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The role of forest stand density in controlling soil erosion: implications to sediment-related disasters in Japan

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Abstract The role of forest stand density in controlling soil erosion was investigated in Ehime Prefecture, Japan. The main objective was to compare soil erosion under different forest conditions including forest type, species composition, and stand density as influenced by thinning operations. Relative yield index (Ry) was used as an indicator of stand density to reflect the degree of management operations in the watershed. Eleven treatments were established based on the above forest conditions. Soil loss was collected in each of the 11 treatments after each rainfall event for a period of 1 year. The paper presents summary data on soil loss as affected by forest conditions and rainfall patterns. Findings showed that an appropriate forest management operation, which can be insured by stand density control, is needed to reduce soil loss. The present study plays an important role in clarifying technical processes related to soil erosion, while it helps linking these elements to current Japanese forestry issues and bringing new inputs to reducing sediment-related disasters in Japan.

Keywords Thinning operation · Stand density · Soil erosion · Forest management · Sediment-related disasters

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Introduction

With volcanic soil base vulnerable to erosion combined with large portion of precipitation concentrating in relatively short period of time of the year (rainy season, typhoon season), Japan has experienced countless natural disasters originating in mountainous areas since the dawn of its history (Imaizumi 2001a). Although prevention of natural disasters has always been recognized as the most important function of forests by the people in Japan during the recent few decades (Imaizumi 2001a), problems due to sediment-related disasters are still important threats in Japan.

Mainly sediment-related disasters often occur following an important amount of rainfall and leave important damages. This case often occurs during heavy rains brought by typhoons hitting Japan. In 2004, one of the ten typhoons that hit Japan left a lot of damages in the Ehime Prefecture in Shikoku Island (Ehime Prefectural Government 2006), where the present study has been conducted. According to the statistics, 14 people were reported dead, ten others injured during the event. Costs of direct damage were estimated at 19 billion yen (Ehime Prefectural Government 2004). However, the question remains: whether the sediment-related disasters are related to forest characteristics or forest management? Although this affirmation is far from being unanimously accepted by concerned researchers, some studies reported that sediment-related disasters occurring in Japan is related to forest management (e.g., Ohta 2006; Ehime Prefectural Government 2006).

This study is focusing on the clarification of the effect of forest types, species composition, and forest management operations (these three components are referred as "forest condition" in the paper) on soil erosion. Related outputs are considered important to combat sediment-related disasters in Japan. Therefore, the relationship between soil erosion and the occurrence of sediment-related disasters is not the main purpose of this study. However, the paper would focus on linking technical data on forest condition, soil erosion, and its relevance to forest policy.

Poorly managed cypress plantations in Japan suffer from surface erosion, as first noted by Akenaga and Shibamoto (1933). Also, surface erosion generally does not occur in forests because forest litter and undergrowth form a protective surface cover. However, Japanese cypress plantations have little surface cover, in part, because cypress litter decomposes into small pieces within 2 or 3 months (Sakai and Inoue 1988) and a rapid disappearance of its leaf litter from the soil surface on the slope has long been recognized (Tsukamoto 1991). In addition, some silvicultural practices like the introduction of undergrowth and increase of litter on the forest floor are suggested so far; the effects, however, are not made clear quantitatively and forest management has not been established from the view of soil conservation in Japanese cypress plantations (Hattori et al. 1992). The significance of cover near the ground for erosion processes on slopes has previously been pointed out in artificial rainfall experiments (Mihara 1951; Kawaguchi and Takiguchi 1957; Murai and Iwasaki 1975). Tsukamoto (1991) found that rain factor had strong influence on Japanese cedar and especially cypress litter movement. Miura et al. (2003) reported the importance of forest cover conditions on young cedar plantations; Tsukamoto (1991) pointed out that, in the case of cedar species, litter does not move easily because it remains attached to branches on the forest floor for a long time. Also, previous studies showed that more mass mortality of trees especially due to xylem degradation seem to increase in the future in unmanaged conifer forests (Kuroda 2003); however, Sato (2007) reported that thinning prevents insect and disease outbreaks. This information is important when considering forest stability and its fragility in time of disasters. Furthermore, preliminary results in the study area determined that poorer soil physical properties were found in forest plantations without thinning compared to those with thinning operations (Razafindrabe 2004; Razafindrabe et al. 2006a, b).

