Estimation of Carbon-14 Transfer from Agricultural Soils to Crops Using Stable Carbon Isotope Ratios -10346

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ABSTRACT

It is important to know carbon-14 (C-14) transfer from the soil to the edible parts of crops, since C-14 transfer from radioactive waste disposal sites is expected. Using C-14 in radiotracer experiments would be the most suitable to obtain transfer factors (TFs), however, using radiotracers in open fields is nearly impossible. In this study, we estimated TF of carbon for several agricultural crops using stable carbon isotope ratios. The estimated average TF value for white rice was 0.11±0.04 and that for upland field crops (including leafy vegetables, fruit vegetables, root crops, tubers, legume, wheat and barley) was 1.0±0.6. The results showed that the estimated values agreed well with previous values for radish, 0.16-1.5, by Sheppard et al. (1991). Thus we concluded that the estimated values would be applicable for TF of C-14 in agricultural systems.

INTRODUCTION

From the viewpoint of radiation dose assessment for humans from transuranic waste disposal sites, carbon-14 (half-life: 5730 y) in organic forms is thought to be one of the most important radionuclides. Recently, it was reported that C-14 release as low molecular weight organic compounds was possible [1]. Thus, understanding the C-14 fate in soil-to-crop systems is important since C-14 might transfer from waste disposal sites to crops through the soil environment (Fig.1). Previous studies, however, have not yielded many data on root uptake of soil origin C-14 by plants. Radiotracer experiments for C-14 root uptake studies can be carried out in controlled areas [2-4], however, it is not clear whether the data are applicable to open fields or not because laboratory experiments are usually small scale and the ambient conditions are controlled.

To estimate C-14 transfer from soils to crops in agricultural fields, we used carbon isotope ratios ($^{13}C/^{12}C$) in crop and soil samples. It is well known that ^{13}C and ^{12}C are fractionated in the photosynthesis process at a certain ratio, depending on plant types, i.e. C3, C4 and CAM plants [5]. If all the carbon in crops originated only from the air, the $^{13}C/^{12}C$ ratio would take a constant value; however, if there were any contributions from soil carbon, the ratio would be changed. Indeed, we previously found that carbon isotope ratios for white rice and soil showed a weak correlation which may indicate a potential carbon supply from soil to rice [6].

There are two pathways of soil carbon transfer to plants, that is, direct absorption of soil carbon species by roots and absorption of discharged CO_2 from the soil as shown in Fig.1. It should be noted that the photosynthesis process is important for carbon fixation by plants. Any carbon species taken up by roots would be used for photosynthesis, physiological activities of the plant, or discharged to the environment; however, the carbon used in photosynthesis would have a longer half-life in the plant body than the carbon used in other paths. Thus, we focused on the photosynthesis process in this study.

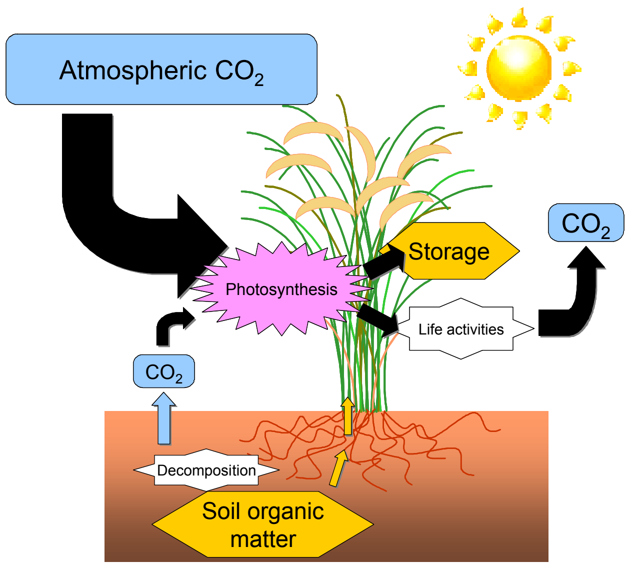

Fig.1. Schematics of carbon transfer to plants.

