Changes in the Energy Efficiency of Regional Crop Production in Japan

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Abstract: Examining agricultural efficiency in terms of energy balance will be a first step in helping to find a solution to the sustainable development of agriculture, and to environmental problems such as the exploitation of natural resources especially in developed countries. This study attempts to define regional energy efficiency based on the regional input-output energy ratio (output/input), which is calculated by the input fossil fuel energy and output food energy of all crops produced in a region. It also investigates the changes in regional energy efficiency of the prefectures in Japan from 1970 to 1990. By inspecting typical combinations of crops, the regional energy efficiency, which will be an index for examining the temporal and spatial changes of regional crop production, is divided into four categories: high (regional input-output energy ratio: more than 2.7 in 1970 and 1990), middle (1.8–2.6 in 1970, 1.7–2.5 in 1990), low (0.7–1.7 in 1970, 0.7–1.6 in 1990) and very low (under 0.6 in 1970 and 1990). Applying these categories to the prefectural level, specific features were seen in the decrease of the prefectures with middle efficiency in the southern Kanto Region and the appearance of prefectures with very low efficiency in the southeastern part of Japan over two decades. It is considered that the decline of energy efficiency was caused mainly due to the increase in the percentage of greenhouse crops planted in the prefectures that are active in the production of paddy rice and horticultural crops. The emergence of the prefectures with very low efficiency in 1990 also implies that intensive crop production reinforces the impact on the natural environment by the usage of fossil fuel energy especially in the region that has high economic land productivity.

Key words: crop production, input-output energy ratio, fossil fuel energy, food energy, regional energy efficiency, environmental geography

Introduction

A great amount of fossil fuel energy is used in modern agriculture. From an ecological point of view, the fossil fuel energy fixed in agricultural materials such as pesticides, herbicides, and oils for agricultural machines has diminished the energy efficiency of agriculture in particular in developed industrial countries (Odum 1971). In an ecological sense, the increase of input fossil fuel energy means the reinforcement of the impact on the natural environment since it modifies the natural formation of land and the natural growth of plants and domestic animals (Giampietro et al. 1992b). Presenting the energy efficiency of agriculture by specific values will be one of the first steps to future work on environmental geography and a new aspect of agricultural geography.

The input-output energy ratio that is calculated by input fossil fuel energy and output food energy has been used to show the ineffic-teness of crop production in developed countries (Pimentel et al. 1973; Lockeretz 1977; Bayliss-Smith 1982). Although energy efficiency is sometimes defined as energy used per ton of crop produced (Swanton et al. 1996; Bonny 1993), the values of input-output energy ratio (energy output per energy input) have been regarded as a lucid and representative way of capturing the characteristics of crop production in the context of energy efficiency. In this sense, this study considers that high energy output/input indicates higher efficiency, and the values explain the amount of yielded energy against a unit of input fossil fuel energy. The values of input-output energy ratio often exceed 1.0, though crop systems which are the basis of the calculation of the input-output en-
nergy ratio are considered as open systems at crop land level (Loomis and Connor 1992; q.v. Bertalanffy 1968). This is caused by not all the input energy being counted. Significant exclusion of input energy is directed to solar energy and human labor. To isolate the impact of fossil fuel energy on crop production, the amount of solar radiation and photosynthesis rates are often removed from the calculation of energy efficiency of crop production (van Ittersum and Rabbinge 1997). Human power should be treated in a similar way to other indices such as working hours, since the energy differs among individuals and the living standards of society (van Heemst et al. 1981; Fluck 1981; Giampietro and Pimentel 1990). The energy from human labor and animal power should be considered in self-sufficient agriculture along with the small energy input originating from industrial products (Jones 1989).

The value of input-output energy ratio varies temporally and spatially in accordance with the kind of crops and the amount of input fossil fuel energy (Hudson 1975; Zuccheto and Jansson 1979; Dovring 1985; Newcombe 1976; Deleage et al. 1979; Blaxter 1975; Avlani and Chancellor 1977). Considering the crop production of Japan, we should comprehend that the energy efficiency is declining with the increase of input fossil fuel energy. Since the period of high growth in the Japanese economy, the working hours for paddy rice have been reduced largely because of the wide adoption of industrial products such as chemical fertilizers, pesticides and agricultural machines (Yamamoto et al. 1988). Since the enactment of the Agricultural Basic Act in 1961, capital-intensive horticultural sectors such as vegetables and fruits flourished through subsidies for the Selected Expansion Sectors (Saito 1996). It is indispensable to the horticultural farms that they introduce new technology and industrial products one after another to sustain their productivity (Nihei 1998). The tendency for capital and labor intensive crop production may have reduced the energy efficiency of crop production.

