Introductory Remarks on Interactions between Crop Cultivation and the Environment: Nutrio-physiological Principles and Some Examples

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Keywords: agriculture, degraded soil, environment, permanent crop, tropics

ABSTRACT

Involvement in environment issues and population-carrying capacity were analyzed based on three typical agricultural systems: slash-and-burn semi-sedentary agriculture, recycling agriculture in which organic materials are re-used, and non-cyclic agriculture in which nutrient supply depends chiefly on chemical fertilizers. Our analysis showed that, due to its high productivity, non-cyclic agriculture is obligatory to support an ever-growing population and to offset the resultant continuous loss of arable land per person. Fertilizers to be applied should be quantified to exactly meet the balance between plant requirements and natural supply. Over-fertilization should always be avoided. Degradation of soils in the tropics is caused mainly by water and wind erosion, and to a lesser extent from nutrient disturbance (mainly from shortages). The environmental-protective effects of permanent crops are shown using two examples. One is in Erimo, Hokkaido, where fishermen have revived their local fisheries by reforesting the coastline, and the other in Tanzania where indigenous people thrive on the permanent culture of bananas. In the tropics, the use of vegetation as soil cover confers advantages in highly fragile areas, if only because of protection from erosion. The introduction of permanent crops is an alternative to establishing co-existence between agriculture and the environment.

Introduction

Agriculture is essential to provide food for human beings, but, at the same time, unavoidably involves some disturbance of the environment. The close association between agricultural activity and the environment is similar in temperate and tropical regions. In this introductory presentation to the seminar, I will show some nutrio-physiological principles of typical agricultural systems and explain how permanent crops can contribute to sustaining the environment.

Climate and nutrients are the major environmental factors controlling plant growth and hence crop production. The dominant climatic factors are solar radiation, temperature, and precipitation, and these dictate the presence and type of natural vegetation. Sixteen inorganic elements are known to be essential to plant growth. The fact that they are essential suggests that plant growth is impossible if any of them is lacking. These elements are released in forms that are usable by plants through soil weathering and biological activity. Certain quantities of the natural supply of nutrients are already available, so that some plants growth is possible, depending on their availability, even without the addition of nutrients (i.e., without artificial fertilization) (Fig. 1). Note that nutrient availability is closely linked to climatic factors. In terrestrial ecosystems, forest, savanna, etc., develop as a result of the prevailing climatic and nutritional conditions.

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1. Crop productivity in relation to nutrient availability

When human beings began to expand their territory from Africa, uninhabited land stretched before them wherever they migrated (Fig. 2). Their livelihood was mostly hunting-and-gathering. Under these conditions, anthropological activity had no or only minimal effect on the natural environment, since human life totally depended on nature. When our ancestors started to settle down and cultivate crops, however, a close association between their activities and the environment was established: for instance, by use of fertilizers.

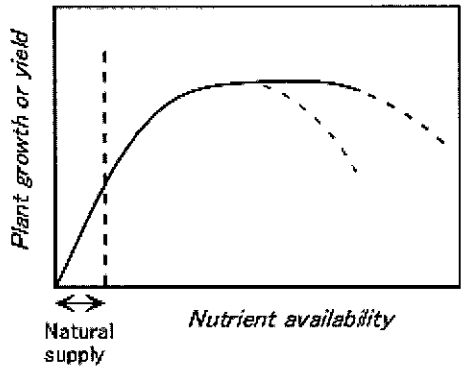

Fig. 1. Relationship between nutrient availability and plant growth (or yield). Natural supply of nutrients is variable depending on environmental conditions.

Agricultural history can be traced back about 10,000 years, but the close association between agriculture and the environment has a relatively short history of only a few decades: arable land development has reached a ceiling but the population continues to expand. The most significant event in agricultural history was the creation of chemical (inorganic) fertilizers, which made it possible to support an ever-growing population. At the beginning of the use of chemical fertilizers, no agricultural activity caused pollution of the natural environment, even though the environment did suffer from the industrial revolution. Since sometime in the 1980s, when there was a growth surge in Japan, mismanaged agricultural activities have had an adverse affect on the environment.

