Study on the potential of farmland soils as non-point sources of nitrogen and phosphorus in Japan

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Abstract The amounts of N and P accumulated in farmland soils of 50 cm depth were equivalent to the amount of chemical fertilizer supplied for 50–70 years. The values of N/P of surface soils in farmlands were 1.0–4.3, lower than expected. The median diameter of soil particles in run-off waters was generally less than 10 μm. The mean values of particulate fractions over 1 μm and over 0.22 μm were 19% for N, 27% for P, and 39% for N, 64% for P respectively. Fine particles of soil containing concentrated phosphorus should be carefully monitored as potential sources related to eutrophication.

Keywords Eutrophication; farmland; nitrogen; paddy field; phosphorus; run-off

Introduction

Eutrophication is still a worldwide problem and it is largely related to the modernized agriculture relying on chemical fertilizer. It is reported that phosphorus (P) concentration of farmland soils has been still increasing in Japan, although that of nitrogen (N) has been at steady state. It is easily understood if we consider the run-off rate of P from farmland is estimated to be 2–3% of the supply of fertilizer (Ukita and Nakanishi, 1999; Ukita and Prasertsan, 2002). This study aimed at confirming such situations in nearby areas around us, through the investigation of soil profiles in various farmlands and surveys on run-off waters from various farmland areas. In particular we focused on the accumulation of N and P in farmland soils and the run-off of soil particles containing highly concentrated phosphorus. As for the run-off of P from farmlands, many reports were already published (Sharpley, 1995; Weld *et al.*, 2001; Beckmann *et al.*, 2003).

Materials and methods

Survey on soil profiles

Representative fields were selected from various categories of farmlands and also from forests in Yamaguchi Prefecture near E131° 15′, N34° 05′ as summarized in Table 1. Samplings were conducted mainly in April 2000. Surface soils were sampled with a sampler of 5 cm depth and 100 ml volume at three points in each field. Composite samples were prepared for chemical analyses. Samples for soil profile were taken partly among those fields using a sprit-type core sampler of 8 cmϕ, 50 cm long and a screw-drill-type sampler of 120 cm. Grass and fallen leaves were sampled in the quadrate of 30 × 30 cm square. These samples were analyzed for moisture, ignition loss (IL), Kjeldahl nitrogen (Kj-N), ammonium nitrogen (NH_4-N), nitrite and nitrate nitrogen ($NO_{2,3}$-N), total phosphorus (TP), phosphate phosphorus (PO_4-P). Water soluble N and P were analyzed for 4 g of wet soil extracted with 100 ml of distilled water after shaking for 30 min and then filtrated with GA100 (pore size 1 μm) and measured for inorganic N and P. For available

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Table 1 Sampling points for the survey on soil profiles in Yamaguchi Prefecture in Japan sampled in Apr. 2000

Categories		Grass & fallen leaves	Surface soil	Soil profile
Paddy field	Reductive wet	1 field * 3 points	1 field * 3 points	1 point
	Oxidative dry	1 field * 3 points	1 field * 3 points	1 point
	Before improvement works	1 field * 3 points	1 field * 3 points	1 point
	After improvement works	1 field * 3 points	1 field * 3 points	1 point
	Organic culture	–	2 fields * 3 points	2 points
	Ordinary culture	–	4 fields * 3 points	4 points
	Ibid. with barley culture	–	1 field * 3 points	1 point
Dry field	Vegetables	–	5 fields * 3 points	2 points
	Fruits orchard	3 fields * 3 points	6 fields * 3 points	5 points
	Pasture	3 fields * 3 points	3 fields * 3 points	3 points
	Tea garden	–	3 fields * 3 points	2 points
Forest	Deciduous broad leaf	2 fields * 3 points	2 fields * 3 points	1 point
	Evergreen broad leaf	6 fields * 3 points	6 fields * 3 points	1 point
	Evergreen needle leaf	3 fields * 3 points	4 fields * 3 points	3 points
	Bamboo	–	2 fields * 3 points	–

N and P, 2 g of wet soil and 100 ml of 0.0005 mol l^{-1} H_2SO_4 were used instead of water for extraction.

Surveys on run-off water

Run-off surveys were conducted in 10 rain events from May to October 2001 at six fields shown in Table 2 and Table 3. Surface run-offs were taken and partly subsurface penetrated waters were also taken for dry field A1, paddy field A and the upper part of dry field F. The tributary areas of subsurface run-off were not necessarily clear.

