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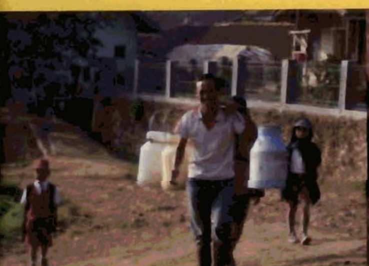

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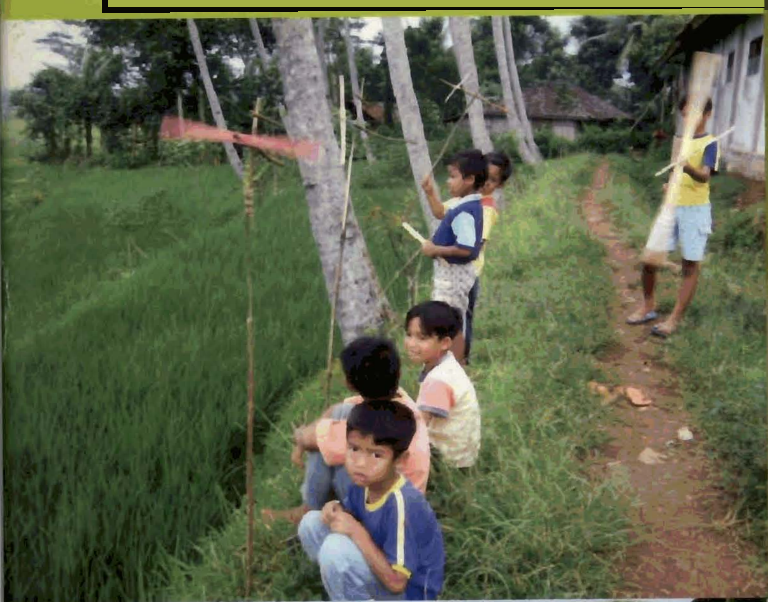

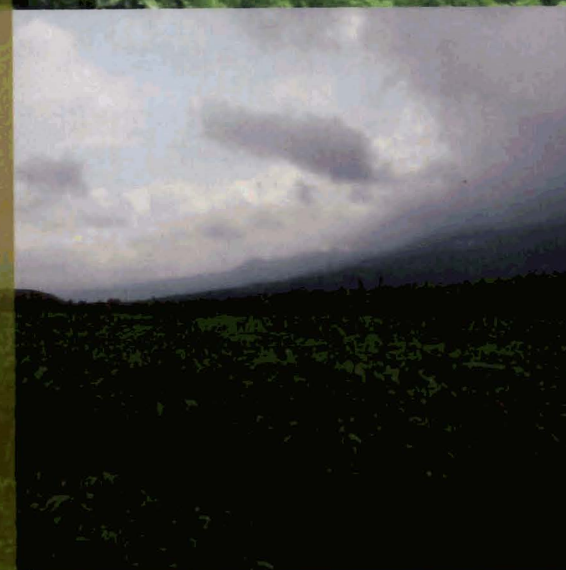

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Graduate School of Agricultural and Life Sciences
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Issues on Environmental Changes and Sustainable Development in a Tropical Agricultural Watershed

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Abstract

Investigation results of four issues on environmental changes in Cidanau watershed, which have been originally found through our cooperative research, are introduced and discussed: (1) water level and environmental changes in Rawa Danau, (2) variable acreage of cultivated paddy fields depending on preceding precipitation, (3) does paddy field increase or decrease water resource?, and (4) changes in nitrogen cycle due to prevalence of chemical fertilizer. Whereas former two are special issues important in Cidanau watershed, the results of latter two issues must be general and commonly important among tropical agricultural watershed where paddy field spread. Necessary measure for sustainable development on each issue is also discussed.

Keywords: *tropical watershed, paddy field, water resource, evapo-transpiration, nitrogen cycle*

Introduction

Cidanau watershed, the study area of us, may have aspects that are common among watershed of monsoon Asia; paddy field spreads under the tropical climate where half of the year is wet season and the other half is dry season (Fig.1); increasing population, scarcity of water resource with developing industry. Paddy field cover 28% of the watershed of 221 Km^2. Temperature in the watershed is high and constant (26 C) all year around, which is about 11 C higher than average in Japan. Therefore, since rice cultivation is not limited by temperature, rice can be sown and grown throughout the year, but it is limited by availability of water during dry season. Mean annual precipitation is about 2600 mm (fluctuating between 1000 and 3900 mm during 10 years); about 1400 mm of which evaporates and the rest 1200 mm runs off.