Although soil erosion researches have been done on various forested mountains in Japan (Mihara 1951; Murai and Iwasaki 1975; Miura 1995; Okura et al. 1996; Kitahara et al. 2000; Miura et al. 2003), there are scarce information showing the relationship between soil erosion and stand density, especially using *relative yield index* (Ry) as an indicator of stand density. *Relative yield index* gained trust for its ability to characterize forest plantations for an objective of forest management aiming at timber production (Ando 1982). This indicator is widely used by forest managers in the country, supported by the Ministry of Agriculture, Forestry, and Fisheries of Japan. Two models for Japanese cedar and Japanese cypress, applicable for the area of Shikoku Island in Japan, were used to calculate *relative yield index* for each site. Ry values were extracted from the density management curve developed by Ando (1982) based on stem density (trees per hectare), standing volume (m^3/ha), tree height (m), and diameter at breast height (DBH; cm). Since forest plantations with late thinning operations occupy a vast area among total forest cover in Japan (Tanaka and Otsuka 1997), more studies are needed to clarify their contributions to sediment-related damages or disasters occurring in low-stream areas.

We focused on the assumption that soil loss is sensitive to forest conditions change, especially on stand density. Therefore, this study compared soil loss in natural broad-leaved forest and Japanese cedar and cypress plantations with different stand density, mainly following forest thinning operations. For that, soil loss collected after rainfall events from October 2005 to September 2006 was compared in Japanese cedar and cypress plantations with different stand density as well as natural broad-leaved forest.

State of Japanese forests and related issues

Approximately 25 million hectares, corresponding to two thirds of Japan's national land area is covered by forests, most of which are located in steep mountainous areas. Approximately ten million hectares of forests or 41% of the total forest area are planted mainly with conifer trees. Those man-made forests are mainly composed of two species: Japanese cedar (*Cryptomeria japonica* D. Don, Taxodiaceae) covering 44% of total man-made forests and Japanese cypress (*Chamaecyparis obtusa* Sieb. & Zucc. Endl., Cupressaceae) with 24%. Approximately 30% of the total forest area is owned by the national government, and the rest are private forests (Japanese Forestry Agency 2004). Within Japan's policy framework, "private forest" is defined as any forest other than those owned by the national government. Therefore, in addition to privately owned forests, "private forests" also include forests publicly owned by prefectural or municipal governments and those owned by communal bodies (Imaizumi 2001a). Most of the nationally owned forests are managed by the Forestry Agency, but some are managed by other government agencies such as the Ministry of Education, Culture, Sports, Science, and Technology mainly as University Forests and the Defense Agency mainly as training fields (ibid).