Suspended solid (SS) was filtered by GA100. Distribution of particle size was measured by using an apparatus of Horiba LA-920. Kj-N, NH_4-N, $NO_{2,3}$-N, TP, PO_4-P, soluble Kj-N (SN) and soluble TP (SP) were measured. The latter two were measured for the filtrate of SS measurement. Surface soils of the top 1 cm were sampled and measured for TN and TP and used in the experiments of washed-out load.

Results and discussion

Survey on soil profiles and accumulation of N and P in soils

Table 4 shows the results of estimating the accumulation of N and P in various surface soils of the top 5 cm. In this table dry field includes orchard and tea garden too. Accumulation of N in the 5 cm layer of soil ranges from 0.95 t ha^{-1} in paddy fields to 2.12 t ha^{-1} in dry fields. Accumulation of P ranges from 0.22 in forests to 1.06 t ha^{-1} in dry fields. Accumulation of soluble inorg-N ranges from 0.72 kg ha^{-1} in paddy fields to 73 kg ha^{-1} in dry fields. Accumulation of PO_4-P ranges from 0.02 kg ha^{-1} in forests to 27 kg ha^{-1} in dry fields.

Table 2 Fields for the surveys on run-off water

Categories	Location	Area (ha)	Gradient	Crop	Soil
Paddy field A	Hikino Ajisu	0.4	almost flat	rice	
Paddy field F	Fujigochi Ube	0.25	almost flat	rice	
Dry field A1	Hikino Ajisu	0.15	almost flat	onion, tobacco	reddish clay
Dry field A2	Hikino Ajisu	0.03	5.5°	tobacco	reddish clay
Dry field F	Fujigochi Ube	1.41	5 °(4 terraces)	tobacco, garlic, radish	sandy clay
Tea garden	Fujigochi Ube	2.21	7.4 – 11°	tea	

Table 3 Rainfall data during run-off survey

	May 21	May 30	June 13	June 19	July 6	July 12	Aug. 3	Sep. 14	Sep. 30	Oct. 9
Total rainfall (mm)	33	43	39	158	75.5	85.5	30	68	48	53
Max. intensity (mm/h)	6.5	9.5	11	41	16.5	20.5	7.5	60	9.5	11.5
Mean intensity (mm/h)	3	3	4	9	5.5	6	3	17	5	5.5
Duration of rainfall (h)	12	14	10	18	14	14	11	4	9	10
Preceding fine weather (day)	12	2	6	0	0	0	3	6	14	7
Preceding rainfall (mm)	3	2.5	5.5	7	21.5	12	0.5	0.5	1.5	8.5
Sampling period	17:45–2:20	18:00–0:45	19:10–23:45	9:45–20:24	9:55–15:30	6:20–7:55	16:00–20:50	21:10–22:45	12:04–18:10	12:48–19:50
Intensity during survey	1.0–1.5	5.3–1.0	9.0–3.0	6.9–13.0	0.5–0.5	16.0–16.5	3.5–0.5	2.5–0.5	1.0–1.5	8.5–10.0

Table 4 Accumulation of nutrients and organic matter in various surface soils of 5 cm (Apr. 2000)

Category	Number of samples	IL %	TN kg·ha^{-1}	TP kg·ha^{-1}	Available N (kg·ha^{-1})			Water soluble (kg·ha^{-1})		
					NH_4-N	$NO_{2,3}$-N	PO_4-P	NH_4-N	$NO_{2,3}$-N	PO_4-P
Paddy field	6 × 3	7.30	951	365	0.81	1.59	11.4	0.35	0.37	2.79
		10	22	20	95	92	80	61	99	50
Dry field	12 × 3	14.39	2,117	1,064	29.0	55.9	53.6	25.7	46.9	27.0
		86	79	61	197	220	89	200	244	165
Pasture	3 × 3	12.28	1,426	831	0.85	8.93	4.4	0.36	2.63	3.58
		36	14	54	82	80	87	110	124	108
Forest	11 × 3	13.80	1,107	216	1.88	1.35	1.10	0.49	0.65	0.02
		31	27	87	72	96	95	107	127	332

* Lower lines are coefficients of variance (%)

The values of N/P are smaller than expected: 2.6, 1.0, 1.4, 4.3 and 1.7 for paddy fields, dry fields, orchard and pastures respectively. Forest soils contain a high amount of N and N/P ratio is 12.7.

