Sediment Discharge from a Ridged Field with an Andisol

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Abstract: Soil erosion in ridged field plots with Kuroboku soil, an Andisol, was observed between May and October for 3 years at a cropland site in northwest Kanto, Japan. The amount of sediment yield from the plot planted with cabbage was much less than that from the bare plot. The observed results suggest that the rates of ridge erosion, detachment, and transport of soil particles due to surface runoff in the furrow channels of the planted plot were less than those of the bare plot. Soil erosion on the bare plot during most events was a transport-limited process. The Yang sediment transport equation effectively estimated the sediment yield from the bare ridged plot with Kuroboku soil when a transport-limited process was considered to be dominant. The equation is likely to be suitable to estimate the sediment transport capacity of furrow channel flow for the study soil. The equation overestimated the sediment yield for the planted plot. To estimate sediment yield for the planted ridged field in the study site, soil erosion prediction models including a routine taking into account the soil detachment rate and sediment transport capacity of furrow channel flow are needed.

Keywords: erosion, sediment, ridged field, Andisol

1 Introduction

Soil erosion by water is a frequent problem in agricultural fields in northwest Kanto, Japan. The region is an agricultural area where cabbage and other vegetables are produced under cool summertime conditions. The site is in a mountainous area, with elevations ranging from 700 to 1,400 m and rolling topography. The dominant soil in the region is Kuroboku soil, an Andisol. The soil is a volcanic ash soil with an organic matter content of 10% or more, low in bulk density, and easily erodible. Heavy rains in the rainy season, showers in the summer, and typhoon rains in the autumn cause soil erosion. This erosion results in a loss of topsoil, and the suspended load in streams resulting from the erosion may damage downstream water quality. The planning and design of erosion control measures require quantitative information on sediment yield from fields.

Soil erosion models based on hydrological and erosion processes (Nearing et. al, 1989; Morgan, 1994) are valuable tools for estimating sediment yield from cropland fields for the planning and design of erosion control measures. Recently, Nakao *et al.* (1996) and Takagi *et al.* (2001) assessed the efficacy of soil erosion models on a field scale in Japan. However, few studies have been conducted to estimate soil erosion or to obtain sediment yield characteristics on cropland fields in this region with Kuroboku soil by using such models.

The objective of this study was to clarify the fundamental characteristics of soil erosion on a cropland field in this region through field plot observation and to discuss the applicability of the Yang sediment transport equation (Yang, 1973) for estimating sediment yield. The results of this study will make it possible to develop a method for sediment yield prediction for cropland fields with Kuroboku soil.

2 Observations and methods

2.1 Observations at field plots

Field plot observations were conducted between May and October each year from 1998 to 2000. The study site was a cropland field with Kuroboku soil, described above, in northwestern Kanto, Japan. Two plots, 29 m long, 1.3 m—1.8 m wide, 8% slope, were laid out with the long side parallel to the direction of the slope. The plots were plowed each May to create ridges and furrows parallel to the slope. The width of one ridge and the adjacent furrow was 0.46 m. One plot was bare throughout the observation periods, and the other was planted with cabbage, the dominant crop in this region. The cabbage was planted in the middle of May and harvested in the middle of August. The residue was left until the end of each observation period.

Rainfall, surface runoff, sediment yield from the plots, crop cover ratios in the planted plot, and cross sections of the bare plot were observed during each period. Rainfall was measured with a rain gauge. Runoff at the lower end of each plot was measured with Parshall flumes during each rainfall event. Sediment was collected in sediment tanks at the downslope end of the plots at intervals of about 2 weeks, and sediment yield was determined as the dry mass of the sediment. Cross sections of the bare plot were measured 2 or 3 times during each observation period.

2.2 Method for calculating sediment yield

When erosion of a field is assumed to be transport limited, sediment yield from the field can be estimated by using the concept of sediment transport capacity. The sediment transport capacity of the water flow at a given point equals the maximum sediment concentration that the flow can carry. The Yang sediment transport equation (Yang, 1973) was used to calculate sediment yield due to furrow channel flow in this study. This equation is as follows:

$$\begin{aligned}\log C_t &= 5.435 - 0.286 \log(\omega d/\nu) - 0.457 \log(U_*/\omega) \\ &\quad + \{1.799 - 0.409 \log(\omega d/\nu) - 0.314 \log(U_*/\omega)\} \log\{(P - P_{cr})/\omega\}\end{aligned} \tag{1}$$

where C_t is sediment concentration in ppm by weight, P (= VS_f) is the unit stream power, P_{cr} is the critical unit stream power for incipient motion, ω is the terminal fall velocity in water of the sediment median particle diameter, d is the median particle diameter of sediment, ν is the kinematic viscosity of water, $U_* = (gRS_f)^{1/2}$ is the share velocity, V is the velocity of flow, S_f is the energy gradient, g is gravity acceleration, and R is the hydraulic radius.

