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Historical Changes of Sediment Accumulation in Lake Shirarutoro Due to Land Use Development in the Forest Catchment, Kushiro Mire in Northern Japan

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Eleven lake sediment core samples were obtained and analyzed to develop a chronology using ^{137}Cs (in 1963) and two tephra layers (Ko-c2 in 1694 and Ta-a in 1739). Sedimentation rates estimated for the past *ca* 300 years in Lake Shirarutoro indicated that catchment development has influenced the shallowing process in the lake by increasing sediment production. The sediment yield under initial land-use development conditions for the first two periods was estimated as 514 tons yr^{-1} from 1694 to 1739 and 542 tons yr^{-1} from 1739～1963. The development of the Shirarutoro catchment intensified in the 1960s with deforestation and agriculture activity leading to an increased sediment yield of 1261 tons yr^{-1} after 1963. The sediment yields after intensified land use development, such as forestry and agricultural development, were about 2 times higher than that under initial development conditions, leading to accelerated lake shallowing over the last ca 50 years. Sedimentation rates differed with location in the lake because of spatial variation in the sediment flux from the contributing rivers and their catchments. The sedimentation rates before 1963 were low in all sites except for one site close to the Shirarutoroetoro River. The sedimentation rate in 1739～1963 was accumulated mostly at the inflow of the Shirarutoroetoro River by sediment production associated with forestry for charcoal production and initial agricultural development. The sedimentation rate after 1963 increased. In particular, the southern zone of the lake near the conjunction with the Kushiro River had a high sedimentation rate, which is attributable to sediment inflow back from the Kushiro River during floods.

Key words : sediment accumulation, land use, ^{137}Cs dating, tephrochronology, lake shallowing, Kushiro Mire

INTRODUCTION

Lakes and reservoirs provide flood control, navigation, and recreational opportunities. However, large volumes of fine sediment produced by forestry, changes in land use and river channels in a catchment (Slaymaker, 1982; Nakamura *et al.*, 1997, 2004) can lead to shallowing of lakes, loss of a reservoir's capacity, or even fill lakes and reservoirs (Duck and McManus, 1990; Chambers, 1999). Moreover, water can be polluted by nutrients adsorbed by fine sediments (Dillon and Kirchner, 1975; Whigham *et al.*, 1988), and aquatic habitats can deteriorate because fine sediments plug the interstitial spaces of bed materials (Lemly, 1982; Yamada and Nakamura, 2002). Under these conditions, the ecological viability of lakes

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and reservoirs is vastly reduced and their economic value to a region can be almost completely lost (Hitzhusen *et al.*, 1995; Palmieri *et al.*, 2001). In order to prevent further degradation of lake environments and the local economy, it is very important to understand the effect of land use change on lake sedimentation.

Fine sediment can be deposited in lakes and wetlands without mixing with bed materials (Nakamura *et al.*, 1997, 2004). Because fine sediment such as wash load is transported in suspension, it reflects various erosion processes in the catchment that can change greatly with land use development. Fine sediments are produced from the catchment and can accumulate in geomorphic storages such as lakes and marshes. The sedimentary record preserved under depositional environments, such as lakes, reservoirs, and river floodplains, is a valuable basis for reconstructing a longer-term sediment response (Page *et al.*, 1994; Walling *et al.*, 1998, 2003; Owens *et al.*, 1999; Ahn *et al.*, 2006). The use of lake sediment cores to investigate changes in sedimentation rates associated with land use alteration in catchments is well established over a range of different time scales.