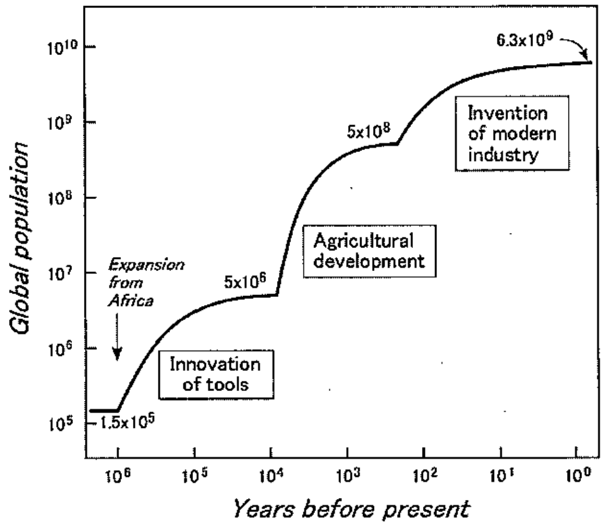

Fig. 2. Growth curve of global population (Modified from Keits (1992)).

1-1. Tracing back to agricultural history

Several indigenous peoples still live by hunting and gathering. They are, however, few in number, and thus are disregarded in this text because its major focus is the close association between anthropological activities and the environment. Currently prevailing agricultural systems can be classified into three groups: slash-and-burn semi-sedentary agriculture, recycling agriculture, which re-uses organic materials within a closed ecosystem, and non-cyclic agriculture that depends chiefly on chemical fertilizers. In the following, the nutrient balance of these three agro-systems will be analyzed from the nutrio-physiological aspect, together with their crop productivity and population-carrying capacity.

Slash-and-burn semi-sedentary agriculture was practiced in Japan in the past, but it is rare now. In Asia, due to population pressure, it holds only a minor place among various agricultural systems, although it still survives. In contrast, in Africa and Latin America, many farmers engage in this type of agriculture, since low population density allows it. After cutting trees and bushes, letting them dry and burning them, people grow crops for several seasons but eventually abandon what have become unproductive fields (Fig. 3). Nutrients contained in the ash are absorbed by crops and removed from the fields. The farming period is often limited to one to three crops in many regions in the tropics: after that, yields fall below economic levels (Fig. 4). The fallow period needed for nutrient recovery in the ecosystem is 10-30 years. The duration of cropping and fallowing depends entirely on natural conditions (climatic factors and the nutrient status of soils) and the exploitation of nutrients by crops.

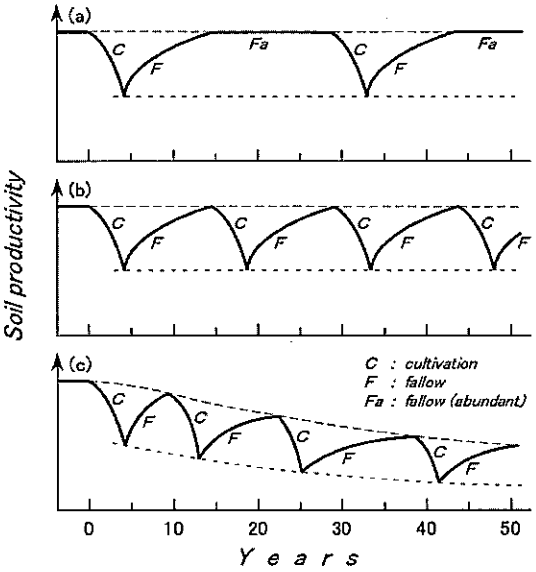

Fig. 3. Relationship between length of fallow period and soil productivity in slash-and-burn semi-sedentary cultivation (Ruthenberg, 1976). (a) and (b) denote the maintenance of soil productivity with abundant fallow and with marginally sufficient fallow periods, respectively, and (c) denotes a continuous decline with short, insufficient fallow periods.