MATERIALS AND METHODS

One hundred and forty two crop samples (63 rice and 79 upland field crop samples, C3 type) and associated soil samples were collected throughout Japan in 2002-2006. These crop samples were washed with deionized water to remove dust and soil particles on their surfaces. After water removal using paper towels, six samples (4 leek samples, 1 Japanese radish sample and 1 carrot sample) were separated into two parts, that is, white and green parts for leeks and leaves and roots for root crops. Then, these samples were freeze-dried. The soil samples were air-dried and passed through a 2-mm mesh sieve. All crop and soil samples were thoroughly ground into fine powder. The numbers of samples for upland field crops were: leafy vegetables (e.g., cabbage, Chinese cabbage, and lettuce), 22; fruit vegetables (e.g., tomato, cucumber, and egg plant), 18; root crops (Japanese radish, carrot and onion), 18; tubers (potato, sweet potato and taro), 11; legumes (soybean and peanut), 7; wheat and barley, 9. For leeks, the white part data were classified into root crops and green part data were classified into leafy vegetables.

To measure the carbon isotope ratios and total C concentrations, an elemental analyzer connected to an isotope ratio mass spectrometer (Thermo Fisher Scientific, Flash EA and Delta V Advantage) was used. Carbon isotope ratios were reported in $\delta^{13}C$ notation (‰) relative to the Vienna peedee belemnite standard (VPDB). The equation is as follows.

$$\delta^{13}C=(R_{sample}-R_{VPDB})/R_{VPDB}x1000$$

where $R_{sample}={}^{13}C/{}^{12}C$ in a sample and R_{VPDB}=0.0112372.
We made two sub-samples for each sample; 2 mg of each crop sample or 10 mg of each soil sample were weighed into a tin container. The measured $\delta^{13}C$ and carbon concentration values in this report were averages of the two measurements.

RESULTS AND DISCUSSION

Using 13 rice grain samples, we measured $\delta^{13}C$ values for brown rice, white rice (polished rice) and bran, and the average values were -27.3±0.5‰ -27.1±0.5‰ and -29.7±0.5‰, respectively. The $\delta^{13}C$ value for bran was statistically different from the other two sample types by Student's t-test ($p<0.001$). The lower $\delta^{13}C$ value for bran would be due to its lipids, which is known to have lower $\delta^{13}C$ values than its source material, photosynthates. From these results, we concluded that white rice was the most suitable part to be used for estimation of soil carbon transfer to crops because it directly reflects products from photosynthesis.

We also checked suitability of upland field crop parts for the estimation of C-14 transfer from agricultural soils to crops. Preliminarily, we measured $\delta^{13}C$ in each part of five rice plants, such as leaves, stems and roots, collected at harvest. The average $\delta^{13}C$ values were as follows: -27.9±0.2‰ for leaves, -27.4±0.2‰ for stems, -27.9±0.2‰ for roots, -27.2±0.2‰ for ears, and -28.4±0.4‰ for the rest of the rice plant. The $\delta^{13}C$ values for the ears were statistically higher than other parts by ANOVA test ($p<0.001$). For this part, most of the ear weight was from the white rice grains; however, other parts could include a sort of secondary products from photosynthates so that the values differed. From these results, we thought that some edible parts of the upland field crops would have lower $\delta^{13}C$ values than their original photosynthates; however, we did not do any further data selection for upland field crops, since the difference was thought to be small.

The average $\delta^{13}C$ value for each crop type is summarized in Table I together with total carbon concentrations in soil and crop samples (on dry weight basis). Histograms of $\delta^{13}C$ (‰) in white rice, upland field crop samples, paddy field soil and upland field soil samples are shown in Figs.1 and 2. Each distribution pattern for white rice and upland field crop samples was a normal type (see. Fig.1), so we calculated the average $\delta^{13}C$ values, which were -27.1±0.5‰ (range: -28.3 to -26.0‰) and -27.9±1.1‰ (range: -29.8 to -25.0‰), respectively. However, paddy field soil and upland filed soil samples did not show a normal or a log-normal type distribution in their $\delta^{13}C$ values, but the distribution patterns were closer to the normal type. The average $\delta^{13}C$ values in paddy fields and upland fields were -26.0±1.6‰ and -23.5±2.7‰, respectively.

Table I. Stable Carbon Isotope Ratio ($\delta^{13}C$, ‰) and Total Carbon Concentrations in Soil and Crop Samples.

