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Estimation of Nitrogen and Zinc Environmental Assimilating Capacity of Cultivated Soil
—To promote sustainable agriculture in Japan —

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Abstract

To minimize the nitrate stress derived from agricultural production on the environment, especially on the groundwater system, the total amount of nitrogen (chemical fertilizer nitrogen and organic waste manure nitrogen) applied per unit area should be restricted within the range of the nitrogen environmental assimilating capacity (NEAC) of the soil-plant system. We define NEAC as the yearly average rate of total nitrogen applied per year or in one cycle of cropping system, and NEAC satisfies not only productivity requirements but also environmental preservation requirements. We developed criteria to estimate NEAC, and using lysimeter test data, we estimated that the NEAC of a volcanic ash vegetable field in Japan was about 250-350 kg ha^{-1}. The environmental management standard for zinc (Zn) concentration in soil (120 mg kg^{-1}) seems to restrict the beneficial use of organic waste compost on cultivated land in Japan. Monitoring by using the method of evaluating the activity of soil micro-organisms may be useful to review the strict environmental management standard for Zn concentration in soil. Even when we applied sewage sludge and $ZnSO_4$ to some kinds of soil samples up to a level above 120 mg Zn kg^{-1}, the growth of soil micro-organisms was not inhibited in volcanic ash and alluvial soil samples. The environmental management standard for Zn concentration in soil should be determined for each kind of soil.

Discipline: Soils and fertilizers
Additional key words: nitrogen recovery rate, growth rate of micro-organisms

Introduction

Groundwater is one of the major and primary resources, especially for drinking water in rural areas of Japan. However, groundwater contamination by nutrients has become one of the serious environmental problems. Nitrate nitrogen (NO_3-N) is the most widespread contaminant of the groundwater system. Disposal of waste derived from human activities, intensive fertilization and large doses of livestock waste manure contribute to the accumulation of NO_3-N in the groundwater system.

The Ministry of Agriculture, Forestry and Fisheries of Japan decided in 1992 to promote sustainable agriculture, namely agriculture friendly to the environment and agriculture utilizing resources of organic waste. To promote this type of agriculture, it is important to analyze the nitrogen cycle in agricultural ecosystems and to estimate the nitrogen environmental assimilating capacity (NEAC) of the soil – plant system.

An excessive amount of organic waste is released in relation to the cultivated land area in Japan. Organic waste usually contains high concentrations of heavy metals. To recycle nitrogen in organic waste, it is also important to estimate the heavy metal environmental assimilating capacity of cultivated soil in order to protect the recycling function of cultivated land from the toxicity of heavy metals.

In this paper we developed criteria to estimate the NEAC of the soil-plant system to promote the beneficial use of not only chemical nitrogen fertilizer but also organic waste manure or compost and to

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minimize nitrate stress on the groundwater system. We also developed a methodology to estimate the heavy metal environmental assimilating capacity of soil to preserve the material recycling function of cultivated land.

Nitrogen cycle of agricultural ecosystem and nitrogen application in Japanese agriculture

Nitrogen in imported feed and food into Japan is increasing the nitrate stress derived from agricultural production on the environment.

As shown Fig. 1, the nitrogen cycle is not operating effectively in Japan. The flow from livestock waste to the environment is increasing. Iwamoto and Miwa estimated that nitrogen discharge as livestock fecal waste amounted to 724 thousand Mg, of which the beneficial use as animal fecal manure amounted to 300 thousand N Mg, while the rest imposed a nitrate stress on the environment[3]. In addition to the flows shown in Fig. 1, there are other flows from food and agricultural products into cultivated land and the environment which are carried by sewage sludge. The amount of sewage sludge produced in Japan was 2.59 million m^3 in 1990, and is estimated to be 3.31 million m^3, i.e. 90 thousand N Mg in 1995[2].

As mentioned above, Japan now faces a new situation. Consumption of chemical fertilizer nitrogen is below the 700 thousand Mg level per year and is currently decreasing. On the other hand, nitrogen discharged as livestock waste presently exceeds the 700 thousand Mg level per year.