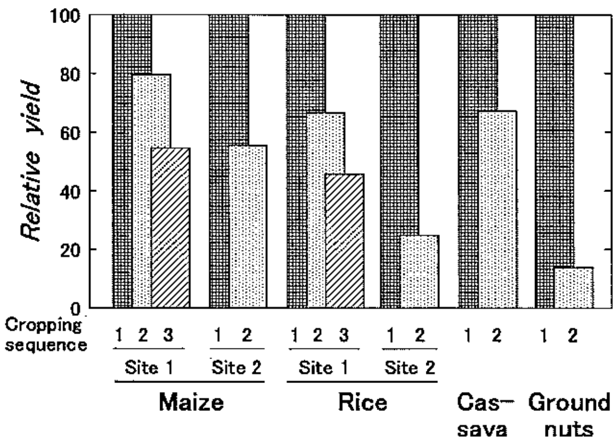

Fig. 4. Yield reduction with continuous cropping in slash-and-burn semi-sedentary cultivation in a tropical rain forest (Ruthenberg, 1980).

Slash-and-burn agriculture is a well-established system, and allows repeated crop production provided an appropriate fallow period is guaranteed. However, it readily degrades the land if the fallow period is shortened. Frequent cropping without the necessary fallowing period gradually results in exhaustion of fertility, and eventually in desert. Land of this type is observed everywhere in the world.

Humans originated the technique of fertilizer application on arable fields to cope with the food shortages that resulted from limits to land availability and population growth. In this system, crop residues and excreta of animals and human beings are actively returned to cropping fields, sometimes supplemented with forest underbrush (Fig. 5). A close association is formed among cropping fields, animals (including human beings) and the environment, where all nutrients are fully recycled in the form of organic material within the system. Hereinafter this will be called recycling agriculture.

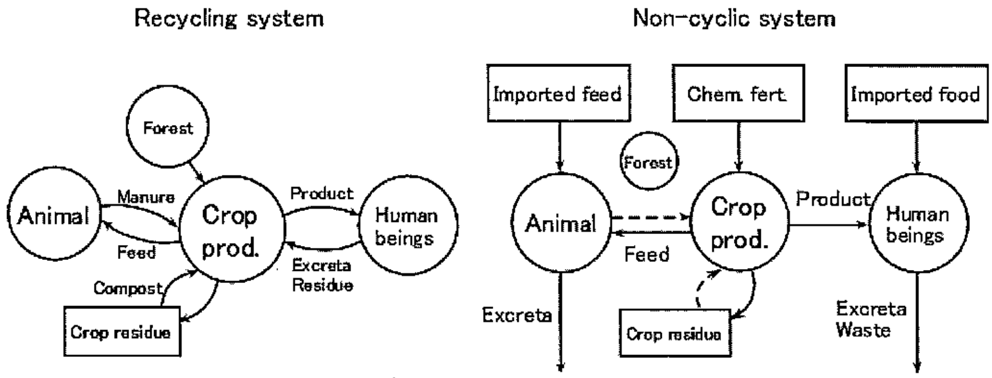

Fig. 5. Crop production in recycling and non-cyclic agricultural systems

More recent advancements in urbanization have made food-producing and -consuming areas remote, and at the same time, even within rural areas, crop cultivation and animal raising areas are separated for reasons of economic efficiency. This tendency has prevented the recycling of organic materials between arable fields and animals. Nutrients needed for crop production are entirely supplied in the form of chemical fertilizers from outside the crop-and-animal association. In other words, the emergence of chemical fertilizers has make urbanization possible. Under this system, human excreta is treated in sewage facilities and released into the environment, and feeds for animals are provided as imported commodities produced elsewhere, even abroad. Therefore, urban areas, animal raising sites and arable fields become independent of each other, and material cycling among them becomes impossible. Note that animal excreta should be recycled to saving precious natural resources because they contain large quantities of nutrients.

1-2. The population-carrying capacity of agricultural systems

Before discussing further, several nutrio-physiological aspects of plants will be reviewed. First, the nutrient concentrations in agricultural products do not vary much according to production site or cultivar: they remain constant at a level that is specific to each plant species. This fact suggests that the nutrients needed to obtain a given yield are the similar for a given plant species and climate (Table 1). Because of this, double the quantity of nutrients is needed to double yield, for instance. Second, nitrogen, phosphorus and potassium are often called the major component of fertilizers: these elements are present in high concentrations in plants and are deficient in many soils worldwide. Nevertheless, elements other than these are deficient in some soils: if this is the case, the deficient element is what limits plant growth. Third, fertilizers added to arable fields do not automatically match the plants' needs. Although improvement of the nutrient absorption efficiency is an important target in fertilizer science, this topic is skipped in this text.