Table 5 shows the standing stock of grass and fallen leaves on the surface of farmlands in April. The amount of biomass as dry matter ranges from 3.1 $t\,ha^{-1}$ for dry fields and 9.1 for forests. The values versus the accumulation in the 5 cm layer of soil range from 5.2 to 20%. Similarly, the values of N accumulation were 41–84 $kg\,ha^{-1}$ and correspond to 3.8–8%. Similarly, the values for P range from 19 $kg\,ha^{-1}$ for paddy fields to 71 $kg\,ha^{-1}$ for pastures and correspond to 4–37%. As these values seem to fluctuate seasonally, and are not so large, further discussions are omitted.

Table 6 shows the accumulation of I.L., N and P in the soil of 0–50 cm. Density distributions were considered in the estimation (Shi *et al.*, 2002). I.L. accumulation ranged from 291 $t\,ha^{-1}$ in paddy fields to 848 $t\,ha^{-1}$ in tea gardens. Kj-N accumulation ranged from 13 $t\,ha^{-1}$ in paddy fields to 20 $t\,ha^{-1}$ in tea gardens. P accumulation ranged from 1.0 $t\,ha^{-1}$ in forests to 11 $t\,ha^{-1}$ in tea gardens. It should be noted that forest soils accumulate rather large amounts of N of 9.9 $t\,ha^{-1}$. The percentage of 5 cm layer versus 50 cm layer was 10–14% for I.L., 13–26% for Kj-N and 9–34% for TP. Figure 1 shows the vertical distribution of TP, available and water soluble PO_4-P in various soils. Figure 2 shows the vertical distribution of N as well. As general tendencies, the soluble fractions are larger for P than for N in paddy fields, dry fields, orchards and pastures. Available and soluble P distribute more highly near the surface, whereas those for N sometimes distribute more highly in deeper layers.

Survey on run-off water from farmlands

Table 7 shows the results of run-off surveys under rainy weather. PP or PN is the difference between T-P or T-N and S-TP or S-TN respectively. As soluble fractions were measured for the filtrate through GA-100 of 1 μm, the particulate fractions of P and N

Table 5 Standing stock of grass and fallen leaves (biomass) in various fields

Category	Number of samples	Biomass		TN		TP	
		$t\cdot ha^{-1}$	%	$kg\cdot ha^{-1}$	%	$kg\cdot ha^{-1}$	%
Paddy field	4 × 3	5.2	14.6	41	4.0	19	6
Farm land	3 × 3	3.1	5.2	66	4.5	24	4
Pasture	3 × 3	4.1	8.1	76	3.8	71	6
Forest	11 × 3	9.1	20.3	84	8.0	32	37

*Percentage of grass and fallen leaves versus stock in surface soil of 5 cm

Table 6 Accumulation of organic matter, nitrogen and phosphorus in various lands in 0–50 cm soil

	Number of samples	IL		Kj-N		T-P	
		IL($t\cdot ha^{-1}$)	%	Kj-N ($t\cdot ha^{-1}$)	%	TP ($t\cdot ha^{-1}$)	%
Paddy fields	6	291	10	5.7	13	2.5	12
Dry fields	2	313	11	6.7	23	6.6	34
Orchard	4	439	12	8.4	17	5.9	21
Tea garden	2	848	11	20	26	10.6	9
Pasture	3	530	14	12	20	5.9	25
Forest	3	619	13	9.9	16	1.0	13

The values of %: the part of accumulation in 0–5 cm versus accumulation in 0–50 cm

