Large wood, sediment, and flow regimes: their interactions and temporal changes caused by human impacts in Japan

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Abstract

Water, sediment, and large wood (LW) are the three key components of dynamic river-floodplain ecosystems. We examined variations in sediment and LW discharge with respect to precipitation, the presence of dams, land and river use change, and related channel incision and forest expansion on gravel bars and floodplains across Japan. The results indicated that unit sediment discharge and unit LW discharge were smaller in southern Japan where precipitation intensity is generally much greater. Effective precipitation, an index that takes current and antecedent precipitation into account, was a strong predictor of discharge in small watersheds, but not in larger watersheds. However, precipitation intensities related to unit sediment discharge in intermediate and large watersheds were smaller than those associated with unit LW discharge, which we attribute to differences in particle shape and size and also transport mechanisms. The relationship between river flow and discharge of sediment and LW lead us to posit that discharges of these components are supply limited in southern Japan and transport limited in northern Japan. The cross-sectional mean low-flow bed elevation of gravel-bed and sand-bed rivers in Japan decreased by ~0.71 and 0.74 m on average, respectively, over the period 1960-2000. Forest expansion on bars and floodplains has been prominent since the 1990s, and trees apparently began to colonize gravel bars ~10 to 20 years after riverbed degradation began. Forest recovery in headwater basins, dam construction, gravel mining, and channelization over the past half century are likely the dominant factors that significantly reduced downstream sediment delivery, thereby promoting channel incision and forest expansion. Changes in rivers and floodplains associated with channel incision and forest expansion alter the assemblages of aquatic and terrestrial organisms in riverine landscapes of Japan, and climate change may contribute to this change by intensified precipitation. Additionally, regime shifts of water, sediment, and LW may continue or they may reach a dynamic state of quasi-equilibrium in the future. Continued monitoring of these three components, taking into account their geographic variation, is critical for anticipating and managing future changes in river-floodplain systems in Japan and

around the world.

Keywords: regime shift; channel incision; forest expansion; sediment discharge

1. Introduction

River and floodplain ecosystems are sustained by water and material flows delivered from contributing watershed areas. Among those flows, water is the most fundamental component because it transports materials that shape heterogeneous structures and various functions of river-floodplain ecosystems. Water transports organic matter, nutrients, and organisms from headwater basins to lowland rivers (Vannote et al., 1980). Among these materials transported by water flows, sediment is an essential component in creating river and floodplain morphology (Leopold et al., 1964) and provides substrates for organisms. Large wood (LW) is another major contributor to instream and floodplain habitat diversity and disturbance regimes (Gregory et al., 2003).

Water, sediment, and LW are the three key components that provide templates for river-floodplain ecosystems to function (Gurnell et al., 2002; Fig. 1). Streamflow carries sediment and LW pieces and determines the landscape patterns of bars, floodplains, and LW distributions (Nakamura and Swanson, 1993). Additionally, variation in streamflow supplies moisture for riparian forests (Shin and Nakamura, 2005), may disturb riparian forest patches, and can transport LW pieces into streams. In turn, variations in flow depth and velocity, channel units (e.g., pools, riffles), and the extent of the hyporheic zone are largely determined by sediment and LW accumulations (Wondzell and Swanson, 1996). Sediment deposits provide germination sites for riparian trees, although excessive deposition may bury and destroy some riparian trees (Nakamura et al., 2007). Conversely, riverbank and floodplain deposits are stabilized by root networks. During floods, riparian trees function as roughness elements that reduce flow velocity, promoting sediment deposition and storage. Large wood pieces on bars and floodplains promote deposition and erosion of sediment, resulting in heterogeneous substrate patches at the local scale (Gurnell et al., 2005).

Among the three components, water has received the most attention by ecologists because organisms living in rivers and on floodplains exhibit life history traits attuned to variation of water discharge (Poff et al., 1997). Thus, the natural flow regime and its roles in river and floodplain ecosystems have been examined for various organisms (Lytle and Poff, 2004). The adverse effects of dams on river-floodplain ecosystems as a result of altering the natural flow regime have also been noted (Bunn and Arthington, 2002; Poff et al., 2007).

By contrast, although sediment regimes have been a research focus for geomorphologists, they have received relatively little attention from ecologists (Wohl et al., 2015), except for the effects of fine sediment on periphyton biomass (e.g., Yamada and Nakamura, 2002), benthic invertebrates (e.g., Wood and Armitage, 1997) and salmonid spawning habitats (e.g., Suttle et al., 2004). Many studies have focused on ecosystem recovery after sediment-related disturbances, such as sedimentation and debris flows (Lamberti et al., 1991). However, those studies dealt with single disturbance events rather than sediment regimes. Additionally, many studies have focused on the dynamics and distribution of LW, roles of LW in habitat formation, and modification of movement and transformation of energy, nutrients, and food for stream dwelling organisms (Maser and Sedell, 1994). However, the LW regime at the watershed scale has been scarcely investigated (Benda et al., 2003).

River-floodplain systems undergo major shifts in regime in response to natural and human-induced changes in the contributing watershed that affect water, sediment, and LW regimes. Changes in these regimes cascade downstream through river networks, affecting aquatic and riparian ecosystems (Nakamura et al., 2000). Special circumstances in Japan provide an unusual opportunity to interpret such changes – more than 40 years of record of water and sediment discharge and a decade-long record of LW discharge at dams in small and large watersheds spanning nearly 20° of latitude and a range of climatic settings across Japan document rather systematic and dramatic change in river-floodplain characteristics.

This study aims to examine 1) spatial patterns in sediment and LW regime responses to precipitation over the gradient of latitude spanning Japan, 2) impacts of dams on the transfer of sediment and LW and their cascading effects on river morphology, 3) temporal trajectories of change in river morphology and riparian vegetation in response to human activities on the timescale of decades, and discuss possible future changes in the river-floodplain ecosystem.

2. Methods

We divide the analysis of long-term sediment and LW discharge and precipitation records for two sets of watersheds upstream of sampled reservoir sites: (i) the subset of quasi-natural watersheds without dams and limited land use in order to assess discharge relationships to precipitation independent of these human influences, and (ii) the full set of records to assess influences of upstream dams and reservoir management. We also use data sets on the history of changing river morphology and riparian forest cover to understand their relation to land use on the timescale of decades.

2.1. Study area

The Japanese archipelago runs from latitude 26°N to 45°N in the northwestern Pacific Ocean and precipitation varies along this latitudinal (LAT) gradient. The annual rainfall in southern and central Japan (south of 36°N latitude) ranges from ~2000 to 4000 mm, while annual precipitation in northern Japan (north of 36°N latitude) ranges from ~1000 to 2000 mm. The precipitation pattern is controlled largely by the frequency of typhoons. Southern and central Japan are frequently hit by typhoons, causing serious floods in summer and autumn. Northern Japan experiences few typhoons and precipitation is dominated by snowfall in winter, which result in snowmelt floods in spring.

2.2. Large wood and sediment regime responses to precipitation at a national scale

We compiled a database of sediment and LW discharge, which have been monitored at reservoir sites on a yearly basis since the 1980s by local reservoir management offices. Sediment accumulation beneath the water surface generally was surveyed using the weight-drop method or a single/multibeam echo sounder, and sediment discharge (m^3 y^{-1}) was calculated based on net changes in volume between two consecutive years. Large wood accumulation was estimated from a survey of the water surface area occupied by driftwood pieces or was calculated by counting the number of trucks filled with driftwood pieces after their removal from each reservoir. The volume of LW was converted to biomass weight using a conversion factor (0.4 Mg m^{-3}; Harmon et al., 1986; Seo et al., 2008). Annual discharge values were converted to a per unit of watershed area basis with SED discharge as m^3 km^{-2} y^{-1} and LW discharge as kg km^{-2} y^{-1}.

To examine the influence of precipitation variability on unit SED and LW discharge under quasi-natural conditions, we first extracted from the database only the undammed watersheds (i.e., no dams upstream of the reservoir study site). Then we calculated the ratios of forested area (Fa) of the riparian zone to total riparian zone area (Ra) using the method given in Seo et al. (2012). Here, we treated the riparian zone as extending 200 m from the channel bank. To identify watersheds with minimal land use effects, we selected cases with Fa/Ra values >0.85. Targeting the undammed watersheds with Fa/Ra values >0.85, we compiled daily precipitation (*DP*) data collected by the local reservoir management offices. In the few cases without meteorological monitoring systems, *DP* data were collected from the Japan Meteorological Agency station closest to the study watershed. From the *DP* data, we also calculated effective precipitation (*EP*), which is commonly used as an index to predict the occurrence of sediment-related disasters in Japan (Tsukamoto and Kobashi, 1991), and is expressed as follows;

$$EP_t = DP_t + \sum_{i=1}^{x} a_i \cdot DP_t$$

where a_i is the reducing coefficient of i (1,2,3,…., x) day(s) before day t. Daily *EP* values (*EP* on day t (EP_t, mm)) takes into account current and antecedent precipitation, which is useful for interpretation of initiation of various types of mass movement processes, such as landslides and debris flows. See Seo et al. (2012) for more detailed information.

We selected only quasi-natural watersheds (undammed watersheds with forested riparian zone) for analysis with precipitation data, which total 154 watersheds throughout Japan for which we have sediment discharge and 104 watersheds with LW discharge. Using the methods of Seo and Nakamura (2009), we classified these watersheds in three size classes, based on watershed area: small (<20 km^2), intermediate (20–100 km^2), and large (>100 km^2).

Then we examined the relation of watershed size to sediment and LW discharge. To examine the effects of the latitudinal gradient on sediment and LW discharge, we obtained the latitude of all dam sites using channel network data (1:25,000) derived from a digital elevation model (50×50 m resolution), provided by the National Land Numerical Information of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan.

