Effect of deforestation on the transport of particulate organic matter inferred from the geochemical properties of reservoir sediments in the Noto Peninsula, Japan

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The effects of artificial deforestation in the 1970s and the subsequent recovery process on the transport of particulate organic matter were investigated using reservoir sediments obtained from the Noto Peninsula in Japan. In 1975, the sedimentation rate increased to about 2.7 times its previous value because of deforestation and plantation activities in the catchment. The sedimentation rate remained high until 1991, suggesting that the erosion rate of soil and organic matter increased during the 15 years after the deforestation. This intensive erosion was induced by exposure of bare soil, forest management activities to remove understory vegetation, and heavy rainfall. Conversely, the δ13C and δ15N of the sediment organic matter has continued to decrease from the mid-1980s to the present time, despite the fact that the sedimentation rate has recovered to pre-deforestation levels. The decrease of the δ13C and δ15N of the sediment organic matter reflects a decrease in the contribution of soil organic matter, although post-depositional diagenesis and variability of the isotopic composition of the aquatic organic matter also affect the δ13C and δ15N. The decrease in the soil organic matter contribution suggests gradual recovery of vegetation, accumulation of forest floor organic matter, and reduction of soil erodibility. These results indicate that the change in the transport of organic matter continued for at least 35 years after the deforestation and plantation.

Keywords: deforestation, reservoir sediment, particulate organic matter, δ13C, δ15N

INTRODUCTION

Changes in terrestrial environments affect material transport in river catchments. The disturbance of catchment vegetation caused by deforestation, clear-cutting, and tree plantation affects erosion and the transport of soil (Beschta, 1978; Miller, 1984) and particulate organic matter (Bormann et al., 1974; Yanai and Terazawa, 1998). It also affects the chemistry of stream water, such as the amounts of dissolved organic matter and nutrients (Likens et al., 1970; France et al., 2000; Tokuchi and Fukushima, 2009). Changes in the discharge of these materials affect material cycles and biological productivity in downstream and coastal areas. It is therefore important to clarify the long-term effect of changes in catchment vegetation on the transport of organic matter to achieve proper management of river watersheds and coastal zones.

However, long-term records of the transport of organic matter induced by the disturbance of catchment vegetation obtained by real-time field observations over the past several decades are limited, except for some experimental forests (e.g., Bormann et al., 1974; Likens et al., 1978). Hence, we focused on the geochemical records of artificial reservoir sediments in river catchment systems. The geochemical and physical properties of lake and reservoir sediments have been used to reconstruct past environmental changes. Because of their sensitivity, small reservoir catchment systems are especially suitable for use in clarifying responses to artificial and natural envi-
ronmental changes (Shotbolt et al., 2005). The organic geochemical properties of lake sediments, including the total organic carbon (TOC), total nitrogen (TN), and carbon and nitrogen isotope ratios, have been used widely to reconstruct ancient and recent environmental changes (e.g., Meyers and Ishiwatari, 1993; Enters et al., 2006). These parameters are also used as tools for evaluating soil erosion (Meusburger et al., 2013). Forest disturbance is also imprinted in the δ13C and δ15N of lake sediments (Lane et al., 2004; Routh et al., 2007). The physical properties (e.g., grain size, sedimentation rate) of lake and reservoir sediments have been used to assess hydrogeomorphological changes such as precipitation, sediment yield, and land transformation in catchment areas (e.g., Page et al., 1994; Kashiyaya et al., 1997; Lamoureux, 2000; Peng et al., 2005). An artificial reservoir in an intensely disturbed catchment may therefore contain information on the responses to the disturbance.

In Japan, the fuel transition from woody biomass to fossil fuels and the national plantation undertaken based on forestry policies have resulted in catchment vegetation changes since the mid-1950s (Forestry Agency, Japan, 2012). Additionally, the number of artificial forests without sufficient management practices has increased with the recent decrease in agricultural and forestry activities and the aging of the population. An increase in unmanaged artificial forests decreases the understory vegetation and infiltration capacity, thereby promoting overland flow and soil erosion (Yukawa and Onda, 1995; Onda et al., 2005).