The Kushiro Mire, the largest wetland in Japan, embraces a diversity of wetland habitats for many types of wildlife. It was designated a national park in 1987. However, excessive production and subsequent influx of fine sediment, in association with agricultural development, channel projects, and the resultant extensive colonization of alder forests, are the most serious environmental problems that the Kushiro Mire faces (Nakamura *et al.*, 2002, 2004). There are three lakes on the eastern side of the mire, and recently all of them have suffered from accelerated sedimentation and a decline in water quality due to the flooding of nutrient-rich turbid water into the lakes (Takamura *et al.*, 2003; Ahn *et al.*, 2008). Lake Shirarutoro drains water from the Shirarutoroetoro River and other small tributaries and flows into the Kushiro River; however, at very high water levels, water from the Kushiro River frequently flows back into Lake Shirarutoro. Therefore, Lake Shirarutoro is influenced by the inflow from its catchment as well as from the Kushiro River.

This study was undertaken at Lake Shirarutoro in the Kushiro Mire to clarify history of lake sedimentation using ^{137}Cs and tephrochronology. First, I reconstructed the sediment yields at Lake Shirarutoro over the last *ca* 300 years and clarified the influence of land use change on the sediment yields. Second, I investigated spatial and temporal variability of sedimentation rate in the lake with reference to land use alteration in contributing catchments. In addition, I estimated the shallowing of Lake Shirarutoro by the sedimentation rates of initial and intensified development conditions.

MATERIALS AND METHODS

The Kushiro Mire (194 km^2) lies in eastern Hokkaido, northern Japan, and drains into the Kushiro River. The Kushiro district is in the Pacific coast climate zone, with an annual mean air temperature of 6.0°C during 1971 to 2006 (Japan Meteorological Agency, 2007). The annual mean precipitation is 1037 mm, with a range of 705～1,378 mm. Lake Shirarutoro is a small lake with an area of 1.8 km^2 and drains a 66.8 km^2 catchment into the Kushiro River at the eastern margin of the Kushiro Mire (Fig. 1 and Table 1). The maximum water depth measured in this investigation was 3.0 m.

To evaluate sedimentation rates in Lake Shirarutoro, sediment cores were collected from 11 points in 2007 (Fig. 1). Core samples were extracted using 7.2 cm diameter polyvinyl chroride tube. All core samples were dissected into 1 cm-thick slices and were preserved in a sealed container at −10°C. Dry bulk density was calculated after drying for 24 h at 105°C.

The most distinctive and widespread tephras over the study areas were Komagatake-c2 tephra (Ko-c2, 1694 AD) and Tarumae-a tephra (Ta-a, 1739 AD). All core samples in Lake Shirarutoro contained two tephra layers. Tephra is fragmental material produced by a volcanic eruption. The use of tephra layers, which bear their own unique chemistry and character, as temporal marker horizons in archaeological and geological sites is known as tephrochronology. Ahn *et al.* (2006) identified two tephra layers from Lake Takkobu in the Kushiro Mire using the refractive indices of tephra glasses. The lower tephra layer was identified as Ko-c2 (1694) and the upper tephra layer as Ta-a (1739). The dry bulk density of the tephra sediment in Lake Takkobu was high compared with that of the fluvial sediment transported from the catchment (Ahn *et al.*, 2006). To