Explanatory variables that are likely to have substantial influence on unit SED discharge or unit LW discharge were analyzed using a generalized linear mixed model (GLMM; Crawley, 2005) with a Gaussian error distribution and an identity link function, in which the reservoir site was incorporated as a random effect. The response variable was unit SED discharge or unit LW discharge. The explanatory variables were (i) cumulative *DP* or *EP* greater than or equal to *a* mm (i.e., $DPc \geq a$ or $EPc \geq a$), (ii) LAT category (i.e., lower- and high-LAT zones with a threshold of 36°N latitude); and (iii) interactions between variables (i) and (ii). Here, the *a* value in $DPc \geq a$ varied from 0 to 150 mm at 10-mm intervals (i.e., 0, 10, 20, …, 150 mm), and the *a* value in $EPc \geq a$ varied from 0 to 300 mm at 10-mm intervals (i.e., 0, 10, 20, …, 300 mm). The best model was determined by Akaike's Information Criterion (AIC) in a best-subset selection procedure (Burnham and Anderson, 2002). Prior to the analysis, unit SED discharge and unit LW discharge were $\log_{10}(x)$-transformed to stabilize variances and improve normality, and $DPc \geq a$ and $EPc \geq a$ were $\log_{10}(x+a)$-transformed to promote linearity and avoid discontinuity in the model. The statistical analyses were conducted using the statistical program R (http://www.r-project.org).

2.3. Watershed fragmentation by dams and their effects on the transfer of sediment and large wood

Sediment and LW delivery from the upstream watersheds are interrupted by dams, which is referred to as watershed fragmentation in this study, following the concept of Nilsson et al. (2005). Using GIS, the original natural watersheds were divided into subwatersheds at the locations of reservoir dams, and dam watersheds were delineated to express the fragmentation of natural watersheds. Many watersheds in Japan are fragmented by dams, and the effects of dams on the transfer of sediment and LW can be examined by comparing sediment and LW discharge between dammed and undammed watersheds.

We obtained spatial data on the distributions of large reservoirs from the Japanese Dam Almanac (Japanese Dam Foundation, 2015). We ignored small check dams (Sabo dams) built in headwater areas to reduce sediment-related disasters.

The degree to which the presence of an upstream dam(s) in a watershed interrupts the passage of sediment and LW during floods was investigated by distinguishing dammed watersheds and undammed watersheds. Finally, we selected 195 watersheds (41 dammed and 154 undammed) for analysis of sediment discharge and 137 watersheds (33 dammed and 104 undammed) for analysis of LW discharge. These watersheds are well distributed throughout Japan.

To examine differences in sediment and LW discharges between dammed and undammed watersheds, a GLMM with a random effect was used to build best models. The response variable was unit SED discharge or unit LW discharge in all watersheds (including both dammed and undammed watersheds) with Fa/Ra values >0.85. The explanatory variables were drainage area (DA; km^2), category of upstream dam presence (UD; 0 or 1), and the quadratic term of the DA parameter to express the curve response. We tested the impact of an upstream dam on sediment and LW discharges and their curvature variations as a function of DA, based on differences in AIC, including or excluding the UD categorical variable and the DA's quadratic term. Similar to the previous model selection, all variables (i.e., unit SED discharge, unit LW discharge, and DA), except for the UD categorical variable, were $\log_{10}(x)$-transformed to stabilize variances and improve normality, and this statistical analysis was conducted using the statistical program R (http://www.r-project.org).

2.4. Temporal trajectories of river morphology and riparian vegetation adjustment to land cover change

Land use change associated with human activities (e.g., forest cutting, farmland development or abandonment) is one of the predominant drivers that regulates sediment production. We used the land use information database built by Himiyama (1995) to analyze a century of historical land use change in Japan. To determine the approximate trends of land use change at the watershed scale, we chose four predominant land use types from 35 types identified by Himiyama (1995): coniferous forest, conifer-broadleaved mixed forest, broadleaved forest, and wastelands (areas of low vegetation cover resulting from severe land use and soil erosion). Because both coniferous and mixed forests are mainly artificial forests, we grouped them as conifer-dominant forest. We also obtained a 40-year history of forest change in Japan from a database provided by the Japanese Forest Agency (http://www.rinya.maff.go.jp/j/keikaku/genkyou/h19/2.html). This data set shows variation of wood volumes of plantation (conifers) and natural forests (mainly broadleaf) over the past 40 years. To complement these quantitative data, we also collected and compared old and current photographs displaying typical mountain and river landscapes in Japan over the past century.

The MLIT has compiled data sets on river morphology, providing longitudinal and cross-sectional riverbed profiles in class I rivers, which are the major river systems in Japan and are noted for their importance in disaster prevention and economic development. We use field survey data from 109 class I rivers collected at 200-m intervals since the 1960s by MLIT. The interval between surveys in the 1960s and 1970s was approximately once every 10 years, and surveys have been conducted more frequently since the 1980s, including after large floods. We divided the bed profile records into five periods: 1960–1974 (I), 1975–1989 (II), 1990–1995 (III), 1996–2000 (IV), and 2001–2005 (V). The bed elevation changes (aggradation or degradation) at 1-km intervals of river length were examined separately for gravel-bed rivers (mainly braided rivers on alluvial fans) and sand-bed rivers (mainly meandering rivers with natural levees and back-marsh areas). We compared bed profile change among only the first four periods, because the 2001–2005 data are not yet available, and conducted a *t*-test to determine whether changes of bed elevation between the two periods were significantly different from zero (no change).

The MLIT investigated forest colonization on bars and floodplains in class I rivers because trees can slow river discharge and thereby increase flooding. The investigation was conducted using (i) interpretation of a time series of aerial photographs since the 1960s, and (ii) the vegetation map in the biological database called 'National Census of River Environment', which was initiated by MLIT in 1991 for the 109 class I rivers (Nakamura, 2012a). We carefully checked the quality of each data set and excluded outliers and obvious mistakes. We selected six rivers (the Satsunai, Omono, Iwaki, Yura, Ohta, and Yoshino rivers) with good records and representative conditions for detailed analysis. These rivers provide a sample covering northern to southern Japan with full ranges of records from 1960 to 2005, and we analyze the data using the same time periods as used for the bed profile survey records.

The percentage of forested area in the administrative river management zone designated by MLIT in the five periods was calculated from the data set, and the temporal changes of forest expansion were estimated. To clarify the temporal changes of riparian forest area, we built a generalized linear mixed model for each river with the reach ID as random intercept. The response variable was percentage of riparian area in forest, and the explanatory variable was each of the five periods. Here, we assigned numerical variables (i.e., 1 to 5) for each period. We decided that a model in which the 95% CI of the period parameter coefficient does not include zero indicates a significant change in riparian forest area over a given period.

3. Results

The Japanese archipelago spans nearly 20^{o} of latitude with a corresponding gradient in annual precipitation from ~2000 to 4000 mm in southern and central Japan (south of 36°N latitude) to ~1000 to 2000 mm in northern Japan (north of 36°N latitude). We first present relationships between precipitation and sediment and LW discharge regimes at the national scale. Second, the effects of dams on the transfer of sediment and large wood are examined by comparing the discharges in dammed and undammed watersheds. Third, we present information on a century of land use change in Japan, which may have altered sediment and LW regimes, and 40-year changes in riverbed elevation and forest expansion on gravel bars and floodplains to understand possible cascading effects on river morphology and riparian vegetation.

3.1. Sediment and LW discharge with respect to precipitation

We examined sediment and LW regime responses to precipitation along gradients of watershed size and latitude. In this section, we combine results from a previous analysis of precipitation effects on LW discharge (Fig. 2, the right figures are from Seo et al., 2012) with those from a new analysis on the effects of precipitation on sediment discharge to establish the nature of latitudinal trends across Japan. In small watersheds, the unit LW discharge did not vary with latitude, and effective precipitation was a strong predictor of LW discharge (Seo et al., 2012). By contrast, unit LW discharge in intermediate and large watersheds varied with latitude, and the cumulative *DP* was the strongest predictor for unit LW discharge. Moreover, in the range of comparable precipitation intensities shaded in Fig. 2, unit LW discharge was greater in the high-LAT zone than in the low-LAT zone in intermediate and large watersheds. Seo et al. (2012) interpreted these results as reflecting a supply-limited situation in southern Japan (low-LAT) and a transport-limited in northern Japan (high-LAT).

The same analysis conducted for sediment discharge revealed similar to those of LW discharge (Fig. 2). Unit SED discharge was greater in the high-LAT zone than in the low-LAT zone, and effective precipitation was a significant, strong predictor in small watersheds (Table 1). However, several differences were found. Unit SED discharge exhibited larger variation than does unit LW discharge along the precipitation gradient. Unit SED discharge varied between high- and low-LAT in all sizes of watersheds, including small watersheds, but corresponding slopes of the regression models were similar between the two latitudinal zones. However, the regression slopes for unit LW discharge differed substantially in intermediate and large watersheds. Moreover, the daily precipitation intensities most related to the unit SED discharge in intermediate and large watersheds were ≥20 and ≥30 mm, respectively; whereas those for unit LW discharge were ≥40 and ≥60 mm, requiring greater precipitation for transport.

3.2. Effects of dams on sediment and LW discharge

The natural watersheds in Japan are substantially fragmented by dams (Fig. 3), which should alter downstream transport of sediment and LW. Effects of dams on sediment and LW discharge were examined by comparing the unit SED and LW discharges between dammed and undammed watersheds. Unit SED discharge decreases linearly with increasing watershed area, and unit LW discharge trends can be expressed by quadratic curves (Fig. 4). Among the models to predict unit SED and LW discharges, the best model with the lowest AIC included UD, suggesting that dams significantly reduce unit sediment and LW discharges (Table 2).

3.3. A century of forest land use change in Japan

Land use change in a watershed affects sediment and LW production and transport in streams and rivers. A century-long record of land use change in Japan covering almost the entire archipelago clearly showed that wastelands decreased from 11.8% to 3.7% of Japan’s total area, whereas conifer-dominant forests increased from 37.7% to 51.0% (Fig. 5A). Almost all coniferous forests are artificial plantations, which increased significantly after World War II owing to harvesting of original broadleaved-forests and planting of conifers. Based on the data set provided by the Japanese Forest Agency, the volumes of natural forest (broadleaved) and plantation forest (conifer) increased from 1329 million to 1780 million m^3 and from 558 million to 2651 million m^3, respectively, over the past 40 years (Fig. 5B). A pair of photographs taken in Shiga Prefecture gives a representative, early twentieth century view of the wasteland category, a mountain landscape denuded by poor land management, followed by establishment of vigorous broadleaved forest by the beginning of the twenty-first century (Fig. 6).