Our study area, namely, the Noto Peninsula in central Japan, is a region of progressive catchment vegetation change related to national plantation activities (Ishikawa Prefecture, 2009) and a decrease and aging of the population over the past several decades (Ishikawa Prefecture, 2012). Therefore, the objective of this study was to investigate the reservoir sediments in the Noto Peninsula to determine the effect of artificial deforestation and the subsequent recovery process on the transport of particulate organic matter over the past several decades. The present research may become a test case and its results can be applied to other regions experiencing similar problems.

**STUDY AREA**

Our study area was the river catchment system of the Kumaki and Hiyou rivers, which drain into the Nanao Bay (Fig. 1). This catchment system experienced significant deforestation of broadleaf forests and subsequent cedar plantations during the 1970s. The artificial Bishaguso-ike reservoir used for agricultural irrigation in the Kumaki-Hiyou river catchment system was selected as the study site. The water and catchment areas of the reservoir are about 1,500 m² and 48,800 m², respectively. Because of the relative shallowness of the reservoir (its maximum depth is about 2 m), it contains many submerged and floating aquatic plants. According to the local community that manages the reservoir, dredging of accumulated sediment has not been performed since the reservoir has been in use, and this suggests the preservation of a continuous sediment sequence. However, remarkable vegetation changes have occurred in this catchment. Figure 2 shows aerial photographs and estimated vegetation types in the Bishaguso-ike catchment in 1968, 1975, 1982, and 2006 (Geospatial Information Authority of Japan). The vegetation consisted mostly of broadleaf for-
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ests and paddy field until 1975. However, the 1982 photograph (Fig. 2c) shows that most of the forest had disappeared and that young cedar trees had been planted. This is an indication of the deforestation and plantation of Japanese cedars in the reservoir catchment between 1975 and 1982. By 2006, most of the vegetation consisted of cedar forest. A new road was constructed on the northern edge of the catchment between 1982 and 2006. These data suggest the occurrence of large changes in ground conditions that affected the transport of organic matter.

SAMPLES AND METHODS

Sediment Core B (26 cm long) was obtained from the center of the reservoir (Fig. 1b) using an HR-type (11 cm diameter) core sampler (Rigo, Japan) on October 14, 2009. Changes in organic properties of this core were analyzed. Core B11-3, which is longer (88 cm long), was additionally taken from the same point using a Satake-type (5.2 cm diameter) core sampler (Rigo, Japan) on December 15, 2011, to support the age model of Core B based on

Fig. 2. Aerial photographs of the Bishaguso-ike reservoir catchment area in (a) 1968, (b) 1975, (c) 1982, and (d) 2006 (Geospatial Information Authority of Japan). The notations on the maps indicate the types of vegetation (bl: broadleaf forest, cd: cedar plantation, bs: bare soil or new plantation, pf: paddy field). The dashed lines indicate the catchment area of the reservoir. The open and closed circles indicate the sediment and soil sampling points, respectively.
radioactivity analysis. Sediment Cores B and B11-3 were sliced into 1 and 2 cm interval subsamples, respectively. Soil samples were obtained from the different types of topographies (ridge, slope, and valley) in the catchment area on December 6, 2010 (Figs. 1b and 2). The soil samples were obtained using a stainless steel tube (diameter 4.7 cm), with care taken to exclude litter, and the top 5 cm of the soil was used for analyses. Terrestrial plants (grasses and leaves of broadleaf and cedar trees) were also collected from the soil sampling locations. Planktonic materials and aquatic plant samples were collected from the reservoir on September 26, 2011, using a small plankton net (mesh size of 0.072 mm, Rigo, Japan).