In spite of the awareness of forest policy makers on the need for forest operations in Japan, especially thinning, by elaborating "Measures for thinning" in 1971 or the "Forest stand improvement project" in 1976, "Core Forest Development Region", the "Pilot project for the Promotion of Stable-distribution of Thinned Logs" in 1977 (Handa 1988) and in 1985 the "New comprehensive project for the Promotion of Thinning", several issues still occurred. These are mainly caused by the lack of silvicultural tending (Sasse 1998). The same author reported that, around 1988, about 60% of the plantations in Japan are in the 16–35-year age group and are due, or overdue, for thinning. One of the reasons for the appearance of the thinning problem is also the insufficient knowledge and technology about thinning on the side of the forest owners (Handa 1988). Other reasons are the lack of workers to do the work because the size of the workforce has declined and the average age of workers has increased. Recruitment of forestry labor has been poor because of the relatively low pay and conditions compared with other industries and the continuing decline in rural populations since the beginning of the manufacturing boom in Japan has shrunk the pool of potential labor (Sasse 1998). Murashima (1997) reported that Forestry in Japan is different from its equivalent in other advanced countries due to natural conditions and its extremely small scale and faces serious problems referred to as "forest abandonment" due to the drastic changes brought by industrialization to the ownership structure and management, with many finding it difficult to continue forestry under private management. Another reason is the declining price of logs in Japan (Fujisawa 2004). The same author argued that the profitability of forestry as an industry has decreased consistently which further discouraged forest owners from forestry, and hence forestry itself is experiencing a tremendous decline. The Forest Planning System in Japan is regulated by the following procedures: the Minister of Agriculture, Forestry, and Fisheries prepares a "nationwide forest plan," followed by the "regional forest plan" made by the prefectural governor and the "local forest improvement plan" made by the head of the local government (Fujisawa 2004; Imaizumi 2001b). Thinning operations figures among the activities in the planning. These plans are realized through silvicultural practices for commercial forestry where the respective forest owner voluntarily executes the silvicultural plans (approved by the mayor).

Materials and methods

Study area

The study site was located 18 km northeast of Matsuyama City in Ehime Prefecture (Shikoku Island, Japan). Located in the Ehime University Forest, it contains warm to cool temperate natural forests and plantations of Japanese cedar and cypress. Annual average temperature was 15.98°C; annual average rainfall and evapotranspiration[1] were 1,332.99 and 1,148.98 mm, respectively.[2] The area is exposed to heavy rainfall during rainy season from June to July (Kurahashi et al. 2008). The study area consists of a small watershed of 191.46 ha (Fig. 1); the elevation ranges from 515 to 950 m above sea level, with slopes ranging from 30° to 50°. Forest age ranged from 22 to 62 years for Japanese cedar (*C. japonica*, Taxodiaceae) and Japanese cypress (*C. obtusa*, Cupressaceae). Natural broad-leaved forests were much older with an age range of approximately 120 years.

The area has a brown forest soil type B_C to B_D (d) corresponding to weakly dried brown forest soil to moderately moist brown forest soil, according to the classification of forest soils in Japan (Forest Soil Division 1976) with dominant granite parent material (Ehime University Forest 2002). Soil texture[3] was composed of medium sandy loam and sandy clay loam in areas with lower densities whereas high-stand-density areas showed coarse sandy loam.

[1]Evapotranspiration was calculated by Penman Monteith Equation (http://www.fao.org/docrep/X0490E/x0490e06.htm).

[2]Data are available in the Japan Meteorological Agency website (http://www.jma.go.jp/jp/amedas/).

[3]Based on Gee and Bauder (1986).

Since soil loss did not occur for rainfall intensity (r_i) less than 1.5 mm/10 min, the present study focuses on soil loss generated by rainfall intensity of 1.5 mm/10 min or above. Since only one rain gauge was available to collect all rainfall data in the study site, rainfall characteristics for natural forest and Japanese cedar and cypress plantations were the same.

Methods

Model and treatment description

Based on forest type/species composition and Ry, 11 treatments with different forest conditions were identified within the first and second subdivisions of the university forest. According to Ando (1982), Ry varies from 0.1 indicating stands with high stem density but with very low standing volume to 1.0 corresponding to the fully packed stand. Two models for Japanese cedar and Japanese cypress, applicable for the area of Shikoku Island in Japan, were used to calculate *relative yield index* (Ry) for each site. In this study, low Ry values showed mature stands having experienced a high thinning intensity added with those having experienced damage due to typhoons and gradually reducing as Ry values increased. *Relative yield index* values close to 0.80 and 0.90 represented stands without experiencing any thinning operations. Ry values were extracted from the density management curve developed by Ando (1982) based on stem density (trees per hectare), standing volume (m^3/ha), tree height (m), and DBH (cm). Characteristics of main variables considered in this study are shown in Table 1.