To confirm the decline of energy efficiency in Japanese crop production, Nihei (2000) demonstrated a calculation of the input-output energy ratio for 32 crops every five years from 1970 to 1990 with reference to the studies of input-output analysis and process analysis (Leontief 1951; Krenz 1974; Bullard and Herendeen 1975; Chapman 1975; Uchiyama 1996) and to the studies of calculating the input-output energy ratio in Japanese crop production (Udagawa 1976; Resources Council, Science and Technology Agency, Japan, 1979; Yoshino 1980; Kimura 1993). The former study defines the “regional input-output energy ratio” and the results show that it declined especially in the prefectures located in the southeastern part of Japan; in particular, the values of regional input-output energy ratio declined to less than 0.5 in Kochi, Kumamoto and Okinawa Prefectures. This remarkable decline of the regional input-output energy ratio implies a contradiction to the concept of sustainable development. That is to say, to sustain modern agriculture, we tend to depend on the input of fossil fuel energy. This is a phenomenon going against the low-input practice, the essence of sustainable agriculture, which does not depend much on the input of industrial material (Lockeretz 1988; Gibbon et al. 1995).

The former study, however, did not explain the energy efficiency of isolated values of the regional input-output energy ratio. For example, the regional input-output energy ratio was of the order of 0.8 in Wakayama in 1990. The values can be placed at twice the efficiency in comparison with the order of 0.4 in Kumamoto in 1990. However, it is obvious that these isolated values do not give a particular explanation for energy efficiency. To make certain the decline of energy efficiency of regional crop production in Japan, a standard has to be established to define the absolute energy efficiency for the regional input-output energy ratio whose values changes temporally and spatially.

The following is a study that attempts to determine a standard of energy efficiency for the values of the regional input-output energy ratio of crop production. This is practiced simply by inspecting the relationships between the values of regional input-output energy ratio and the combination of typical crops in Japan (i.e. paddy rice, wheat and barley, potatoes, field and greenhouse vegetables). Then, the availability of the standard is discussed by applying
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it to the real crop production in 1970 and 1990, namely, it is verified with the percentage and planted area of crops, and kinds of typical crops planted in prefectures. The discussion extends to a tentative interpretation of the declining process of energy efficiency from the point of view of economy and ecology (i.e. gross profit of crop production and output food energy). Making a regional energy efficiency standard and discussing its declining process will lay the groundwork for future planning on regional agriculture in the context of human society and the natural environment, which present studies of energetics are hoping to address (Pimentel et al. 1994; Giampietro et al. 1992a).

Regional Energy Efficiency of Crop Production

Regional input-output energy ratio

The input-output energy ratio of crop production in Japan was calculated on the grounds of cropland unit (i.e. crop systems) by Nihei (2000). The fossil fuel energy used in the production and shipment of industrial goods was taken into account, namely, they are seeds and seedlings, chemical fertilizer, agricultural chemicals (e.g. pesticides and herbicides), fuel and electric power, horticultural facilities, and agricultural implements (e.g. tractors and heating systems). Table 1 shows the summarized results of calculation in order of the average input-output energy ratio of groups of crops in selected two years. The values of input fossil fuel energy and output food energy are used as basic data to show the regional input-output energy ratio. Since energy is not influenced to a great extent by monetary inflation rates, each crop does not show large differences in the amount of input and output energy over two decades, as the average input-output energy ratio in total is given by 0.3 each year. However, depending on the kind of crops, the amount of energy produced changes from 0.8 to 15 GJ/10a, and the amount of energy required largely varies from 0.6 to 222 GJ/10a. Considering the order and values of the input-output energy ratio, the groups of crops can be classified into four categories; “high efficiency crops” for potatoes, “middle efficiency crops” for grain and beans, “low efficiency crops” for fruits and field vegetables, and “very low efficiency crops” for greenhouse vegetables.

The regional input-output energy ratio is indicated by the fossil fuel energy used and the food energy produced by all crops produced in a region. This plain notion is defined by Nihei (2000) as:

\[ Q = \frac{\sum e_i S_i}{\sum e_i S_i} \] (1)

where \( Q \) is the regional input-output energy ratio, which is denoted by the first decimal place, \( e_i \) is the output energy of crop \( i \) (J/m²), \( e'_i \) is the input energy of crop \( i \) (J/m²), \( S_i \) is the planted area of crop \( i \) (m²) and \( n \) is the number of crops produced in the region. The variable \( S_i \) can be substituted for the percentage of the planted area of crop \( i \). In order to apply the equation to real regions, the following assumptions by Nihei (2000) are used:

(1) The energy intensity of agricultural materials is uniform in all crop production. For instance, the agricultural chemical sector is subdivided into ammonia fertilizer, ammonium sulfate, urea, phosphorus acid nitrogen fertilizer, etc. However, this method assumes those materials have the same energy intensity. To improve the accuracy, it is necessary to use the Input-output Tables with a more detailed classification for the subdivisions.

(2) If the same crops are grown, the amount of input and output energy is uniform in all places. The amount of input-output energy is calculated not by each region but for the average in Japan. To improve the accuracy, it is necessary to use the Production Cost of Crops for each place.