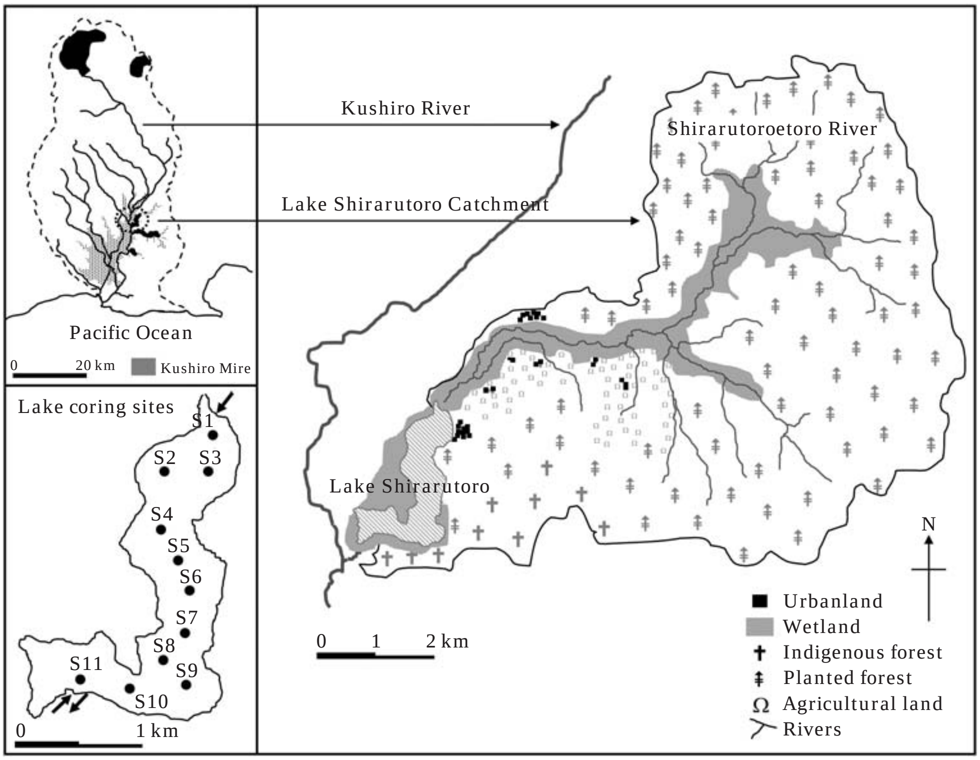

Fig. 1. Location of Lake Shirarutoro and the lake coring sites.

Table 1. Site characteristics of Lake Shirarutoro.

Elevation (m)	8.0	Transparency (m)	>1.5
Lake area (km^2)	1.8	pH	7.0
Water volume (m^3)	3.3×10^6	Total nitrogen (mg L^{-1})	0.42
Maximum water depth (m)	3.0	Total phosphorus (mg L^{-1})	0.073
Average water depth (m)	1.9	Chl-*a* (μg L^{-1})	8.7
Catchment area (km^2)	66.8		
Water retention time (days)	18		

remove the effects of possible sediment compaction on the dry bulk density distributions during sampling, cumulative dry mass depth was used.

^{137}Cs (half-life 30 years) is an artificially created radionuclide which was released by a series of atmospheric nuclear tests during the mid-twentieth century. Atmospheric deposition of ^{137}Cs first began in 1954, with one peak in fallout occurring in 1963. The sediment-associated ^{137}Cs represents radiocaesium originating as fallout over the surface of the upstream catchment, which has been adsorbed by sediment particles and subsequently mobilized by erosion and transported downstream as part of the fine sediment load of the rivers. This fine sediment load and its associated ^{137}Cs will be deposited in the lake during flooding events. The ^{137}Cs peak concentration profile in the lake was found in the 1963 surface (He *et al.*, 1996; Walling *et al.*, 2003; Ahn *et al.*, 2006; Mizugaki *et al.*, 2006). ^{137}Cs concentrations in sediment have been measured by a number of researchers to estimate the sedimentation rates which have occurred in the past 40 years (He *et al.*, 1996; Walling *et al.*, 2003; Ahn *et al.*, 2006; 2009: in press). The ^{137}Cs content of the cores were measured over 2～3 cm intervals. ^{137}Cs concentrations were assayed by gamma spectrometry at 662 keV using HPGe detectors coupled to a multichannel analyzer. The average sedimentation rate was calculated using the chronological dates as follows:

