−266.9
IV. C in irrigated water					
(a) inflow C	1.2	31.5	32.7		
(b) outflow C	0	23.1	23.1		
(c) percolated C	0	25.8	25.8		

*: C balance in soil = (IIa + IVa − IIb − IVc)

2 Natural supply of nitrogen in paddy fields

Based on 73 benchmark experiments on rice fertilization in Japan, Toriyama (1997) reported that the average natural nitrogen supply from −N plots was 69 kgN/ha per year. It was considered that the natural nitrogen supply is relatively higher in clayey soils than coarse-textured soils and relatively low in Yellow soils and in Andic soils. Due to the relatively ample natural nitrogen supply and high efficiency of nitrogen fertilizer, less than 100 kgN/ha of nitrogen fertilizer is needed to obtain 5 ton/ha of husked rice yield. This abundant and stable supply of natural nitrogen is considered to be one of the main causes of sustainability of paddy fields and is assumed to be associated with nitrogen fixation by algae in ponded water. The annual nitrogen fixation in paddy fields was estimated at around 40 kgN/ha by Iimura (1982) based on the long term N balance in −N plots, and 25-35 kgN/ha by Ono (1984).

3 Water purification function of paddy soil

Pollutants brought into paddy fields with irrigation water are cleaned in surface flow and also in percolating flow into soil layers. Flocculation, deposition and filtration of suspended materials, decomposition, nutrient absorption by algae and phosphate adsorption by soil act as cleaning processes, and the denitrification of nitrate in reduced soil layers plays a major role in water purification.

In Japan, it is considered that the water purification capacity of paddy fields plays a very significant role in water quality in rivers and underground, because many of the paddy fields located in lowlands receive and clean nitrate-polluted water derived from the upper surfaces on which orchards and vegetable fields are cultivated with heavy application of fertilizer and manure (Fig. 4). Under these conditions, it was found that around 300 kg/ha/yr of NO_3-N was removed in paddy fields (Hidaka, 1996).

The nitrogen removal capacity of ill-drained paddy fields represented by the following equation has been proposed (Tabuchi *et al.*, 1993).

$$R = Ro \cdot F \cdot P$$

$$Ro = aoX$$

Here, R : nitrogen removal rate ($gN/m^2 \cdot day$)

Ro : denitrification rate ($gN/m^2 \cdot day$)

X : nitrate concentration (mgN/l)

ao : factor for water temperature and soil type

F : factor for field conditions (1-4)

P : factor for surface flow on field (0-1)

It was observed that the concentration of NH_4-N, NO_3-N and phosphate-P in irrigation water decreased below 10% by surface flow of more than 20 m in uncultivated paddy fields (Hidaka, 1995).

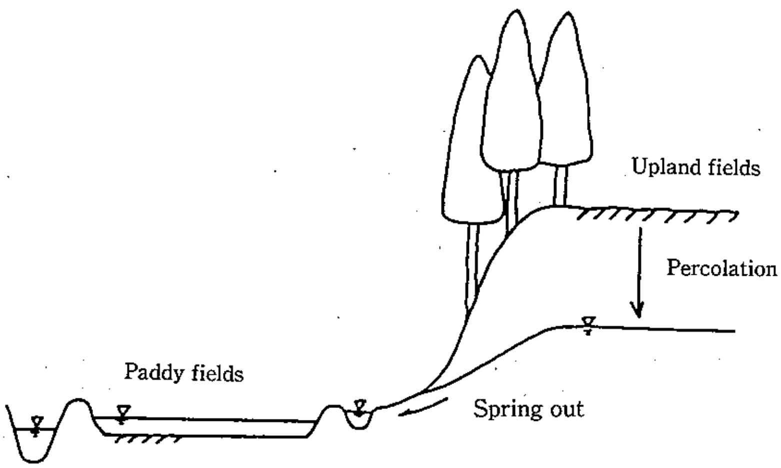

Fig. 4 Topographic sequence of upland fields and paddy fields
Source: (Tabuchi et al., 1993)

Conclusions

Main characteristics of paddy fields are associated with water supply by flooding which requires special facilities for irrigation and structures in the field. Also water flooding induces peculiar metabolic systems on the soil surface, in ponding water and in reductive soils. The ecological functions beneficial to the environment and the sustainability of paddy fields which are related to these characteristics are summarized as follows.

1) The temporary water storage capacity of paddy fields is estimated at around 200 mm on average, and accounts for 10% of the total national temporary water storage capacity.

2) The slope changes into terraces contribute to preservation of soil and water under rice cultivation. However, these structures hamper the conversion to other land uses and when abandoned the slopes may collapse.

3) The sustainable productivity of paddy fields is based on the preservation of soil organic matter level, high natural nitrogen fixation ability and other functions induced by flood irrigation.

4) The water purification capacity of paddy fields is mainly associated with the denitrification in reductive soil layers and plays a major role in the maintenance of the water quality of rivers and groundwater in Japan.

5) A national consensus should be reached for the preservation of a considerable area of paddy fields not only for food security but also for environmental security.

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