As shown in Table 1, the amount of nitrogen in sewage sludge is not large compared to the amounts of nitrogen from chemical fertilizer and livestock waste. However, the amount of sewage sludge is increasing. The nitrogen rate in Japan is calculated

Table 1. Amount of nitrogen in various forms and rate of nitrogen to cultivated land area

Nitrogen form	Amount of N[a]	Rate[b]	Ratio (%)
Chemical fertilizers	680	142	41
Crop residues	150	31	9
Livestock waste	724	151	44
Sewage sludge	90[c]	19	6
Sum	1,644	343	100

a): 1,000 Mg, b): kg ha^{-1}, c): Estimated for 1995.

Table 2-a. Estimated amount of nitrogen applied to common crops in the latter half of the 1980s

Crop	Range[a]	Average[b]	Cropped area[c]
Rice	40–140	89	2,235
Wheat	40–165	93	384
Sweet potato	20–150	52	66
Potato	55–210	119	128
Cereals	10–150	49	29
Beans	10–130	36	272

a), b): kg ha^{-1}, c): 1,000 ha.

Table 2-b. Estimated amount of nitrogen applied to non-common crops in the latter half of the 1980s

Crop	Range[a]	Average[b]	Cropped area[c]
Vegetables			
Open-field	110–600	213	627
Covered	75–510	266	42
Fruit trees	65–320	171	399
Industrial crops	40–600	214	142
Tea	120–1,000	580	62
Mulberry	60–400	270	114
Tobacco	71–320	126	57
Forage	20–400	109	331
Pasture	30–400	82	718

a), b): kg ha^{-1}, c): 1,000 ha.

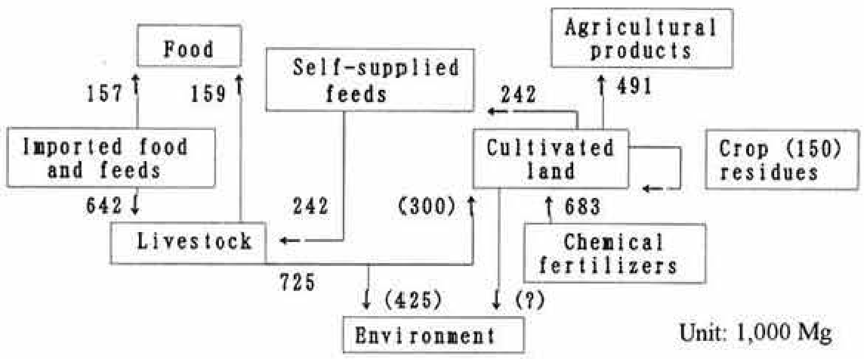

Fig. 1. Nitrogen cycle in Japan
Numbers in parentheses indicate estimated values.

to be 343 kg ha^{-1} (total nitrogen content divided by cultivated land area).

As shown in Table 2, the average amount of applied nitrogen is estimated to be less than 150 kg ha^{-1} for rice, wheat, potatoes, cereals and beans and the effect on the environment may be negligible. However, the average amount of applied nitrogen is estimated to exceed 200 kg ha^{-1} for growing vegetables, tea and mulberry. Farmers growing vegetables apply a larger amount of nitrogen per year because of the continuous vegetable cropping system. Due to intensive fertilization and large doses of livestock waste manure applied, the concentration of nitrate nitrogen in the groundwater system in various vegetable fields and animal husbandry farms is higher than that of paddy fields.

Nitrogen environmental assimilating capacity in vegetable field

To minimize the nitrate stress derived from agricultural production on the environment, it is necessary to estimate the nitrogen environmental assimilating capacity (NEAC) in every soil type and under various climatic conditions. We define NEAC here as the yearly average rate of total nitrogen applied per year or in one cycle of cropping system, and NEAC satisfies not only productivity requirements but also environmental preservation requirements.