Measurement of transported materials

We used sediment traps to measure transported materials. Two rectangular traps (1 × 2 m), constructed by plank woods were set up in each of the 11 treatments, each with different slopes (one plot set in midslopes of less than 40°, another one in midslopes equal or more than 40°). One reason for this subdivision was to test whether there is any difference of soil loss between the two slopes based on previous results obtained from the same study area showing higher intensity of soil erosion

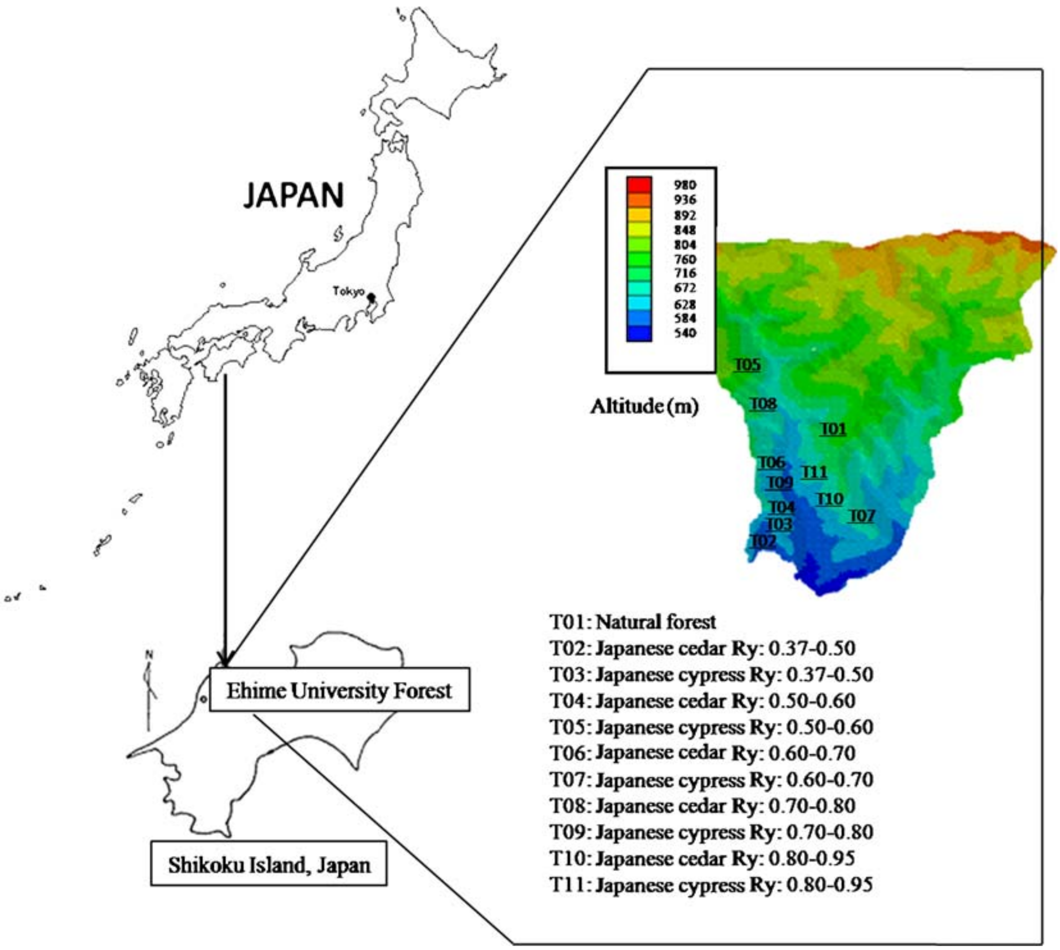

Fig. 1 Map of the study area, locations of plots considered for soil loss measurement

in plantations above 40° (Razafindrabe et al. 2006b). Within the trap, transported sediments during rainfall events were collected at its lower end in a plastic bucket preceded by a metallic tray linking the trap to the bucket. The amount of material transported was measured for 1 year after each rainfall event. In general, sediment collection was done on the following day of the event at the two sediment trap locations in each treatment. Sediments were collected manually from the tray and the bucket without leaving any particle behind. Measurements were not suspended in case of rainfall events lasting more than 1 or 2 days (this special case rarely happened during the experimentation period).