Table. 1. Nutrient requirement for each unit weight of yield (g kg^{-1}) of various crops (Murayama, 1984).

Crop	N	P_2O_5	K_2O
Wheat (grain)	31	11	26
Maize (grain)	24	12	29
Sweet potato (root)	4	1	6
Irish potato (tuber)	5	2	7
Pea (bean)	50	13	24
Adzuki bean (bean)	57	22	65
Rapeseed (seed)	76	38	93
Rice (grain)	21	8	23

Table. 2. Fate of chemical fertilizers applied to soil.

Element	Plant absorption	Soil fixation	Release to air	Leaching
N	40~50	5~10	20~30	3~10
P_2O_5	5~15	85~90	0	0.1~3
K_2O	40~50	40~50	0	3~10

The population-carrying capacity of land under the three agricultural systems will be analyzed on the basis of crop productivity, as represented by the grain yield of cereal crops per unit field area. The grain yield of the slash-and-burn agricultural system is about 1 ton ha^{-1} in most locations. Assuming that, for sustainability, one cropping cycle lasts 10 years, the crop production of this farming system is 0.1 ton ha^{-1} per year. Although the maximum yield from the recycling system is 5 ton ha^{-1} or greater under favorable conditions, the average grain yield is more likely to be 2-3 ton ha^{-1}. This yield level is close to the rice yield in the 17^{th}-19^{th} century in Japan (Table 3), a level that farmers worked extremely hard to maintain. However, a more plausible yield would be 1-2 ton ha^{-1} under present global conditions (Fig. 6). When crop production depends largely on chemical fertilizers, as in most non-cyclic systems, its yield level is likely to be 3-4 ton ha^{-1}. The record is 10 ton ha^{-1} or more in many trials, and Japan's national average is 7-8 ton ha^{-1}. Yields higher than this, though, are rare. Besides, to reach such high yields, the quantity of fertilizers applied needs to meet or exceed demand: actual fertilizer consumption is lower.

Table. 3. Past and present status of crop production in Japan.

Time[1)]	(Farming system)[2)]	Total area of crop field[3)] (10^6 ha)	Grain yield (ton ha^{-1})	Total crop production (10^6 ton) (A)	Total population (10^6) (B)	Crop production per person (kg) (A/B)
17^{th}–19^{th}	(Recycling)	3	2	6	30	200
Recent	(Recycling)	6	2.5	15	120	125
	(Non-cyclic)	5	5	25	120	210

1) Edo era and since about 1960, respectively. 2) Non-cyclic : depended largely on chemical fertilizers. Recycling system in recent years is rarely practiced. 3) Maximum area of paddy and upland field is about 3 million ha each, respectively, in modern Japan, whereas paddy field is about 2 million ha today.

For calculation of population-carrying capacity, annual food consumption is often assumed to be 250 kg of grain per person. When a farming system is able to produce this quantity of grain, the system is also able to deliver staple foods and all other food commodities (i.e., vegetables, oils, etc.). Based on this assumption, the population-carrying capacity is calculated at 0.4 person per ha with the semi-sedentary slash-and-burn farming system, and 4-8 and 12-16, respectively, for the recycling and non-cyclic farming systems (Table 4). Because the average grain yield is 3.1 ton ha^{-1} (averaged over 1997-2001) worldwide, the present cropped area is shared almost equally between the recycling and non-cyclic agricultural systems.

