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THE INFLUENCE OF THE GRAVEL SEDIMENT SHORTAGE IN MIDSTREAM RIVER CHANNELS ON RIPARIAN VEGETATION COLONIZATION

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ABSTRACT
Steep slope segments of rivers with large sediment inflow or gravelly rivers transport gravelly sediments and fill up the river channel. Originally, the vegetation cover was low in these gravelly areas. However, severe vegetation encroachment can currently be seen on these riparian areas. Therefore, we hypothesized that gravelly sediments inhibit vegetation colonization and that a reduction in movable gravelly sediments caused the change. Accordingly, the objective of our study was to assess the effect of sediment deposition and erosion on vegetation colonization. To achieve this objective, the recovery process of herbs and trees after sediment deposition or erosion was investigated using aerial photos from six rivers. A field investigation was conducted before and after a large flood at depositional and erosional locations. The aerial photo survey elucidated that the recovery of herbs or woody vegetation after flushing is substantially delayed at sites where gravel is deposited in comparison to eroded sites. The recovery of vegetation was relatively fast in sandy rivers compared to gravelly rivers. Tree recovery slowly began mainly from new recruitment at deposited sites of gravelly sediments, whereas in eroded sites, new shoots sprouted in the next spring from the collapsed live trees, achieving a rapid recovery of tree density in the succeeding years. The nutrient and moisture content of the sediment was significantly higher in the eroded sites in comparison to gravel deposited sites. The above results provided sufficient information on the effect of gravel deposition for vegetation colonization in riparian zone. The gravel layers are deposited after washing and being segregated from fine sediments during floods. Thus, they are low in moisture and nutrients compared to eroded sites in which the underlying sediments are exposed by the flood. Fine sediments released by an upstream dam enhance the nutrient and moisture contents to increase vegetation colonization. Therefore, the reduction of gravelly sediments due to gravel mining, river regulation and modifications of river basins can have a substantial effect on vegetation colonization.

Keywords: gravel sediment, steep rivers, vegetation recovery, colonization delay, riparian vegetation, nutrient and moisture

1 INTRODUCTION

The riparian vegetation in the river channel often depends on the hydrological regime and plays a major role in the hydrological cycle. When the characteristics of a river are modified or changed, the structure of the riparian community structure is reduced to a poor ecological status (Bornette & Puijalon 2011). Therefore, to maintain and support healthy ecosystems the ecological and hydrological functions of rivers need to be understood. However, very often, development and water management do not pay much attention to the complexity and multiple processes in riparian ecosystems (Richter et al. 2003). The greatest challenge is to understand the physical and ecological processes within these systems and the interactions and feedbacks of those processes. However, this is vital for the preservation of riparian ecosystems or the restoration of ecosystems to their typical form.

River basins have been gradually de-forested over a long period, and the fine sediment inflow to river channels has increased. In fact, rivers flowing in large flat areas transport only fine sediments, which are deposited and accumulate along the shoreline, narrowing the channel width (Prosser et al. 2001). As these fine sediments contain enough nutrients and moisture, vegetation can easily colonize this area (Asaeda et al. 2015b).

In contrast to long and flat continental rivers, Japanese rivers are short and steep, and the riparian area was originally covered with gravelly sediments. However, these gravelly habitats have recently been covered with thick vegetation compared to the 1950s, when the fraction of vegetation cover was nearly zero (Asaeda et al. 2013). Nevertheless, the exact reason is not yet clear. In the meantime, extensive river gravel mining in the recent past, intensive river regulation activities and afforestation in river basins, which limit sediment production, have occurred in almost all rivers in Japan (Asaeda & Sanjaya 2015). Therefore, we hypothesized that the reduction of gravelly sediments in river channel may have significantly contributed the difference in Japanese rivers. Then, an investigation was carried out to understand whether the course sediment and its interaction with riparian vegetation colonization in the context of Japanese rivers could be a better example for filling the information gap between gravelly sediment and vegetation colonization resistance.

2 METHODOLOGY

2.1 Site selection

Site selection was based on the availability of contiguous aerial images at suitable scale (less than 1:20000) and resolution (less than 1 m) for 5 to 10 years after a major flood event, the availability of flood level data for the period of the aerial images obtained, and the bed sediment type of the rivers. These factors were crucial for evaluating the period of vegetation colonization after erosional or depositional processes. The selected rivers for the analysis are shown in Figure 1.