3.4. Channel incision and forest expansion on gravel bars and floodplains

To evaluate the long-term elevation changes of riverbeds, we compared the mean low-flow bed elevations of Japanese rivers between the 1960–1974 period and other periods

(1975–1989, 1990–1995, and 1996–2000; Fig. 7). The cross-sectional mean low-flow bed elevation of gravel-bed and sand-bed rivers significantly decreased between periods, by ~0.71 and 0.74 m on average between the first (1960–1974) and fourth (1996–2000) periods (Table 3). Most of the river reaches incised over these periods, and reaches experiencing bed aggradation were very limited. Pictures illustrating river landscapes in the 1950s were scarce, but we found an illustrative photograph of an aggraded, gravel-bed reach of the Yoshii River, Okayama Prefecture, in the 1950s. This aggradation probably resulted from a long history of poor land use practices, resulting in accelerated soil erosion (Fig. 8A). Present river landscapes are far different from past landscapes (Fig. 8). The gravel-bed section of the Toyohira River, Hokkaido Prefecture (Fig. 8B) is an example of many rivers in Japan demonstrating channel incision and sediment starvation. These past and present river landscapes are in good agreement with the observed bed elevation changes (Fig. 7).

The extent of forest cover along most of the six rivers we closely investigated has increased progressively, especially since the 1990s (the third period), except for the Ohta River, Chugoku district, where the forested area did not increase until the 2000s. The forest expansion appears to be ~10 to 20 years after riverbed degradation (Fig. 9). An increase in forested area over time was statistically significant in all six rivers (Table 4). Forested areas are increasing with time, but their increase rate will slow after trees have colonized most of gravel bars. Gradual forestation of gravel bars is clearly illustrated in the case of the Satsunai River (Figs. 9 and 10).

4. Discussion

4.1. Broad spatial patterns of sediment and large wood regimes in response to precipitation

The responses of sediment and LW discharge to precipitation differ with watershed size and latitudinal location (Fig. 2). In small watersheds with narrow valley floors and low water discharges, mass movements (such as landslides and debris flows triggered by intense precipitation) are major factors in the production and transport of sediment and LW

(Tsukamoto and Kobashi, 1991). Effective precipitation is widely used to predict the risks of large mass movements in Japan. This index reflects the assumption that large mass movements are influenced by current precipitation and by antecedent precipitation that has infiltrated into the soil. Although LW discharge did not vary with latitude, sediment discharge was higher in the high-LAT zone. Tree biomass in national forest lands, which cover 31% of the forested area in Japan, does not differ significantly between northern and southern Japan (about 100–250 m^3/ha in northern Japan and 150–250 m^3/ha in southern Japan (http://www.rinya.maff.go.jp/j/kikaku/toukei/youran_mokuzi.html)); but sediment accumulation on hillslopes may differ between the two regions, likely because lower precipitation characteristic of northern Japan may limit landslide frequency, allowing sediment to be retained on hillslopes. Nakamura (1990) calculated the average recurrence interval of landslides in Hokkaido (northern Japan) and estimated recurrence at 630 and 370 years for hillslopes underlain by sedimentary rock and with steepness >30° . Watanabe and Seo (1968) estimated a 30-year recurrence interval for landslides on granitic hillslopes in Kobe Prefecture (southern Japan), and Shimokawa et al. (1989) estimated 80–120 year recurrence for pyroclastic rock hillslopes in Kagoshima Prefecture (southern Japan). Thus, heavy rainfall events on hillslopes in northern Japan initiate relatively massive landslides, but at low frequency, with the net effect of higher sediment production than in southern Japan.

In intermediate and large watersheds with wide valley floors and high water discharges, heavy rainfall and subsequent floods achieve sufficient shear stress to transport sediment and buoyant depth to initiate LW movement (Braudrick and Grant, 2001). In southern Japan, heavy rainfall accompanying typhoons and torrential downpours frequently scour riverbed sediment and transport instream LW pieces; therefore, their discharges are supply limited (Seo et al., 2012). Conversely, in northern Japan, where typhoons and major seasonal rain fronts are rare, sediment and LW can be stored on wide valley floors, and their movement is transport limited.

Seo et al. (2015) examined differences in LW distribution as a function of channel morphology in six watersheds located in southern and northern Japan. The results clearly showed that floodplains were wider and gravel bars narrower in northern Japan, suggesting that a large amount of sediment is stored in floodplains and its residence time is longer. Similarly, LW pieces accumulate in logjams on wide valley floors, particularly in floodplains that support mature forests, resulting in larger LW accumulations and longer residence times in northern watersheds. Conversely, the narrower floodplains of southern Japan suggest limited storage of and shorter residence times for sediment and LW compared to those in northern Japan.

The reasons for variability between sediment and LW discharge, slopes of their regression lines, and differences in precipitation intensity as predictors are not clear. However, we speculate that these differences stem from differences in sample size (greater for sediment discharge), differences in particle shape (small spherical vs. large cylindrical forms of inorganic sediment and LW, respectively), and differences in transport mechanisms (shear stress vs. buoyant force). Low stream power in areas with low precipitation intensity (~20–30 mm/d) can transport small gravel downstream, but generally cannot float LW pieces. To initiate LW movement, higher precipitation (~40–60 mm/d) is needed. However, further research is required to fully explain these differences.

4.2. Impacts of watershed fragmentation by dams on the transfer of sediment and large wood and their cascading effects on river morphology

Dams disrupt the continuity of material flows. The majority of bedload sediment and LW transported from upper basins is trapped by these reservoirs, and downstream transport below dams can be greatly reduced. Water released from dams may scour the downstream reaches, resulting in increased sediment transport until local sources are exhausted. Moreover, riparian forest expansion below dams may increase LW abundance owing to recruitment of LW associated with bank erosion, channel incision (Hupp, 1992), and tree mortality. In very limited cases sediment is excavated from reservoirs and placed just downstream of the dam to maintain downstream sediment movement. By contrast, no similar activities are found for LW in Japan.

The results of sediment and LW discharge in dammed watersheds showed that reaches downstream of dams receive less sediment and LW pieces (Fig. 4). This is likely because the trapping effects of reservoirs, which can profoundly affect river morphology and riparian tree dynamics in reaches downstream of dams. Fujita et al. (2009) investigated sediment accumulations in reservoirs across Japan and concluded that the total volume stored in reservoirs in 1999 had reached 1.18 billion m^3. Numerous uncertainties complicate how these trends will develop in the future. Currently, reduced sediment and LW appear to create river reaches characterized by channel incision and limited habitat diversity and few pieces of instream LW.

Dam construction and reservoir management may be important causes of channel incision. Large reservoir and check dams (Sabo dams) built along mountain streams for sediment-related disaster prevention (e.g., debris flows) can reduce sediment transport from headwater basins. The number of check dams in Japan is enormous; more than 90,000 check dams have been built by MLIT, and the Japanese Forest Agency has constructed many additional check dams. These sediment and water regulation structures retain sediment and LW at dam sites, promoting channel incision in downstream reaches.

4.3 Temporal trajectories of river morphology and riparian vegetation adjustment to human activities over timescales of decades

Dams and other land use activities can alter water, sediment, and LW regimes at the watershed scale. The imprint of human influence in the mountainous landscape of Japan has changed drastically over the past 100 years (Fig. 5). From the beginning of the twentieth century to the 1950s, overharvesting of forests, failure to reestablish forests, and air pollution caused by mining and processing of mineral resources denuded extensive lands in Japan (Fig. 6), resulting in a large amount of sediment transported to streams and rivers. Thus, by the 1950s, gravel bars had developed extensively over the valley floor (e.g., as seen in the 1963 panel in Fig. 10), and channel aggradation was prominent (Fig. 8A). After the 1950s, Japanese society began to use inexpensive imported timber, and the remaining natural forest was preserved. In some cases, restoration projects were carried out on denuded lands. Currently, forest biomass and the forested area in Japan are at their maximum levels in at least the past 100 years (Fig. 5), and denuded lands are scarce (Ohta, 2012). Thus, sediment production rates have likely declined drastically over the past half century, potentially contributing to channel incision in Japanese rivers (Fig. 8B).

Engineering modification of rivers became an important land use in the mid-twentieth century. Most of the check dams in headwater streams and large dams on major rivers have been constructed since the 1950s, at the same time that reforestation work was beginning to reduce the delivery of sediment to channels. Channelization and gravel mining were other dominant activities in the 1950s and 1960s that significantly changed sediment regimes in Japan. Fukushima et al. (2005) investigated sinuosity loss associated with channelization in Hokkaido Prefecture using topographic maps made in 1950 and 2000. They concluded that portions of reaches in almost all rivers in Hokkaido were channelized and morphological diversity was reduced by 73% on average. The total length of the Ishikari River, the largest river in Hokkaido, has been reduced from 364 to 268 km since the 1910s (Nakamura, 2012b). Channelization, together with artificial levee and/or spur dike construction, increases shear stress on the riverbed by straightening the river corridor, thereby steepening the gradient (Brookes, 1988). Modifying low-flow channels with revetments narrows the flow width and constrains lateral channel migration. All of these engineering approaches likely promote channel incision (Simon and Rinaldi, 2006). Gravel mining of river sediment that prevailed in Japan in the 1960s and 1970s is another likely factor that altered natural sediment regimes and accelerated channel incision (Kondolf, 1997). Fujita et al. (2009) investigated gravel mining of river sediments across Japan and concluded that the total volume of gravel mining over the past 50 years reached ~1.13 billion m^3.

We believe that channel incision has been an important driver of forest expansion on floodplains and gravel bars over the past 50 years (Comiti et al., 2011). Channel incision enhances channel capacity and increases the elevation difference between low-flow channels and adjacent floodplain surfaces. Thus, floodplain vegetation along incised rivers experiences less frequent flood disturbances, thereby giving trees more opportunity to establish and grow, and reducing the extent of lateral erosion, removal of established forest, and formation of new gravel bars. Additionally, flow regulation by dams should contribute to forest colonization on floodplains by reducing disturbance by flooding (Johnson, 1994). As indicated by Lytle and Poff (2004), large reservoirs can greatly alter natural flow regimes as water discharge is managed for power generation, flood control, and water usage. Takahashi and Nakamura (2011) examined the impacts of a dam on the Satsunai River and observed that reduced frequency of flooding resulted in increased extent of riparian vegetation and decreased area of active channel (Fig. 10).

5. Cascading effects on river-floodplain ecosystems and concluding remarks

Over the past century in Japan, land use outside of river channels (e.g., forestry and agriculture), in headwater channels (e.g., Sabo dams), and along main river channels (e.g., dam/reservoir influences on flow, sediment, and LW discharge) have contributed to changes in river-floodplain systems. The first half of the century may have been a period of high sediment production in response to land use practices outside river and riparian areas, and a combination of factors over the past half century has created a major shift toward channel incision and forest development on gravel bars and floodplains. The data sets tracking river flow, sediment, and LW across Japan provide insights regarding how these critical components of river systems are changing and how they vary over large geographic areas.