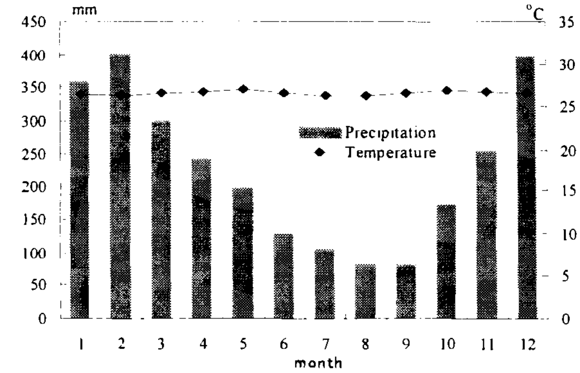

Fig.1 Monthly average temperature and precipitation in Cidanau

The watershed was geologically a caldera of the Danau volcanic complex, bounded by a caldera rim and adjacent high volcanic terrain (Fig.2). Because of this unique topography, not only the hydrosphere but also the biosphere is well segmented and isolated. The Cidanau River flows out from the caldera through a waterfall in a narrow valley located in the outer rim of the caldera, which then flows into the Sunda Strait. Near the mouth of the Cidanau River, there is an intake weir owned by PT. Krakatau Tirta Industri (KTI), the local water supply company. KTI distributes water to all industries in Cilegon city as well as domestically to cities, but shortage of water during dry season has been a problem (Budi et al. 1999).

It is important to derive general method or knowledge from the case study in the watershed as well as to recognize specific feature and solution for the watershed. Here we will discuss on four topics in context of environmental changes and sustainable development in Cidanau watershed, which were originally obtained by the corroborate research.

1. Water level and environmental changes in Rawa Danau

Rawa Danau is a large tropical fresh water swamp, which is precious in Indonesia. The swamp with the surrounding area has been appointed as a natural reserve because of its precious ecosystem including distinct fauna and flora. It exists in the bottom of Cidanau River Basin, a large caldera. Cidanau River flows from the swamp to the exit of caldera, where a waterfall exists, named Curug Betung.

There was a large lake existed between the exit of the basin and Rawa Danau. An artificial drainage channel had been excavated at the exit, in order to lower water level and create paddy fields by extinguishing the lake. The excavation of the channel was commenced by the Dutch Colonial government and completed by the Japanese Army in 1940s, made the water level inside basin about 2-3 m lower (water level at upstream of the drainage channel now fluctuates by about 1.5 m with discharge although it had been not only high but also stable due to much wider width of the old river at the exit).

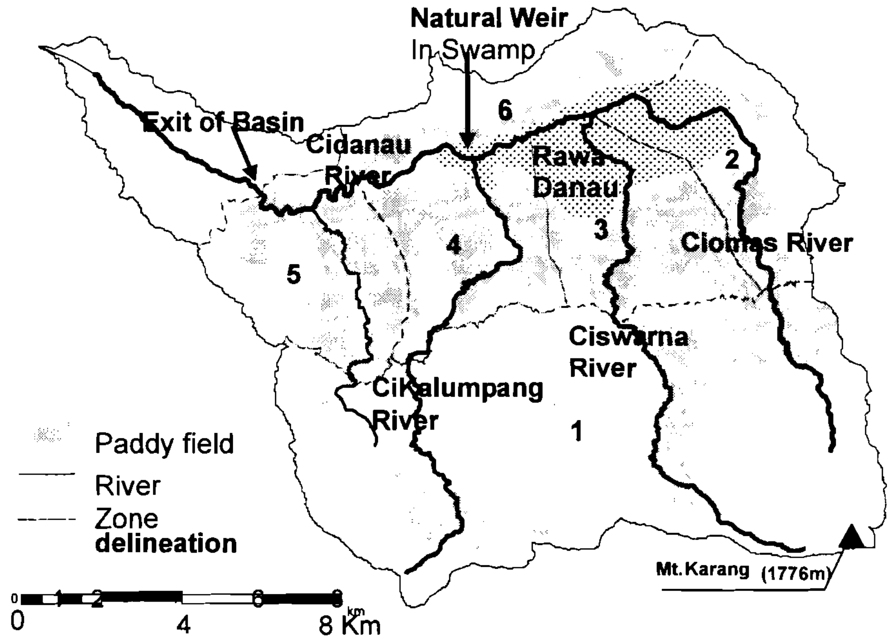

Fig.2 Map of Cidanau watershed

Creating paddy area with diminishing the large lake by lowering water level of the river must have been the biggest environmental change due to development of human being in Cidanau watershed. It is written in a literature (UNEP, 1999) that lowering water level of Cidanau River by the drainage channel also had lowered water level in Rawa Danau and significantly changed environment of the swamp. This must had been a preoccupation without scientific ground but believed among researchers interested in the swamp. No exploration or analysis had been conducted to know how much the water level had been lowered in the swamp. Also, it was not known how much water level in the swamp fluctuates with discharge, and how much water surface area spreads, which determines hydrological role of the swamp for downstream of Cidanau River. Therefore, making scientific answers to these questions was our research objectives.