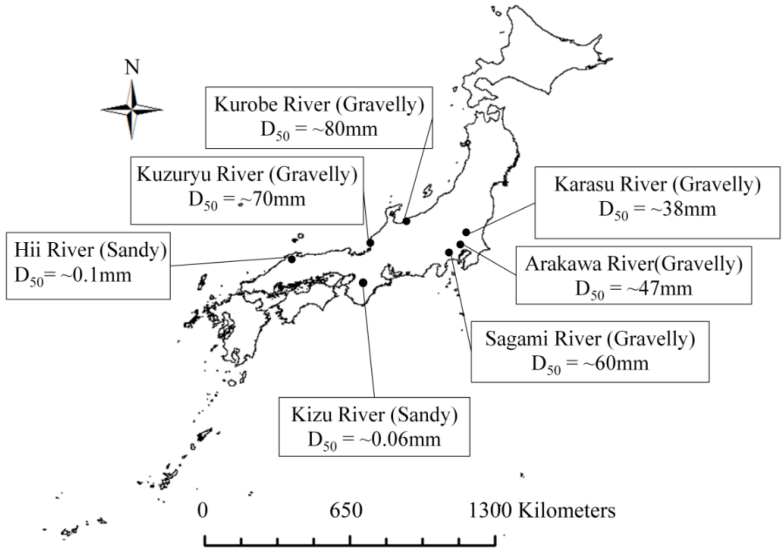

Figure 1. The distribution of the studied rivers in Japan (D_{50} denotes the 50% particle size in each river)

2.2 Aerial photo survey

For the aerial photo analysis, contiguous aerial photos were obtained from the Geo Spatial Information Authority of Japan (http://mapps.gsi.go.jp/maplibSearch.do#1), and the flood level data for the relevant rivers were gathered from the Water Information System MLIT, Japan (http://www1.river.go.jp/). ArcGIS 9.3 (ESRI Inc., USA) software was used for georeferencing and processing the aerial photos. The deposition or erosion was identified by comparing the characteristics of the channel and the vegetation in a particular area before and after the flood. In addition, the river cross sectional data obtained in every five year intervals supported for confirming the erosions and depositions. Then, the vegetation transition was observed over time, starting from the year the deposition or erosion was identified. Then, the number of years that it took for trees and herbs to invade approximately 10% of the total area were count as the delay time (Müllerová et al. 2005). The aerial photos were obtained for the analysis for Arakawa River from1976-1987, Kurobe River from 1993-2007, Sagami River from 1972-2000, Kuzuryu River from1982-1994, Hii River from1976-2004 and Kizu River from 2004-2012 respectively. Altogether, 34 independent depositional locations and 35 erosional locations were studied by contiguous aerial photographs.

2.3 Field survey

In addition, field investigations were carried out at Kumagaya Sandbar in Arakawa River and a sandbar in Karasu River. All trees on the Kumagaya Sandbar were surveyed in January 2007 to obtain their GPS location, height and diameter at breast height. There was a large flood on 7 to 9 of September 2007, and the entire sandbar was inundated. All individual trees after the flood were surveyed from November 2007 to January 2008. New recruitments and the vegetative recruitments from fallen but live trees were also recorded. The elevation of the sandbar from the mean water level was surveyed in 2007 and 2008. Herbs were sampled in 2010 and 2014 at 16 points across the bar with 50 cm × 50 cm quadrats from July to October, when the herbs retain their largest biomass. The collected herbs were carefully cleansed by tap water. Then, they were separated into species and subdivided into above and belowground biomass. The dry weight was measured for the above and belowground biomass after drying at 85°C for 48 h in an oven until constant weight was obtained. A known volume of sediments was sampled separately for stones and fine sediments (approximately less than 1 mm in diameter) at herb sampling points. Sizes of all stone samples were measured and the fine components were sieved, according to (ASTM 2002) , to obtain the mean particle size distribution. Particles less than 0.2 mm in diameter were weighed before and after drying to obtain the moisture content, and they were used to measure the total carbon and total nitrogen contents by CHN coder (Yanaco, MTA 330 C).