The values of the regional input-output energy ratio intricately change in accordance with the area planted and the kinds of crops. To grasp the change in a simple way, this study pays attention to two kinds of crops. Paddy rice, which is cultivated in the widest area in Japan, has been selected as the standard crop for this examination. Assuming that a particular region cultivates paddy rice and another group of crops, an investigation was conducted
Table 1. Input-output energy ratio in Japanese crop production

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<td></td>
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<td>Input fossil fuel energy (MJ/10a)</td>
<td>Output food energy (MJ/10a)</td>
<td>Energy ratio (output/input)</td>
<td>Input fossil fuel energy (MJ/10a)</td>
<td>Output food energy (MJ/10a)</td>
<td>Energy ratio (output/input)</td>
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<tr>
<td>High</td>
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<tr>
<td>Sweet potatoes</td>
<td>1.263</td>
<td>12,427</td>
<td>9.8</td>
<td>2.133</td>
<td>14,868</td>
<td>7.0</td>
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<td>White potatoes</td>
<td>1.315</td>
<td>11,000</td>
<td>8.4</td>
<td>2.140</td>
<td>13,997</td>
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<td>Av. (Potatoes)</td>
<td>1.289</td>
<td>11,173</td>
<td>9.1</td>
<td>2.157</td>
<td>14,433</td>
<td>6.8</td>
<td></td>
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<tr>
<td>Middle</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Paddy rice</td>
<td>2.788</td>
<td>7,154</td>
<td>2.6</td>
<td>3.147</td>
<td>7,830</td>
<td>2.5</td>
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<td>Wheat</td>
<td>1.976</td>
<td>3,733</td>
<td>1.9</td>
<td>1.508</td>
<td>5,335</td>
<td>3.5</td>
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<td>Six-row barley</td>
<td>2.329</td>
<td>4,864</td>
<td>2.1</td>
<td>1.695</td>
<td>3,658</td>
<td>2.2</td>
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<td>Naked barley</td>
<td>1.621</td>
<td>3,268</td>
<td>2.0</td>
<td>1.919</td>
<td>4,467</td>
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<td>Two-row barley</td>
<td>1.721</td>
<td>4,141</td>
<td>2.4</td>
<td>1.412</td>
<td>4,495</td>
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<td>Av. (Grain)</td>
<td>2.087</td>
<td>4,632</td>
<td>2.2</td>
<td>1.936</td>
<td>5,157</td>
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<td>Soy beans</td>
<td>609</td>
<td>2,844</td>
<td>4.7</td>
<td>1,709</td>
<td>3,612</td>
<td>2.1</td>
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<td>Azuki red beans</td>
<td>706</td>
<td>2,425</td>
<td>3.4</td>
<td>1,488</td>
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<td>Kidney beans</td>
<td>703</td>
<td>2,563</td>
<td>3.6</td>
<td>1,418</td>
<td>2,466</td>
<td>1.7</td>
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<td>Av. (Beans)</td>
<td>673</td>
<td>2,611</td>
<td>3.9</td>
<td>1,538</td>
<td>3,203</td>
<td>2.1</td>
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<td>Low</td>
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<td>Unshu mandarins</td>
<td>6,237</td>
<td>5,314</td>
<td>0.9</td>
<td>5,990</td>
<td>6,260</td>
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<td><em>Natsudaidai</em></td>
<td>5,078</td>
<td>4,183</td>
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<td>12,342</td>
<td>5,104</td>
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<td>Apples</td>
<td>3,933</td>
<td>5,885</td>
<td>1.5</td>
<td>5,336</td>
<td>5,835</td>
<td>1.1</td>
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<td>Japanese pears</td>
<td>4,971</td>
<td>6,725</td>
<td>1.4</td>
<td>7,407</td>
<td>4,245</td>
<td>0.6</td>
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<td>Peaches</td>
<td>6,048</td>
<td>3,917</td>
<td>0.6</td>
<td>5,965</td>
<td>3,905</td>
<td>0.7</td>
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<td>Grapes</td>
<td>16,808</td>
<td>2,910</td>
<td>0.2</td>
<td>6,602</td>
<td>3,757</td>
<td>0.6</td>
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<tr>
<td>Av. (Fruits)</td>
<td>7,179</td>
<td>4,822</td>
<td>0.7</td>
<td>7,274</td>
<td>4,851</td>
<td>0.7</td>
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<tr>
<td>Cucumbers</td>
<td>16,419</td>
<td>3,702</td>
<td>0.2</td>
<td>21,102</td>
<td>4,635</td>
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<td>Tomatoes</td>
<td>11,788</td>
<td>4,288</td>
<td>0.4</td>
<td>12,269</td>
<td>4,082</td>
<td>0.3</td>
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<td>Eggplants</td>
<td>9,041</td>
<td>5,795</td>
<td>0.6</td>
<td>19,681</td>
<td>7,231</td>
<td>0.4</td>
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<tr>
<td>Sweet peppers</td>
<td>9,430</td>
<td>2,369</td>
<td>0.3</td>
<td>11,501</td>
<td>5,092</td>
<td>0.4</td>
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<td>Cabbages</td>
<td>3,871</td>
<td>4,046</td>
<td>1.0</td>
<td>3,610</td>
<td>4,839</td>
<td>1.3</td>
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<td>Chinese cabbages</td>
<td>2,870</td>
<td>2,865</td>
<td>1.0</td>
<td>5,640</td>
<td>3,590</td>
<td>0.6</td>
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<td>Welsh onions</td>
<td>5,611</td>
<td>4,180</td>
<td>0.7</td>
<td>8,929</td>
<td>3,392</td>
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<td>Lettuces</td>
<td>3,802</td>
<td>781</td>
<td>0.2</td>
<td>4,048</td>
<td>999</td>
<td>0.2</td>
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<td>Onions</td>
<td>3,248</td>
<td>5,919</td>
<td>1.8</td>
<td>3,854</td>
<td>9,131</td>
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<td>Spinach</td>
<td>2,867</td>
<td>1,311</td>
<td>0.5</td>
<td>3,596</td>
<td>1,657</td>
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<td>Japanese radishes</td>
<td>3,652</td>
<td>5,245</td>
<td>1.4</td>
<td>5,212</td>
<td>6,594</td>
<td>1.3</td>
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<tr>
<td>Carrots</td>
<td>5,765</td>
<td>4,383</td>
<td>0.8</td>
<td>5,521</td>
<td>6,857</td>
<td>1.2</td>
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<td>Taros</td>
<td>4,331</td>
<td>3,416</td>
<td>0.8</td>
<td>3,590</td>
<td>4,649</td>
<td>1.3</td>
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<td>Av. (Field vegetables)</td>
<td>6,361</td>
<td>3,715</td>
<td>0.6</td>
<td>8,350</td>
<td>4,837</td>
<td>0.6</td>
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<tr>
<td>Very low</td>
<td>Cucumbers (Greenhouse)</td>
<td>117,323</td>
<td>4,618</td>
<td>0.04</td>
<td>222,360</td>
<td>6,692</td>
<td>0.03</td>
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<tr>
<td>Tomatoes (Greenhouse)</td>
<td>87,574</td>
<td>5,841</td>
<td>0.07</td>
<td>120,079</td>
<td>6,411</td>
<td>0.05</td>
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<tr>
<td>Eggplants (Greenhouse)</td>
<td>216,317</td>
<td>6,477</td>
<td>0.03</td>
<td>167,349</td>
<td>8,859</td>
<td>0.05</td>
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<tr>
<td>Av. (Greenhouse vegetables)</td>
<td>140,405</td>
<td>5,645</td>
<td>0.04</td>
<td>169,929</td>
<td>7,321</td>
<td>0.04</td>
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<tr>
<td>Av. (All crops)</td>
<td>17,563</td>
<td>4,643</td>
<td>0.3</td>
<td>21,267</td>
<td>5,569</td>
<td>0.3</td>
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</table>