We installed water level sensors in the swamp and around the exit. We conducted ground level survey in the two areas. However, it was difficult to obtain reliable elevation difference between two benchmarks of ten kilo meters apart, one is near the swamp and the other is at the exit (Shiozawa et al. 2004). Recent use of interference GPS made it possible to measure elevation difference of two points of such apart, with an error within 2 cm (after geoid correction). Finally, we have obtained elevation profile of Cidanau River from Rawa Danau to the exit of the basin, as drawn in Fig.2, in which we can compare the elevation of water level of the swamp with that of the old lake (it can be known from the elevation of old river bed at the exit). Then, the followings are figured out:

(1) Water level in Rawa Danau is 0.9-1.6 m higher, depending on discharge, than that of the old lake, indicating that the excavation of the drainage channel at the exit of the basin had no effect on water level in the swamp. Water level of the swamp now must be the same as 100 years ago.

(2) At the end of Rawa Danau, around the point of merge of Cikalumpang River, Cidanau River is narrow and the river bed is shallow (about 0.6 m deep for base flow) as if this part is

a natural weir. Along downstream side of 1.0 km from this part hydraulic gradient is steep (about 1/1000) while in the upstream side (in the swamp) river water depth is deep (about 2.1 m deep for base flow) and hydraulic gradient is flat (about 1/10000). Water level (as function of discharge) in the swamp is controlled by hydraulics of this part; Manning equation (an equation that gives discharge as function of water depth and gradient depending on river properties of cross sectional shape and roughness coefficient) applied at this part gives theoretical water level as a function of discharge (Fig.4), which well describes observed water level. Observed water level in the swamp varied by 1.3 m, between minimum (discharge of Q=2.0 m^3/s) and maximum (Q=45 m^3/s) flow rate observed.

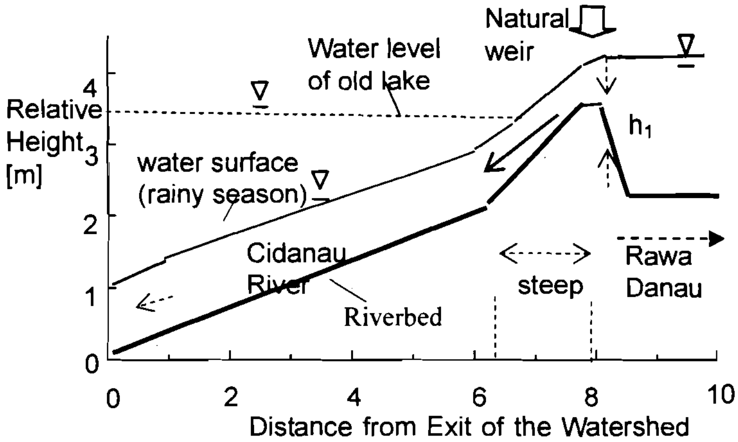

Fig.3 Schematic illustration of riverbed and water level profiles along Cidanau River

(3) For base flow water surface in the swamp stays within narrow river, indicating that the swamp has no effect to increase base flow (storage capacity is little). However, when flood (Fig.4-a), the water surface spreads over a large area of the swamp, indicating that the swamp has significant effect to decrease flood for downstream (storage capacity is large). For example of observed flood, an estimated flood discharge of 104 m^3/s that flowed into the swamp was reduced to 44 m^3/s that flowed out of the swamp, with increasing water depth over the swamp by 0.3 m/d.