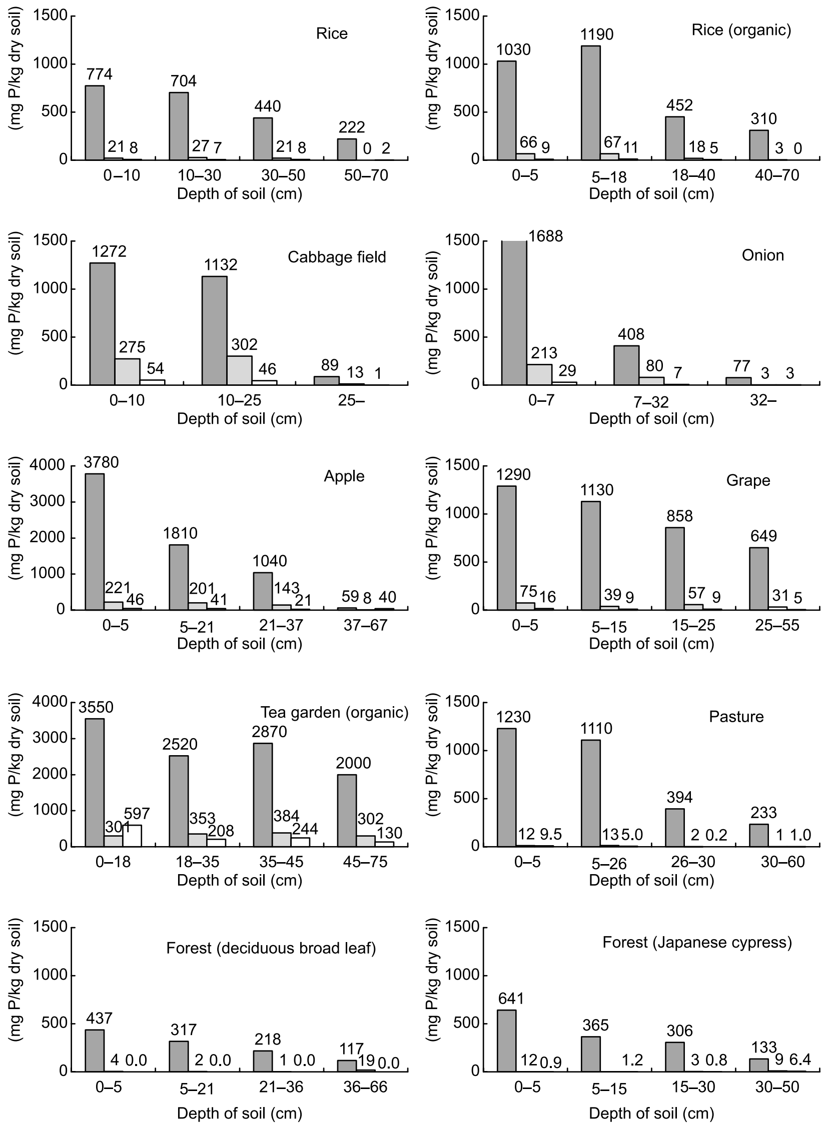

Figure 1 Vertical distribution of TP, available P and water soluble PO_4-P in various soils (Bars from left to right side represent TP, available P and soluble P respectively)

were relatively small, 10–50% for P and 10–62% for N. Median diameters of SS ranged from 1.2 to 7.3 μm; generally less than 10 μm.

Table 8 shows regression equations for various relationships among flow rate, suspended solids and size of particulate matter in run-off from farmland. SS loading is generally proportional to specific flow rate q_s or q_s^2. Median diameter tends to be larger as SS concentration becomes larger, and the larger the diameter of particulate matter, the larger becomes the P content in soils.

As the fraction of PP was smaller than expected, we tried to use filters with smaller pore size. Table 9 shows the particulate fraction through the filter of pore size 0.22 μm. As mean values, the fractions increase from 27(15–45) to 64(49–77)% or from 36(4–66) to 54(12–93)% for P. In the second case, the fractions of particulate matter increase from 19(1–48)% to 39(17–74)% for N.