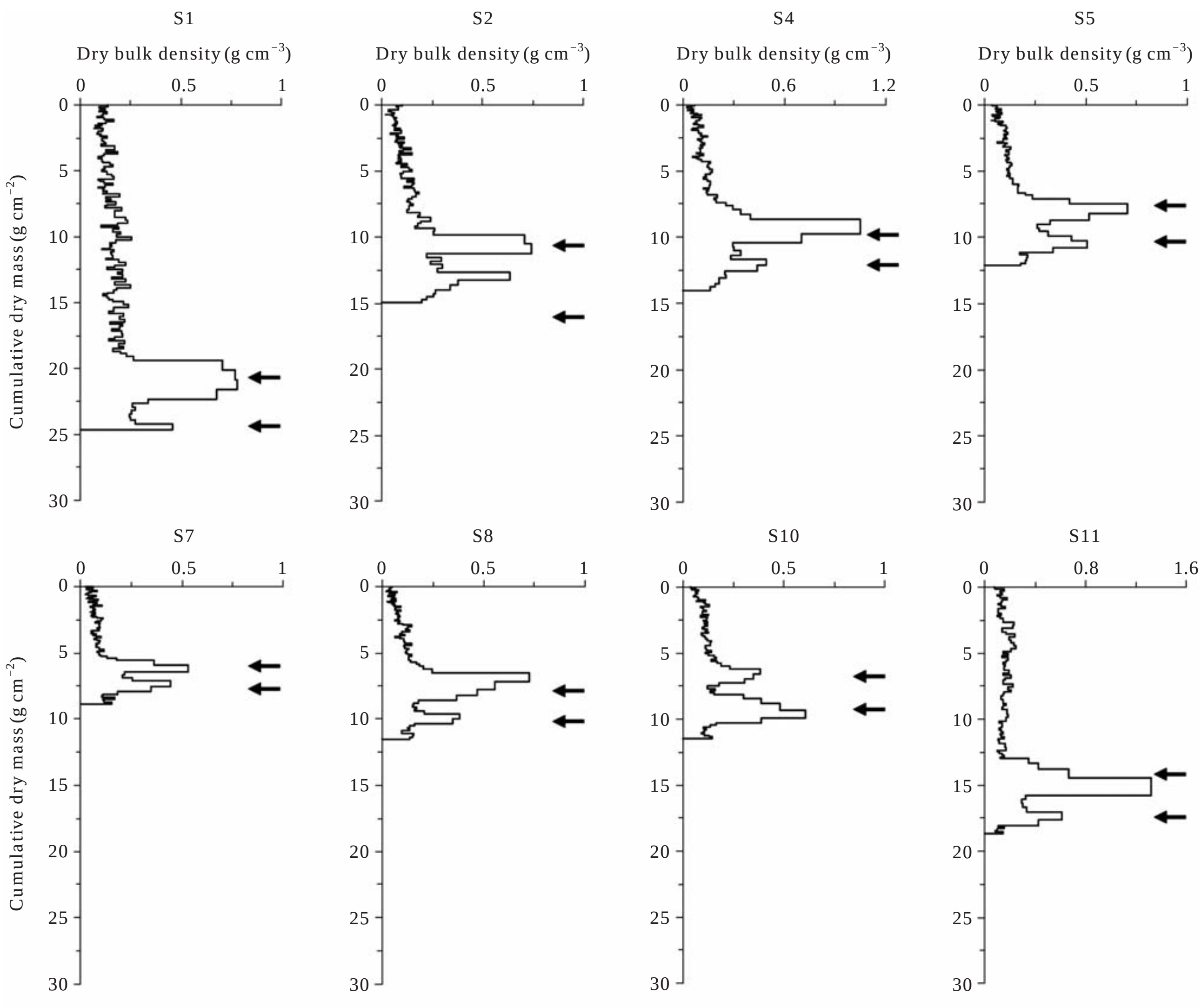

Fig. 2. Dry bulk density of the lake sediment. The arrow denotes a tephta.

$$SR_i = \frac{D_i}{T_i}$$

where SR_i is the average sedimentation rate, D_i is the depth between markers, and T_i is the chronological time interval. To calculate the sediment yield, the lake was divided into polygons using the Thiessen method, with each coring point located in the center of each polygon (Ahn *et al.*, 2006). The sediment yield was estimated by multiplying the polygon area represented by each coring point with the average rate of sedimentation at that point.

The years of shallowing (SY) were estimated using the following formula:

$$SY_i = \frac{WD_i}{SR_i}$$

where WD_i is the water depth at each coring site and SR_i is the sedimentation rate from 1694～1963 and 1963～2007 at each coring site.