Data Source: Nihei (2000).

on the changes in the values of the regional input-output energy ratio corresponding with the transition of the planted area of paddy rice. When \( S_r \) and \( S_o \) denote variables for the percentage of paddy rice and another group of crops respectively, equation (1) is transformed into
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Figure 1. Percentage of selected crops planted and regional energy efficiency.

Data Source: Table 1.

Then, several groups of crops that are classified from high to very low efficiency were selected as another group in combination with the paddy rice. This study takes potatoes, wheat and barley, field vegetables and greenhouse vegetables into account. When the equation (2) is accompanied by the 1990 values, the curves 1 to 4 in Figure 1a describe the solutions.

In the combination of paddy rice and high efficiency crops, the values of regional input-output energy ratio declined in accordance with the increase in the percentage of paddy rice (Figure 1a: curve 1). The values of regional input-output energy ratio fluctuated less in the combination of paddy rice, and wheat and barley (curve 2), and the values became larger in accordance with the increase of paddy rice in the combination of paddy rice and field vegetables (curve 3). In the combination of paddy rice and greenhouse vegetables, the values of regional input-output energy ratio increased drastically when the percentage of paddy rice reached more than about 90 percent (curve 4). That is to say, a few increases in the percentage of greenhouse vegetables resulted in a great decrease in the regional input-output energy ratio.
Definition of regional energy efficiency

The four curves in Figure 1a represent the values of the input-output energy ratio of several typical combinations of crops in Japan, namely, (1) paddy rice, barley and sweet potato, (2) paddy rice and wheat, (3) single-crop farming of paddy rice, (4) paddy rice and field vegetables, (5) single-crop farming of field vegetables, and (6) paddy rice and greenhouse vegetables. Assuming that a region in which paddy rice, barley and sweet potato are cultivated with one third of the planted area each, the regional input-output energy ratio will indicate the order of 3.6, based on the presumption that paddy rice and barley had the same value in energy balance (Figure 1a: point A). In the double-crop farming region of paddy rice and wheat, it is assumed that 50 percent of the cropland consists of the two crops, and the regional input-output energy ratio will be of the order of 2.6 (point B). In the single-crop farming region of paddy rice, it can be assumed that 100 percent of the cropland consists of paddies for rice, and the regional input-output energy ratio will indicate the order of 2.5 (point C). This study defines the values of regional input-output energy ratio that exceed both of the points B and C as the “high efficiency region” (regional input-output energy ratio in 1990: more than 2.7). It is expected that high and middle efficiency crops such as potatoes, paddy rice, barley and wheat are to be typical products of the high efficiency region.