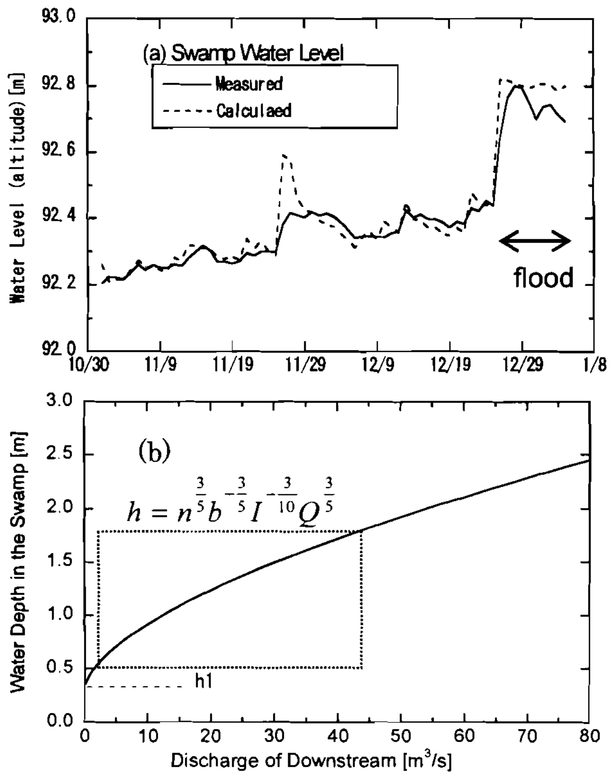

Fig.4 Water level in Rawa Danau. (a) Observed and calculated water level in rainy season of 2003-2004. (b) Relationship between discharge and water depth calculated by Manning Equation (h_1=0.3 m, b=10m, n=0.03, I=1/1000). Dotted square indicates observed range.

Although the water level in the swamp has been the same as in the past, water quality in the river and nitrogen cycle in the swamp has been changed greatly, as a result of prevalence of chemical fertilizer into paddy fields over the watershed, air pollution due to industry and cars, and increased population. While total nitrogen (TN) concentration of river water in the swamp is 0.2 –0.4 mg/l (still lower than river water that flow into the swamp), the concentration must had been almost zero in the past before chemical fertilizer prevailed. Nitrogen input into the swamp through river and from atmosphere (wet and dry deposition) has been significantly increased to make the swamp nitrogen rich. As a result of eutrophication, water plants spreads over the water surface of the river in the swamp. KTI gets rid of weeds from water surface of the river in the swamp every year now; otherwise, the water surface would be completely covered by water plants. Major path of nitrogen load that increases TN concentration of environmental water in the watershed (and that in Rawa Danau), and the effective way to reduce it is discussed in the latter section on nitrogen cycle.

Another environmental problem is illegal deforestation to develop paddy field at the edge of the swamp forest. Satellite remote sensing analysis indicated that land use proportions in the whole watershed have not been subjected to significant changes from logging or development of agricultural field since 1970s (Tsuyuki et al. 2003), but deforestation at the edge of the swamp is evident; old stumps of the forest trees are recognized in paddy fields a couple of hundred meters from the edge of the swamp forest. Deforestation there has been induced by the local population increase driven by economic crisis in 1997-1998, and is a social problem (Yoshino et al. 2003). It is a big problem against conservation of the precise environment of the swamp forest. However, expansion of paddy field there has no effect to deteriorate water quality (in terms of nitrogen) in Rawa Danau because the farmers there do not use chemical fertilizer, differently from upstream farmers; paddy cultivation, without fertilizer, reduces nitrogen in water effluent from the field through harvest, as well as denitrification.

2. Variable acreage of cultivated paddy fields depending on preceding precipitation

Since rice has a higher minimum temperature requirement than any other grain crop, the rice growing period is limited by the lower temperature during winter in temperate climatic regions. Accordingly, rice cultivation is undertaken just once a year with transplantation in spring and harvest in autumn. On the other hand, in tropical regions, where temperatures are high and nearly constant all year round, rice can be sown and grown throughout the year, but only if sufficient water is available. Consequently, in the tropics, the number of crops (rice) planted per year on the same parcel of land, and hence the annual gross acreage of paddy cultivation in a given area, depends on just the availability of water. If water is sufficient even in dry season three times cropping in a year is possible while only once in rainy season if availability of water is limited.

In paddy field in Cidanau watershed plot-to-plot irrigation system utilizing spring water in mountain foot, where dry season cultivation is feasible, developed while rain fed paddy fields spread, where rice cultivation is limited within rainy season (Kuroda and Fukuda, 2003). It was difficult to estimate area of cultivated paddy field over the watershed, which is varying in a year and among years with variable amount of rainfall.

Yoshikawa and Shiozawa (2006) successfully estimated the area of cultivated paddy field by using satellite remote sensing images. While satellite data is best suited for creation of land cover classifications, it is still not easy to distinguish cultivated land, especially in tropical regions where various growth stages of planted rice coexist. In their newly developed algorism they uses NDVI (Normalized Difference Vegetation Index), the most commonly used index for surface vegetation, to identify rice plant cover of grown stage, and uses middle infrared band, which is sensitive to water surface, to identify land of puddling or early-grown stage of rice planting, for which water surface occupies high rate of land cover. Then, they found strong correlation between the estimated area of cultivated paddy field (or the ratio of cultivated paddy) and preceding 90-day cumulative precipitation until the day (Fig.5).

