B-6.2.1 Carbon budgets and sequestrration in upland and paddy agricultural ecosystems in Japan

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Total Budgets for FY1996-FY1998 7,505,000 Yen (FY1998; 2,515,000 Yen)

Key words Carbon budget, Single-cropping, Double-cropping, Soil respiration

Abstract

Carbon dioxide evolution rates from a double cropping, upland rice and barley, field were determined in central Japan from June 1992 to May 1994, and regression models were developed to predict soil respiration rate. Diurnal patterns of hourly soil respiration rates (SRh) showed similar trend with those of soil surface temperatures. Daily soil respiration rate (SRd) obtained by integrating SRh varied 0.3 to 15.6 g CO2 m^{-2} d^{-1} for the two years. In summer cropping period, SRd had positive correlation with daily mean soil surface temperature and negative correlation with volumetric water content in soil. Moreover, this relationship was able to be expressed as a multiple-factor model with an Adj-R^2 of 0.925. On the other hand, in winter cropping period, SRd was able to be represented by a single factor model using soil surface temperature and an Adj-R^2 value was 0.854.

Carbon dynamics and budgets were investigated in upland and paddy agricultural ecosystems in Japan. The experiments were carried out in upland single- and double-cropping fields and paddy single-cropping fields in central Japan, between May 1991 and April 1997. Carbon budgets were different between the upland crop field and the paddy crop field. The annual carbon balance was estimated to be -270~-320 gCm^{-2} for the upland single-cropping field, -160~-270 gCm^{-2} for the upland double-cropping field, and only -20 gCm^{-2} for the paddy rice single-cropping field. These results suggest that effective agronomic measures are needed to maintain the carbon balance in prevailing upland agro-ecosystems in order to sustain soil fertility, and the upland agro-ecosystems may contribute to the increase in the carbon dioxide concentration of the atmosphere as the carbon accumulated in the soil is constantly being released in the atmosphere, and improved management is capable of increasing C levels on existing agricultural soils in Japan. On the other hand, the carbon balance for the paddy agro-ecosystem was in good agreement, sometimes resulting in a positive increase in

carbon. This is caused by a decrease in the heterotrophic respiration in the soil deoxidized under the flooding water and carbon fixation by photosynthesis of algae. The paddy rice field may be well-carbon balanced agricultural system and this may permits a sustainable land use for long period more than hundreds years.

Carbon dioxide evolution from upland rice-barley double-cropping field in central Japan

1. Subject

Carbon dioxide evolution from agricultural soils has been observed for a long time as a source of CO_2 for photosynthesis of crop 1), 2). The carbon dioxide in soils is produced mainly by soil organisms and plant roots. Soil respiration is represented as the total of all soil processes in which CO_2 is produced 1). In recent years, several researchers have been measured soil respiration rates under cultivated lands, to be shown below, to understand the carbon dynamics and budgets, because CO_2 is the primary contributor to the global warming process. Double cropping systems are commonly practiced in upland fields in central Japan. However, only limited information is available about carbon dioxide dynamics and budgets in the agricultural ecosystems in Japan. The objectives of this study are to measure the carbon dioxide fluxes from the double cropping field using the open-flow IRGA method 3) and to elucidate the effects of abiotic factors, temperature and soil moisture, on soil respiration. Based on these relationships, furthermore, multiple and single factor models are developed to estimate the seasonal changes and the amount of soil respiration in this cultivated land. The discussion will focus on the amount of CO_2 evolved from cultivated soils and the comparison of the values obtained from several agricultural ecosystems in the world.

2. Materials and Methods

The study was conducted at the National Institute of Agro-Environmental Sciences (NIAES) in Tsukuba City, central Japan (36° 01'N and 140° 07'E, about 25 m above sea level) during June 1992 to May 1994.

Measurement of carbon dioxide evolution rate from the experimental field was made using the open-flow infra-red gas analyzer method (OF-method 3)). The measurement was conducted approximately monthly, except during the winter cropping period (Nov.-May) in 1994, when the interval was approximately three months.

Air, soil surface and soil temperatures were measured using the copper-constantan thermocouple at the same time of the CO_2 evolution measurement. The measurements of air (TA) and soil surface temperatures (TF) were determined at 5 and 0 cm high, respectively, and soil temperature (TS) was measured at a depth of 5 cm. Soil moisture was measured at times of measuring the evolved CO_2.