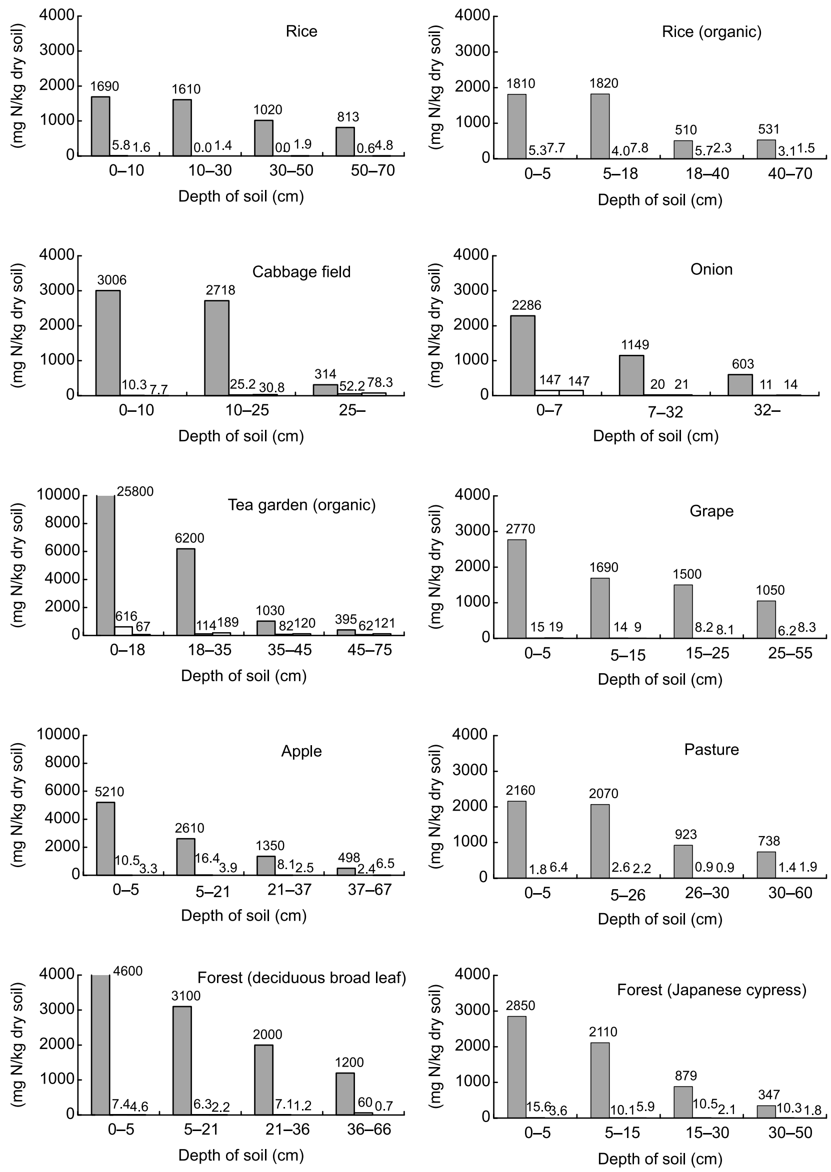

Figure 2 Vertical distribution of Kj-N, available and water-soluble inorg-N in various soils (Bars from left to right side represent Kj-N, available inorg-N and soluble inorg-N)

Figure 3 shows the comparison of run-off events at the beginning of rice cultivation with overlying water and before harvest without overlying water in a paddy field in the campus of Yamaguchi University. It should be noted that turbidity and TP concentration of run-off water on Oct.16 were clearly larger than those on Jun.19; nevertheless the rainfall intensity was rather smaller. This explains the environmental friendliness of paddy fields with overlying water.

We tried to measure the easily-washed-out fraction in soils, considering the importance of the potential source of P. 2 g of surface soil of 1 cm was taken to a vessel with a lid and 1L of distilled water added. After mixing, and leaving for 10 or 35 min, water in the upper 3 cm depth was sampled, by considering precipitation velocity using Stokes' law. Table 10 shows the result of such experiments. Comparing the particle size of

Table 7 Results of survey on run-off from farmland under rainy weather from May to Oct. 2001