Crop types	n	$\delta^{13}C$ value (‰)		Total carbon concentration (g/g)	
		Soil	Crops	Soil	Crops
Leafy vegetables	22	-23.2 ± 2.1	-27.8 ± 1.2	0.033 ± 0.022	0.38 ± 0.02
Fruit vegetables	18	-23.3 ± 4.1	-28.5 ± 1.0	0.037 ± 0.021	0.40 ± 0.02
Root crops	18	-22.9 ± 2.1	-28.0 ± 1.3	0.038 ± 0.024	0.39 ± 0.02
Tubers	11	-23.3 ± 1.7	-27.4 ± 0.9	0.027 ± 0.016	0.39 ± 0.01
Legumes	7	-24.6 ± 2.0	-27.7 ± 0.4	0.035 ± 0.015	0.48 ± 0.06
Wheat and barley	9	-24.6 ± 2.8	-27.9 ± 0.7	0.027 ± 0.016	0.41 ± 0.01
White rice	63	-26.0 ± 1.6	-27.1 ± 0.5	0.028 ± 0.018	0.41 ± 0.01

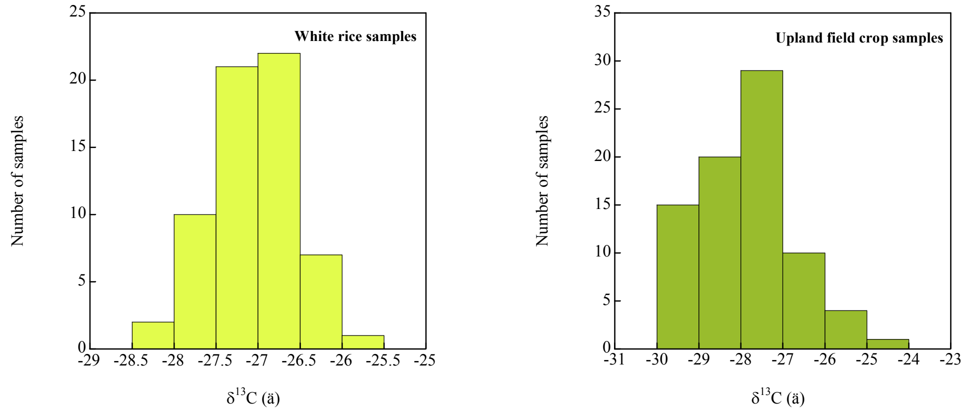

Fig.2. Frequency distributions of d[13]C in white rice (left) and upland field crops (right)

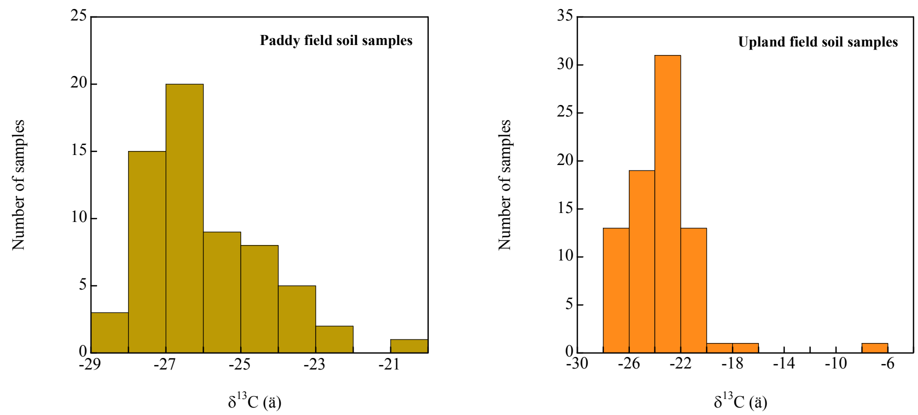

Fig.3. Frequency distributions of d[13]C in paddy fields (left) and upland fields (right)