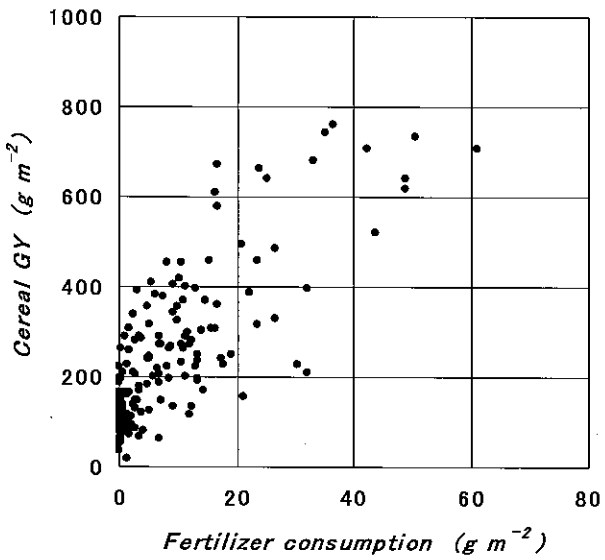

Fig. 6. Relationship between fertilizer consumption and cereal grain yield among various countries (averaged over 1997-2001) (FAO, 2005).

Table. 4. Crop productivity and population carrying capacity of various agricultural systems.

Agricultural system	Input level	GY[1)] (ton ha^{-1})	PCC[3)] (人 ha^{-1})
Slash-and-burn semi-sedentary	Low	0.1[2)]	0.4
Recycling (of organic matrial)	Meduim	1～2	4～8
Non-cyclic (chem. fertilizer)	High	3～4	12～16

1) Grain yield for each unit area. 2) Assuming that grain yield is 1 ton ha-1, and cropping and fallow period are one and nine years, respectively. 3) Population carrying capacity of land, assuming that annual grain consumption is 250 kg per person.

An almost constant arable land area over the past few decades and an ever-growing population have caused arable land area per person to decrease (Fig. 7). Increasing crop productivity per unit area, supported by the use of chemical fertilizers, has relieved people from hunger. This fact implies that 100% dependence on the recycling system (organic or natural farming) would not support the current global population. Note that the contribution of the slash-and-burn semi-sedentary system to the global food supply is negligible.

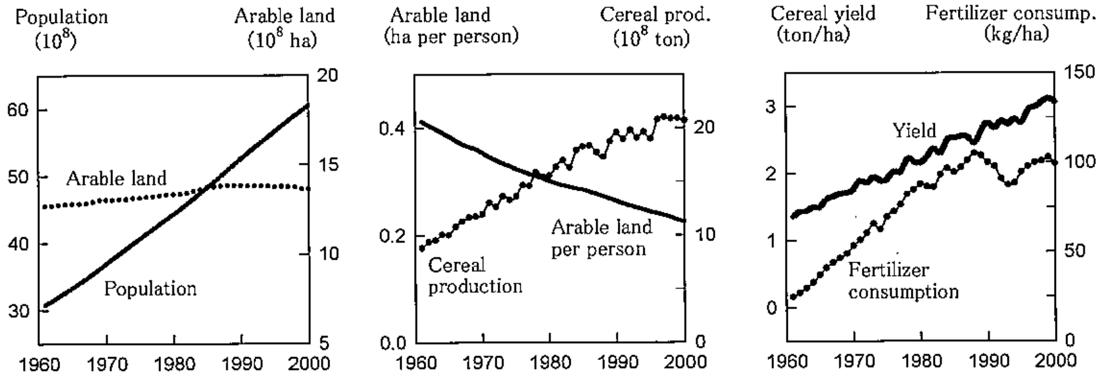

Fig. 7. Changes in total population, arable land area, production and yield of cereal crops, and fertilizer consumption in the world between 1961 and 2000 (FAO, 2005).

1-3. Pollution due to agricultural practices

As mentioned above, chemical fertilizers contribute greatly to food supply, and their use will be even more necessary in future due to increasing scarcity of land. From this aspect, they are an inevitable good provided they are properly used, although they may also be called a necessary evil. An appropriate usage rate of chemical fertilizers comprises a balance between nutrient demand, target yield and the natural supply of nutrients. Fertilizer science has devoted itself to sustaining fertility (or co-existence with nature) throughout its history: the industry has never recommended over-dosing. Provided fertilizers are added as a supplement, their effect on the environment is minimal. If over-applied, the result is obvious: environmental pollution. In Japan, agricultural products and fertilizer prices are both higher than the international market price, with the former being relatively more expensive than the latter. This state of affairs tends to encourage over-dosing with chemical fertilizers, especially with the major elements: crop yield is not greatly decreased even beyond the optimum level when an application level is not too large.