Following the high efficiency region, the combination of paddy rice and field vegetables is taken into account. It is empirically considered that paddy rice will be a major crop in the combination when the planted area of paddy rice exceeds 75 percent (Figure 1a: point C to D). The values of the regional input-output energy ratio that surpass the point C and fall below those of the high efficiency region are entitled the “middle efficiency region” (regional input-output energy ratio in 1990: 1.7–2.6). Middle efficiency crops especially paddy rice and wheat will be main production of this category.

As the percentage of field vegetables increases, the regional input-output energy ratio of paddy rice and field vegetable region declines, and it becomes the order of 0.6 when field vegetables occupy all of the cropland (Figure 1a: point E). The range of the values between paddy rice and field vegetable region (field vegetable main) and the single-crop farming region of field vegetables is considered as the “low efficiency region” (regional input-output energy ratio in 1990: 0.7–1.6). Middle and low efficiency crops, paddy rice and many kinds of field vegetables in particular, will be dominant in this category.

This study defines the values lower than the single-crop farming region of field vegetables as the “very low efficiency region” (regional input-output energy ratio in 1990: under 0.6). This can be the category characterized not only by field vegetable but also by greenhouse vegetable production. The combination of paddy rice and greenhouse vegetables generally indicates the lowest values of the regional input-output energy ratio. Since a huge amount of fossil fuel energy is used in greenhouse vegetable cultivation, a small increase in the planted area makes the regional input-output energy ratio decline considerably. For example, if greenhouse vegetables become 10 percent in planted area, the regional input-output energy ratio declines to the order of 0.4 in a single-crop farming region of paddy rice (Figure 1a: point F), and to the order of 0.5 in a region outstanding in the production of paddy rice, barley and sweet potatoes.

Limitation of regional energy efficiency

In addition to the above, the combination of crops based on the percentage of paddy rice gives the regional energy efficiency for 1970 as shown in Figure 1b. The values of the regional input-output energy ratio that determine the four categories of energy efficiency show little difference when compared with 1990. Typical crops in the four categories of energy efficiency are assumed as described also in Figure 1b. Although beans and fruits are excluded from examination, they will be substituted respectively by grain and field vegetables whose energy balances are classified into the same categories. For example, if paddy rice and fruit are cultivated in a region by 50 percent of the
planted area each, the regional input-output energy ratio will become the order of around 1.0 and be classified as low efficiency.

However, the kinds of crops cultivated in a region cannot be ascertained by investigating the values of the regional input-output energy ratio. One reason for this is the wide extent of the values taken by the regional input-output energy ratio. For instance, when the percentage of paddy rice changes, the curves 1 and 4 in Figure 1a indicate the margin of the regional input-output energy ratio. Therefore, if the regional input-output energy ratio takes the order of 0.5, the range of paddy rice varies from zero to 93 percent. Although the regional input-output energy ratio is categorized as very low in efficiency, there is a possibility that a middle efficiency crop such as paddy rice might occupy almost all of the cropland.

The other reason is that many kinds of crops are cultivated in a region. Since farmers produce crops with various rates in a region, the values of the regional input-output energy ratio cannot give a precise explanation for the types and the percentage of crops planted. Actually, even in traditional rice-wheat-potato producing regions, the regional input-output energy ratio never exceeds the order of 4.0, and seldom exceeds the order of 3.0. This is because they cultivate low efficiency crops such as field vegetables besides grain and sweet potatoes. Moreover, when vegetables are cultivated only in open fields, the regional energy efficiency may be classified as very low if they produce vegetables such as lettuces and sweet peppers whose input-output energy ratio indicates lower values than the average for field vegetables.

Still more, since the energy efficiency is classified based on the planted area of typical crops in Japan, the category will not be applied to the regions or foreign countries in which other types of crops occupy a large part of the cropland. Other standard crops should be selected to examine the energy efficiency in these cases. The solutions for these limitations will be ground for future work. At all events, however, the classification of the regional energy efficiency presented could be used as an index that gives brief explanations for the characteristics of regional crop production, although it requires a reference to the types of crops besides the values of the regional input-output energy ratio.

Changes in the Regional Energy Efficiency of Crop Production

Application

The regional energy efficiency defined in the previous chapter was applied to the prefectures of Japan in 1970 and 1990. This two year analysis will present a distinctive figure of changes in the energy efficiency of Japanese agriculture, because the horticultural sector (i.e. low and very low efficiency crops) was developed through subsidies from the Japanese Government, whereas the planted area of paddy rice (i.e. middle efficiency crops) was greatly reduced by the set aside program in the 1970s and 1980s. The regional input-output energy ratio of prefectures in 1970 ranged from 3.1 in Kagoshima to 1.0 in Kochi. The regional energy efficiency of crop production was classified into high to low (Figure 2a). Looking at the average percentage of crops planted in Japan, paddy rice, which is the major crop in Japan, occupied more than 60 percent (Table 2).