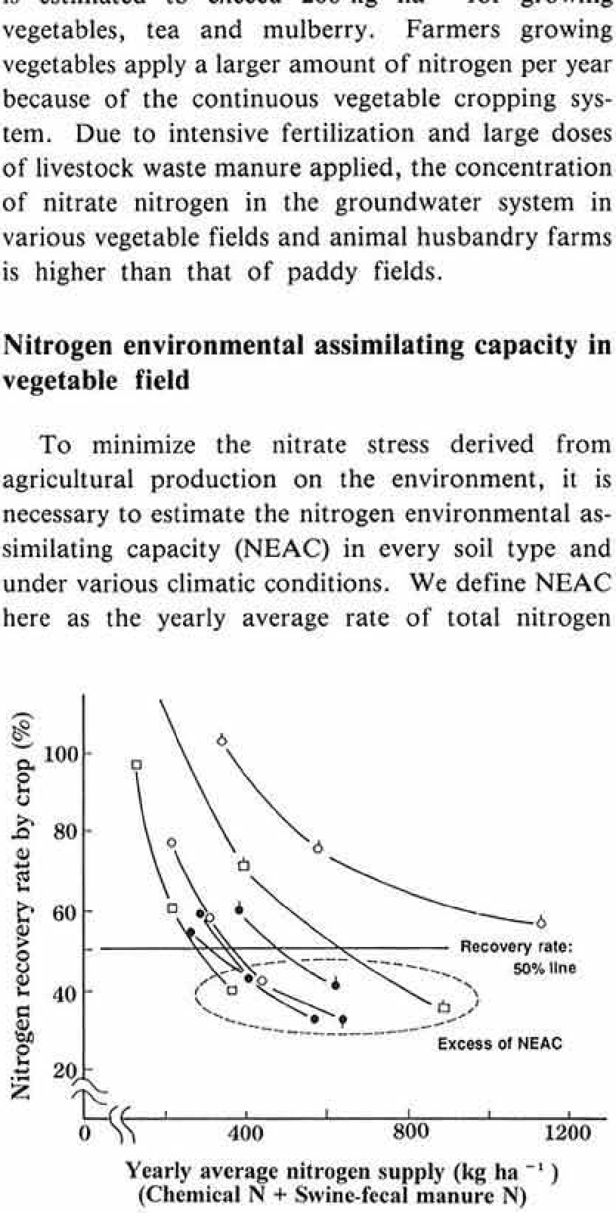

Fig. 2. Yearly average nitrogen supply and average nitrogen recovery rate by crop

Pefecture	Crop type		
	Forage	Common crops	Vegetables
Iwate	○	□	●
Yamanashi	–	–	⚲
Ohita	♁	⊥□	⚲̇

Using lysimeter test data, we developed criteria for the estimation of NEAC as follows:

1) Nitrogen recovery rate by crop to total amount of nitrogen applied with not only fertilizer but also organic waste manure should be higher than 50%. This recovery rate should not decrease year by year.

2) Average of estimated NO_3-N concentration in water percolating into the groundwater system should not exceed that fixed in the environmental water quality standard type V in Japan, i.e. 10 mg NO_3-N L^{-1} set up by the National Environmental Agency. This nitrate concentration should not increase year by year.

3) Actually it is very difficult to determine the NO_3-N concentration in percolated water, especially in the case of a cropping field. The average concentration of NO_3-N in percolated water depends on the amount of non-recovered input-nitrogen in soil and amount of precipitation. Volume of percolated water is nearly equal to half of precipitation in Japan. Therefore, in order to maintain the NO_3-N concentration in percolated water below the environmental water quality standard for lakes and reservoirs, i.e. 10 mg NO_3-N L^{-1}, the amount of non-recovered input-nitrogen (kg N ha^{-1}) per year should not exceed appreciably the value calculated from the following equation:

Annual precipitation (mm) × 0.5 × 0.1.

We estimated the NEAC of a volcanic ash vegetable field by applying the criteria outlined above to nitrogen balance data from experiments on the cultivation of forage crops, common upland crops and vegetables. These experiments were carried out using lysimeters filled with volcanic ash soil (smallest area 10 m^2, depth 1 m) in 1974–1981 at Iwate (northern part of Japan, aver. annu. precip., about 1,250 mm), Yamanashi (central part of Japan, aver. annu. precip., about 1,250 mm) and Ohita (southern part of Japan, aver. annu. precip., about 1,650 mm) Prefectural Agriculture Experimental Stations. Nitrogen was applied using ammonium sulfate and dried swine fecal manure.