Herb biomass and soil sampling was conducted in one of the major tributaries of the Tone River, the Karasu River, near its confluence with the Tone River (36°16'1.12"N, 139°10'39.10"E). Ten 50 cm x 50 cm quadrats, Q1 to Q10, were sampled along a cross-section from the levee to the shoreline, with approximately 20 m spacing between quadrats covering the eroded, deposited and undisturbed sandy soil. The sampling was conducted August 4, October 5 and November 16, 2012. During this period, three floods occurred, on September 1, September 5 and September 21, in which 8 of the 10 quadrats were inundated, with the two at the highest elevation remaining unflooded Q1 and Q2 were located in the relatively elevated area. The flood recurrence is approximately once in 10 years in this area. Q2, Q3 and Q4 were on the river terrace, covered with herbs. From Q1 to Q4 were composed of sandy soil. From Q5 to Q8 were on deposited gravel, which were transported by the floods. Finally, Q9 and Q10 were at the shoreline and eroded by the flood. Particle size, total nitrogen, total carbon and moisture content were analyzed for selected quadrats, including the erosional and depositional sites.

2.4 Statistical analysis

The collected data were statistically analyzed by SPSS for Windows (release 13, SPSS INC., Chicago, IL) software. The homogeneity of variances and the normality of data were tested by Levene’s test prior to statistical analyses. A one-way ANOVA, together Tukey’s post-hoc test, were used to compare means and all p-values were considered significant at <0.05.

3 RESULTS AND DISCUSSION

Two types of tree recruitment occurred after the 2007 flood in Kumagaya Sandbar in Arakawa River. Little new recruitment of trees from seeds was observed, with most growth from the sprouting of fallen trees. Vegetative growth was the dominant type in both the depositional and erosional sites. Most of the collapsed trees were buried and died in the depositional sites, whereas in the erosional site, the trees were alive, although collapsed, and new leaves emerged the following spring. Therefore, there was a resistant for new recruitment of trees in the depositional site. In addition, the new recruitments from seeds were significantly suppressed in depositional site in comparison to erosional site (Figure 2).

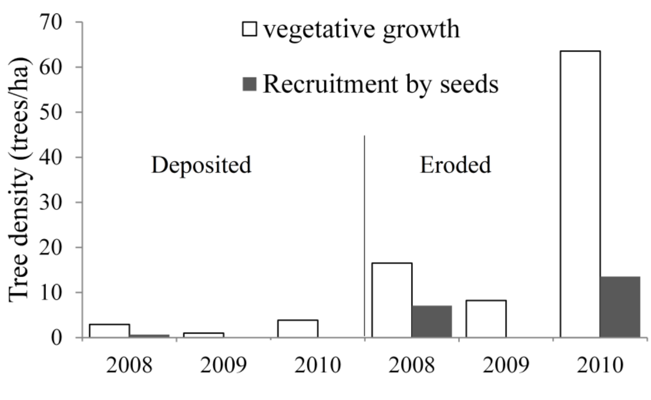

Figure 2. Observed tree density in consecutive years after the flood on the depositional site and erosional site at Kumagaya Sandbar in Aarakawa River

In the sediment samples collected from the sandbar, three years after the flood, fine sediment was a greater fraction at the erosional site, with D_{50} (50% sediment particle sizes) values of 4.7 ± 1.1 cm and 1.7 ± 0.7 cm at the depositional and erosional sites, respectively, in the Arakawa River, whereas at the Karasu

River sites, D_{50} was 3.32 ± 2.44 cm at the depositional sites and 0.047 ± 0.013 cm at the erosional sites as sandy sediments were deposited at the former.