Kagoshima and Hokkaido were classified as high efficiency prefectures in 1970. The percentage of crops indicated high values in paddy rice, potatoes, wheat and barley. In particular, the percentage of potatoes was about five times larger than the country’s average. The planted area of sweet potatoes in Kagoshima (43 thousand hectares), and the planted area of white potatoes in Hokkaido (68) was the largest in Japan. Middle efficiency regions in 1970 consisted of 29 prefectures located mainly in the Tohoku, Hokuriku, Chugoku Regions and the northern part of Chubu Region. The percentage of crops planted in the prefectures with middle efficiency was almost consistent with the country’s average. Low efficiency regions in 1970 consisted of 16 prefectures located mainly in the Pacific Ocean Belt. The percentage of crops planted in this category indicated high values in fruits and field vegetables, whose values were four to five percent higher than those of the country’s average.
In 1990, the regional input-output energy ratio of prefectures ranged from 2.3 in Hokkaido to 0.2 in Okinawa, and the regional energy efficiency was classified into middle to very low. The groups of crops that increased percentage during the two decades were beans and horticultural crops, namely, fruits, field vegetables and greenhouse crops (i.e. greenhouse vegetables and fruits). One of the reasons for the increase in beans is ascribed to the cultivation of soybeans in rice paddies that were designated through the set aside program. The emergence of very low efficiency and the disappearance of high efficiency prefectures were a distinctive feature of the 1990’s map (Figure 2b).

Eight prefectures located mainly in the Pacific Ocean Belt were categorized into very low.
in 1990, i.e. Tokyo (the regional input-output energy ratio: 0.5), Yamanashi (0.5), Shizuoka (0.6), Aichi (0.6), Osaka (0.6), Kochi (0.4), Kumamoto (0.5) and Okinawa. The percentage of crops was high in fruits, field vegetables and greenhouse crops, and the percentage of greenhouse crops was about three times larger than that of the country's average. The number of prefectures with middle efficiency decreased to nine in 1990. They remained mainly along the Japan Sea coast from Hokkaido to the middle part of Japan. Middle efficiency regions in 1990 included the prefectures that had a large area of rice paddies. In particular, Hokkaido (143 thousand hectares), Niigata (126), Akita (103) and Miyagi (92) were the top four prefectures in paddy rice production. Low efficiency prefectures increased to 30 in 1990, expanding around the low efficiency prefectures of 1970 and the very low efficiency prefectures in 1990. Comparing the percentage of crops planted in this category with those in 1970, greenhouse crops increased more than twice, and wheat, barley and other grain decreased by five percent.

**Changing patterns**

The results of the application seem to support the relationship between assumed typical crops and the category of regional energy efficiency.

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*Figure 3. Changes in the energy efficiency and crop production in prefectures.*

Combinations of typical crops are determined by a modified Weaver's Method by Doi. Each letter represents: P-potatoes, R-paddy rice, W-wheat, barley and other grain, B-beans, F-fruits, V-field vegetables.

Data Sources: Table 1, Figure 2, and Census of Agriculture.
However, the average percentage of crops does not express each prefecture's crop production precisely. Here a detailed examination is given for the changing patterns of energy efficiency and typical crops produced in prefectures. Setting up crop combinations by Weaver's Method is one of the appropriate ways to examine the typical crops produced in a region (Weaver 1954a, 1954b). This study applies a modified Weaver's Method by Doi (1959, 1970) to estimate typical crops, since it can specify the number of crops in any case of planted ratio. The capital letter symbols stand for seven groups of crops: P- potatoes, R- paddy rice, W- wheat, barley and other grain, B- beans, F- fruits, and V- field vegetables. Except for major two combinations R and RW, this study expresses crop combinations as "complex type" to give a plain explanation for changing pattern.

Crop combinations in the high efficiency prefectures in 1970 were represented by complex types of high and middle efficiency crops (Figure 3). Although these prefectures changed into middle and low efficiency regions in 1990, their crop combinations were also represented by complex types of high and middle efficiency crops (i.e. PRWB in Hokkaido and PR in Kagoshima). Most of the middle efficiency prefectures in 1970 were represented by R and RW. Among 24 prefectures of R and RW, eight prefectures remained unchanged, 13 prefectures changed into low efficiency region with R and RW, and three prefectures changed into low efficiency regions with complex types of middle and low efficiency crops. Among the five middle efficiency prefectures in 1970 were represented by complex types of high, middle and low efficiency crops. The prefectures changed into low and very low efficiency, and most of their crop combinations were represented by complex types of middle and low efficiency crops. Among the 16 prefectures with low efficiency in 1970, nine remained at low efficiency, and seven changed into very low efficiency in 1990. While most of their crop combinations were represented by R, RW, and complex types of middle and low efficiency crops in 1970, complex types of middle and low efficiency crops dominated in 1990.