Water, sediment, and LW are essential components in understanding the structure and dynamics of river and floodplain ecosystems. Natural and managed flow regimes altered by dams and their impacts on aquatic and terrestrial organisms have been well investigated by ecologists over the past several decades. In contrast, sediment and LW regimes are poorly understood, especially with respect to their roles in maintaining the foundations of river and floodplain ecosystems. Thus, there is a knowledge gap regarding the effects of human activities (e.g., dams and land use) that alter river flow, sediment, and LW regimes and in turn modify river and floodplain ecosystems.

Changes in the geomorphic dynamics of river and floodplain systems can alter the assemblages of aquatic and terrestrial organisms. For example, aquatic ecosystems may experience a shift in energy flow from a dominance of autochthonous production in gravel- or sand-bed rivers with little forest influence to allochthonous input dominant in forested rivers. This shift can alter macroinvertebrate assemblages from a strong grazer component in high-light environments to a more prominent shredder community that processes forest litter (Arscott et al., 2003). *Salix arbutifolia* (classified as vulnerable by the IUCN Red List), one of the rare and flagship species in Hokkaido, Japan, faces a serious recruitment problem because preferred germination sites are unforested gravel bars (Takagi and Nakamura, 2003). Plant species such as *Aster kantoensis* and *Ixeris tamagawaensis* (Muranaka and Washitani, 2004) and insect species such as *Eusphingonotus japonicas*, which favor gravel-bed habitats, are locally endangered in Japan (Yoshioka et al., 2010). Species richness and fish abundance can be reduced because of limited habitat diversity and high water velocity within narrow, incised river channels (Shields et al., 1994). At higher trophic levels, the abundance of migratory birds, such as *Charadrius placidus*, *Charadrius dubius*, and *Actitis hypoleucos*, substantially decreases with forestation because they need gravel bars for nesting (Yabuhara et al. 2015).

Anticipating future change in river dynamics is greatly complicated by the variety of factors involved, potential feedback mechanisms, and environmental change. Continued trapping of sediment and LW in reservoirs is likely to continue, unless major policy changes occur. However, some new sources of LW may become significant, if, for example, the trees growing on gravel bars are delivered to rivers by fluvial or other tree-mortality processes. The observation that sediment and LW discharges may be regulated by either supply-limited (southern Japan) or transport-limited (northern Japan) conditions is potentially relevant to projecting future change in delivery of these components to river systems. For example, climate projections for the twenty-first century in Japan indicate that mean precipitation may increase by more than 10% (Kimoto et al., 2005), thereby potentially reducing the transport limitation. A further consideration of future change is the potential for channel incision to be arrested by encountering hard bedrock, but we have observed cases of incision proceeding into soft bedrock (see Fig. 8B). Alternatively, the sediment routing system may achieve a new equilibrium between sediment supply and transport capability, leading to reduced incision.

In planning for the future we should note that after flow, sediment, and LW regime shifts occur, it is difficult to rebalance these components to preserve or restore biodiversity and ecosystem functions. For example, even if we restore the flow regime in incised rivers, the effects on organisms may be limited because habitat diversity provided by sediment deposition (or scouring) would not necessarily recover. Thus, we must carefully examine the balance among the three components and a new dynamic state of quasi-equilibrium that provides diverse habitats for various organisms, including endangered species, and ecosystem functions that maintain a healthy environment. Monitoring of flow, sediment, and LW regimes is critical for understanding, anticipating, and managing future changes in river-floodplain systems in Japan and around the world. The monitoring systems account for the geographic variation in the regimes, including watershed area and precipitation regimes, as we show for Japan.

Acknowledgements

We thank the Ministry of Land, Infrastructure and Transport and the Water Resources Environment Center for providing the large wood, sediment, and river survey data sets. Sincere appreciation goes to the anonymous reviewers for comments that improved the manuscript. This research was funded in part by the Water Resources Environment Technology Center and the Environment Research and Technology Development Funds (S9 and 4-1504) of the Ministry of the Environment of Japan.

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Table 1

The 10 best models selected from the GLMM of precipitation patterns and intensity regulating SED discharge in small, intermediate, and large watersheds[a,b]

Watershed size	Construction of parameters in the model	AIC	ΔAIC
Small	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 110)$ + LAT	**202.09**	**–**
Watersheds	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 130)$ + LAT	**203.42**	**1.33**
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 130)$	204.26	2.16
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 120)$ + LAT	205.26	3.17
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 110)$	205.32	3.23
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 100)$ + LAT	205.44	3.35
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 130)$ + LAT + $\log_{10}(EPc \geq 130)$:LAT	205.52	3.43
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 120)$	206.05	3.95
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 170)$ + LAT	206.10	4.01
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 170)$	206.68	4.59
Intermediate	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 20)$ + LAT	**196.63**	**–**
watersheds	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 20)$ + LAT + $\log_{10}(DPc \geq 20)$:LAT	198.64	2.01
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 0)$ + LAT	201.04	4.41
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 0)$ + LAT	201.97	5.35
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 0)$	202.01	5.39
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 0)$ + LAT + $\log_{10}(DPc \geq 0)$:LAT	202.84	6.21
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 20)$	203.05	6.42
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 0)$	203.23	6.60
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 10)$ + LAT	203.58	6.96
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 0)$ + LAT + $\log_{10}(EPc \geq 0)$:LAT	203.81	7.18
Large	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 30)$ + LAT + $\log_{10}(DPc \geq 30)$:LAT	**412.29**	**–**
watersheds	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 30)$ + LAT	**413.21**	**0.92**
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 40)$ + LAT + $\log_{10}(DPc \geq 40)$:LAT	414.52	2.23
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 150)$ + LAT	414.54	2.25
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 150)$	414.65	2.36
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 70)$ + LAT + $\log_{10}(DPc \geq 70)$:LAT	415.02	2.73
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 30)$	415.21	2.92
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(EPc \geq 140)$ + LAT	415.35	3.06
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 40)$ + LAT	415.96	3.67
	$\log_{10}$(unit SED discharge) ~ $\log_{10}(DPc \geq 80)$ + LAT + $\log_{10}(DPc \geq 80)$:LAT	415.97	3.68

[a]*Abbreviations*: unit SED discharge = sediment discharge per unit watershed area; $DPc \geq a$ = cumulative daily precipitation greater than or equal to a mm; $EPc \geq a$ = cumulative effective precipitation greater than or equal to a mm; LAT = latitude; $\log_{10}(DPc \geq a)$:LAT or $\log_{10}(EPc \geq a)$:LAT = interaction between $\log_{10}(DPc \geq a)$ (or $\log_{10}(EPc \geq a)$) and LAT.

[b]ΔAIC refers to the difference between the AIC values of the best fit model and each of the other models in the set. The regression models with ΔAIC<2 were considered to be as

equally influential as the best-fit model.

Table 2

Models selected from the GLMM of SED and LW discharges along the gradient of watershed area in dammed watersheds (having at least one dam upstream) and undammed watersheds (having no dams upstream)[a,b]

Construction of parameters in the model	AIC	ΔAIC
[*Sediment discharge*]		
$\log_{10}$(unit SED discharge) ~ $\log_{10}$DA + $(\log_{10}\text{DA})^2$ + UD + (1|Reservoir_Site)	3861.073	5.045
$\log_{10}$(unit SED discharge) ~ $\log_{10}$DA + $(\log_{10}\text{DA})^2$ + (1|Reservoir_Site)	3868.216	12.188
$\log_{10}$(unit SED discharge) ~ $\log_{10}$DA + (1|Reservoir_Site)	3863.297	7.269
$\log_{10}$(unit SED discharge) ~ $\log_{10}$DA + UD + (1|Reservoir_Site)	3856.028	–
[*LW discharge*]		
$\log_{10}$(unit LW discharge) ~ $\log_{10}$DA + $(\log_{10}\text{DA})^2$ + UD + (1|Reservoir_Site)	2049.233	–
$\log_{10}$(unit LW discharge) ~ $\log_{10}$DA + $(\log_{10}\text{DA})^2$ + (1|Reservoir_Site)	2054.029	4.796
$\log_{10}$(unit LW discharge) ~ $\log_{10}$DA + (1|Reservoir_Site)	2061.985	12.752
$\log_{10}$(unit LW discharge) ~ $\log_{10}$DA + UD + (1|Reservoir_Site)	2058.515	9.282

[a]*Abbreviations*: unit SED (or LW) discharge = sediment (or large wood) discharge per unit watershed area; DA = drainage area; UD = category of upstream dam presence (0 or 1).

[b]The squared term represents the square of the $\log_{10}$ transformed term. The notation "1|Reservoir_Site" in the model represents a random effect.

[c]ΔAIC refers to the difference between the AIC values of the best-fit model and each of the other models in the set.

Table 3

The 95% confidence intervals (95% CIs) of mean low-flow bed elevation change in gravel-bed and sand-bed rivers

Periods[a]	Mean (m)	95% CI 2.5%	95% CI 97.5%	Number of reaches	*P value*
Gravel-bed Rivers					
Ⅱ - Ⅰ	-0.58	-0.63	-0.53	1036	<0.01
Ⅲ - Ⅰ	-0.54	-0.60	-0.48	606	<0.01
Ⅳ - Ⅰ	-0.71	-0.78	-0.64	812	<0.01
Sand-bed Rivers					
Ⅱ - Ⅰ	-0.52	-0.55	-0.48	2857	<0.01
Ⅲ - Ⅰ	-0.62	-0.66	-0.58	1921	<0.01
Ⅳ - Ⅰ	-0.74	-0.78	-0.70	2326	<0.01

[a]Note：Ⅰ,1960-1974; Ⅱ,1975-1989; Ⅲ,1990-1995; Ⅳ,1996-2000

Table 4

Percent changes in forest cover in the riparian zone; the 95% confidence intervals (95% CIs) of period parameter coefficients in each model

River name	95%CI		Number of reaches
	2.5%	97.5%	
Satsunai R.	0.085	0.110	38
Omono R.	0.015	0.025	130
Iwaki R.	0.011	0.020	68
Yura R.	0.002	0.016	58
Ohta R.	0.014	0.023	77
Yoshino R.	0.004	0.017	108

Figure captions

Fig. 1. Large wood, sediment, and flow regimes providing templates for river-floodplain ecosystems.