Sediments were brought to the laboratory, oven-dried, and weighed. To understand the characteristics of detached particles, oven-dried samples taken during the month of July 2006 (rainy season in the study area) were separated into three size classes, fine sand (<2.0 mm), fine gravel or litter (2.0–6.0 mm), and large gravels or litter (>6.0 mm). This classification was inspired from Miura et al. (2003) focusing on studies of the effect of floor cover against soil erosion in Japanese cypress and other species plantations. Table 2 summarizes the different characteristics of each treatment analyzed in the study.

Determination of soil organic matter

Soil organic matter, through the consideration of C/N ratio, was determined by using the CN Analyzer (MT-700 II, Yonaco, Japan). Samples

Table 1 Description of variables considered in this study

Variables	Descriptions/range (for this study)	Units
Forest type	Natural or artificial forest	–
Forest species	Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*)	–
Forest operations	Activities conducted in the forest plantations mainly concerning the reduction of number of trees (forest thinning operations)	–
Stand density	Density of tree plantations mainly based on stem density and standing volume	Trees per hectare; m^3/ha
Relative yield index	Values reflecting stand density and tree characteristics (height and diameter at breast height), comprised between 0 and 1	Dimensionless
Soil texture	Relative proportion of different grain sizes of mineral particles in a soil	–
Soil color	Observed color of the soil, based on Munsell Soil Color Charts	–
Soil organic matter	Amount of organic matter in the soil (ratio)	Dimensionless
Soil loss	Amount of soil detached and collected in a trap (bucket) after rainfall events	g/2m^2
Detached particles	Soil particles detached after rainfall events and subdivided into fine sand, fine gravel, large gravels	mm
Soil infiltration rate	Velocity or speed at which water enters into the soil after rainfall events	mm/10 min
Rainfall amount	Total amount of rainfall recorded in the rain gauge localized in the study site	mm
Rainfall intensity	Amount of rain falling within a unit of time	mm/10 min

were taken from midslopes close to traps to collect transported materials in each of the 11 treatments.

Data analysis

Statistical analyses were conducted using the Statistical Package for the Social Sciences (ver. 11.0). Most analyses were based on the two classes of slope, above 40° and below 40°. Firstly, soil loss in the 11 treatments was analyzed regardless of rainfall intensity and rainfall amount. Rainfall amount for 6 h (preceding) was chosen as an indicator of rainfall characteristics added by rainfall intensity (mm/10 min) since most rainfall in 1-day event was concentrated in 6 h preceding the maximum 10-min rainfall intensity. To be able to understand the effect of rainfall characteristics, slopes, and forest type/species to soil loss, a regression analysis with dummy variables was also conducted. Three dummy variables were considered: (1) dummy "forest type" where soil loss in natural forests is given the value of 1 and 0 in others; (2) dummy "forest species" with the value 1 in Japanese cedar and 0 in others; and finally (3) dummy "slope angle" where soil loss in areas with slope angle 40° and above (above 40°) are attributed the value of 1 and 0 in others.

Moreover, to compare soil loss recorded for each forest condition, which is the amount of soil that is lost during a rainfall event within the traps, regression analysis (with stepwise method) with soil loss as dependant variable and rainfall intensity, *relative yield index*, and rainfall amount (for 6 h) was conducted. Means of soil loss under the different classes of rainfall intensity were analyzed, based on each forest condition. General linear model analysis of variance (two-way analysis of variance) was chosen in order to test whether soil loss was statistically different between the 11 treatments. In case of significance, mean values were compared using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$. The objective was to know which treatment showed the extreme values as far as soil loss is concerned.