	Specific flow (mm h^{-1})	Median diam. (μm)	SS (mg l^{-1})	PO_4-P (mg l^{-1})	S-TP (mg l^{-1})	TP (mg l^{-1})	PP/TP (%)	$NO_{2,3}$-N (mg l^{-1})	S-TN (mg l^{-1})	TN (mg l^{-1})	PN/TN (%)
Paddy field A	1.60	2.3	26	0.29	0.33	0.47	27	0.3	0.6	0.9	32
(surface)	2.33	1.7	30	0.22	0.23	0.30	19	0.5	0.5	0.5	18
Paddy field A	0.17	1.2	2	0.03	0.04	0.05	17	0.9	1.0	1.1	10
(submerged)	0.13	0.3	3	0.02	0.02	0.03	18	0.6	0.6	0.7	13
Paddy field F	5.98	1.3	3	0.14	0.18	0.20	16	2.5	2.7	2.9	12
(surface)	4.26	0.8	3	0.19	0.21	0.21	9	5.6	5.2	5.5	11
Dry field A1	1.38	3.7	89	6.09	6.45	7.22	10	14.4	16.4	18.8	13
(surface)	1.17	1.9	75	1.87	1.95	2.23	9	15.6	17.8	21.9	12
Dry field A1	3.85	3.7	130	4.51	4.80	6.38	24	4.6	6.0	7.8	29
(submerged)	5.09	1.4	77	2.59	2.78	3.05	19	6.3	5.3	5.2	18
Dry field A2	4.38	7.3	1,175	3.59	4.22	7.85	50	2.9	3.9	9.1	62
(surface)	2.93	2.2	989	3.64	3.79	4.63	20	3.2	3.7	3.6	30
Dry field F	1.98	6.0	267	0.85	0.92	1.75	35	2.7	3.4	5.9	36
(surface)	2.62	4.1	380	0.33	0.32	1.00	28	3.1	2.9	4.6	29
Dry field F	0.31	1.9	17	0.24	0.32	0.38	16	2.7	3.1	3.5	16
(submerged)	0.23	2.0	19	0.20	0.20	0.21	9	5.5	4.7	4.9	13
Tea garden F	0.47	4.5	80	0.40	0.47	0.66	30	5.5	7.6	8.9	18
(surface)	0.59	5.6	119	0.45	0.53	0.55	25	4.7	5.7	5.6	18

A: Ajisu area, A1: plain field, A2 inclined field, F:Fujigochi area, terrace field; Upper lines: mean values, Lower lines: standard deviation

Table 8 Relationship among flowrate, suspended solids and size of particulate matter in run-off from farmland

	Run-off	Sample	q_s (mm hr^{-1})–SS load (g m^2 hr^{-1})		SS (mg/l)–median diameter (μm)		Median diameter (μm)–P contents (%)	
			Equation	R^2	Equation	R^2	Equation	R^2
Paddy field A	surface	21	$y = 0.0037e^{0.63x}$	0.82	$y = 0.054x + 0.93$	0.89	$y = -0.525x + 7.93$	0.06
	submerged	15	$y = 0.0002x^2 + 0.0018x$	0.25	$y = 0.036x + 1.13$	0.09		
Paddy field F	surface	18	$y = 0.0016x^{070}$	0.50	$y = 0.068x + 1.16$	0.07	$y = 9.2x^{-0.217}$	0.05
Dry field A1	surface	7	$y = 0.163x$	0.99	$y = 0.59 \ln(x) + 0.92$	0.10		
	submerged	16	$y = 0.044x^2 + 0.036x$	0.92	$y = 0.87 \ln(x) + 0.061$	0.12		
Dry field A2	surface	7	$y = 0.227x^{1.95}$	0.58	$y = 0.61x - 0.053$	0.22	$y = 9.0x^{-0.45}$	0.09
Dry field F	surface	30	$y = 0.334x$	0.41	$y = 1.89 \ln(x) - 1.96$	0.79	$y = 6.46x^{-0.356}$	0.39
	submerged	26	$y = 0.0177x^{1.40}$	0.63	$y = 0.050x + 0.217$	0.20	$y = 5.00x^{-0.388}$	0.25
Tea garden F	surface	22	$y = 0.150x^2 + 0.0247x$	0.97	$y = 0.036x + 1.65$	0.58	$y = 5.82x^{-0.359}$	0.35

A: Ajisu area, A1: plain field, A2 inclined field, F: Fujigochi area, terrace field

Table 9 Particulate fraction through different sizes of filter

Experiment	Filter size	Paddy A	Paddy B	Dry field A1	Dry field A2	Dry field B	Tea garden F	Average (%)
1st P	1 μm	15	20	22	45	30	29	27
	0.22 μm	70	55	49	70	61	77	64
2nd P	1 μm	9	51	66	47	4	42	36
	0.22 μm	12	61	93	76	30	51	54
2nd N	1 μm	1	2	26	10	26	48	19
	0.22 μm	74	17	32	19	36	58	39