From these results, three typical changing patterns that have influenced the decline of energy efficiency are extracted: (1) from middle efficiency region with R and RW to low efficiency region with R and RW, (2) from middle efficiency region with R, RW and with complex types to low efficiency region with complex types, and (3) from low efficiency region with complex types to very low efficiency with complex types. Considering percentage of crops planted, the average of crop groups in the 13 prefectures of pattern 1 changed as follows: 2.2 to 0.7% in high efficiency, 85.1 to 84.5% in middle efficiency, 12.6 to 13.7% in low efficiency, and 0.1 to 1.1% in very low efficiency crops. Although the changing range was small, considering the large amount of input fossil fuel energy, increase in greenhouse crops is ascribed as the main cause of pattern 1. In the seven prefectures of pattern 2, the average percentage of crop groups changed as follows: 7.7 to 5.0% in high efficiency, 72.7 to 64.6% in middle efficiency, 19.4 to 28.7% in low efficiency, and 0.2 to 1.7% in very low efficiency crops. From the same view, in the seven prefectures of pattern 3, the average of crop groups changed: 5.5 to 2.6% in high efficiency, 65.2 to 51.2% in middle efficiency, 28.4 to 41.4% in low efficiency, and 0.9 to 4.9% in very low efficiency crops. Consequently, increase in the percentage of low and very low efficiency crops is ascribed as the main cause of patterns 2 and 3.

Considering planted area of crops, the total of seven groups declined from 4,571 to 3,074 thousand hectares in two decades. Except for greenhouse crops, which increased in 34 thousand hectares, the planted area of all other groups declined. Increase in the planted area of greenhouse crops is considered as a main reason for the changing pattern 3, since 10 thousand hectares of the increase concentrated in the seven prefectures with very low efficiency. Decrease in the planted area of paddy rice, which amounted to 1,050 thousand hectares, resulted in the increasing of the percentage of low efficiency crops planted in the prefectures of patterns 2 and 3.

The seven prefectures of pattern 3 include eminent production centers of greenhouse crops in Japan. Although it did not appear in
the crop combinations by modified Weaver's Method by Doi, "very low efficiency" might be used as an index that represents the regions active in the production of greenhouse crops. For example, although Kochi is a well-known prefecture for the production of greenhouse vegetables, its typical crop in 1990 was represented only by R. As mentioned in the previous chapter, a small increase in the percentage of greenhouse crops leads to a great reduction of the regional input-output energy ratio, and this may form the characteristics of regional division by energy efficiency.

**Decline of the energy efficiency of crop production in Japan**

Although it will need more examinations of smaller scale regions, the result of mapping seems to substantiate one aspect of regional crop production in Japan. Namely, the decline of energy efficiency, which was seen especially in the southwestern part of Japan, corresponds with the prefectures whose gross profit of crop production per harvested area show high values (Figure 4). Horticulture that requires high input fossil fuel energy and produces low output energy is accompanied by labor and capital intensive practices, and results in high economic return per cropland. Therefore, the regional energy efficiency is in inverse ratio to the economic land productivity.

The increase of horticulture, especially vegetable and fruit production in greenhouses, is relevant to the changes of the agro-political structure of Japan after 1970, i.e. the enlargement of subsidies for horticultural management, the reinforcement of the set aside program for paddy rice, and the increase of imported crops such as wheat and barley. However, it is probably due to the high economic return that such cultivation is undertaken by farmers. A case study of greenhouse horticulture in Asahi City, Chiba Prefecture, showed that cucumber production in greenhouses produced sales of four million yen per 10a, which was about 28 times larger than that of paddy rice production. The horticultural farmers could own only 50a upland field on average.

![Figure 4](image-url)
The introduction of winter vegetables with plastic greenhouses and heating systems was the best action taken by the farmers who had to utilize small lots to oversee farm and family budgets. To maintain intensive crop production, farmers introduced new technology one after another from nursery companies, material sellers and agricultural cooperatives, and their management depends greatly on agro-companies outside the farm (Nihei 1998).

Apart from producing calorific values, producing vitamins and protein may be advantageous for modern farming in the Japanese socioeconomic context. Greenhouse horticulture, which recently increased in planted area, is probably the best method of obtaining such benefits. Freshness is the market value of the crops produced in greenhouses, and these crops usually contain a little food energy per weight. Even when produced in winter, greenhouse crops can produce equal or higher food energy per planted area than grain on account of the large amount of input fossil fuel energy. The winter vegetables produced in greenhouses by burning fossil fuel are probably the most expensive crops in terms of their ecological impact. Though this is an extreme example, it took 2,200 kcal of energy to produce 1 kcal diet soft drink (Soussan 1992). The winter vegetables produced under the controlled temperatures of greenhouse facilities may be compared to cold diet drinks sold by vending machines.

In the past Kawakita (1949) explained that the potential index of harvest (i.e. output food energy per hectare) in Japan was in direct proportion to the warmth index (i.e. a kind of cumulative temperature). His ecological aspect results also in inverse proportion to the map of energy efficiency based on input fossil fuel energy and output food energy. Fossil fuel energy fixed in industrial products makes it possible to practice high productive agriculture that does not depend much on latitude and ecological productivity. This implies an increase of the impact on the natural environment. Input of industrial products into arable land diminishes the diversity of microbes in the soil, and will cause "death of the soil" from the ecological point of view (Hattori 1972). Within the conduct of modern agriculture, we use more chemical substances in order to restore the dead soil. This cycle, which will result in a greater impact on the natural environment, may keep industrial agriculture going nowadays, and a large amount of input fossil fuel energy substantially supports the cycle.