Sediment yield SY_c, dry mass of sediment, for each period when sediment was collected was calculated by using equation (1), and the result was compared to the corresponding observed sediment yield. SY_c was calculated as follows:

$$SY_c = \int NC_tQ\ \rho\, \mathrm{d}t \tag{2}$$

where N is the number of furrows in the observation plot, Q is the runoff rate at the end of a furrow channel, ρ is the density of water, and t is time. The unit stream power P in equation (1) was calculated according to a method similar to that of Moore and Burch (1986). When quasi-steady shallow flow in a rectangular channel is assumed, R and S_f can be approximated by the depth of water flow in the furrow channel h and the slope of the soil surface S, respectively. Average flow velocity V and runoff rate Q at the end of each furrow channel were calculated by following respective equations.

$$V = (1/n)\, h^{2/3}\, S^{1/2}, \tag{3}$$

$$Q = Vhb = (1/n)\, h^{5/3}\, S^{1/2}\, b \tag{4}$$

where n is Manning's roughness coefficient, and b is the width of the furrow channel. Using equation (4), the unit stream power for water flow at the end of a furrow channel is

$$P = VS = (Q/b)^{2/5}\, (1/n)^{3/5}\, S^{13/10} \tag{5}$$

Other parameters for the calculation are shown in Table 1.

Table 1 Parameter values used in the calculation

Parameter	Value	Source
P_{cr}	$0.002\text{m} \cdot \text{s}^{-1}$	Assumed
ω	$0.042\text{m} \cdot \text{s}^{-1}$	calculated by rubey's equation
ρ_s	$1.85\text{g} \cdot \text{cm}^{-3}$	measured as wet bulk density of aggregates
d	0.50mm	measured as aggregates
v	$1.0 \times 10^{-6}\text{m}^2 \cdot \text{s}^{-1}$	kinematic viscosity of water
b	0.10m	measured
S	0.083	measured
n	0.025	assumed

3 Results and discussion

3.1 Observation results

A summary of the observation results for rainfall, runoff, and sediment yield is shown in Table 2. The total amount of rainfall during the observation periods ranged from 664 mm to 889 mm. The total amount of runoff ranged from 141 to 200 mm for the bare plot and from 50 to 116 mm for the planted plot. Total sediment yield was between 2.18 and 5.50 $\text{kg} \cdot \text{m}^{-2}$ for the bare and between 0.03 and 0.76 $\text{kg} \cdot \text{m}^{-2}$ for the planted plot. The crop cover ratio in the planted plot increased after planting, became full (= 100%) in the beginning of July, and decreased from the beginning of September of each observation period.

Table 2 Observation results for rainfall, runoff and sediment yield

Observation period	Rainfall (mm)	Runoff(mm)		Soil loss($\text{kg} \cdot \text{m}^{-2}$)	
		Bare plot	Planted plot	Bare plot	Planted plot
1998.5.18—10.13	888.7	170.0	66.6	2.18	0.03
1996.6.10—10.12	884.9	199.7	116.4	3.77	0.76
2000.6.14—10.4	663.7	141.1	50.3	5.50	0.40

Differences in runoff amounts for the bare and planted plots were large. The average runoff coefficient for the three observation periods was 0.21 for the bare plot and 0.09 for the planted plot. Fig. 1 shows the relationship between the amount of rainfall and runoff for each rainfall event for each plot. Little surface runoff occurred until the accumulated rainfall exceeded 20 mm or 30 mm in the bare plot and 50 mm in the planted plot. Amounts of runoff from the bare plot were larger than those from the planted plot for most events. Moreover, certain hydrographs showed that the runoff rate at the lower end of the planted plot was less than that for the bare plot while the surface runoff continued in each plot. These results suggest that initial abstraction was large in the planted plot compared with the bare plot and that the runoff rate in the planted plot was smaller than that in the bare plot.

Average sediment yield for the three observation periods was 3.82 and 0.45 $\text{kg} \cdot \text{m}^{-2}$ for the bare plot and for the planted plot, respectively. The soil erosion process in both ridge and furrow areas was considered to affect the observation results. In a ridged field, the ridge erosion rate, expressing the transport rate of eroded material from the ridge to the furrow, on a planted ridge is less than that from a bare ridge (Shiono *et al.*, 1999). In a furrow, surface water flow detaches soil particles from the soil surface and transports them from the ridge and the surface of the furrow downslope. Past research has shown that both the detachment and transport rates of soil particles due to surface water flow increase with the flow rate (Morgan, 1995). Consequently, the amount of eroded material reaching the lower end of the planted plot should be less in comparison with the bare plot.