If fertilizers remain after plant uptake, a certain quantity is adsorbed by the soil particles. Because there are limits to soil adsorption, the surplus elements are released to the environment. Over-dosing, frequently practiced in vegetable and tea gardens, need to be stopped as soon as possible.

Excreta from animals (including dairy farming) represent an additional problem in so-called developed countries. For example, Japan's dependency on imported grain has reached nearly 70% of total feed. Huge quantities of mineral elements are also imported that are present in crop grains. Mineral elements in excreta are the same as those contained in imported feed, since adult animals excrete all the minerals they ingest. The maximum amount that can be retained in soils, for example, is known to be about 300 kgN ha^{-1}, and so any quantity that exceeds this rate is discharged to outside of the farm. Excreta produced in Kyushu and many other parts of Japan exceed the allowed level even they were distributed evenly over all arable fields. In addition, over-supply is a major problem in dairy farms, since they are distant from arable fields.

Pollution caused by animals is the worst in Europe, where water pollution reached serious levels in the early 1980s and needed to be controlled by recycling of excreta, fertilizer taxation, etc. In the US, the rate of fertilizer application is not so large and the land area is vast, so pollution is still not a serious problem except in some areas. Because of this background difference, the authorities are taking action against environmental issues (nitrate pollution, global warming, etc.) in Europe, but their counterparts in the US are imposing only very mild measures against it. Japan's position is closer to the European side.

Anthropogenic soil degradation in the tropics is mainly due to water and wind erosion, and partly due to chemical factors (Table 5). Loss of topsoil and land degradation reduce crop productivity and cause environmental damage. In chemical degradation, nutrient loss or deficiency is the dominant factor on the global scale, whereas environmental pollution caused by over-dosing with fertilizers as mentioned above is seen only in limited areas like Europe and Japan. Salinization is serious in many irrigation schemes in arid and semi-arid regions, but is not covered in this study.

Table. 5. Proportion of causes of anthropogenic soil degradation in the tropics (Oldeman *et al*., 1991)[1)]

Cause of degradation[2)]	Tropical America	Africa	Tropical Asia	Whole
Water erosion	59	46	75	56
Wind erosion	6	38	7	28
Chemical factors	32	13	17	12
Physical factors	4	4	1	4

1) Proportion over the total area of anthropogenic degradation.
2) Details: Water erosion: loss of topsoil (47%) and land deformation (8.8%); Wind erosion: loss of topsoil (23%) , land deformation (4.2%) and sand cover (0.6%); Chemical degradation: Nutrient loss (6.9%), salinization (3.9%), acidification (0.3%) and soil pollution (1.1%); Physical degradation: compaction (3.5%), inundation (0.5%) and subsidence (0.2%).

2. The contribution of permanent crops to environmental protection

Most food is currently produced from annual crops. After sowing an annual crop, the soil is exposed for a certain period, making the land prone to water and wind erosion and thus to nutrient loss. In primitive and small-scale slash-and-burn agriculture, a mixture of permanent crops (including trees) and annual crops are protected from such a hazards. Permanent crops will persist for a long period under stable conditions once they are established. The following two examples will provide clues to solving the prevailing problem of environmental protection.

2-1. Revival of prosperity from the sea by reforestation

The area around Cape Erimo, Hokkaido, was in the past covered with broad-leaved trees, including several species of oak (*Quercus dentata* and *Q. crispula*) and white birch (*Betula tauschii*). After the trees were exploited for firewood and the land was used for grazing by cattle and sheep, the area became a desert. The Cape is subject to a harsh climate, in which strong winds (10 m s^{-1}) blow for 270 days a year. Because the sea became turbid with mud caused by desertification, the kelp beds died and fish catches shrank.

Fishermen were forced to choose between abandoning their homes or reforestation. They started a reforestation project in 1953 to save the sea on their own initiative. They first tried to change the desert into grassland. Seeds were protected with screens of marsh reeds or tree twigs, but few of them rooted because of the strong winds. They sowed and re-sowed, but without any success.