The freeze-dried sediment and soil samples were ground and treated with 1 M HCl to remove inorganic carbon for analyses of the TOC, TN, and stable carbon and nitrogen isotope ratios. The samples of planktonic materials and terrestrial and aquatic plants were also freeze-dried and ground for analyses. The TOC and TN contents were measured using an elemental analyzer (2400 Series II, PerkinElmer, USA). The precisions of the TOC and TN measurements were ±0.08% and ±0.01%, respectively. The stable carbon and nitrogen isotope ratios were analyzed using a mass spectrometer (IsoPrime EA, GV Instruments, UK). These ratios were expressed as $\delta^{13}C$ and $\delta^{15}N$ values relative to Vienna Pee Dee Belemnite (VPDB) and atmospheric N$_2$, respectively:

$$\delta^{13}C, \delta^{15}N = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000.$$

where $R_{\text{sample}}$ and $R_{\text{standard}}$ are the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ atomic ratios of the sample and the international standard, respectively. USGS40 ($\delta^{13}C_{VPDB} = -26.39, \delta^{15}N_{air} = -4.52$) was used as the reference material for calibrating the measurements. The precisions of the $\delta^{13}C$ and $\delta^{15}N$ analyses were ±0.05‰ and ±0.18‰, respectively. The C/N ratios, $\delta^{13}C$, and $\delta^{15}N$ values of the sediment and soil samples, respectively, indicate the TOC/TN ratio, $\delta^{13}C$ of the organic matter, and $\delta^{15}N$ of the total nitrogen in the following discussion.

The grain size of the mineral fractions of the sediment was analyzed after removal of the organic matter and biogenic silica using 10% H$_2$O$_2$, 1 M HCl, and 2 M Na$_2$CO$_3$ solutions. A laser diffraction particle size analyzer (SALD-2200, Shimadzu, Japan) was used for the grain size analysis. The median size was used to represent the grain size of each sample. The radionuclide activity concentrations ($^{210}Pb$ and $^{137}Cs$) were also measured to estimate the sedimentation rates and age of the cores. The ground samples were pressed and sealed into a disc shape. After establishing the radioactive equilibrium between $^{222}Rn$ and $^{218}Pb$ (about one month), the activity concentrations of $^{210}Pb$ (46.5 keV), $^{214}Pb$ (352 keV), and $^{137}Cs$ (661.6 keV) were determined by gamma-ray spectrometry.
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using Ge detectors (LO-AX-51370-20, ORTEC, USA). The activity of the excess $^{210}\text{Pb}$ ($^{210}\text{Pb}_e$) was estimated by subtracting the activity of $^{214}\text{Pb}$ from that of $^{210}\text{Pb}$. Only the radionuclides of the upper 40 cm of Core B11-3 were analyzed to cover the period by which it is older than Core B.

Precipitation data obtained from the cities of Nanao and Wajima (Fig. 1a) were provided by the Japan Meteorological Agency. Considering that the observation of precipitation in Nanao only began in 1979, data from Wajima were used for the period before 1979. The aerial photographs and map data were obtained from the Geospatial Information Authority of Japan.