As shown in Fig. 2, the nitrogen recovery rate decreased with the increase of nitrogen application in every prefecture and also in every crop. Based on the first criterion outlined above, the amounts of nitrogen applied in the following cases were estimated to exceed NEAC; 440 kg ha^{-1} applied to forage crops, 380 kg ha^{-1} applied to common crops and more than 410 kg ha^{-1} applied to vegetables in Iwate; more than 650 kg ha^{-1} applied to vegetables and tuber crops in Yamanashi; 890 kg ha^{-1} applied to common crops and 630 kg ha^{-1} applied to vegetables in Ohita. As shown in Table 3, the index of temporal changes in Yamanashi was very low because a hailstorm occurred in 1979. When 228 kg ha^{-1} was applied to common crops in Iwate, the index of temporal changes was also low, but the average nitrogen recovery rate in this case was not low compared with the other rates, and the average amounts of nitrogen in percolated water in Iwate and Yamanashi were comparatively small as shown in Table 4. As mentioned above, we can not conclude that 271 kg N ha^{-1} applied to vegetables and tuber crops in Yamanashi and also 228 kg N ha^{-1} applied to common crops in Iwate exceeded NEAC.

According to our second and third criteria, Table 4 shows that the amounts of nitrogen applied in the following cases exceeded NEAC; 1,136 kg ha^{-1} applied to forage crops, 393 kg ha^{-1} applied to common crops and 378 kg ha^{-1} applied to vegetables in Ohita.

The above data indicate that the NEAC in the

Table 3. Nitrogen recovery rate by crop (%) each year and temporal changes

Prefecture	Crop type	Nitrogen supply[a)]	Year				Average[b)]	Temporal changes[c)]
			1976	1977	1979	1980		
Iwate	Forage	218	42.0	101.3	83.5	218.3	78.1	2.11
		308	34.0	100.0	70.3	104.4	58.1	1.30
	Common crops	126	85.1	103.0	85.3	87.1	97.0	0.92
		228	60.6	80.3	55.2	30.7	59.3	0.61
	Vegetables	288	30.4	63.4	67.2	30.1	59.0	1.04
Yamanashi	Vegetables	271	33.0	113.5	10.9	49.6	54.8	0.41
Ohita	Forage	338	118.4	77.1	115.6	102.5	102.1	1.12
		582	140.1	51.1	142.3	109.2	75.2	1.31
		1,136	157.0	71.5	301.4	129.8	58.2	1.89
	Common crops	147	129.3	167.4	98.0	77.2	128.4	0.59
		398	74.9	70.7	55.7	47.7	70.6	0.71
	Vegetables	378	75.5	29.6	74.8	60.4	59.7	1.29

a): Yearly average kg ha^{-1}. b): Average from 1976 to 1980.
c): Temporal changes calculated based on (1979 + 1980)/(1976 + 1977).

Table 4. Nitrogen in percolated water (kg ha^{-1}) and temporal changes

Prefecture	Crop type	Nitrogen supply[a)]	Year				Average[b)]	Temporal changes[c)]
			1976	1977	1979	1980		
Iwate	Forage	218	8.0	6.0	3.0	2.0	4.0	0.36
		308	7.0	5.0	5.0	2.0	5.0	0.58
	Common crops	126	25.0	19.0	88.0	24.0	32.0	2.55
		228	25.0	22.0	88.0	25.0	33.0	2.40
	Vegetables	288	9.0	141.0	21.0	22.0	42.0	0.29
Yamanashi	Vegetables	271	22.0	60.0	277.0	46.0	74.0	3.95
Ohita	Forage	338	26.0	55.0	20.0	78.0	36.0	1.21
		582	82.0	123.0	43.0	65.0	65.0	0.53
		1,136	440.0	208.0	355.0	103.0	228.0	0.71
	Common crops	147	71.0	22.0	19.0	65.0	43.0	0.90
		393	42.0	43.0	68.0	159.0	63.0	2.67
	Vegetables	378	264.0	172.0	134.0	256.0	169.0	0.89

a): Yearly average kg ha^{-1}. b): Average from 1976 to 1980.
c): Temporal changes calculated based on (1979 + 1980)/(1976 + 1977).