Figure 5 shows the relationship applied to topographically subdivided zones 2 and 5 in Fig. 2. The slope of the regression line, which differs depend on zones in the watershed, indicates degree of dependency of the paddy cultivation on the amount of preceding rainfall. In zone 5, located in the west of the plain paddy field area, the cultivated paddy field ratio was highly sensitive to preceding precipitation with a slope coefficient of 0.00061; paddy fields of this zone is basically rain fed and most of them are not cultivated during dry season. Contrarily, the sensitivity was considerably lower east of the paddy field area in zones 2 and 3 (0.00009 and 0.00028, respectively). These zones are benefited with an abundant groundwater supply from upstream; reflected by the high y-intercept value (0.79 for zone 2); most of the paddy fields there are cultivated even in dry season. The other zones, zone 4, the plain paddy field area between zones 3 and 5, zone 1, relatively sloped terraced paddy field areas, and zone 6, areas adjacent to the outer rim of the watershed, were characterized by medium sensitivity (0.00037, 00032, and 0.00034, respectively).

The differences resulted from the runoff and water storage characteristics of each zone. In areas with low sensitivity, water is supplemented, even in the dry season, by the affluent stock of groundwater upstream of the plot-to-plot irrigation. On the other hand, the supply of ground water is limited in the low sensitivity areas and paddy fields here are mainly rainfed. Especially zone 2 is benefited with an abundant groundwater supply from upstream; reflected by the high y-intercept value (0.79). We should also note that zones 2 and 3 are situated at the foot of the highest volcano in the watershed, Mt. Karang (1778m). Generally, volcanic ash soil, if thick, forms a

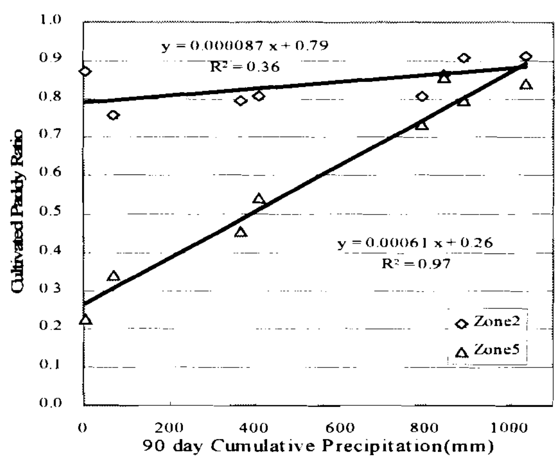

Fig. 5 Correlation between 90-day cumulative precipitation and the cultivated paddy field ratio (cultivated area/area of paddy field) of zones with the highest and lowest sensitivity to precipitation (Zones 2 and 5) (Yoshikawa and Shiozawa, 2006)

groundwater aquifer with a large storage capacity because of its high permeability and large porosity. There are many groundwater springs on the slope and at the foot of Mt. Karang. Thus, the analysis allowed us to realize the difference in hydrological characteristics within the watershed and its effect on rice cultivation.

3. Does paddy field increase or decrease water resource?

Water resource of a river is evaluated not by average flow but by base flow (nearly minimum). Dry season base discharge of Cidanau river is 2.0 m^3/s (discharge is lower than the value about 1/10 of the days in a year or 0.8 mm/d for 220km^2 area catchment. This discharge is large among watersheds nearby with the similar precipitation (Goto et al. 2001). The relatively large base flow rate is responsible for the large storage capacity of groundwater of volcanic mountain as described in the previous section. However, the base flow discharge is not sufficient for the demand of water supply.

A question may arise whether paddy field increases or decreases water resource for downstream. It is generally an important question for tropical watershed where about half of the year is dry season, especially in Cidanau watershed, which provide water for industry and city of downstream and the water resource shortage of which is a big issue.

As the authors' consideration, cultivated paddy field never increases water resource. Evapo-transpiration from cultivated paddy field is the potential (maximum) value for the given weather, as almost same as in forest, and, on the other hand, it impedes infiltration and thus reduces groundwater recharge, which is different from forest. Therefore, paddy field, if cultivated, consume the same water as forest during dry season, but allow less groundwater recharge (less increase in groundwater storage) than forest during rainy season.

However, paddy field if it is not cultivated during dry season, must increase water resource compared with forest or coved by rice or glass. The paddy field becomes bare soil with no vegetation, if it is not cultivated during dry season. Evaporation from such dry bare soil is considerably less than transpiration from field covered by vegetation. Dry soil layer at the surface prevent evaporation, while even in such condition plant can uptake sufficient water from deeper soil by root and evaporate it from leaf stomata. Thus, uncultivated paddy field (dry bare soil) reduces evapotranspiration, compared with it were covered by vegetation (natural condition of Cidanau), and increase base flow rate of the river by the reduced amount of evapo-transpiration.