RESULTS

Age-depth model of the sediment cores

To establish the age-depth model of the cores, the $^{210}\text{Pb}$ (Krishnaswamy et al., 1971; Appleby and Oldfield, 1978) and $^{137}\text{Cs}$ methods (Ritchie and McHenry, 1990) were used. Figures 3a and b, respectively, show the vertical changes in the activity concentrations of the $^{210}\text{Pb}_e$ and $^{137}\text{Cs}$ as a function of the mass depth for Core B and Core B11-3. The mass depth is the downward cumulative dry mass per unit area from the surface. Here, it was calculated using the dry mass of each subsample and the cross-sectional area of the core. The $^{210}\text{Pb}$ age was estimated using the constant initial concentration (CIC) model (Pennington et al., 1973; Appleby and Oldfield, 1983). The regression lines show the fitting results obtained by the CIC model. The open circles indicate the constant $^{210}\text{Pb}_e$ values, which suggest that the corresponding sample layers were disturbed by bioturbation and event deposition. These layers were therefore excluded from the fitting. The bottom of Core B was estimated to date from 1984 (Fig. 3a). The activity concentration of $^{137}\text{Cs}$ increases with depth, and the bottom layer exhibits the highest activity. This suggests that the bottom layer is younger than the fallout peak of $^{137}\text{Cs}$, which occurred in 1963 in Japan (Katsuragi, 1983; Katsuragi and Aoyama, 1986; Igarashi et al., 1996), and thus supports the $^{210}\text{Pb}$ age of Core B. The sedimentation rate was relatively high at 0.292 g·cm$^{-2}$·y$^{-1}$ until 1991. It then decreased to 0.0656 g·cm$^{-2}$·y$^{-1}$ beginning in 1991, and then increased again.
The bottom of the analyzed interval of the 210Pb CIC model (0–36 cm) of Core B11-3 was estimated to date from 1939 (Fig. 3b). The 137Cs fluctuation first appears at 32 cm and peaks between 25 and 27 cm. These two points correspond to the beginning of the 137Cs global fallout in 1954 (Ritchie and McHenry, 1990) and the fallout peak in 1963, respectively. These observations also agree with the age calculated using the 210Pb CIC model. The sedimentation rate was relatively low at 0.0697 g·cm–2·y–1 until 1975. It then increased to 0.186 g·cm–2·y–1 beginning in 1975, and decreased again to 0.0254 g·cm–2·y–1 beginning in 1991. Based on the age-depth models of the cores, there was a high sedimentation rate interval between 1975 and 1991. In Core B, the sedimentation rate increased again between 2007 and 2010. This might have resulted from sediment focusing because the event was not observed from Core B11-3. The 210Pbex inventories of the analyzed parts of Core B (0–26.5 cm) and Core B11-3 (0–42 cm) are 2.34 and 1.95 Bq·cm–2, respectively. The inventory of Core B is higher than that of Core B11-3, although Core B is shorter than Core B11-3. This also supports the occurrence of the sediment focusing observed from Core B.

**Fig. 5.** (a) δ13C-δ15N and (b) δ13C-C/N ratio plots of the sediment and organic matter sources in the Bishaguso-ike reservoir. The closed circles correspond to the sediment samples, and the open circles, squares, crosses, and triangles correspond to soil, planktonic materials, aquatic plants, and terrestrial plants, respectively.

**Table 1.** Carbon and nitrogen isotopes and C/N ratios of organic matter sources

<table>
<thead>
<tr>
<th>Sample</th>
<th>n</th>
<th>δ13C (%)</th>
<th>δ15N (%)</th>
<th>C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface soil</td>
<td>7</td>
<td>-27.2 ± 0.8</td>
<td>3.9 ± 1.2</td>
<td>20 ± 3</td>
</tr>
<tr>
<td>Terrestrial plants</td>
<td>10</td>
<td>-30.4 ± 0.9</td>
<td>13.5 ± 2.0</td>
<td>66 ± 35</td>
</tr>
<tr>
<td>Aquatic plants:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floating-leaved</td>
<td>2</td>
<td>-26.2 ± 1.1</td>
<td>0.2 ± 0.7</td>
<td>34 ± 2</td>
</tr>
<tr>
<td>Submerged</td>
<td>1</td>
<td>-35.2 ± 1.2</td>
<td>8.8 ± 2.0</td>
<td>58</td>
</tr>
<tr>
<td>Planktonic materials</td>
<td>1</td>
<td>-40.2 ± 1.2</td>
<td>0.1 ± 0.7</td>
<td>5</td>
</tr>
</tbody>
</table>

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range of C/N ratios corresponds to the mid-range of values between those of algae and terrestrial plants (Meyers, 1994). The $\delta^{13}C$ and $\delta^{15}N$ values changed from $-30.2\%$ to $-32.4\%$ and from $0.3\%$ to $-1.1\%$, respectively. The median grain sizes of the mineral fractions show that the sediment consists of silt-sized clastic materials, the grain size of which decreased slightly with time, from 7.5 to 8.0. The median grain sizes are shown on the $\phi$-scale, where the smaller the value, the larger the grain size.