3. Results and discussion

There have been few studies to measure the daily change of hourly soil respiration rates (SRh). The present study has demonstrated the diurnal and seasonal variation of SRh (Figs. 1 & 2). The daily changes of SRh corresponded to those of temperature. The SRh was higher in a day time and lower in a night time. The similar diurnal trends have been observed by other researchers [4], [5]. Moreover, in the present study, the daily soil respiration rate (SRd) had the highest correlation with daily mean temperature through a year (Table 1). This is in agreement with previous studies in agricultural fields [6], [7], [8], [9], [10].

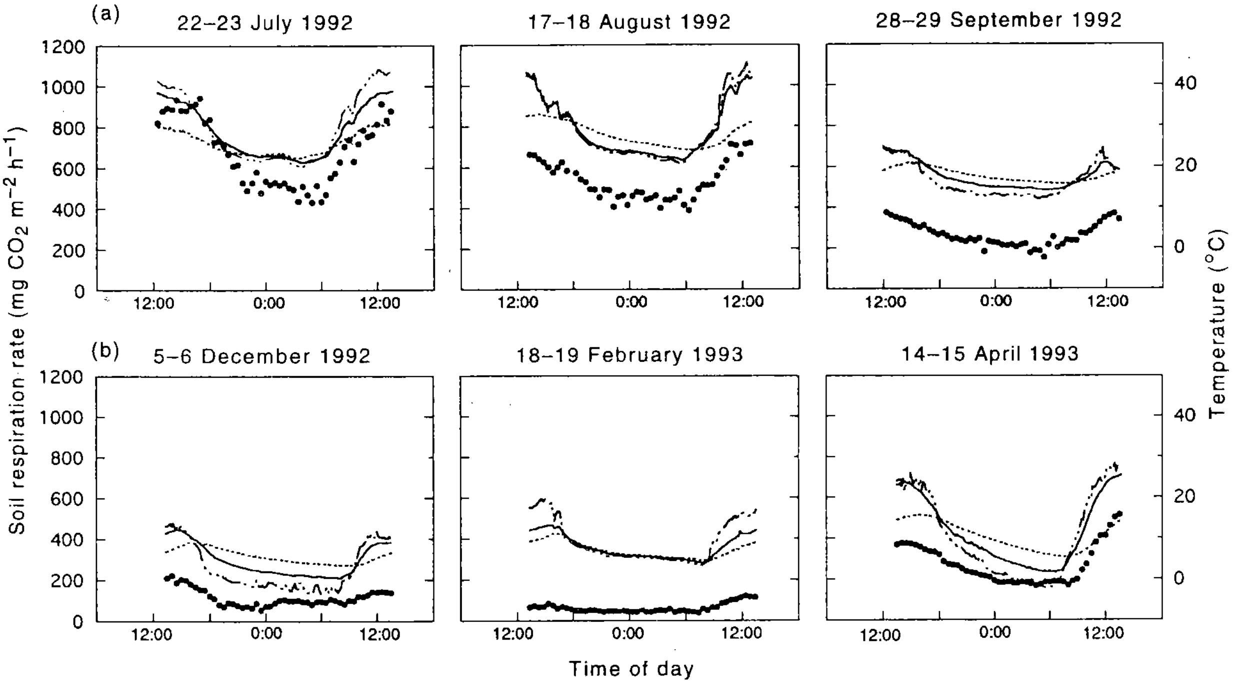

Fig. 1. Examples of diurnal changes in hourly soil respiration rate (●) and air temperature at 5 cm height (—···—), soil surface temperature (——) and soil temperature at 5 cm depth (·····) in (a) summer and (b) winter months.

Soil moisture is known to influence strongly a soil microbial activity. A positive correlation between soil moisture and soil respiration had been observed in incubated soil samples [11], [12], [13], in which soil moisture was expressed as gravimetric water content or water potential. On the other hand, there are few in situ studies to verify the influence of soil moisture on soil respiration, and these results showed the various relationships. Rout & Gupta (1989) [14] and Grahammer et al. (1991) [5] reported the positive relationship between mass basis water content (Wm) and soil respiration in a forest and a grassland ecosystems, respectively. In the present study, the SRd during summer cropping period showed relatively better negative correlation with the volumetric water content (Wv, Adj-R^2=0.692), and with the Wm (Adj-R^2=0.452) (Table 1). Kowalenko et al. (1978) [15] described that soil respiration has negative correlation with water content (% mm) in a fallow field in Ottawa. Seto (1982) [16] observed that the SRh reduced rapidly after a heavy rainfall in an open land. The Wv was strongly related to the air filled porosity (AFP) of the cultivated soil in the present study (Wv