Keeping above in mind, explorations had been conducted to compare the rate of dry season evapo-transpiration from cultivated (irrigated) and from uncultivated (not irrigated) paddy field in most downstream of the watershed (zone 5 in Fig.2), where there used be the large lake. Summarized result is shown in Fig.6. Evapo-transpiration rate from cultivated (irrigated) paddy field is about 5 mm/d, regardless of with or without rice canopy, which is the value of potential evaporation rate. On the other hand, the rate from uncultivated paddy field is 2.0-2.5 m/d, about half of cultivated field. Surface condition of uncultivated paddy field was dry with

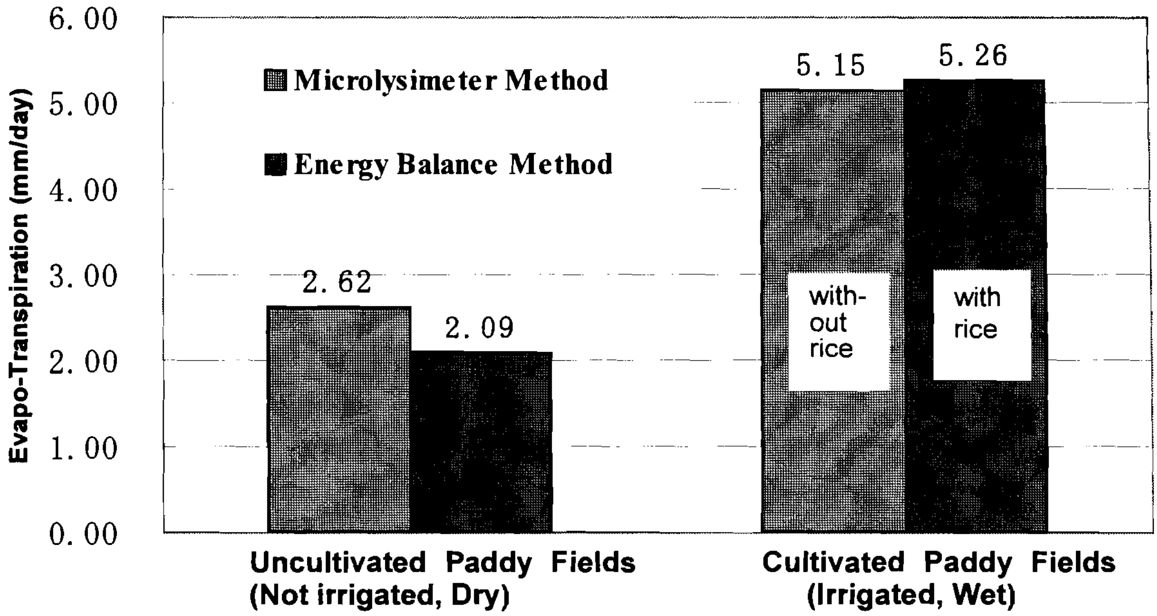

Fig.6 Comparison of evapo-transpiration rates between cultivated (irrigated and wet) and uncultivated (not irrigated and dry) paddy fields in dry season. Both wet and dry data were measured nearby on the same days in several fields in zone 5 of Fig.2 in 2006 and 2007, and averaged. Depths of groundwater table were about 70 cm for dry fields.

large cracks although the depth of ground water table was as shallow as 0.7 m deep from ground surface. Forming dry soil surface, in spite of shallow groundwater table, may be the result of very low saturated hydraulic conductivity of highly swelling clay soil there.

In most dry season, approximately 50% of paddy field area is not cultivated in the watershed (Yoshikawa and Shiozawa, 2006). This area occupies 14% (paddy field is 28%) of the watershed. Assuming 2.5 mm/d reduction of evapo-transpiration rate for uncultivated paddy field, contribution of total uncultivated paddy field to reduce the watershed average evapo-transpiration rate is calculated to be 0.35 mm/d. Although reduction of evapo-transpiration in uncultivated paddy field does not directly increase minimum discharge of Cidanau River, the effect is not small. The effect of increasing river discharge is direct when it is compared with the case for which the paddy field is irrigated by the river water.

In downstream area of Cidanau River (zone 5), most of the paddy field (80%) is not cultivated and dry in most dry season. In the past there was a large lake, as mentioned, and Cidanau River run through the lake. In the lake, about 5 mm/d of water was lost due to evaporation. Given that the area of the lake was 10 km^2, the minimum discharge of Cidanau River that flowed out from the watershed must have been abut 0.6 m^3/s less than present due to loss of evaporating water in the lake.