Based on Schultz and Cruse (1993), rainfall intensity was also classified as very low (VL), low (L), medium (M), high (H), and very high (VH) to better understand soil loss according to classes

Table 2 Characteristics of the treatments analyzed in the study

Treatments	Forest type/species	Slope angle (degree)	Volume (m^3)	Stem density (trees per hectare)	Age (years)	Ry	Clay (%)	Silt (%)	Sand (%)	Texture (0–25-cm depth)
T01	Natural forest	40 33	–	–	120	–	38.91	5.38	55.71	Sandy clay
T02	Japanese cedar	40 35	83	1,568	51	0.44	15.86	19.99	64.15	Medium sandy loam
T03	Japanese cypress	40 35	88	1,620	24	0.46	16.44	19.58	63.98	Medium sandy loam
T04	Japanese cedar	40 35	195	1,324	62	0.58	31.74	12.36	55.90	Sandy clay loam
T05	Japanese cypress	40 36	288	570	51	0.51	19.05	14.28	66.68	Medium sandy loam
T06	Japanese cedar	41 37	198	2,103	32	0.67	26.23	18.30	55.47	Sandy clay loam
T07	Japanese cypress	42 38	300	930	22	0.61	18.26	19.55	62.20	Fine sandy loam
T08	Japanese cedar	42 38	242	2,214	51	0.76	9.08	26.63	64.29	Medium sandy loam
T09	Japanese cypress	42 38	197	2,665	32	0.73	7.09	20.61	72.31	Coarse sandy loam
T10	Japanese cedar	45 37	520	1,641	32	0.85	5.13	26.10	68.77	Coarse sandy loam
T11	Japanese cypress	44 38	300	1,995	32	0.82	3.32	31.14	65.55	Coarse sandy loam

of rainfall intensities (expressed in millimeter per 10 min) of <2, 2.5 to 3, 3.5 to 4, 5.5 to 7.5, and >8, respectively.

Results

Regardless of forest stand density and rainfall intensity, results showed that soil loss recorded in Japanese cypress were the highest ($F = 4.580$; $p < 0.01$), followed by Japanese cedar. Natural forest showed the lowest values of soil loss. Results showing the influence of stand density and rainfall intensity are shown below.

Soil loss recorded in each treatment

For slope classes above 40°, the highest soil loss recorded was found in T11 corresponding to Japanese cypress with Ry 0.80–0.90 which accounted for more than one fifth of the total soil loss in the whole area in a year (Fig. 2). The second one was found in the same cypress species with Ry 0.70–0.80 (insufficient thinning operation) accounting for 18.53% of total soil loss. These results suggest that cypress species are more subject to soil erosion than other areas. As for Japanese cedar, the highest loss recorded was in plantations with Ry 0.80–0.90 accounting for 15.07% of total soil loss. Areas where thinning operations have not been conducted accounted for 64.16% of total soil loss, mostly occurring in cypress plantations (corresponding to 40.32% of total soil loss, against 23.84% for cedar species). The lowest value was found in natural forest (921.93 g/2m^2 per year), followed by cedar with Ry 0.60–0.70 (1,251.97 g/2m^2 per year) accounting for 1.83% and 2.49% of total soil loss, respectively. Similar tendencies were found for the second slope class (<40°).

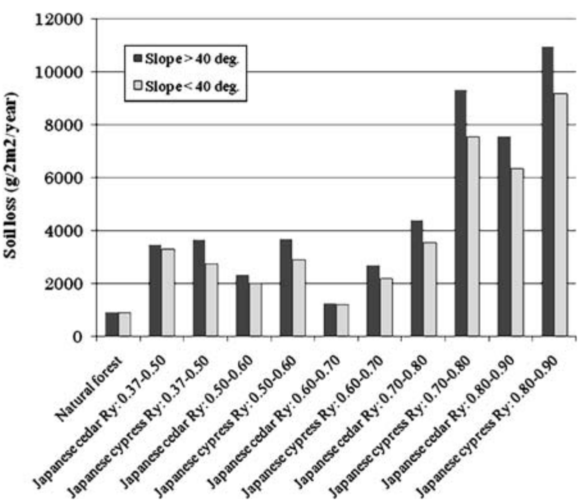

Fig. 2 Total soil loss recorded in each treatment from October 2005 to September 2006 in slope class >40°