RESULTS

1. The distribution of dry bulk density of the lake sediments

The cumulative dry mass in the lake sediment profiles varied from 8.9 to 24.7 g cm^{-2} (Fig. 2). Two tephra layers were identified in all the profiles (Table 2) and they showed a unique whitegray color unlike the lake sediment. The tephra layers were synchronous with a high dry bulk density (Fig. 2). Point S1, located near the inflow of the Shirarutoroetoro River, exhibited the tephra layers at its deepest layers, followed by Point S11 located near the inflow of the Kushiro River (Table 2). In contrast, the shallowest tephra layers were found at Point S7 in the middle zone with the pronounced dry bulk density peaks at a depth of 5.5～6.4 g cm^{-2} and 7.1～7.9 g cm^{-2}, respectively.

Table 2. Cumulative dry mass depth of the ^{137}Cs peak and tephra.

Core point	^{137}Cs (g cm^{-2})	Tephra (g cm^{-2})	
	^{137}Cs peak	Ta-a	Ko-c2
S1	1.0～1.4	19.4～22.3	24.2～24.7
S2	3.8～4.0	9.8～11.3	12.6～13.3
S3	2.0～2.2	11.5～12.3	14.3～15.0
S4	2.5～2.7	8.7～10.4	11.7～12.6
S5	1.1～1.2	7.1～8.9	9.9～11.2
S6	1.9～2.1	8.8～10.4	12.1～14.7
S7	1.7～1.9	5.5～6.4	7.1～7.9
S8	1.9～2.1	6.5～8.6	9.6～10.3
S9	1.4～1.6	6.7～8.6	8.1～10.5
S10	2.3～2.5	6.2～7.3	8.1～10.3
S11	6.5～7.0	13.0～15.7	17.0～18.1

2. ^{137}Cs dating

A clear peak in the ^{137}Cs concentration was detected at all the sampling points as the sediment surface from 1963 (Fig. 3). The peak ^{137}Cs concentration ranged from 0.029 Bq g^{-1} at Point S10 to 0.120 Bq g^{-1} at Point S7, which was substantially higher than the ^{137}Cs concentrations of their surface sediments (Fig. 3). I assumed the highest peak concentration in a profile to be the