Figures 5a and b show the $\delta^{13}C$-$\delta^{15}N$ and $\delta^{13}C$-$C/N$ plots, respectively, of the sediment and the expected organic matter sources (soil, terrestrial plants, aquatic plants, and planktonic materials) in the Bishaguso-ike reservoir catchment. Table 1 summarizes the average isotope compositions and C/N ratios of the organic matter sources. The terrestrial plants and soil samples have $\delta^{13}C$ values of about $-30.4\%$ and $-27.2\%$, respectively. The planktonic materials and submerged aquatic plants, which were affected by the dissolved inorganic carbon in the lake water, have relatively low $\delta^{13}C$ values ($-40.2\%$ and $-35.2\%$, respectively) compared to the other plants. The $\delta^{13}C$ of the planktonic materials in the Bishaguso-ike reservoir is lower than the values generally reported ($-30$ to $-25\%$) for other lakes (Meyers, 1994; Meyers and Lallier-Vergès, 1999; Vuorio et al., 2006). The submerged plants have low $\delta^{15}N$ ($-8.8\%$), whereas the planktonic materials and floating-leaved plants have the same $\delta^{15}N$ as the soil and sediments. These results imply that the planktonic materials and submerged plants utilized the $^{15}C$-depleted CO$_2$ and $^{15}N$-depleted dissolved inorganic nitrogen produced by the decomposition of organic matter in the reservoir. The $\delta^{13}C$ and $\delta^{15}N$ of the sediments are between $-32.4$ and $-30.2\%$ and between $-1.1$ and $0.3\%$, respectively, which are within the range of those of the organic matter sources.

DISCUSSION

Effect of deforestation on discharge of soil and organic matter

Figure 4e shows the temporal changes in the sedimentation rates of Cores B and B11-3. The sedimentation rate increased to 2.7 times (Core B11-3) just after the deforestation and plantation of 1975–1982 and remained high until 1991. The sedimentation rate of Core B was also high during the 1980s, and then decreased in 1991. This fluctuation in the sedimentation rate suggests that the erosion rate was increased by the deforestation during the 15 years following its onset. The organic matter sedimentation was also high during this interval. Figure 4f shows the TOC sedimentation flux calculated from the sedimentation rate and TOC content of Core B. The TOC sedimentation flux was high, which corresponds to the sedimentation rate and suggests enhanced organic matter discharge from the catchment and organic production in the reservoir, during the 15 years following the onset of deforestation. The C/N atomic ratio was relatively high during this interval (Fig. 4b), implying that the contribution of allochthonous organic matter (e.g., terrestrial plants and soil organic matter) was relatively high. The high contribution of the allochthonous organic matter can be attributed to the fact that its C/N ratio was higher than that of the autochthonous planktonic materials (see Table 1).

The intensive erosion was induced by the direct exposure of bare soil to rainfall. The impact of raindrops induces the formation of soil surface crust and seals, which decrease infiltration and enhance surface runoff and soil erosion (Singer and Bissonnais, 1998). These erosional factors may decrease gradually with vegetation recovery. On the other hand, the sedimentation rate decreased rapidly in 1991, implying that additional factors affected the soil erosion. Forest management practices such as road construction (e.g., Beschta, 1978) may abruptly affect soil erosion. In this catchment area, a new road was constructed on the northern edge of the catchment between 1982 and 2006. Additionally, the clearing of understory vegetation promoted the growth of cedar trees over a period of between five and 10 years after their plantation (Horiuchi and Nakamura, 2012; local community, pers. comm.). This clearing of understory vegetation might have affected soil discharge because the decrease of understory vegetation and litter promotes soil erosion (Hattori et al., 1992; Yukawa and Onda, 1995; Onda et al., 2005).