Conclusion

Although one of the fundamental purposes of agriculture is to produce food and basic materials for other industries by utilizing solar energy efficiently, the agricultural practices accompanied with large amounts of input fossil fuel energy impair efficiency. In fact, the fossil fuel energy fixed in industrial products such as chemical fertilizers and pesticides has diminished the energy efficiency of agriculture especially in developed countries. Examining agricultural efficiency in terms of energy balance is set for a first step in the practice of low-input sustainable agriculture, which will eventually help to find a solution to environmental problems such as the exploitation of natural resources. This study has tried to define regional energy efficiency based on the regional input-output energy ratio of crop production in Japan, and examines the changes in regional energy efficiency at the prefectural level from 1970 to 1990.

The input-output energy ratio (output/input), which is calculated by input fossil fuel energy and output food energy, has been used as an index to explain the energetic efficiency of agriculture. Energy efficiency of the crops produced in Japan is classified into four categories: high efficiency crops (potatoes: the average input-output energy ratio in 1990 is 6.8), middle efficiency crops (grain and beans: 2.7 and 2.1), low efficiency crops (fruits and field vegetables: 0.7 and 0.6), and very low efficiency crops (greenhouse vegetables: 0.04).

The regional input-output energy ratio is given by all crops produced in a region. Inspecting typical combinations of crops and the values of regional input-output energy ratio, regional energy efficiency is classified into four categories. The high efficiency region (regional input-output energy ratio: more than 2.7 in 1970 and 1990) is categorized as having higher...
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values than single-crop farming of paddy rice and double-crop farming of paddy rice and wheat. It is assumed that high efficiency regions are characterized by the production of middle and high efficiency crops. The middle efficiency region (from 1.8 to 2.6 in 1970 and from 1.7 to 2.6 in 1990) is categorized as having lower values than the high efficiency region and higher values than supposed paddy rice and field vegetable production regions (i.e. paddy rice exceeds more than 75 percent). This category is assumed as the region flourishing in the production of middle efficiency crops. The low efficiency region (from 0.7 to 1.7 in 1970 and from 0.7 to 1.6 in 1990) is categorized as having lower values than middle efficiency regions and higher values than single-crop farming of field vegetables. It is supposed that the productions of low and middle efficiency crops are active in low efficiency regions. The very low efficiency region (under 0.6 in 1970 and 1990) is categorized as having lower values than low efficiency regions and it is characterized by the production of low or very low efficiency crops.

These four categories of regional energy efficiency have been applied to the regional input-output energy ratio of prefectures in 1970 and 1990, and the results give a commendable account of the regional crop production. High efficiency was applied to Hokkaido and Kagoshima in 1970, which are active in white and sweet potato production. Middle efficiency regions consisting of 29 prefectures in 1970 decreased to nine in 1990. Middle efficiency prefectures remained in the northern part of Japan and along the Japan Sea coast, where paddy rice production is still prosperous. Low efficiency regions consisted of 16 prefectures active in the production of field vegetables and fruits in 1970. It expanded to 30 prefectures around the Pacific Ocean Belt in 1990. Very low efficiency prefectures appeared in the southeastern part of Japan, i.e. Tokyo, Yamanashi, Shizuoka, Aichi, Osaka, Kochi, Kumamoto and Okinawa in 1990, of which agricultural production was characterized by field vegetables, fruits and greenhouse crops.

The changing patterns of the decline of energy efficiency are summarized as: (1) from middle efficiency (main crops: paddy rice and wheat) to low efficiency (paddy rice and wheat), (2) from middle efficiency (paddy rice and wheat) to low efficiency (paddy rice, fruits and field vegetables), and (3) from low efficiency (paddy rice, fruits and field vegetables) to very low efficiency (paddy rice, fruits, field vegetables and greenhouse crops). On the basis of the percentage of crops planted, the increase of greenhouse crops was ascribed to the cause of three patterns, and on the basis of the planted area, the decrease of paddy rice caused pattern 2, and the increase of greenhouse crops resulted especially in the cause of pattern 3.

Finally, it seems a specific characteristic that the very low efficiency prefectures are consistent with the regions with high economic productivity of crop production. It may be advantageous for the farmers to adopt intensive agriculture, such as greenhouse horticulture, depending much on fossil fuel energy to undertake farm management in the context of the Japanese socio-economical environment. However, the result also implies the increase of environmental impact by the use of fossil fuel energy has been caused mainly in the southeastern part of Japan, which ordinarily has the ecological potential to produce high yields of food energy.

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Note

1. The reason for the divide is that the regional input-output energy ratio of leading municipalities in field vegetable production in the Kanto Region from 1970 to 1990 indicated smaller values than those of the paddy rice and field vegetable region (paddy rice main) that have 75 percent of paddy rice planted. The agricultural geography of the municipalities is

References


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(J): written in Japanese

(JE): written in Japanese with English abstract