= 65.7 - 0.94AFP, R2= 0.830). Thus, it could be represented that the SRd was higher at 50 %v AFP and decreased with declining AFP to 20 %v. This suggests that the decline of AFP would induce the poor availability of oxygen in the cultivated soil. Linn and Doran (1984) [17] reported that the relative soil CO2 production rate was increased linearly with rising water filled porosity (WFP) from 20 to 60 %v and decreased when WFP was greater than 60 %v. Grant and Rochette (1994) [18] also showed a similar result based on the laboratory experiment using silty clay loam soil.

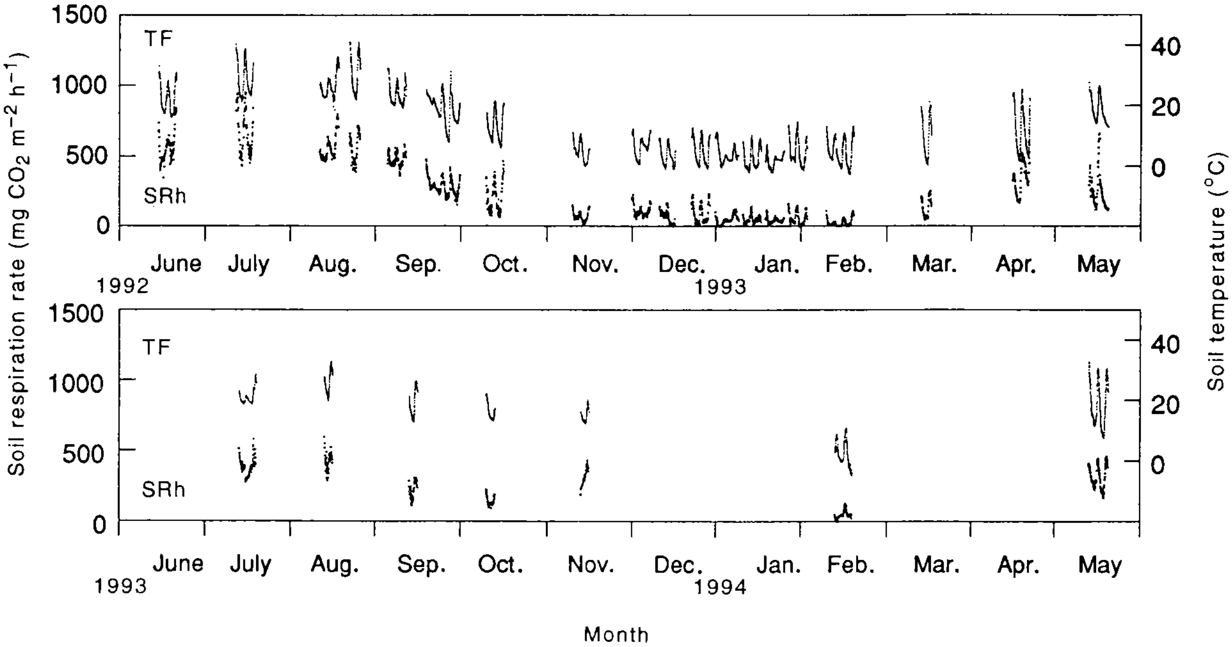

Fig. 2. Seasonal variation in hourly soil respiration rate (SRh) and soil surface temperatures (TF) during the period from June 1992 to May 1994. Each trace indicates diurnal changes of SRh and TF during the measurement period for 1 to 3 days.

The relationship between Wv and SRd was not found in the winter cropping period (Table 1). The range of Wv during the winter season was smaller than those during the summer. It is likely that the narrow range during this period neglects an effect of Wv on SRd. In addition, soil respiration rates under low temperature conditions may be mainly affected by temperature. Grant (1991) [19] reported that the microbial activity was more sensitive to soil water content at higher soil temperature.