The rapid change in soil erosion also seems to have been affected by the precipitation conditions. The high sedimentation rate after deforestation corresponds to the change in the maximum hourly precipitation reflecting the heaviest rainfall event for one year (Fig. 4b). There were some heavy rainfall events between 1983 and 1990, and this corresponds to the high sedimentation rate until 1991. These events are also reflected in the peaks of the fluctuations of the C/N ratio, which are indications of the erosional intensity in the catchment during the mid-1980s. As the vegetation recovered, the effect of rainfall was reduced. Based on these results, the fast decrease in the sedimentation rate may be attributed to the cessation of management activities and/or reduced rainfall, in addition to relatively slow vegetation recovery.

In addition to precipitation fluctuation, several-year to decadal climatic fluctuations, such as the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), may also have affected the local climate in Japan (e.g., Sato et al., 2012). The PDO is a decadal fluctuation in oceanic and atmospheric patterns in the Pacific Ocean, and its pattern underwent changes around 1977 and 1989 (Mantua et al., 1997; Hare and Mantua, 2000).

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Changes in C/N ratio, $\delta^{13}$C, and $\delta^{15}$N of sediments and vegetation recovery process

The C/N ratio, $\delta^{13}$C, and $\delta^{15}$N of Core B have continued to decrease from the mid-1980s to the present, although the sedimentation rate has already recovered pre-deforestation levels (Figs. 4b–d). These trends imply that the process of recovery from deforestation affects the transport of organic matter. To clarify the relationship between these parameters and organic matter transport, it is necessary to discuss the factors that determine the C/N ratio, $\delta^{13}$C, and $\delta^{15}$N of the sediments.

Post-deposition diagenesis may modify the original C/N ratio, $\delta^{13}$C, and $\delta^{15}$N of lake sediments. This prevents the proper reconstruction of the past environment using the above three parameters. Comparisons of the isotopic compositions of the same layer determined from varved lake sediments obtained in different years (Lehmann et al., 2002; Gälman et al., 2009) and the results of decomposition experiments performed on aquatic plants and algae (Fenton and Ritz, 1988) suggest that the effect of diagenesis on the $\delta^{13}$C and $\delta^{15}$N is about 1%. In the Bishaguso-ike reservoir, the $\delta^{13}$C and $\delta^{15}$N increase with depth by 2.5% and 1%, respectively, suggesting that the range of the changes in the $\delta^{13}$C is greater than that of diagenesis. Usually, the C/N ratio decreases with depth because of the preferential utilization of carbon, immobilization of nitrogen, and sorption of ammonium by clay minerals in lake sediments (Müller, 1977; Meyers and Lallier-Vergès, 1999). Conversely, the C/N ratio here increases with depth, and this suggests that the changes in the C/N ratio and $\delta^{13}$C at least reflect the original trend. However, because the range of the $\delta^{15}$N is within the diagenesis effect, its effect requires careful consideration.

The $\delta^{13}$C, $\delta^{15}$N, and C/N ratio of the sediments are within the ranges of those of the organic matter sources (soil, terrestrial plants, aquatic plants, and planktonic materials) in the $\delta^{13}$C-$\delta^{15}$N and $\delta^{13}$C-C/N plots (Figs. 5a and b). This suggests that the Bishaguso-ike sediments consist of a mixture of these autochthonous and allochthonous organic matter. Therefore, the C/N ratio, $\delta^{13}$C, and $\delta^{15}$N of the sediments are determined by the C/N and isotopic changes of each source and the mixing ratio.