Fig. 2. Changes in sediment (A, B and C) and LW discharge (D, E and F) per unit watershed area in relation to precipitation and latitude in small, intermediate, and large watersheds. $DPc \geq a$ (or $EPc \geq a$) represents cumulative daily (or effective) precipitation greater than or equal to a (mm). The low-LAT zone (solid circles) represents the area below 36° N latitude, and the high-LAT zone (open circles) represents the area north of 36° N. The regression lines were based on the data points in each LAT zone (i.e., low-LAT zone, solid line; high-LAT zone, dash-dotted line). Figures (D), (E) and (F) are from Seo et al. (2012).

Fig. 3. Watershed fragmentation by large dams and associated reservoirs in Japan, ignoring small check dams (Sabo dams) built for sediment-related disasters.

Fig. 4. The relationships between watershed area and unit SED and LW discharges. Black circles indicate watersheds having more than one dam upstream, and open circles indicate watersheds having no dams upstream. Solid and dashed lines show equations of the best models in dammed and undammed watersheds.

Fig. 5. A century of land use change in Japan. (A) Areas of conifer-dominant forest, broadleaved forest, and wasteland calculated from the database of Himiyama (1995), and (B) the forest volumes of natural forest (broadleaved) and plantation forest (conifer) (data provided by the Japanese Forest Agency.

Fig. 6. Photographs of the Tateishi mountain range in Shiga Prefecture illustrating drastic change in vegetation cover in the mountain ranges of Japan over the past 100 years (photos

provided by the Shiga Forest Bureau).

Fig. 7. The differences in mean low-flow bed elevation between period I and other periods (II - IV) (I: 1960–1974, II: 1975–1989, III: 1990–1995, and IV: 1996–2000). “Number of reaches” refers to the number of river reaches (sampled at 1-km intervals) in each category of change of low-flow riverbed elevation. Riverbed degradation dominates both gravel-bed and sand-bed rivers.

Fig. 8. Typical Japanese river landscapes of gravel-bed rivers showing: (A) a valley floor in the 1950s covered with sediment as a result of channel aggradation (Yoshii River in Okayama Prefecture), and (B) a deeply incised channel caused by sediment starvation, as viewed in the 2000s (Toyohira River in Hokkaido Prefecture).

Fig. 9. Percentage of forested areas sampled at 1-km intervals along rivers over the past 40 years in six rivers located from northern to southern Japan. I, II, III, IV and V indicate the periods of 1960–1974, 1975–1989, 1990–1995, 1996–2000, and 2001–2005, respectively.

Fig. 10. Forest expansion on gravel bars and floodplains in the Satsunai River (also see Fig. 9). The pictures illustrate conditions on a section of river downstream of a large dam constructed in 1997.

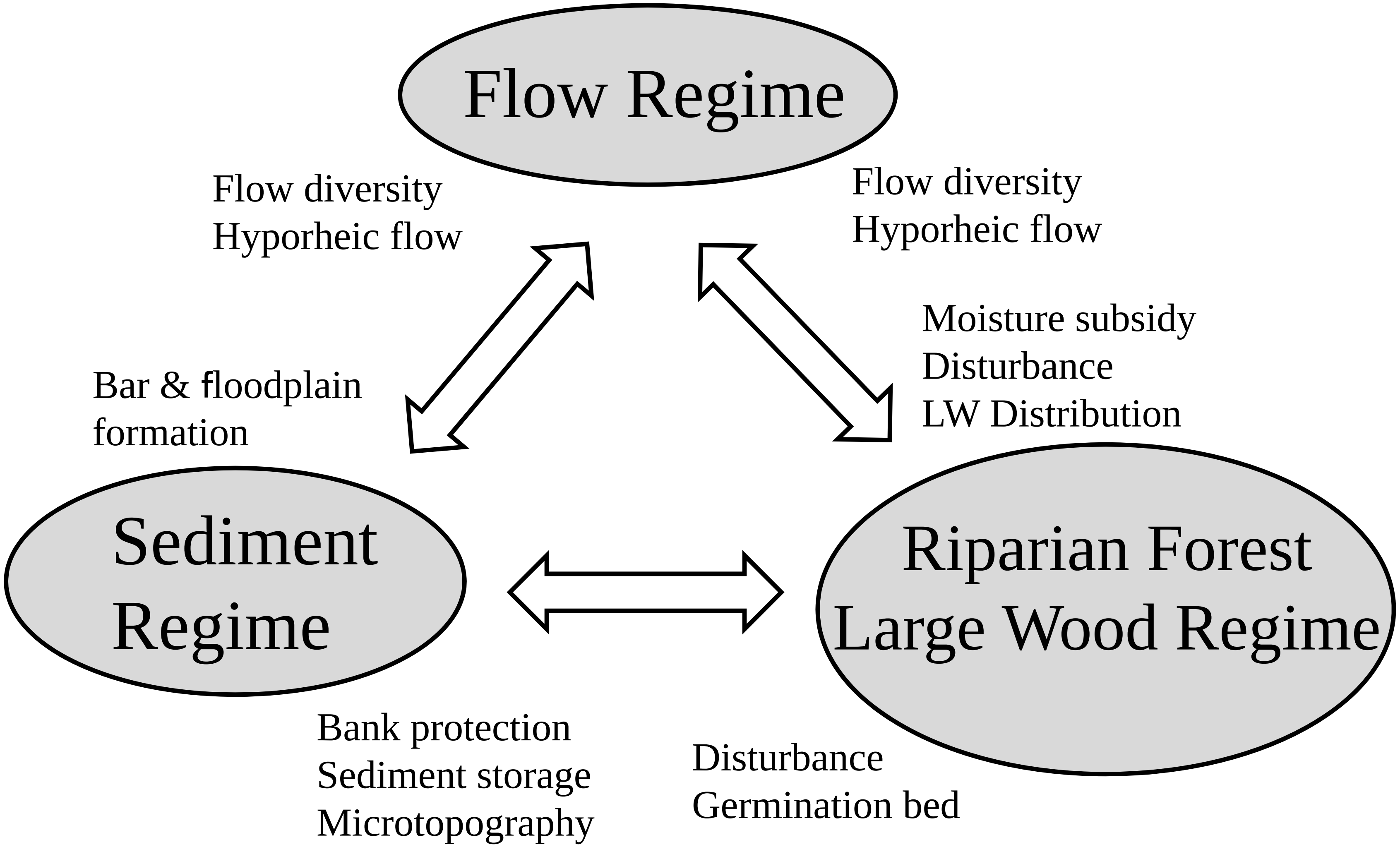
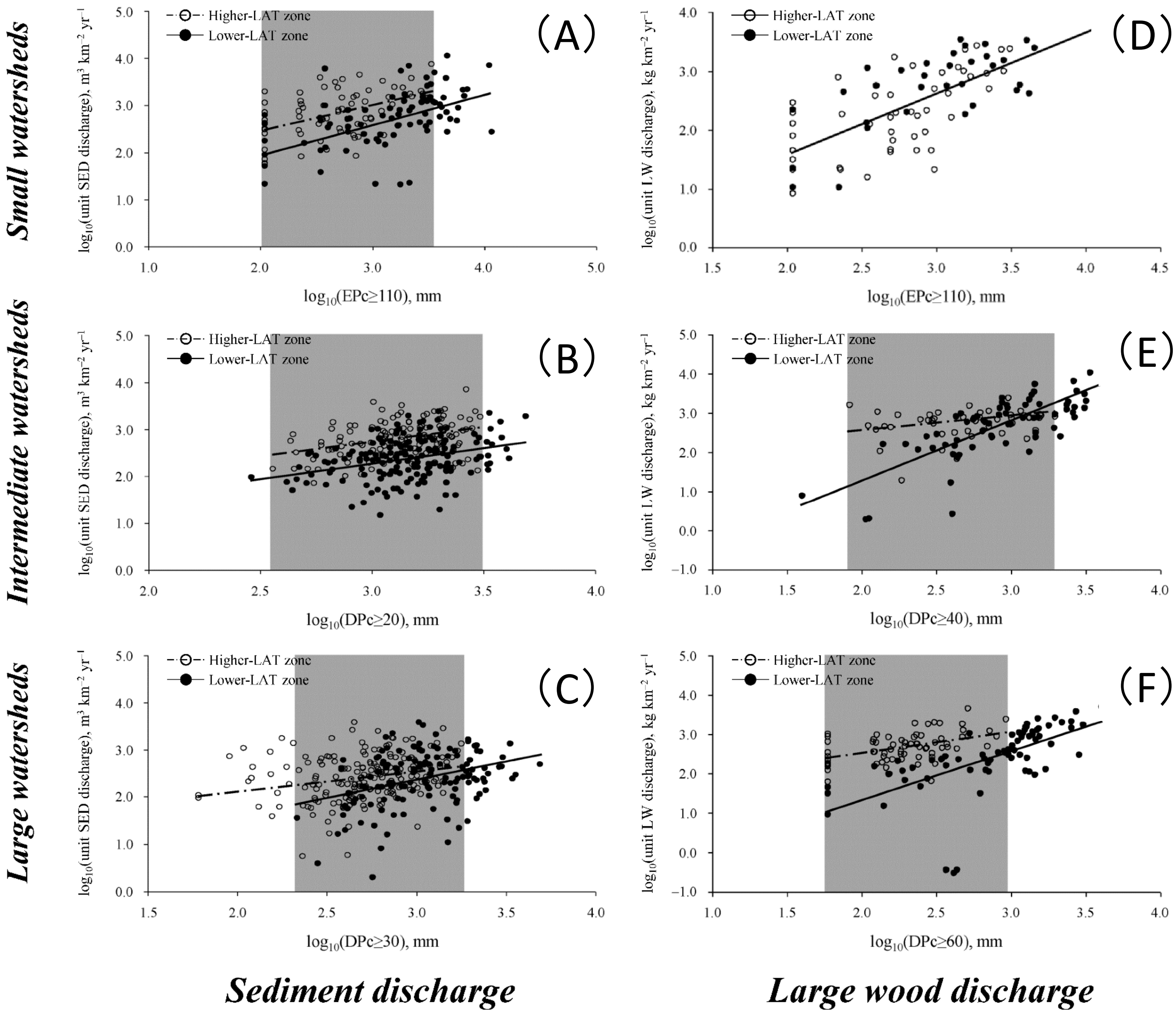