It is possible to irrigate the paddy fields of 700 ha in zone 5 that are not cultivated during dry season now, by pumping up the river water of 0.3-0.4 m^3/s. In this case, we should note that the irrigated water would evaporate in the paddy fields and never return to the river; discharge of the river would be reduced as much. However, it is possible to keep a predetermined minimum discharge by reducing or stopping the intake of irrigation water from the river when the river discharge becomes lower than the minimum value. For example, expected days in which the river discharge becomes lower than 1.5 m^3/s is 20 days in a dry season. Interruption of irrigation for 20 days may not lead to a significant reduction of rice yield in the paddy fields of heavy clay. The minimum value of discharge to be kept in the river can be determined considering and estimating water price occurring during a draught and reduction of rice yield by quitting irrigation.

It should be noted that, generally in tropical climate that has dry season, existence of paddy field that is not cultivated (not irrigated) increase water resource of the river by reducing evapo-transpiration from natural condition of which the land is covered by vegetation.

4. Changes in nitrogen cycle due to prevalence of chemical fertilizer

One of the important results of investigation in Cidanau was nitrogen budget in the watershed (Yoshikawa et al. 2008). The significant feature of nitrogen budget originally found in Cidanau must be common among tropical watershed where paddy fields spread; large amount of biological nitrogen loss to atmosphere due to denitrification and small fraction of outflow with river water (Fig.7-a). The main N input occurs from chemical fertilizer applied to paddy cultivation. It is considered that the nitrogen cycle in tropical agricultural watersheds must have changed drastically after introduction of chemical fertilizer and industrial development. Here we will discuss this change in nitrogen cycle generally occurred in tropical agricultural watersheds as well as in Cidanau.

In the past, when no chemical fertilizer was applied and no air pollution due to industry or cars existed, biological N fixation must have been the major N input into the watershed and it exceeded denitrification (especially in paddy fields); the excess of biological N fixation might balance the sum of the other N export terms of river water flow, rice exports, and atmospheric N emission due to incineration of rice residue and wood fuel (Fig.7-b). However, nowadays, chemical fertilizer application and air pollution have made the watershed nitrogen-rich and the increased TN concentration over the watershed has decreased biological N fixation and increased both denitrification and N flow with river water. Apparently, denitrification has overwhelmed biological N fixation and become the dominant process of N loss from this agricultural watershed.

Scientists studying global N cycle believe that biological N fixation is significant in tropical watershed, where temperature is high and activity of soil microbe is high. However, it is no more true in agricultural watershed. Appling a lot of chemical fertilizer has reduced biological N fixation and increased denitrification; the direction of net N flux, which used be from atmosphere to the watershed, has turned to be from watershed to the atmosphere. Application of chemical fertilizer, which has increased agricultural production, has made the watershed nitrogen-rich and significantly increased net N flux to atmosphere due to denitrification. On the other hand, nitrogen concentration in river flow is low (lower than concentration of rainfall) and the amount of nitrogen flowing with river water is relatively low compared with agricultural watershed of temperate climate; The TN concentration is much lower than typical river water in Europe or USA and it is still lower than paddy field area in

Japan. As a result of high rate of denitrification due to high temperature and wet condition of soil, nitrogen discharge with river flow is lower than in Japan even though similar amount of fertilizer is applied and river discharge is larger due to much larger amount of rainfall. High temperature of the tropical climate in flooded paddy field is favorable for both of different biological processes soil microbes involve, N fixation and denitrification. It used to induce N fixation before chemical fertilizer prevailed, but now accelerates denitrification. These result should be common feature in tropical watershed where paddy fields spread.

Another important issue on N cycle to be discussed is NH_3 volatilization in paddy fields