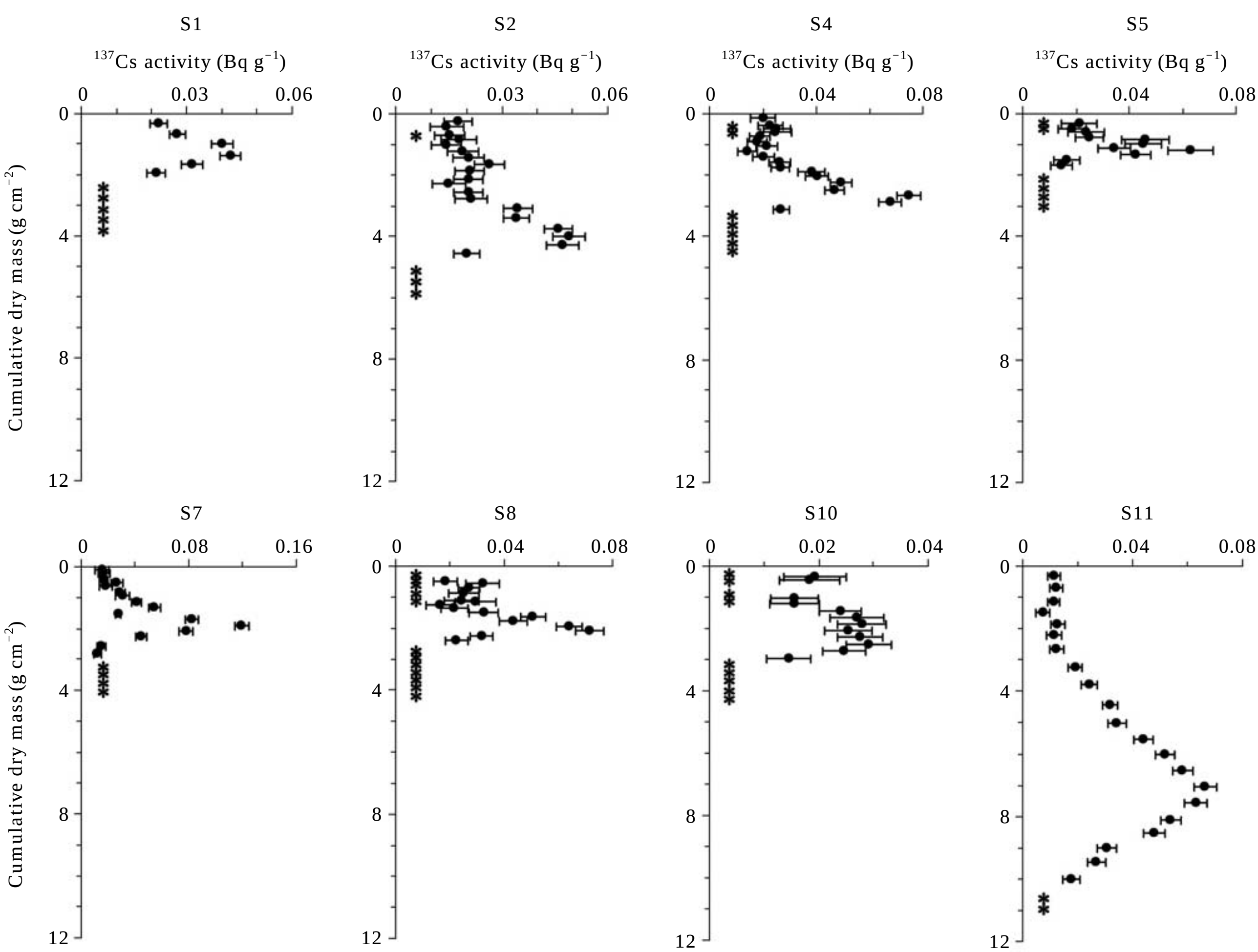

Fig. 3. Profiles of ^{137}Cs concentration in the lake sediment. Asterisk indicates that the ^{137}Cs concentrations are under the detection limit.

Table 3. The average sedimentation rates of Lake Shirarutoro between 1694 and 2007.

Core point	Average sedimentation rate (g cm^{-1} yr^{-1})		
	1694～1739	1739～1963	1963～2007
S1	0.042	0.080	0.031
S2	0.030	0.026	0.091
S3	0.044	0.042	0.050
S4	0.027	0.027	0.061
S5	0 026	0 026	0 027
S6	0.036	0.033	0.048
S7	0.015	0.016	0.043
S8	0.023	0.020	0.047
S9	0.024	0.023	0.036
S10	0.019	0.017	0.057
S11	0.028	0.027	0.160

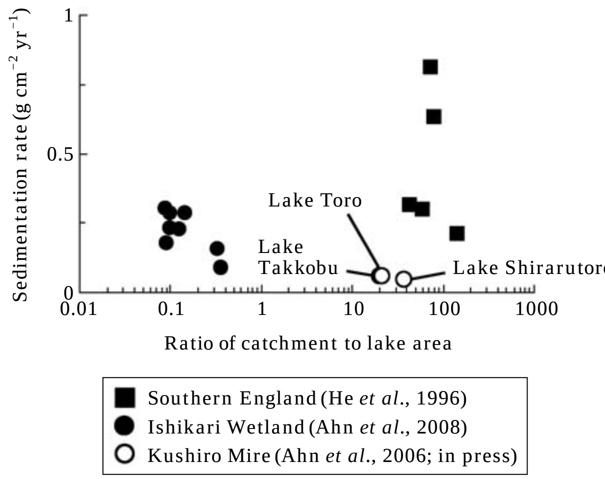

Fig. 4. Sedimentation rate after 1963 and the ratio of catchment to lake area. The sedimentation rates of three lakes in the Kushiro Mire are based on sedimentation rates at the center part in the lakes.