The $\delta^{13}$C of the terrestrial plants reflects the plant type ($C_3$ or $C_4$ plant). The terrestrial plants and soil samples obtained from this catchment have $\delta^{13}$C values of about $-30.4\%$ and $-27.2\%$, respectively, suggesting that the vegetation consists of $C_3$ plants and soil organic carbon that originated mainly from $C_3$ plants. Deforestation and cedar plantation might not have affected the $\delta^{13}$C of the terrestrial plants and surface soil because the understory vegetation, which includes $C_4$ plants, was removed by forest management activities. These values are expected to be representative of the terrestrial plants and soil organic matter in the area because the sources of the materials are within the catchment, which is dominated by almost uniform vegetation. Additionally, the soil samples obtained from the different types of topographies (ridge, slope, and valley), which significantly determine the characteristics of soil organic matter in a uniform-vegetation catchment, are also representative of the catchment.

However, the $\delta^{13}$C and $\delta^{15}$N of plankton and aquatic plants are affected by the isotopic composition and isotopic fractionation assimilation of the dissolved CO$_2$ and nutrients. These conditions can be changed temporally and spatially by the environment of the lake water and species composition of the plankton (e.g., Vuorio et al., 2006). The isotopic changes in the plankton and aquatic plants therefore require careful consideration.

The isotope values of the sediments shifted from the upper right to the lower left in the $\delta^{13}$C-$\delta^{15}$N and $\delta^{13}$C-C/N plots between 1984 and 2007 (Figs. 5a and b). The isotope ratios of the sediments decreased relative to those of the soil, suggesting decreased contribution from the soil. This interpretation is relatively reliable because the $\delta^{13}$C and C/N ratio of soil are less affected by isotopic changes and diagenesis. The decreasing trend of $\delta^{13}$C and $\delta^{15}$N beginning in the mid-1980s is interpreted as a decrease in the contribution of the soil organic matter to the sediment, and this indicates gradual reduction of soil erodibility. Comparison with the observed changes in the vegetation within the catchment area suggests that the gradual reduction of the soil erodibility may be an indication of vegetation recovery, forest regrowth, and accumulation of litter and organic matter on the forest floor. This interpretation is supported by the decreasing trend of the C/N ratio and mineral grain size, which indicate weakening of the erosional capability of the allochthonous materials beginning in the mid-1980s (Figs. 4b and g). Organic matter on a forest floor requires a re-accumulation period of more than 50 years after deforestation to recover the original level (Covington, 1981). The recovery processes are therefore expected to progress relatively slowly. These results suggest that the change in the transport of organic matter continued for at least 35 years after deforestation and plantation.

**Conclusions**

In this study, we investigated the effects of artificial...
deforestation and the subsequent recovery process on the transport of particulate organic matter in the Noto Peninsula in Japan. The sediment record of geochemical properties of the Bishaguso-ike reservoir sediments leads to the following conclusions.

$^{210}$Pb dating of a sediment core showed that the sedimentation rate in 1975 had increased to about 2.7 times the previous value, and this corresponded to the deforestation and plantation that was executed between 1975 and 1982. The sedimentation rate and TOC sedimentation flux remained high until 1991, suggesting that the erosion rate of the soil and organic matter increased during the 15 years following the deforestation. This intensive erosion was induced by the exposure of the bare soil, forest management activities to remove understory vegetation, and rainfall. The rapid decrease of the sedimentation rate may be attributed to the cessation of management activities and/or reduced rainfall during this time.

After the sedimentation rate had recovered to the pre-deforestation level, the $\delta^{13}$C and $\delta^{15}$N of the sediments continued to decrease from the mid-1980s to the present. Although the effect of post-deposition diagenesis on the $\delta^{15}$N and the significant variability of the isotopic composition of the aquatic plants and planktonic materials prevented detailed interpretation of these parameters, the observed changes may indicate decreased contribution of the soil. These observations reflect gradual recovery of vegetation, forest regrowth, accumulation of organic matter on the forest floor, and reduced soil erodibility. These recovery processes progressed quite slowly, and the change in the transport of organic matter continued for at least 35 years after the deforestation and plantation.

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