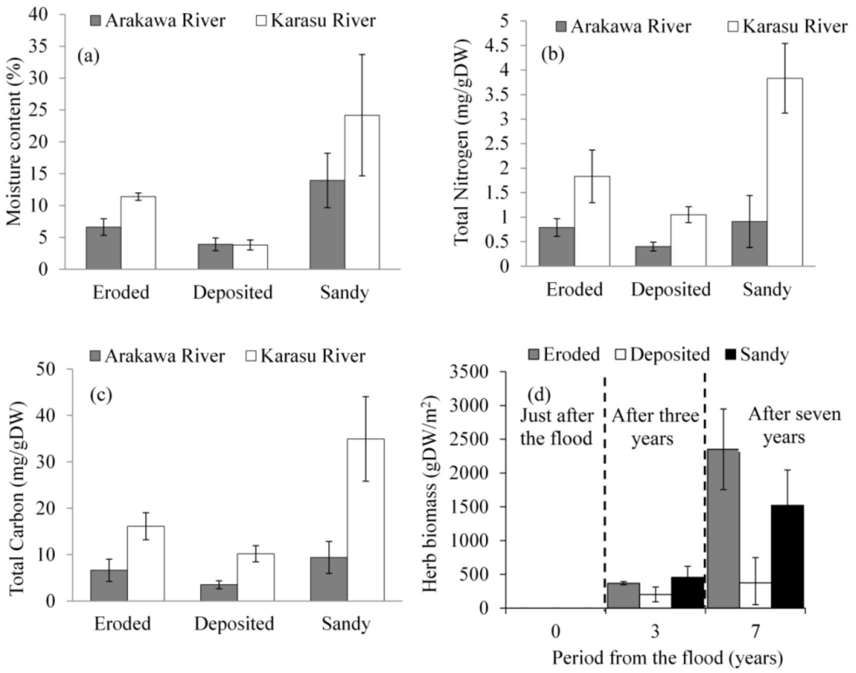

Figure 3. The moisture, total carbon, and total nitrogen contents in the soil in 2010 in the Ara River on the Kumagaya Sandbar, on the sand bar at the conjunction of the Karasu and Tone rivers in 2012 and the herb biomass on the Kumagaya Sandbar, three and seven years after the flood (Error bars indicate standard deviation)

The moisture content and total carbon (TC) and total nitrogen (TN) concentrations of the fine sediment components (less than 0.1 mm) are presented in Figure 3. A higher moisture content was encountered in the sandy and erosional sites, whereas moisture was significantly lower at the depositional sites (F = 24.38, p < 0.0001) in the Arakawa River; similarly, moisture was significantly lower in the depositional areas in the Karasu River (F = 123.1, p = 0.0001). The TC and TN concentrations were significantly higher in the sandy and erosional sites in comparison with the depositional sites (F = 4.80, p = 0.042; and F = 5.76, p = 0.026, respectively, for the Arakawa River; and F = 13.785, p = 0.006; and F = 16.792, p = 0.003, respectively, for the Karasu River). Moreover, the herb biomass was significantly lower at deposited site than in eroded or sandy site even after seven years the flood (Figure 3d).

With the aerial photo survey, it was observed that the sediment deposition suppressed the vegetation colonization in gravelly rivers in comparison to sandy rivers. For instance, a major flood with a maximum discharge of 2943.2m^3/s occurred on 19th September 1991 in Sagami River. The sediment deposition in Figure 4a, was observed after the flood. The next major flood occurred on 16th September 1998 with a discharge of 2646.3m^3/s. After the sediment deposition at the end of 1991, the vegetation colonization was observed by 1997 June. Similarly, a large flood with a discharge of 2100.30 m^3/s occurred on 29th September 2004 in Kizu River and there was not a major flood until the flood occurred on 8th October 2009 with a discharge of 3376 m^3/s. Figure 4b shows the deposition of a sandbar at the 2004 flood in Kizu River. However, the vegetation colonization was observed by 31st October 2005. Therefore, fast vegetation colonization was seen in sandy Kizu River in comparison to gravelly Sagami River.

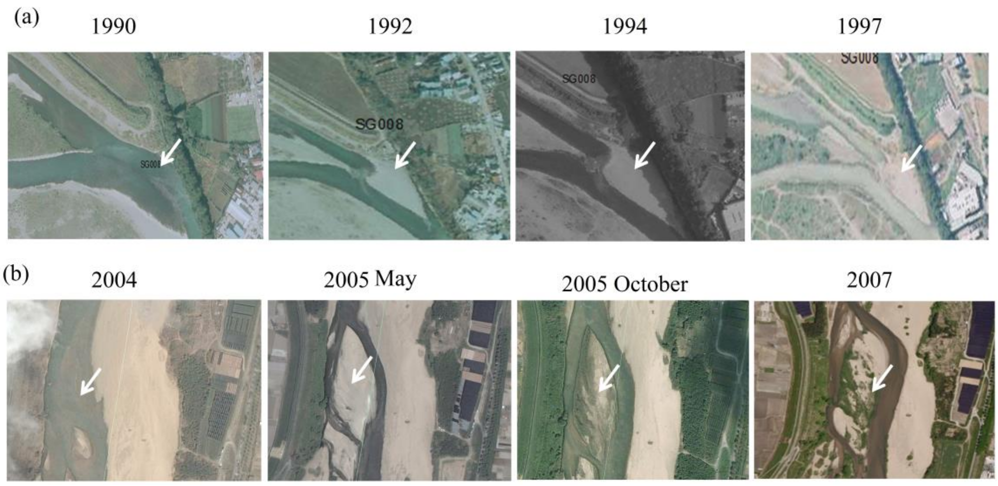

Figure 4. Contiguous observations made from aerial photographs at sediment deposited location in the Sagami River (a) and Kizu River (b) (the arrows indicate the sediment deposited location)