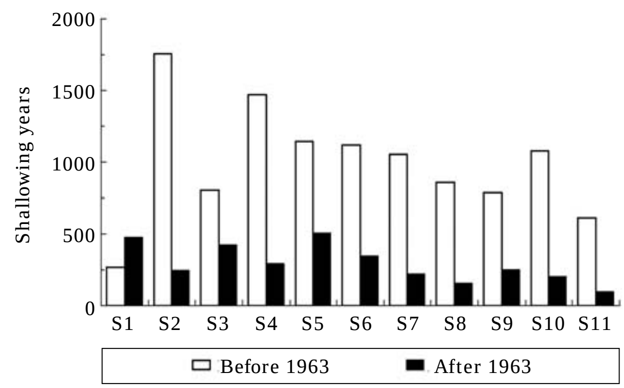

Fig. 5. The estimated fill up periods using the sedimentation rates of 1694～1963 (before 1963) and 1963～2007 (after 1963).

sediment stratum of the 1963 fallout peak (He *et al*., 1996; Walling *et al*., 2003; Ahn *et al*., 2006; Mizugaki *et al*., 2006). The shallowest ^{137}Cs peak among all the samples was observed at Point S5, at a depth of 1.1～1.2 g cm^{-2} (Table 2). Point S11 exhibited a peak concentration within the deepest layer, 6.5～7.0 g cm^{-2}, which was six times deeper than the shallowest peak at Point S5.

The sedimentation rates after 1963 in Lake Shirarutoro varied from 0.031 to 0.160 g cm^{-2} yr^{-1} (Table 3). In comparison with the trend shown by previous studies (Fig. 4), the lakes in Kushiro Mire showed lower sedimentation rates. In particularly, Lake Shirarutoro exhibited low sedimentation rates after 1963 despite a relatively large catchment area.

3. Sedimentation rate

The sedimentation rate over the last 300 years for Lake Shirarutoro was reconstructed for three periods (1694～1739, 1739～1963 and 1963～2007) using tephra and ^{137}Cs as marker layers. The average sedimentation rates before 1963 were relatively low, and sediment transported from the catchment evenly accumulated over the lake bottom, except for Point S1. In contrast, Point S1, situated close to the Shirarutoroetoro River, exhibited high sedimentation rates between 1739～1963. The sedimentation rate after 1963 greatly increased. In particular, the sedimentation rate at inflows from the Kushiro River exhibited high sedimentation rates in this period (Table 3).

The average sediment yield for the first two periods was 514 tons yr^{-1} from 1694 to 1739 and 542 tons yr^{-1} from 1739 to 1963. The development of the Shirarutoro catchment intensified in the 1960s, leading to an increased sediment yield of 1261 tons yr^{-1} (1963～2007). Compared with the sediment yield of 533 tons yr^{-1} prior to 1963, sediment production and delivery accelerated after 1963.

4. Lake shallowing

Lake Shirarutoro exhibited low sedimentation rates after 1963 compared with other lakes (Fig. 4). This may be a result of the limited influence of sediment influx due to the lake being trapped by the surrounding wetlands (Ahn *et al*., 2009) (Fig. 1). However, Lake Shirarutoro, because of its small area and shallow water depth, is significantly influenced by a small sediment influx derived from its catchment (Table 1). In order to examine the effects of catchment land use on lake shallowing in Lake Shirarutoro, I estimated the years of shallowing by sedimentation rates of 1694～1963 and 1963～2007 (Fig. 5). The estimated shallowing at Lake Shirarutoro were 267～1754 years for the sedimentation rates of the period 1694～1963 and 98～506 years for the sedimentation rates of the period 1963～2007 (Fig. 5). The shallowing speed at sampling site close to the inflow of the Kushiro River accelerated by 3～18 times compared with rates before 1963. The high shallowing speed can be attributed to a sediment influx from the Kushiro River.