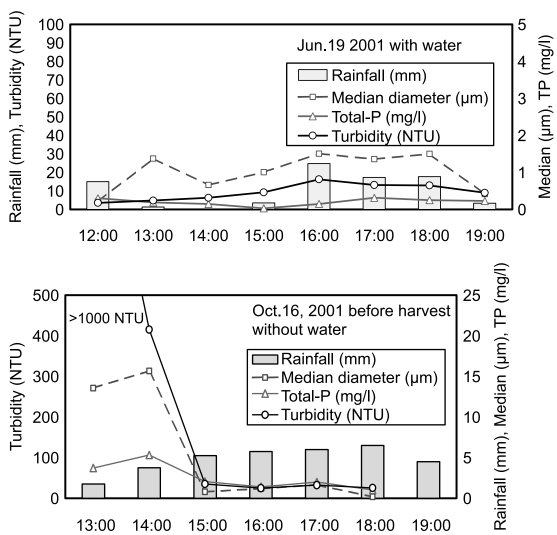

Figure 3 Comparison of two run-off events from paddy field in Yamaguchi Univ.

easily-washed-out fractions targeting less than 5 or 10 μm with those of SS in run-off waters as shown in Table 9, big differences were not found among them except the tea garden, which contained a high amount of organic matter. Moreover, pooling water on the surface of farmland under rain, median diameters of SS were around 5 μm and SS contain 3–4 mg P/g. These fine particles of soil less than 10 μm are incapable of precipitating soon after re-suspension by the turbulence of rain drops. Easily-washed out fractions occupy 3–20% of farmland soil. Anyhow, these fine particles concentrating P by 3–5 mg/g should be monitored carefully hereafter.

Conclusions

The main results obtained in this research are as follows.

- The accumulation of N and P in surface (5 cm) layers of farmland soils was 0.95–2.12 t N ha^{-1} and 0.22–1.06 t P ha^{-1}. Ratios of N/P were rather low at 2.6, 1.0, 1.4, 4.3 and 1.7 respectively for paddy fields, dry fields, orchards, tea gardens and pastures. The value for forests was as high as 12.7.
- Available fractions in surface soil are 0.4–4% for P, 0–0.6% for N in the case of paddy fields, and 2–8.5% for P, 0.1–22.7% for N in the case of dry fields. Generally, the fraction of available P tends to be larger than that of N. Available and soluble P distribute more highly near the surface, whereas those for N sometimes distribute more highly in deeper layers.
- The accumulation of P and N in 0–50 cm layers is equivalent to the amount of chemical fertilizer used for 56 years and 72 years, assuming fertilizer supply to be 44 kg P

Table 10 Comparison of P, easily-washed-out fraction in soils and SS in run-off water

	TP in soil of top 1 cm ($mg\ g^{-1}$)	Exp.1 expecting less than 10 μm			Exp.2 expecting less than 5 μm			Run-off water	
		Median diameter (μm)	PP/SS ($mg\ g^{-1}$)	Easily-washed-out fraction (%)	Median diameter (μm)	PP/SS ($mg\ g^{-1}$)	Easily-washed-out fraction (%)	PP/SS ($mg\ g^{-1}$)	Number of samples
Paddy field A	0.81	7.1	3.4	20	4.7	3.7	16	5.5	34
Dry field F	0.50	4.5	2.7	16	5.3	2.9	13	3.9	38
Dry field A2	0.81	6.1	2.1	5	5.5	3.0	3	3.2	8
Tea garden F	1.39	4.9	20.4	15	1.4	8.0	3	2.3	22

and 85 kg N $ha^{-1}year^{-1}$ in the case of paddy fields, and 56 years and 51 years assuming 80 kg P and 175 kg N $ha^{-1}year^{-1}$ in the case of dry fields respectively.

- Median diameter of soil particles in run-off water was less than 10 μm. The values are 1.2–2.3 μm for paddy fields and 1.9–7.3 μm for dry fields, and tend to be smaller for subsurface run-off and larger for inclined dry fields.
- There were seen certain relationships between specific flow rate and SS loading, SS concentration and median diameter, and median diameter and P contents in SS. Therefore, it is possible to estimate particulate P loading from specific flow rate in each farmland. The overlying water on paddy fields was very effective to decrease SS loading in rainy weather.
- A simple method of measuring the easily-washed out fraction of P was proposed. Targeting the particulate matter less than 10 μm, median diameter ranged from 4.5 to 7.1 μm, and the fractions were estimated to be 5–20% for the surface soils in various farmlands. Fine particles of soil containing concentrated phosphorus should be carefully attended because of the eutrophication factor.

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