If all plant carbon originated from the atmospheric CO_2, the $\delta^{13}C$ values in crops could be calculated using the $\delta^{13}C$ value -8‰ in air [7] and the ^{13}C fractionation ratio in photosynthesis by C3 type plants of -18 to -20‰ [5, 8]. The calculated $\delta^{13}C$ values ranged from -28 to -26‰, and the results implied that no soil carbon contribution was necessary for white rice and many upland field crops. The reason why there were crops having $\delta^{13}C$ values outside the calculated $\delta^{13}C$ range was that upland field possibly crops contained secondary products of the original photosynthates. The crops that had values less than -29‰ were 3 tomato samples (out of 6 samples), 3 egg plant samples (out of 5 samples), 4 Japanese radish samples (out of 7 samples), 2 green part of leek (out of four samples), and one for each of other four crop species (cucumber, spinach, *Nozawana*, and white part of leek). No crops had a $\delta^{13}C$ value of higher than -25‰. Although tomato, egg plant and Japanese radish tended to have smaller $\delta^{13}C$ values than the original photosynthates, we did not exclude these crop species. Then we used a further statistical approach to estimate soil carbon percentages in crops as we had previously done using 39 white rice and associated soil samples [6].

Since carbon fixation by a plant has to be done by photosynthesis, the following equation would be acceptable.

$$\delta C_{crop}=(\delta C_{air}+F_{C13})\times(1-X_i/100)+(\delta C_{soil}+F_{C13})\times X_i/100$$

where δC_{crop}, δC_{air}, and δC_{soil} were $\delta^{13}C$ values in crops (white rice or upland field crops), air and soil, respectively, F_{C13} is the ^{13}C fractionation ratio (-18 to -20‰), and X_i is the soil organic carbon contribution percentage to plant body. X_i was estimated under the reasonable assumptions that the carbon fractionation ratio by C3 crops was an average value of -19‰ and $\delta^{13}C$ of atmospheric CO_2 was -8‰. For paddy fields, we used average δC_{crop} and δC_{soil} values of -27.1 and -26.0‰, respectively, and X_i was calculated as 0.6%. If we included the standard deviation of δC_{crop} for consideration to this statistical approach, the maximum X_i could be 1.3%. Similarly, for upland fields, δC_{crop} and δC_{soil} values of -27.9 and -23.5‰, respectively, were applied and the X_i was 5.8% and its maximum was 7.3% considering standard deviation of δC_{crop}. If we removed all tomato, egg plant and Japanese radish sets, the average δC_{crop} and δC_{soil} values were -27.6 and -23.5‰, respectively, and the X_i was 3.9%.

Using these values, we calculated soil to crop transfer factor (TF) as follows:

$$TF = ([C]_{crop}\times X_i/100) / [C]_{soil}$$

where $[C]_{crop}$ and $[C]_{soil}$ were carbon concentrations in edible part of crop and associated soil samples. The average TF values for each crop are listed in Table II, under the reasonable assumptions that the carbon fractionation by C3 crops was -19‰ and $\delta^{13}C$ of atmospheric CO_2 was -8‰. The X_i values for white rice and upland field crops were 0.6% and 5.8%, respectively, as mentioned above.

Table II. Estimated TF Values of Carbon for Several Types of Crops.

Crop types	TF	Range (min. – max.)
Upland field crops	0.95 ± 0.59	0.24 – 3.6
Leafy vegetables	0.96 ± 0.57	0.24 – 2.2
Fruit vegetables	0.95 ± 0.78	0.31 – 3.6
Root crops	0.84 ± 0.48	0.27 – 1.9
Tubers	1.01 ± 0.75	0.39 – 3.0
Legumes	0.93 ± 0.39	0.52 – 1.6
Wheat and barley	1.07 ± 0.41	0.37 – 1.5
White rice	0.11 ± 0.04	0.02 – 0.19

The TF average value for white rice was 0.11±0.04 (range: 0.02- 0.19) and the maximum available TF values applying X_i value of 1.3% ranged from 0.04 to 0.41 with an average of 0.24. For all upland field crops, the average TF was 1.0±0.6 (range: 0.2- 3.6) and the maximum available TF value applying X_i value of 7.8% ranged from 0.3 to 4.6 with an average of 1.2. The average TF values among upland field crop types were very close as shown in Table II, possibly because the same X_i value was used. To get more precise estimations, the same approach used for white rice is necessary for each crop type; however, up to now, the numbers of samples for each crop are not enough for statistical analysis so that it would be difficult to obtain TF data for this task.

We think, however, the TF values of stable carbon are still valid and would also be applicable for C-14 because the carbon fractionation effect for C-14 would be negligible in carbon transfer. Indeed, reported TFs of C-14 added to soil as an inorganic form to radish were 0.16 - 1.5 on a dry weight basis [3], which were comparable to the present study.

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