The results concerning SRd and abiotic factors lead to an ecological consideration for the cultivation of upland rice-barley, double cropping. This suggests that at least two cropping periods should be distinguished in evaluating soil respiration over a year. During the summer cropping period in upland rice from June to October, soil respiration must be ascribed to both plant roots and soil organisms. The multiple-factor model (Eq. 6 in Table 1) using daily mean soil surface temperature (TFd) and volumetric water content of soil (Wv) parameters shows excellent agreement with measured respiration with an Adj-R^2 of 0.925 during this period. On the other hand, the winter cropping period from November to May includes a season of winter dormancy with little or no activity. During the period of higher temperature, April and May, it is presumed that plant and microbial activities predominate. The single-factor model (Eq. 8) with TFd parameter can satisfactorily predict soil respiration rate with an Adj-R^2 of 0.854 during this period. Because the environmental influences in summer and winter cropping periods may be different, individual models for the two periods are determined.

Table 1 Correlation coefficients and single- and multiple-factor models obtained from evaluating the influences of independent abiotic factors on the amount of soil respiration

Independent factor		Dependent factor SRd (g CO_2 m^{-2} day^{-1})			
		Adj-R^2	Equation	Eqn number	Sample size
Summer cropping period					
Temperature (°C)	+ 5 cm (TAd)	0.773**	$SRd = 0.777\exp(0.111TAd)$	1	10
	0 cm (TFd)	0.808**	$SRd = 1.31\exp(0.0856TFd)$	2	16
	− 5 cm (TSd)	0.707**	$SRd = 1.01\exp(0.0946TSd)$	3	15
Soil moisture (%)	Mass basis (Wm)[1]	0.452*	$SRd = 26.5 - 0.355Wm$	4	16
	Volumetric (Wv)[2]	0.692**	$SRd = 23.5 - 0.425Wv$	5	16
Temperature (°C), soil moisture (%)	(TFd, Wv)[2]	0.925**	$SRd = 7.30\exp(0.035TFd) - 0.196Wv$	6	12
Winter cropping period					
Temperature (°C)	+ 5 cm (TAd)	0.850**	$SRd = 0.937\exp(0.117TAd)$	7	12
	0 cm (TFd)	0.854**	$SRd = 0.965\exp(0.120TFd)$	8	12
	− 5 cm (TSd)	0.852**	$SRd = 0.948\exp(0.126TSd)$	9	12
Soil moisture (%)	Mass basis (Wm)	NS	–		
	Volumetric (Wv)	NS	–		
Temperature (°C) soil moisture (%)	(TFd, Wv)	NS	–		

NS, *and **denote not significant, significant at $P < 0.01$ and at $P<0.001$, respectively.

[1] available range of Wm is approximately 30–60%, [2] available range of Wv approximately 20–40%.

Carbon dynamics and budgets in upland and paddy agricultural ecosystems in Japan

1. Subject

Losses of soil C as a consequence of cultivation are ubiquitous and well documented (Mann, 1986; Davidson and Ackerman, 1993). Historical losses of C observed in many soils were due in part to the low production levels, erosion, inadequate fertilization, removal of crop residues and intensive tillage. Improved management is capable of increasing C levels on existing agricultural soils and reducing decrease on newly cultivated soils. In general, management directed to achieve high residue production, the use of perennial forage crops, elimination of bare fallow periods and reduced tillage will promote C sequestration in soil. Thus, increasing soil C in existing arable soils is a potential CO_2 mitigation option. Emphasis in the present study will be given to clarify carbon balance (budgets) in prevailing different agricultural systems and to quantifying these mitigation potentials.

2. Materials and Methods

The experiments were carried out in upland single- and double-cropping fields and paddy single-cropping fields in central Japan, between May 1991 and April 1997. Carbon fixed by crops was estimated from NPP of each crop measured by the harvest methods and carbon content of each crop measured by CN analyzer. Dark respiration of crops and soil respiration was measured by the open-flow chamber methods using IRGA. Each measurements were carried out at intervals of 2~4weeks.

3. Results and Discussion

Figure 3 represents the carbon dynamics in upland agro-ecosystems. The upper compartment of the diagram represents the carbon fixed by the crops in the upland agro-ecosystem, and the lower compartment represents the storage of carbon in the soil. The absorption through photosynthesis of carbon dioxide in the atmosphere is the gross production. Some of the carbon produced during gross primary production is used by plants for respiration. The gross primary product minus the carbon respired is the net primary product. The net product is, however, further converted into other trophic levels, such as predators and decomposers. The carbon balance of the soil relates the inputs, consisting of various organic materials, such as litter, stubble and roots of crops, and stable manure, to the output of respiration caused by the decomposition of organic matter in the soil. On the other hand, for the paddy ecosystems (Fig. 4), there is another compartment which represents flooding water. The carbon balance of the flooding water relates the inflow from reservoir and rain, to the outflow to reservoir and the penetration to underground water.