DISCUSSION

1. Changes in sediment accumulation over the last *ca* 300 years

The average sediment yields from 1694 to 1739 and from 1739 to 1963 reflect partial deforestation and initial agricultural development, whereas that for 1963～2007 is characterized by intensified agricultural development and deforestation, respectively. In the Shirarutoro catchment, the residents used the area for initial crop cultivation and partial deforestation has occurred before 1960s (Kumagai *et al.*, 2008). Farmland development has expanded in the floodplain and hillslope areas at low and intermediate elevations since land consolidation projects in the 1960s. The sediment yield under initial land-use development was 514 tons yr^{-1} in 1694～1739 and 542 tons yr^{-1} in 1739～1963. Deforestation and farmland expansion caused a further increase of up to 1261 tons yr^{-1} in 1963～2007, as indicated by the two-fold increase in sediment yield.

The sedimentation in Lake Shirarutoro varied with historical land use. The sedimentation rates before 1963 were low and showed few differences among the sites, except at the inflow area of Shirarutoroetoro River (Table 3). This spatial pattern reflects initial development conditions with limited activities by residents. Although average sedimentation rates were still low in 1739～1963 (Table 3), the spatial pattern of sediment accumulation had started to change, as indicated by an elevated sedimentation at a major inflow from Shirarutoroetoro River. This concentrated accumulation of sediment may reflect land use changes in this period. The land use development in the Shirarutoroetoro River catchment was initiated from 1880s, and hillslope areas were cultivated for food production in the 1960s. These initial developments may have delivered pulses of sediment into the lake and deposited at the mouths of Shirarutoroetoro River.

The lake sedimentation after 1963 increased (Table 3). Point S11 in the period 1963～2007 had the highest sedimentation rate among all points because of sediment influx from the Kushiro River into the lake during high flow discharges. Development of the Kushiro River catchment began from 1880 to the 1890s with group settlement and river channel excavation (Koaze *et al.*, 2003). In the 1940s, floodplain wetlands in the Kushiro River catchment were developed into cattle farms, and since the 1960s, land consolidation and the introduction of agricultural machinery were promoted (Nakamura *et al.*, 2004). As catchment development proceeds, the lake shallows with increasing sedimentation rates. Also, Point S2, located near the mouth of the Shirarutoroetoro River, exhibited high sedimentation rates because of deforestation as well as rapid expansion of farmlands in floodplains and adjacent hill slopes in the Shirarutoroetoro River catchment. The lake has suffered from sediment loads from the Shirarutoroetoro River and also from the Kushiro River. However, the sedimentation rates in 1963～2007 at Point S1 decreased in comparison with those before 1963, although other sites exhibited increases (Table 3). As a lake becomes shallow, the sediment trap efficiency can be reduced (Lajczak, 1996). These decreases in the sedimentation rates may be explained by steepening of the lake bottom slope with sedimentation and the resultant reduction of sediment retention capacity.

2. The estimation of lake shallowing

Compared with the shallowing of 267～1754 year until 1963 (initial development condition), intensified development accelerated lake shallowing by 98～506 year (Fig. 5). The estimated shallowing of Lake Shirarutoro indicate that catchment development has strongly influenced the shallowing process of the lake by increasing fine sediment production (Table 3). The highest sedimentation rate was after 1963. The shallowing speed after 1963 was about 3 times faster than those of the initial development condition occurring in 1694～1963, suggesting an accelerated sedimentation occurring over the last 50 years.

Point S11, characterized by shallow water depth and high sedimentation rate, will be filled up first compared to all other core sampling sections, in about 100 years using the sedimentation rate between 1963～2007 (Fig. 5). Generally, other sections will be gradually filled up after 300 years, and Lake Shirarutoro will be filled up completely in about 510 years.

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