Flow Regime
Flow diversity
Hyporheic flow
Flow diversity
Hyporheic flow
Moisture subsidy
Disturbance
LW Distribution
Bar & floodplain
formation
Sediment
Regime
Riparian Forest
Large Wood Regime
Bank protection
Sediment storage
Microtopography
Disturbance
Germination bed

Fig. 1



Small watersheds
Intermediate watersheds
Large watersheds
(A)
(B)
(C)
(D)
(E)
(F)
Higher-LAT zone
Lower-LAT zone
log10(unit SED discharge), m3 km−2 yr−1
log10(unit LW discharge), kg km−2 yr−1
log10(EPc≥110), mm
log10(DPc≥20), mm
log10(DPc≥40), mm
log10(DPc≥30), mm
log10(DPc≥60), mm
Sediment discharge
Large wood discharge

Fig. 2

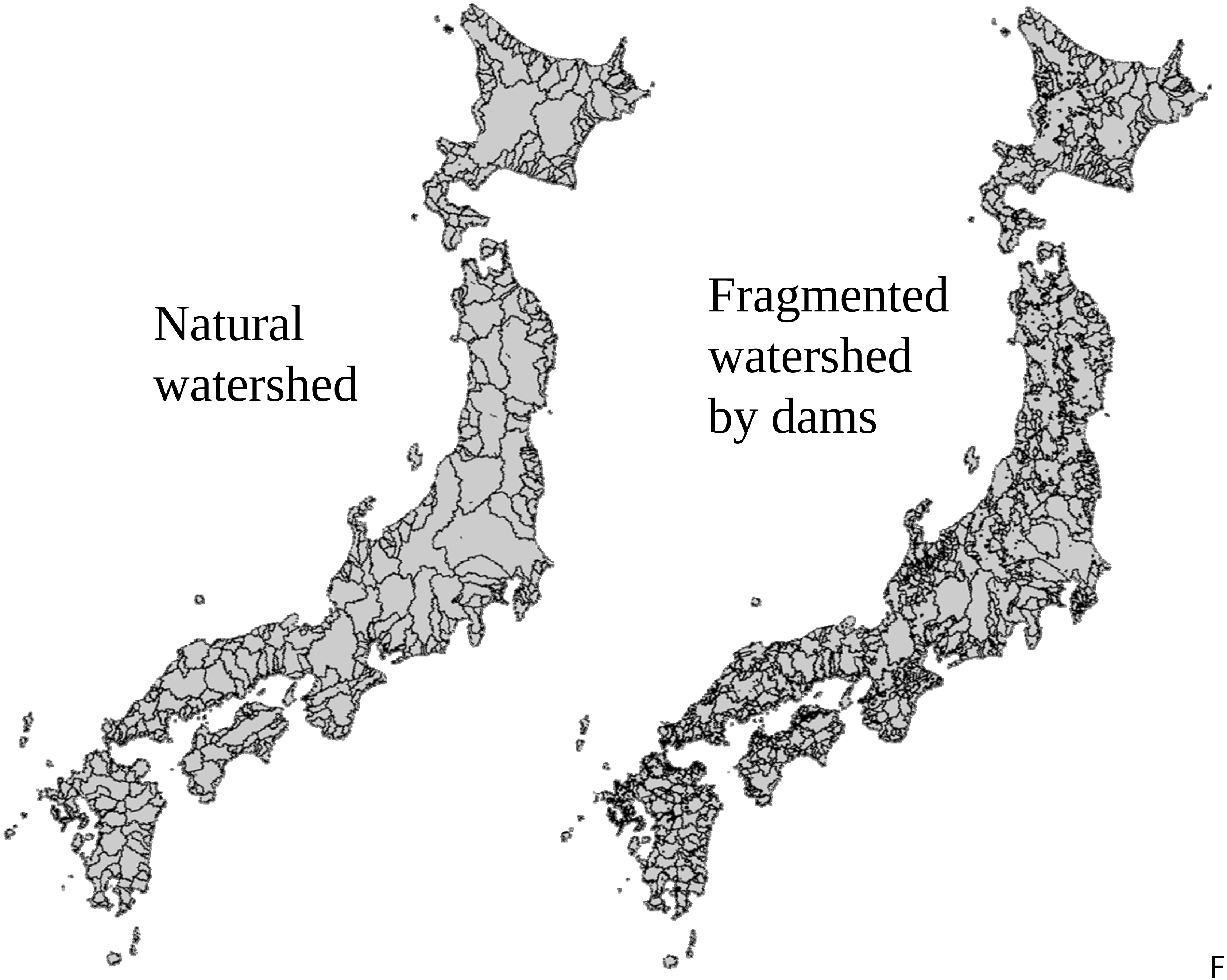
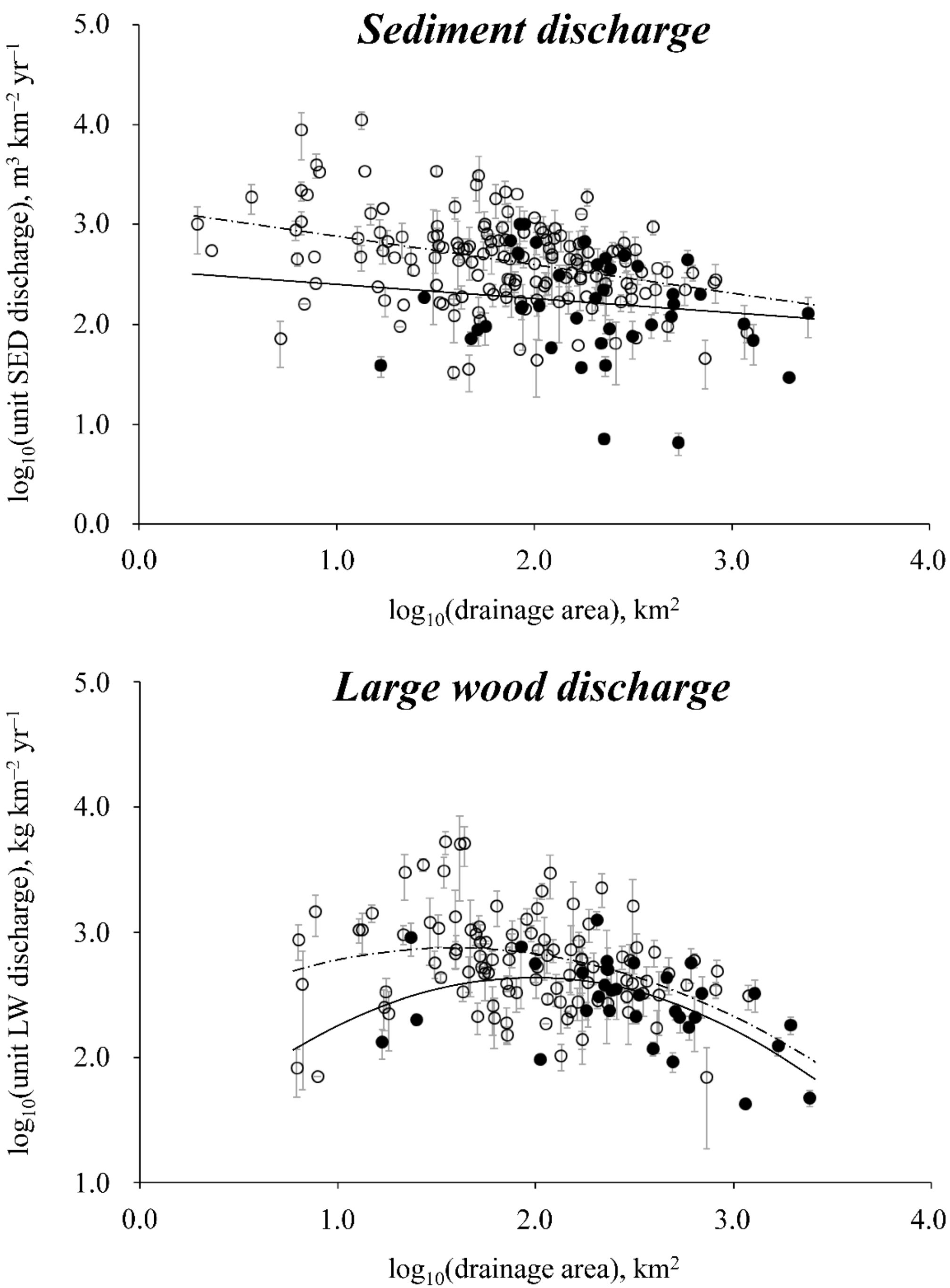


Fig. 3



Sediment discharge
log10(unit SED discharge), m3 km−2 yr−1
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
log10(drainage area), km2
Large wood discharge
log10(unit LW discharge), kg km−2 yr−1
5.0
4.0
3.0
2.0
1.0
0.0
1.0
2.0
3.0
4.0
log10(drainage area), km2