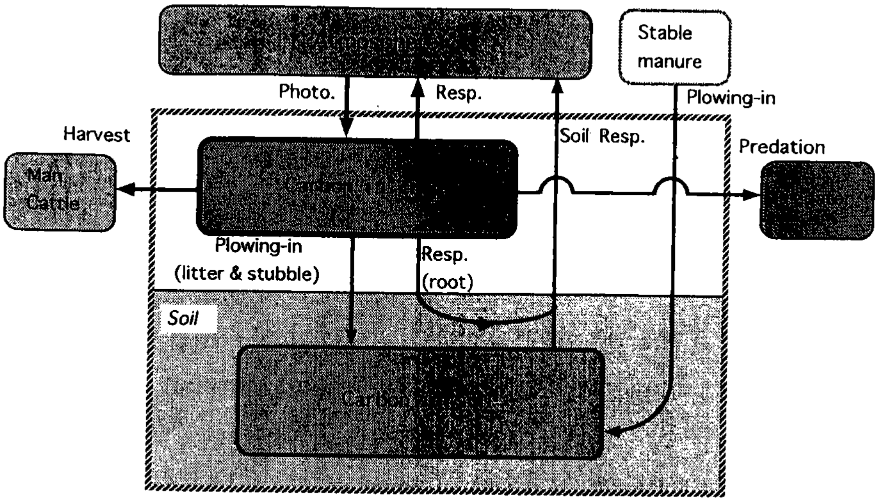

Fig. 3. **Diagram of carbon dynamics in upland crop fields.**

The annual average amount of carbon fixed by the crops (Table 2) were 260~380 gCm^{-2}, 610~790 gCm^{-2} and 750 gCm^{-2} for upland single-cropping systems, upland double-cropping systems and paddy rice system, respectively. The losses by the crop respiration were 180~310 gCm^{-2}, 580~620 gCm^{-2} and 620 gCm^{-2} for upland single- cropping systems, upland double-cropping systems and paddy rice system, respectively.

The amount of carbon supplied to the soil as organic matter (Table 2) was 140~210 gCm^{-2}

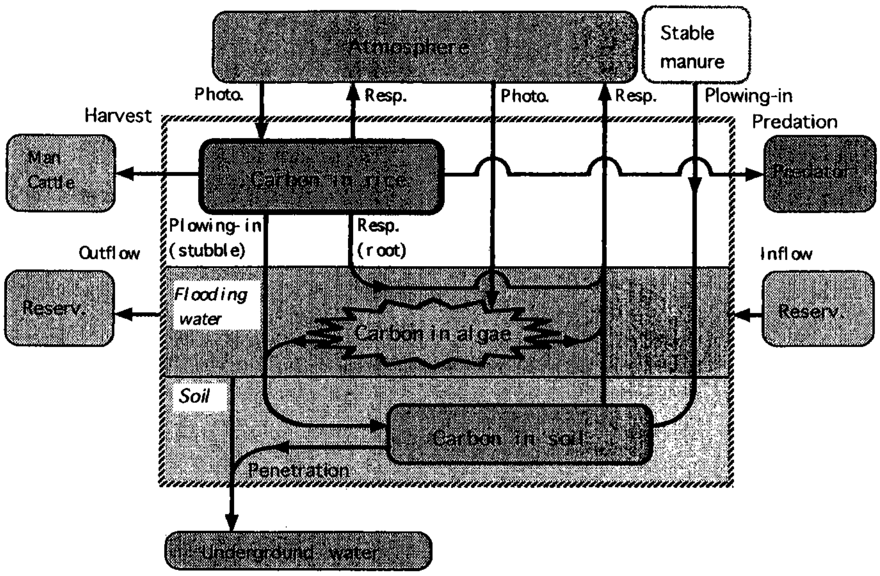

Fig. 4. **Diagram of carbon dynamics in puddy fields.**

for upland single-cropping systems, 330~410 gCm^{-2} for upland double-cropping systems and 210 gCm^{-2} for paddy rice system, respectively. Moreover, for the paddy rice, the amount of 26 gCm^{-2} was supplied as organic carbon fixed by algae in flooding water. However, the amount of carbon by the decomposition of organic carbon in the soil was 460~480 gCm^{-2}, 550~600 gCm^{-2} and 240 gCm^{-2} for upland single- cropping, double-cropping and paddy rice system, respectively. And in the flooding water for the paddy rice field, inflow carbon referred to 33 gCm^{-2}, outflow 23 gCm^{-2} and penetration to underground water was estimated at 26 gCm^{-2}, respectively.