When consider all the deposited and eroded sites observed by aerial photos, herbs grew at the erosional sites even in the first year after the flood, whereas it took approximately 2.9 ± 0.7 years at the depositional sites in gravelly rivers and 1.2 ± 0.4 years in sandy rivers (Figure 5a). The herb colonization delay was significantly higher at depositional locations (F = 119.05, p < 0.0001). The observed delay in tree colonization was approximately 6.5 ± 1.5 years at the depositional sites in gravelly rivers. The shortest herb colonization delay was observed in the Kizu River for both depositional and erosional sites. Similarly, the shortest tree colonization delay was observed in the sandy Kizu River (Figure 5b). Tree colonization was significantly delayed at depositional locations in comparison with erosional locations in gravelly rivers (F = 29.05, p < 0.0001).

Since a significant delay of vegetation colonization was observed at gravelly sediment deposited sites both by field observations and aerial photo survey, elucidating the background reasons are important. The basic requirements for plant growth, such as nutrients and moisture, are crucial factors if a sufficient seed bank exists for vegetation colonization (Goodson et al. 2002). The moisture and nutrient contents were significantly lower on the depositional gravelly sediments, in comparison with the erosional and non-erosional sandy soil of the studied sandbars. In general, the high permeability and the low absorption of moisture in the riparian gravelly substrates account for the low moisture and the low inorganic nutrient availability for vegetation (Toda et al. 2005). Suspended fine sediment and organic matter settle in shallow inundation areas or in areas with declining water levels at the later stage of floods, which gradually increases the fraction of fine sediments that contain moisture and nutrients in those areas.

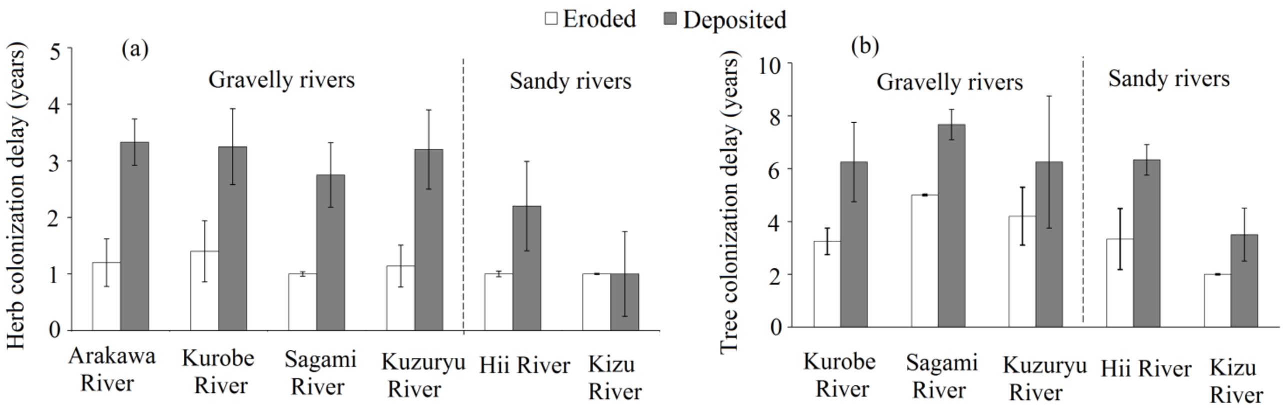

Figure 5. The observed herb colonization delay (a) and tree colonization delay (b) at different depositional and erosional sites in the studied rivers (Error bars indicate standard deviation)

In addition, atmospheric fallout and nitrogen fixation are the primary nitrogen sources in the riparian zone (Asaeda et al. 2015c), except for anthropogenic nitrogen supply. However, fine sediments and nutrients cannot accumulate sufficiently on a gravelly substrate before being disturbed by flood inundation. Therefore, understanding the different mechanisms between erosion and deposition related to nutrients, moisture and seed availability is important.

In our study, vegetation colonization occurred more quickly on erosional sites in gravelly rivers, whereas no significant difference was observed between the erosional and depositional sites in sandy rivers. On erosional sites, the underlying sediments may expose after the removal of the gravelly sediment on the surface. The exposed substrate contains the original seed bank of woody and herbaceous plants, the original levels of organic matter, moisture and nutrients, and fine sediments in the matrix of gravelly sediment, although partially removed by interstitial currents through the surface stone layer (Hill 2011). Therefore, herbaceous vegetation may colonize soon after the flood, even though it requires relatively high amounts of nutrients compared with trees.