Fig. 4

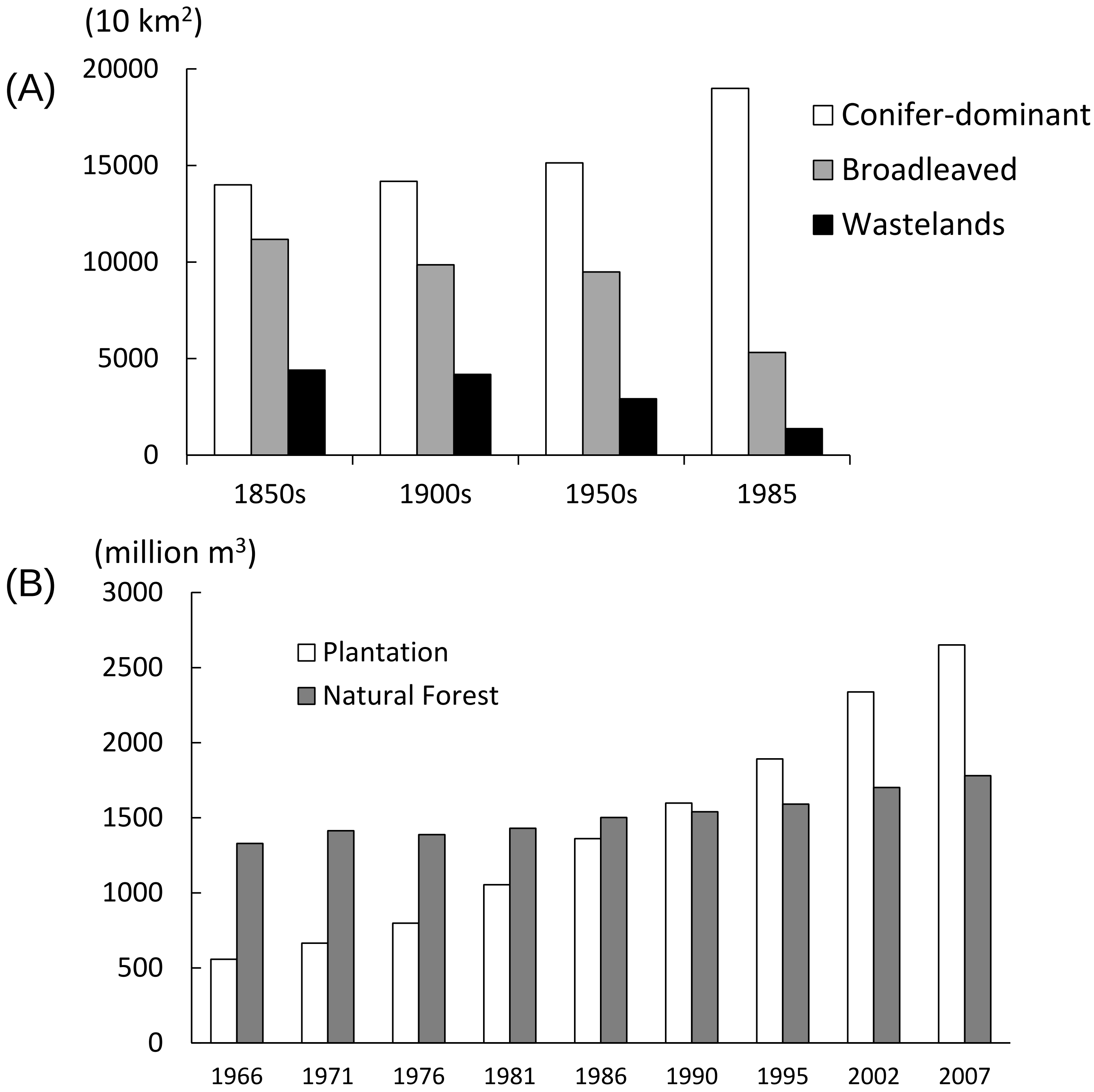

(10 km^2)
(A)
20000
15000
10000
5000
0
Conifer-dominant
Broadleaved
Wastelands
1850s
1900s
1950s
1985
(million m^3)
(B)
3000
2500
2000
1500
1000
500
0
Plantation
Natural Forest
1966
1971
1976
1981
1986
1990
1995
2002
2007

Fig. 5

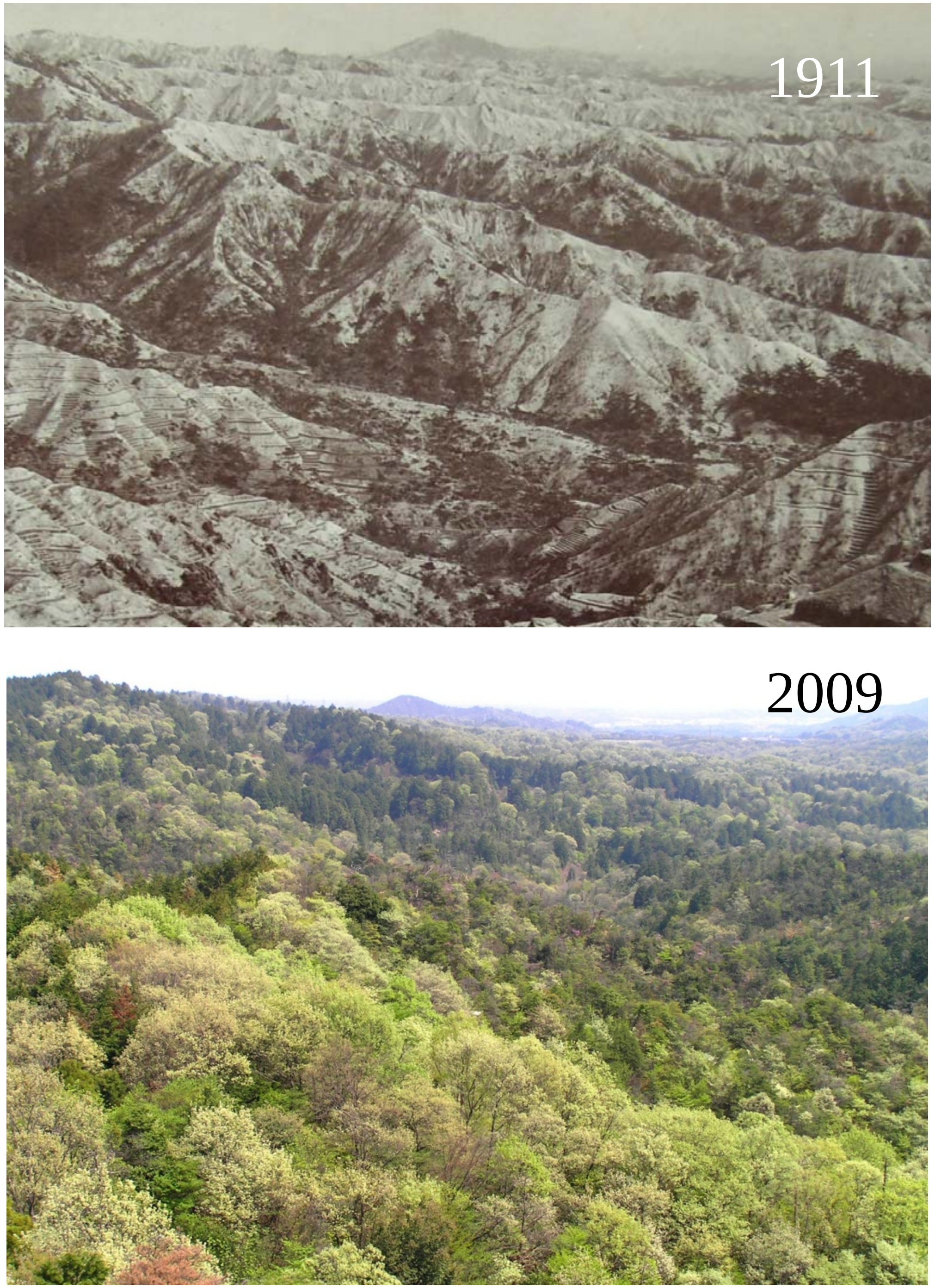
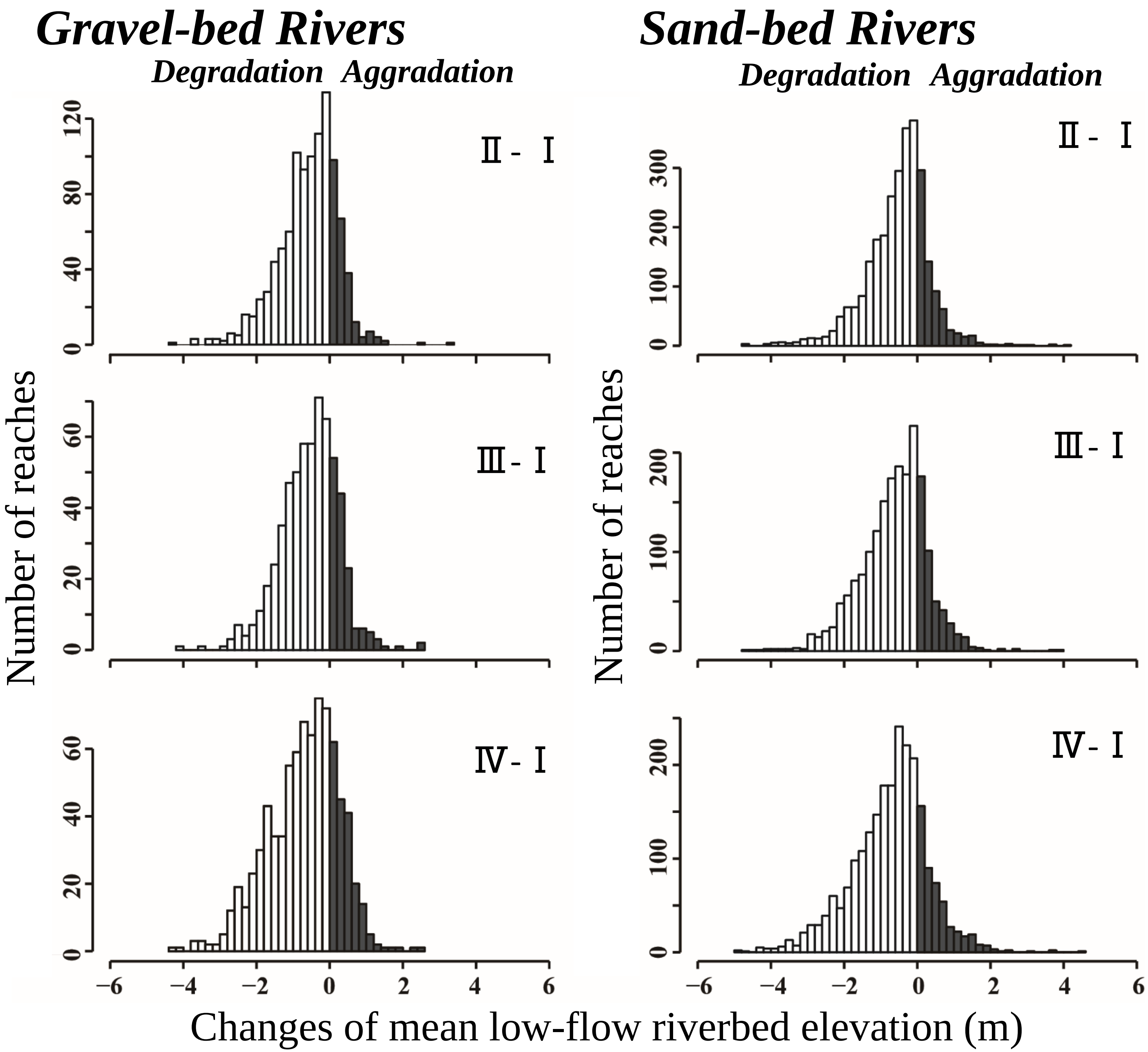