Learning from their past experience, in 1956 they tried to cover the seeded fields with unmarketable kelp: this is now called the Erimo technique for forestation. Kelp acts as a soil stabilizer when it dries out: it also delivers nutrients. It is effective in preventing seeds from being blown away and also cheap. The technique was extensively applied and was a success. About 1970, after grassland had become established, reforestation was begun. After a long period of trial and error, it was discovered that a black pine (*Pinus thunbergii*), which was not native to Hokkaido, could survive in this environment. High planting density

(10,000 trees or more ha^{-1}) and densely arranged fences for wind protection gradually improved the seedling survival rate. So far, more than two million trees have been planted.

With the progress of forestation, the sea regained its original transparency, and fisheries revived: catches grew from 227 ton in 1965 to 1,852 ton in 1996. At the same time, people enjoyed good harvests of marketable kelp. Many people in Japan are now aware of the close association between the sea, forest, and rivers, and various forestation activities similar to Erimo's are now widespread (Fig. 8).

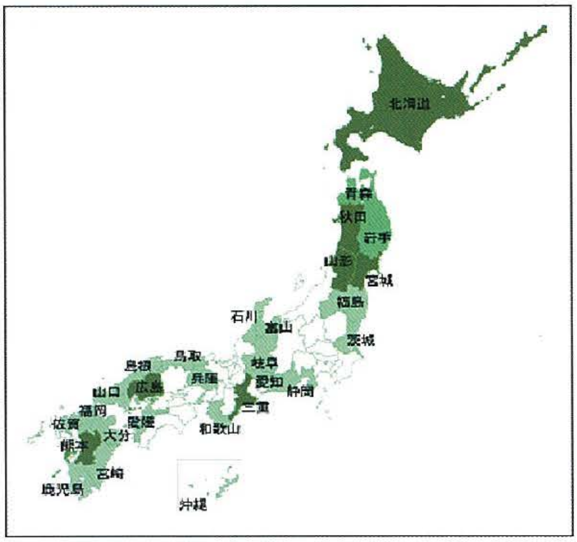

Fig. 8. Re-forestation projects by various communities in Japan. The darker the green, the more extensive the re-forestation activity (Iwate 2001).

2-2. Permanent banana culture in Africa

Several indigenous peoples thrived with farming systems based on banana culture: annual production reaches about one ton per person. Many of them live in east African countries like Kenya, Tanzania and Uganda. Although soil fertility is low in general, farmers input grass and animal excreta into about 20% of the total land. Established banana fields last for several centuries while maintaining constant productivity and support a high population density. In this text, an example of this form of cultivation, practiced by the Haya people in Tanzania, is presented (Fig. 9).

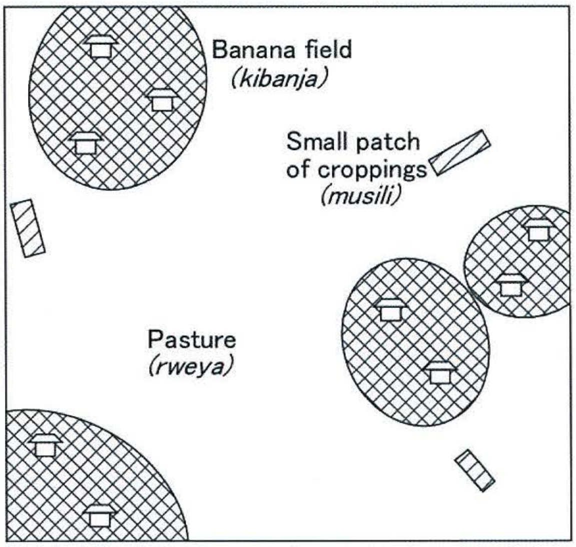

Fig. 9. Land use by the Haya people (illustrative).

In the banana fields, many cultivars with various growth duration (9-21 months) are mixed-cropped at different growth stages (Fig. 10), in a pattern that mimics a forest ecosystem. This system is perhaps the ultimate form of organic farming. Neither chemical fertilizers nor chemicals are applied. The soil surface is covered with a thick mulch formed of grasses and banana pseudostems and leaves, which work well to protect against erosion, even in heavy rain.