volcanic ash vegetable field was approximately 250 (in the northern part of Japan) – 350 (in the southern part of Japan) kg N ha^{-1} per year. This upper value of the estimated NEAC was nearly equal to the nitrogen rate in Japan, i.e. 343 kg N ha^{-1} as shown in Table 1. From now on, the amount of total nitrogen applied per year or in one cycle of cropping system may be restricted within the range of NEAC. It is obvious that the beneficial use of organic waste manure nitrogen on cultivated land should be promoted through competition with chemical fertilizer nitrogen.

Heavy metal concentration in sewage sludge compost and zinc environmental assimilating capacity

Heavy metal concentration in sewage sludge compost is usually higher than in crop residue compost. Therefore, the concentration of heavy metals in sewage sludge compost must be lower than the quality standards for beneficial use on cultivated land according to the Fertilizers Control Law of Japan. Quality standards for heavy metal concentration in sewage sludge compost in Japan are rather strict compared with those in other countries except for As. The recommended standard for the upper limit of Zn concentration in sewage sludge compost and sewage sludge fertilizer has been fixed recently in Japan to 1,800 mg kg^{-1} dry matter, as shown in Table 5.

In addition to the newly recommended standard for the upper limit of Zn concentration in sewage sludge compost, concentration of heavy metals in soil, represented by Zn, must be lower than the management standard, i.e. 120 mg Zn kg^{-1} of dry soil, set up by the National Environmental Agency, as shown in Table 6.

Detailed surveys revealed that the Zn concentration was rather high in the soil derived from Fuji Volcanic Ash in Japan. Average value of Zn concentration was 119 mg kg^{-1} in soil samples collected from Tokyo and Kanagawa. This value was as high as the environmental management standard for Zn concentration in soil. Therefore, a new monitoring method was investigated instead of the digestion method using a mixture of strong acids to determine the Zn concentration in soil samples.

The microbial thermoelectric analysis method is suitable for evaluating the activity of soil micro-organisms based on their growth rate. Using this method, we carried out several experiments with sewage sludge compost and $ZnSO_4$ to estimate the zinc environmental assimilating capacity (ZnEAC) that reduces the growth rate of soil micro-organisms. Table 7 lists the heavy metal concentrations in 2 kinds of sewage sludge compost samples and Table 8 shows some representative chemical properties of the soil samples. We applied various amounts of these sewage sludge compost samples and $ZnSO_4$ above 120 mg Zn kg^{-1} of dry soil. As shown in Figs. 3 and 4, Zn concentration that decreased the growth rate of soil micro-organisms varied with each kind of soil samples. Table 9 shows the ranges of

Table 5. Quality standards of heavy metal concentration in sewage sludge compost for agricultural utilization (mg kg^{-1} of dry solid)

Element	Belgium	Denmark	France	Germany	Netherlands	U.K.	Switzerland	Japan
Hg	10	6	10	25	5	7.5	10	2
Cd	10	0	20	20	5	20	30	5
As	10				10			50
Cu	500		1,000	1,200	600	1,500	1,000	(600)
Zn	2,000		3,000	3,000	2,000	2,000	3,000	(1,800)

Numbers in parenthesis indicate the upper limits of recommended standards.

Table 6. Management standards for heavy metals in sewage sludge applied to agricultural land

1. The index for controlling the accumulation of heavy metals in the soil of agricultural land shall be the zinc content.
2. The management guidelines relating to the control of the accumulation of heavy metals in the soil of agricultural land shall be 120 mg zinc kg^{-1}.
3. The analytical method to measure the zinc content in the surface soil shall be the atomic absorption spectrochemical analysis following the digestion by mineral acids.