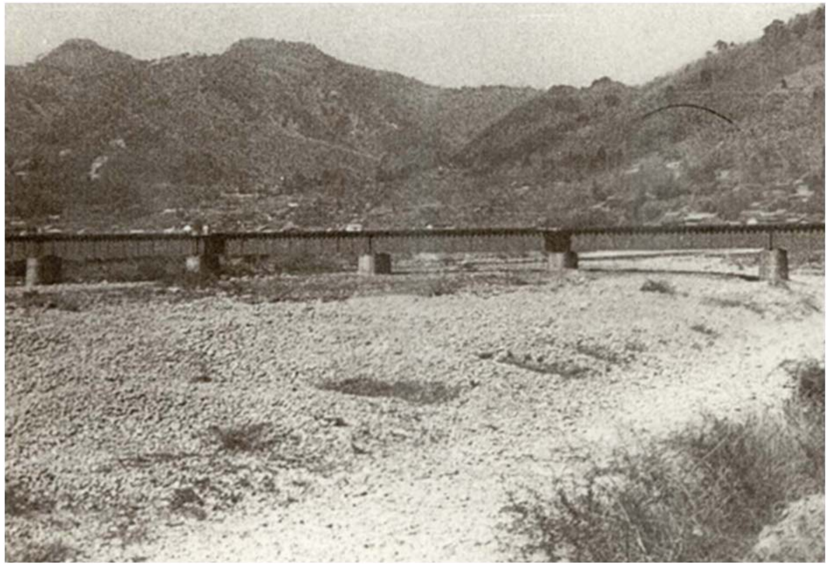
Fig. 6



Gravel-bed Rivers
Sand-bed Rivers
Degradation
Aggradation
Degradation
Aggradation
Ⅱ - Ⅰ
Ⅲ - Ⅰ
Ⅳ - Ⅰ
Ⅱ - Ⅰ
Ⅲ - Ⅰ
Ⅳ - Ⅰ
Number of reaches
Number of reaches
Changes of mean low-flow riverbed elevation (m)

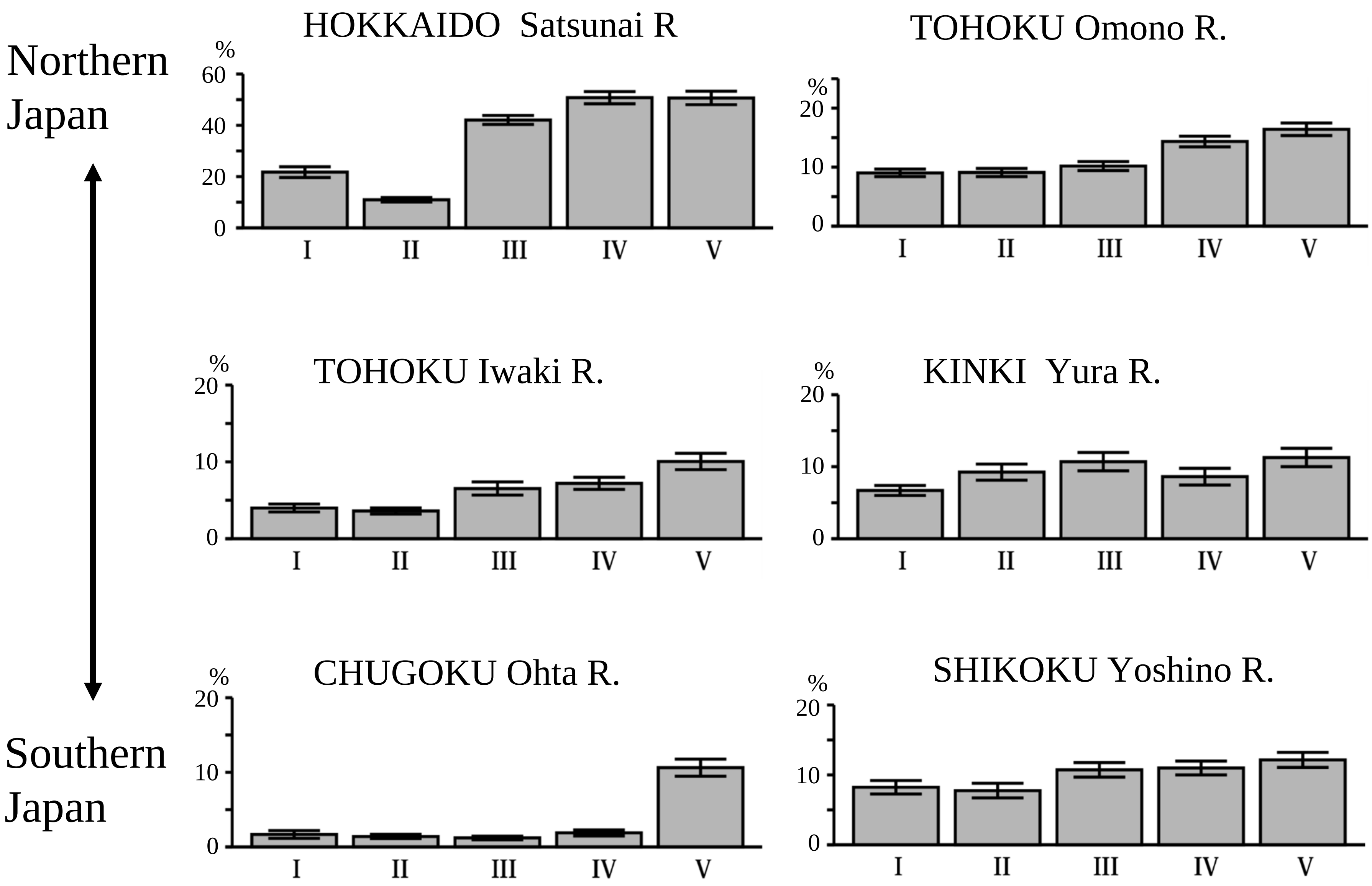
Fig. 7

(A)



(B)

Fig. 8



Northern Japan
Southern Japan
HOKKAIDO Satsunai R
%
60
40
20
0
I
II
III
IV
V
TOHOKU Omono R.
%
20
10
0
I
II
III
IV
V
TOHOKU Iwaki R.
%
20
10
0
I
II
III
IV
V
KINKI Yura R.
%
20
10
0
I
II
III
IV
V
CHUGOKU Ohta R.
%
20
10
0
I
II
III
IV
V
SHIKOKU Yoshino R.
%
20
10
0
I
II
III
IV
V

Fig. 9

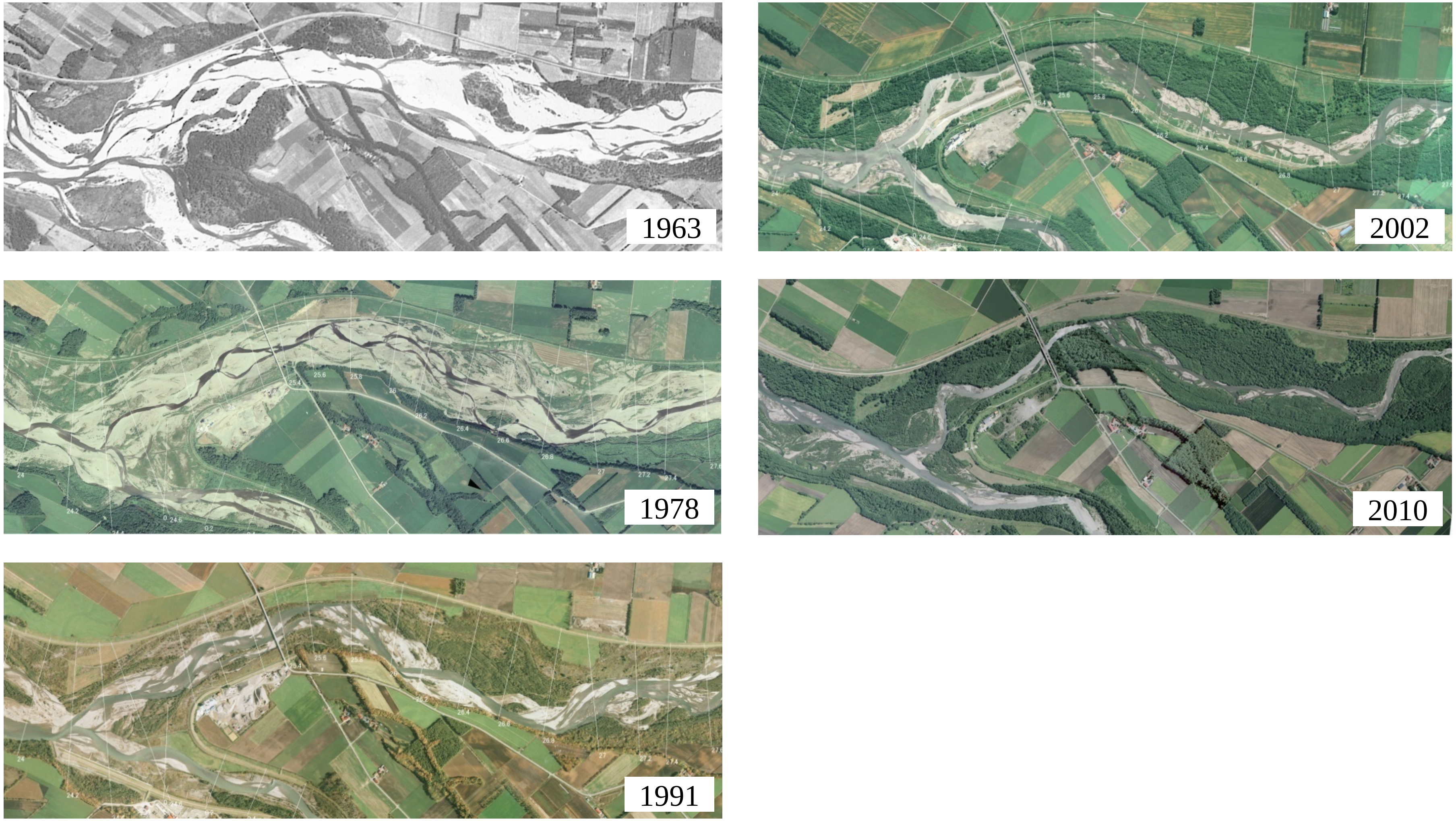


Fig. 10