Total dry weight of biomass is 0.9 kg m^{-2} (9 ton ha^{-1}) (Fig. 11) and annual bunch production (fresh weight) is 3.4 kg m^{-2} (34 ton ha^{-1}). Net dry matter yield (pulp) is 0.38 kg m^{-2} (3.8 ton ha^{-1}) per year, which is comparable to a reasonably good yield of cereal crops in the tropics. However, the banana yield for each unit time should be at least halved, since the plants need one year to produce the above-mentioned yield. Therefore, traditional banana culture can be described as a logical farming system not designed to deliver maximum yield, although it is labor-intensive. Nevertheless, the yield level using this system far exceeds that of slash-and-burn semi-sedentary agriculture.

In conclusion, any farming system should give priority to erosion protection in fragile soils that are commonly seen in the tropics, and the importance of permanent crops should not be overlooked for sustainability.

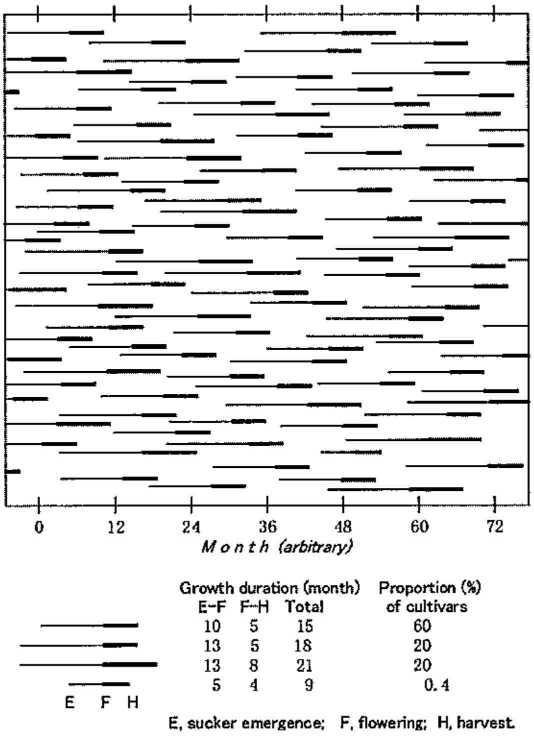

Fig. 10. Schematic illustration of banana growth in an indigenous banana field (kibanja) at the Kamachumu Plateau, northwest Tanzania (Yamachuchi and Araki, 2004). Note that cultivars with various growth durations are randomly mix-grown all the year around.

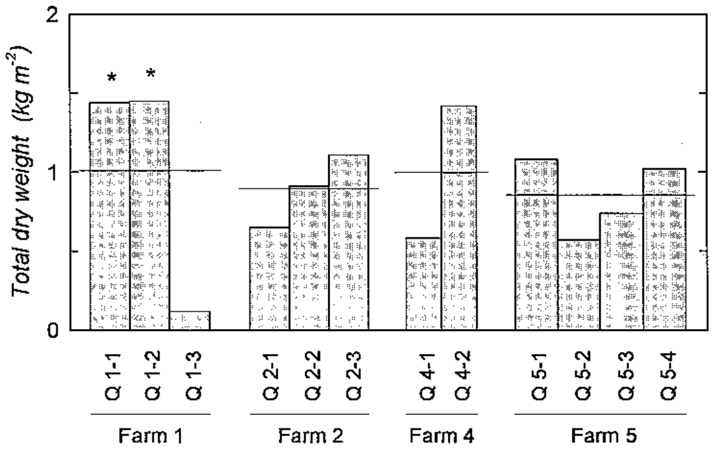

Fig. 11. Total dry weight of banana plants in kibanjas on the Kamachumu Plateau, northwestern Tanzania (Yamaguchi and Araki 2004). Plots applied with manure. Horizontal lines indicate averages for each farm: Introductory Remarks on the Interactions between Crop Cultivation and the Environment: Nutrio-physiological Principles and some Examples

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