Therefore, the annual carbon balance (Table 2) was estimated to be -270~-320 gCm^{-2} for the upland single-cropping field, -160~-270 gCm^{-2} for the upland double-cropping field, and only -20 gCm^{-2} for the paddy rice single-cropping field, respectively. Comparing the carbon balance between the upland single- and double-cropping field and the paddy field, the carbon losses were largest in the upland single-cropping systems, and the losses were larger in double-cropping systems than the paddy rice system. Especially, the carbon balance for the paddy-system was in good agreement, sometimes resulting in a positive increase in carbon. This is caused by a decrease in the heterotrophic respiration in the soil deoxidized under the flooding water and carbon fixation by photosynthesis of algae.

For the upland crop field, the carbon supplied as crop residue and manuring evidently fails to compensate the carbon loss by respiration of heterotrophs in the soil, and the agricultural systems are in a process of degradation. Some of the carbon that has been stored in the soil is consumed every year, and this consumption amount to about 300 gCm^{-2}. In order to maintain soil organic matter at present levels, crop residues of about 750 g dry wt. m^{-2} would have to

Table 2 Annual carbon storage and budgets (gC m^{-2}, mean ± S.D.) of each compartment in each cropping system

	Upland crop fields						Paddy field
	Single-cropping			Double-cropping			Single-cropping
	Upland rice	Maize	Soybean	Upland rice-Barley	Peanut-Wheat	Maize-Barley	Paddy rice
I. Carbon in crops							
(a) Fixed as gross production	436.1±123.6	548.1±150.2	635.9	1257.5±10.6	1187.7±298.1	1396.6±149.0	1372.4±216.0
(b) Fixed as net production	259.1±18.1	381.7±102.2	330.7	641.8±73.0	609.2±111.4	789.1±39.0	749.8±74.7
(i) Removed by harvest	114.8±8.2	179.9±48.3	120.7	310.3±35.3	238.7±43.6	380.6±18.8	543.4±27.1
(ii) Supplied to soil	144.3±10.3	201.8±54.2	210.1	331.5±46.6	370.5±81.4	408.5±15.1	206.4±47.7
(iii) Removed by predation	nil	nil	nil	nil	nil	nil	nil
(c) Respired by crops	177.0±12.1	166.5±48.1	305.2	615.8±62.4	578.5±209.9	607.5±110.0	622.7±141.3
II. Carbon in algae							
(a) Fixed as gross production	0	0	0	0	0	0	36.8±30.9
(b) Fixed as net production	0	0	0	0	0	0	25.7±21.6
(c) Respired by algae	0	0	0	0	0	0	11.1±4.7
III. Carbon in soil							
(a) Supplied as manure	0	0	0	0	0	0	0
(b)Supplied as crop residues	144.3±10.3	201.8±54.2	210.0	331.5±46.6	370.5±81.4	408.5±15.1	206.4±23.1
(c) Supplied as algae dead parts	0	0	0	0	0	0	25.7±21.6
(d) Respired by heterotrophs	459.9±16.2	468.7±15.1	478.9	598.6±24.1	554.1±1.5	568.4±17.3	238.2±13.4
IV. Carbon in flooding water							
(a) Inflow from reservior and rain	1.3±0.2	1.3±0.2	1.3+0.2	1.5±0.3	1.5±0.3	1.5±0.3	34.0±5.3
(b) Outflow to reservior	0	0	0	0	0	0	23.1±5.2
(c) Penetration to underground water	nil	nil	nil	nil	nil	nil	25.8±0.8
V. Balance in agro-ecosystems	-314.3±5.9	-265.6±69.3	-267.6	-265.6±22.5	-182.2±82.8	-158.4±32.4	-21.0±17.6

Each value is the average for 3 years.

be supplied to the soil, assuming the carbon contents of the residues is 40%.

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