Set up by Department of Water Conservation, Environment Agency of Japan.

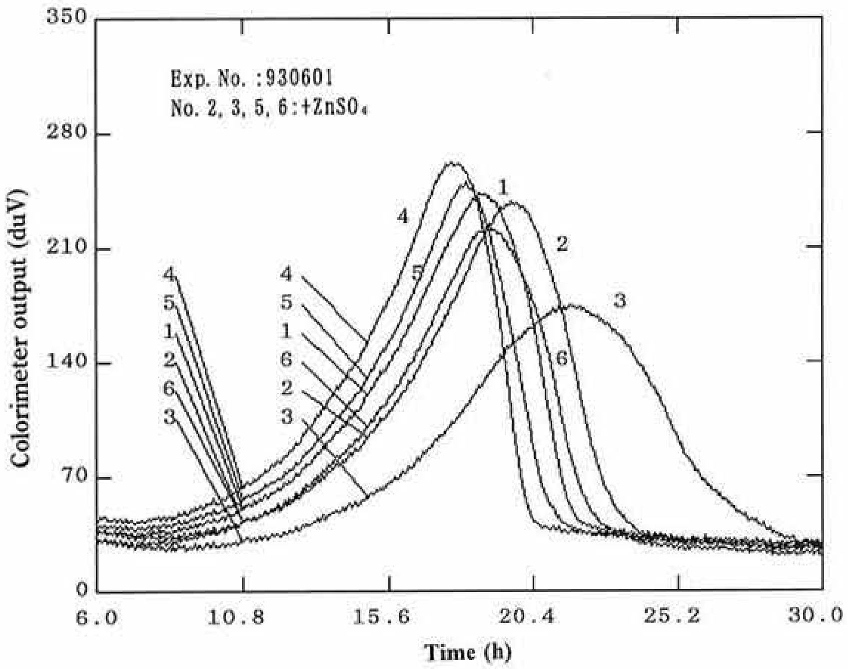

Fig. 3. Growth curves of micro-organisms in volcanic ash soil samples

No.	Soil	mg Zn kg^{-1}
1		73
2	Volcanic 1	208
3		343
4		81
5	Volcanic 2	216
6		351

Table 7. Chemical properties of sewage sludge compost samples

Sewage sludge	pH (H_2O)	T-C (%)	T-N (%)	C/N	Zn (mg kg^{-1})
Limed S. S.	6.5	34.7	6.4	5.4	2,050
Hi-Polymer S. 'S.	10.0	20.5	2.2	9.3	1,430

S. S.· sewage sludge compost sample.

Table 8. Chemical properties of soil samples

Soil	pH (H_2O)	CEC[a)]	T-C (%)	T-N (%)	C/N	Zn (kg^{-1})
Volcanic 1[b)]	5.8	18.6	3.53	0.460	7.7	73
Volcanic 2[c)]	6.1	-	5.24	0.600	8.7	81
Granite	5.6	9.5	1.20	0.234	5.1	32
Alluvial	5.6	10.7	1.60	0.278	5.8	67

a): c mol(+) kg^{-1} at pH 7.0. b): Plant residue compost was not applied.
c): 4 t of plant residue compost were applied annually.