In mountainous islands and peninsulas, such as Japan, rivers are short and steep, and have only a short flat area before flowing into the sea (Yoshimura et al. 2005, Kantoush & Sumi 2010). Particularly in the monsoonal zones, they are often subjected to short but high floods with respect to their catchment size. During these floods, a high gravelly sediment load is widely distributed over and within the midstream channel and the riparian zone (Kale & Hire 2004). Organic matter and fine sediment adsorbed to this gravelly sediment are washed off during transport. Gravelly sediment is transported along the bed surface, whereas litter and seeds float as they are transported, and fine sediment is carried in suspension (Kondolf et al. 2014). Moreover, it is well documented the influence of the soil particle size and nutrient retention in riparian soil (Bechtold & Naiman 2006, Toda et al. 2005). Toda et al. (2005) demonstrate the negative relationship between soil total nitrogen content and particle size in riparian soil when increases the particle size. Therefore, the gravelly sediment lacks fine sediments and organic matter, which otherwise retain moisture and nutrients for a long period after a flood. Thus, the accumulation of fine sediment is required to increase the moisture and available inorganic nutrients before the development of a large colony of herbaceous vegetation is possible. However, accumulation of fine sediment and organic matter is a slow process in the absence of inundation (Asaeda & Rashid 2012). This could be a reason that the vegetation colonization was significantly delayed in the depositional areas in the gravelly rivers compared with the sandy Hii and Kizu Rivers.

Considering these factors, the major driving force of extensive afforestation in Japanese river systems seems related to the major outcome of our study, which was a delay in vegetation colonization on gravel deposits. At the same time, the reasons given by previous studies are equally important. In Japanese rivers, flood control projects curtail the peak discharge of floods, which reduces the flushing effect of streams on riparian vegetation (Azami et al. 2004). However, the reduction in flood levels is not large in many rivers and is compensated for by the intensification of flood peaks due to climate change (Knox 1993, Milly et al. 2002, Ikeda et al. 2005, Luo et al. 2015). Therefore, no clear relationship has existed between peak flood volume and vegetation coverage in the river channel (Asaeda et al. 2013). Although, dam construction stabilizes and fixes in place the migrating downstream channel and increases the vegetation coverage of the riparian zone, the effect is limited to approximately 20 to 30 km downstream from the dam (Uddin et al. 2014). Eutrophication of river water may accelerate the growth of vegetation, but the nutrient concentrations in river water are much less than those in soil pore water, except in highly eutrophic rivers. Thus, no correlation exists between nutrient conditions and pollution levels of water and vegetation coverage (Asaeda et al. 2013). Therefore, other fundamental mechanisms must be considered to understand excessive vegetation colonization along modern rivers.

For centuries, the upstream catchments of Japanese rivers were deforested to meet demand for wood for energy sources and construction (Conrad 1998). Thus, large quantities of sediment were discharged into the river channels. Therefore, just after the World War II, when the old aerial photos were taken, river channels in all parts of Japan were filled with gravelly sediments, mainly because of the large sediment inflows from mountainous catchments with low forest coverage and a limited number of dams. Sediment production in the upstream area has decreased due to the afforestation of mountainous catchments, as in other parts in the world (Piégay et al. 2004). To eliminate the sediment flow, erosion control projects have also been conducted in the upstream areas of steep rivers. The development of the mountain slopes for housing and agricultural lands also reduced the prior sediment production, even in the tributaries in the suburbs of large cities. In addition; large quantities of aggregates were mined from rivers during the post war reconstruction in the 1960s and 1970s. Although sediment mining was prohibited in the 1970s in many rivers, previously constructed dams and weirs continue to cut off gravelly sediment inflows from upstream mountainous reaches. Therefore, the gravelly sediment supply to downstream areas may have decreased. Therefore, the gravelly sediment supply, which can delay vegetation colonization until the next flood renews the habitat, may have reduced. Therefore, the reduction of gravelly sediment inputs may be a major reason for the significant increase of vegetation cover in Japanese rivers.

4 CONCLUSIONS

Unexpectedly, significant afforestation can currently be observed in the riparian zones of all Japanese rivers. Therefore, identifying the cause and effect of this afforestation is crucial to suggesting a solution for managing the system and for future restoration. Our study presents a new hypothesis, and the results were fairly supportive of the hypothesis. Importantly, gravel deposition was the determining factor in the delay of vegetation colonization, and with erosional processes and sand or fine sediments; the vegetation colonization process was faster. The lack of gravel sediment deposition may play a major role in generating thick vegetation in modern Japanese rivers.

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