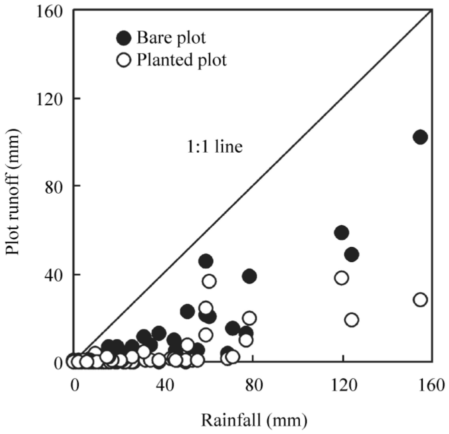

Fig.1 Relationship between amount of rainfall and plot runoff in each rainfall event

3.2 Soil erosion process

Fig. 2 compares cross-section profiles for May 22 and September 14, 2000, at 3.5 m, 12 m, and 23 m above the lower end of the bare plot. The height of the ridge at each distance decreased similarly. This indicates that ridge erosion by rain splash detached surface soil at each distance. However, the change in the height of the furrow at each distance was different. The bed of the furrow was raised at 23 m above the lower end of the plot, but it was lowered at 12 m and 3.5 m, although by only a little in the latter case. This finding implies that a process in which the eroded sediment from the ridge was deposited in the bed of furrow was dominant upstream, that one where detached sediment from the ridge and bed of the furrow was transported downstream was dominant in the middle stream, and that further downstream the sediment concentration in the surface flow was almost the same as the sediment transport capacity of the water flow. Moreover, deposition in the furrows near the lower end of the bare plot was observed for most soil erosion events. This finding is consistent with the above consideration. Thus, soil erosion from the bare plot was considered to be a dominantly transport-limited process.

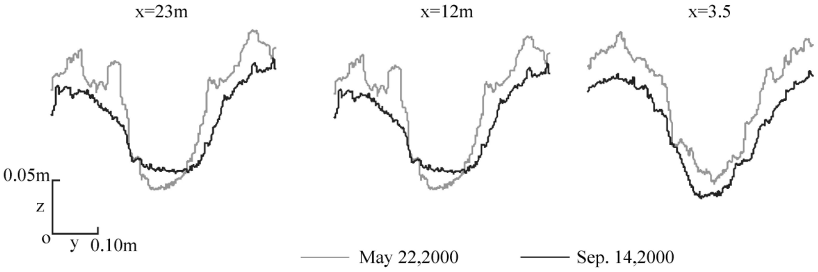

Fig.2 Cross-section profiles at 3.5, 12, and 23 m above the lower end of the bare plot

3.3 Calculation results of sediment yield

Calculated sediment yield per unit width versus observed sediment yield is presented in Fig. 3. Data for events when deposition in the furrow near the lower end of the bare plot was observed were used for this calculation. The calculated values for the bare plot agree fairly well with the observed values. The calculation method using the Yang equation can thus effectively estimate sediment yield from a bare ridged field with Kuroboku soil when a transport-limited process is dominant. Therefore, the Yang equation is likely to be suitable for the estimation of the sediment transport capacity of furrow channel flow for the study soil. Moore and Burch (1986) showed that the Yang equation could be used without calibration to estimate sediment transport capacity for upland erosion with slopes up to 12.1% and particles consisting of aggregated soils. The equation was also employed to express the sediment transport capacity of rill flow in a soil erosion simulation (Takagi et. al, 2001). These studies support the findings of the present study.

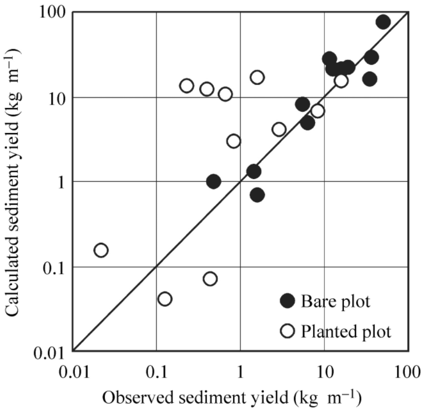

Fig.3 Calculated versus observed sediment yield per unit width for each plot

As shown in Fig. 3, the calculated sediment yield values for the planted plot exceeded the observed values. Assuming that the Yang equation estimates exactly the sediment transport capacity, we propose that a detachment-limited erosion process was dominant for each event in the case of the planted plot. This view is supported by the observation that deposition in the furrows near the lower end of the planted plot, in contrast to the bare plot, was seldom seen. To estimate sediment yield for planted ridged fields, soil erosion prediction models should include a routine that takes into account the soil detachment rate and the sediment transport capacity of furrow channel flow (Lu *et al.*, 1987; Wu and Meyer, 1989; Nakao *et al.*, 1996).

4 Conclusions

Sediment yield for the plot with ridge-and-furrow treatment and planted with cabbage was obviously less than that for a bare plot similarly treated. The observed results suggest that the rates of ridge erosion, detachment, and transport of soil particles by surface runoff in the furrow channel of the planted plot were less than those of the bare plot.

The Yang sediment transport equation effectively estimated sediment yield from the bare ridged plot with Kuroboku soil, when a transport-limited process was considered to be dominant. The equation is likely to be suitable for estimating the sediment transport capacity of furrow channel flow for the study soil.

To estimate sediment yield for the planted ridged field of the study site, soil erosion prediction models that include a routine that takes into account the soil detachment rate and the sediment transport capacity of furrow channel flow are needed.

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