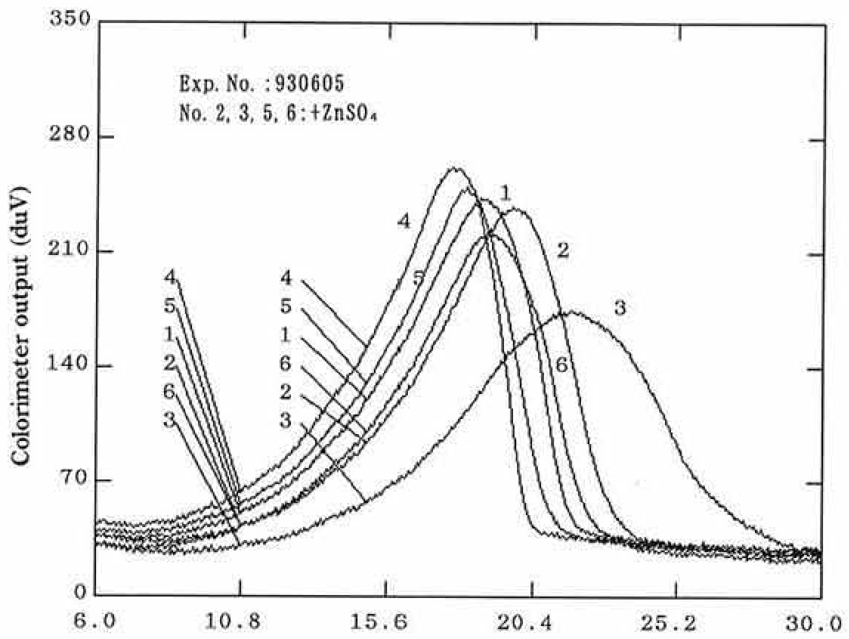

Fig. 4. Growth curves of micro-organisms in granite and alluvial soil samples

No.	Soil	mg Zn kg^{-1}
1		32
2	Granite	77
3		122
4		67
5	Alluvial	112
6		157

Table 9. Estimated Zn environmental assimilating capacity (ZnEAC) (mg kg^{-1})

Source of added Zn	Volcanic 1	Volcanic 2	Granite	Alluvial
$ZnSO_4$	118 – 163	126 – 177	77 – 122	122 – 157
$ZnSO_4$ + Limed S. S.	133 – 178	141 – 186	92 – 137	127 – 172
$ZnSO_4$ + Hi-Polymer S. S.	126 – 171	(179 – 224)	85 – 122	120 – 165
Mean	133 – 163	141 – 177	92 – 122	127 – 157

S. S.: sewage sludge compost sample.

ZnEAC estimated from the experimental results. The estimated ZnEAC for a granite soil sample was lower than the environmental management standard for Zn concentration in soil, i.e. 120 mg kg^{-1}. The estimated ZnEAC for volcanic ash soil sample 2 was the highest, and estimated ZnEAC for alluvial and volcanic ash soil samples was higher than the environmental management standard for Zn concentration in soil. The environmental management standard for Zn concentration in soil should be determined for each kind of soil.

We estimated the ZnEAC under very strict conditions immediately after 1 day of incubation following the addition of sewage sludge compost and $ZnSO_4$ to increase the Zn concentration in the soil samples. Hattori reported that the toxicity of Zn in soil samples decreased after long incubation of the soil samples[1]. Growth rate of soil micro-organisms may decrease by the increase in the concentration of exchangeable or soluble Zn with weak acid and also Zn in organo-mineral complexes but not by the Zn fraction extracted for the first time with a mixture of strong acids. Actual ZnEAC in soils is likely to be slightly higher than the ZnEAC estimated in this experiment.

Conclusion

Agriculture is the only industry endowed with the function of preservation of the environment and also recycling of organic waste. However, excessive nitrogen application and large doses of livestock waste manure are increasing the nitrate stress on the environment. In order to minimize the nitrate stress derived from agricultural production on the environment, the total amount of nitrogen applied with chemical fertilizer and also organic waste manure should be restricted within the range of the nitrogen environmental assimilating capacity of the soil–plant system. We developed criteria to calculate NEAC, and using lysimeter test data, we estimated that the NEAC of a volcanic ash vegetable field was 250–350 kg N ha^{-1}.

To promote sustainable agriculture by recycling organic waste, it is important to protect the recycling function of cultivated soil from the toxicity of heavy metals in organic waste compost. Beneficial use of organic waste compost must also be expanded within the range of the heavy metal environmental assimilating capacity in soil. Soil micro-organisms are endowed with the function of recycling organic waste. Monitoring of cultivated soil based on the soil micro-organism growth rate may be suitable for estimating the zinc environmental assimilating capacity. We estimated that ZnEAC for alluvial and volcanic ash soils was higher than the environmental management standard for Zn concentration in soil, i.e. 120 mg kg^{-1}. The environmental management standard for Zn concentration in soil should be determined for each kind of soil.

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