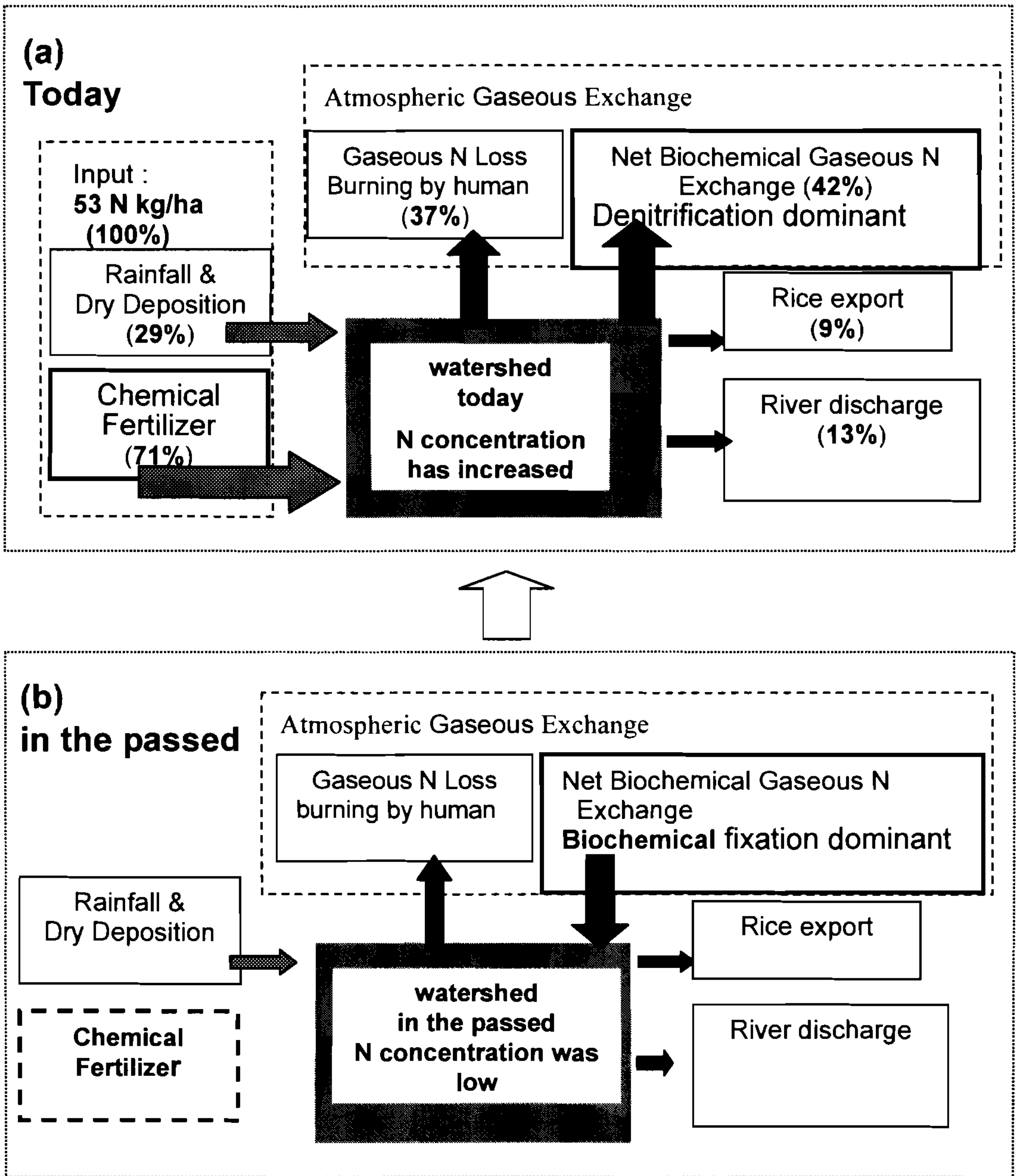

Fig.7 Change in nitrogen budget in the watershed with introduction of chemical fertilizer into paddy cultivation. (a) Real nitrogen budget (quantitative) today in Cidanau watershed (Yoshikawa et al. 2008). (b) Speculated nitrogen budget in the passed before chemical fertilizer prevailed.

and its redeposit around. NH_3 volatilization is loss of N from the paddy field to atmosphere, as well as denitrification, but volatilized NH_3 redeposit into places around the source of volatilization mostly within several hours or days; it simply diffuses around the source. Under high temperature of tropical climate, considerable amount of NH_4-N in applied fertilizer (urea) is lost due to NH_3 volatilization within one week of broadcasting urea (Fillery et al. 1986). NH_3 volatilization is not only loss of fertilizer but also diffusion of NH_4-N to environment and a big source of environmental N load over the watershed, including Rawa Danau. About half of TN contained in rainfall water in the watershed is NH_4-N, which is regarded mostly volatilized from paddy fields in the watershed (the rest half is mostly NO_x originated from cars, industries, and incineration of rice residue and wood fuel). We should note the fact that TN concentration in rainfall water (about 0.8 mg/L) is higher than river water (about 0.4 mg/L); this indicates that rainfall is the major source of nitrogen that increases TN concentration of environmental water over the watershed (there is also some amount of dry deposition of NH_3), so is especially in Rawa Danau, which is surrounded by paddy fields.

NH_3 volatilization in paddy fields varies greatly depending on the method of fertilizer application; substantial NH_3 volatilization occurs where urea fertilizer is customarily broadcast after transplantation of rice. Application of urea into soil can reduce NH_3 volatilization significantly. It is strongly recommended to disseminate method of fertilizer application that reduces NH_3 volatilization, in order to save fertilizer for farmers and to reduce environmental nitrogen load.

Concluding remarks

The research results described here are exciting. Some of them were not expected when we started the investigation. Results of nitrogen budget and nitrogen cycle are very general among tropical paddy culture watershed and firstly found in Cidanau by taking advantages of the characteristic of the watershed (well segmented biosphere, self supply of food and feed). The role of paddy field on water resource in tropical watershed is commonly important, and should be developed more. We have learned a lot from the typical tropical agricultural watershed.

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