Japanese cedar with Ry 0.80–0.90 had 6,327.42 g/2m^2 per year, which accounted for 15.15% of total soil loss. The lowest soil loss recorded was in T1 (natural forest) having a soil loss of 881.17 g/2m^2 per year accounting for 2% of total soil loss. Areas showing too high density, corresponding to Ry close to 1 where thinning operations have not been conducted, showed the highest soil loss recorded (63.59% of total soil loss). Therefore, soil loss recorded in Japanese cypress with high stand density was in general the highest in the area for both slope classes.

Soil loss based on the analysis of dummy variables

Before conducting further statistical analysis, multiple regression using dummy variables gives more precision on the influence of predictors such as forest type, forest species, and slopes. Results showed that the strongest influence on soil loss came from rainfall intensity (about two thirds of influence) at $p < 0.01$. All dummy variables significantly affected soil loss although the R^2 did not change much after input of more dummy variables in the model. Natural forest showed significant negative beta coefficient meaning that soil loss recorded in this category was less than in other categories including Japanese cedar and cypress, regardless of density. Its influence on soil loss had a beta value of −0.231. Similarly, the category of Japanese cedar was showing significantly lower soil loss than cypress with an explanation power of −0.169. Finally, concerning the last dummy variable slope class, a small significant effect of slope was found influencing soil loss with a beta value of 0.068 indicating a higher soil loss in slopes above 40°.

Effects of rainfall intensity, rainfall amount, and stand density on soil loss

To know the effect of rainfall intensity, rainfall amount, and *relative yield index* (stand density) on soil loss, multiple regression analysis with stepwise method was conducted at the 0.05 level.

Results showed that, for soil loss recorded on the first slope class (above 40°), most effects came from rainfall intensity (beta coefficient 0.736 for cedar and 0.777 for cypress) followed by *relative yield index* (beta coefficient 0.271 for cedar and 0.383 for cypress). Rainfall amount did not have any significant effect on soil loss and had been removed automatically from the model due to the stepwise method chosen.

The second slope class (below 40°) had similar results with a main effect of rainfall intensity on soil loss. *Relative yield index* had three times lower explanatory power compared to rainfall intensity for cedar species ($R^2 = 0.609$). However, it showed a higher beta value (0.441) for cypress species, indicating that soil loss was more affected by the stand density in cypress ($R^2 = 0.732$).

Soil loss according to rainfall intensity classes in different forest types

Due to the strong effect of rainfall intensity on soil loss and for further analysis, rainfall intensity class including VL, L, M, H, and VH intensities was used. Soil loss recorded in slope class >40° was in general higher than that of slope <40°, especially during H and VH rainfall intensities.

Slope above 40°

In natural forest, soil loss amount recorded was in small proportion. Japanese cedar showed a different tendency with a higher soil loss amount. VH showed the highest soil loss amount, followed by H with 185.94 g/2m^2. The three other classes (M, L, and VL) did not show significant differences. As for Japanese cypress, soil loss recorded was higher than in cedar; the highest value corresponded to VH with 482.82 g/2m^2 followed by H with 266.94 g/2m^2 and M (96.82 g/2m^2). VL and L were not significantly different at the 0.05 level. Areas experiencing moderate forest thinning operations corresponding to Ry 0.60–0.70 had the lowest amount of soil loss, which was about three to six orders of magnitude smaller than those areas without thinning operations (Ry close to 1).

Slope below 40°

In natural forest, VL, L, and M classes did not show any significant difference among them; however, they were three to five orders of magnitude smaller than that after H and VH intensity. Moreover, Japanese cedar showed higher amounts of soil loss. The three remaining classes (M, L, and VL) did not have any significant difference at the 0.05 level. In Japanese cypress, although a similar tendency with Japanese cedar was observed, the amount of soil loss recorded was found higher. VH showed the highest mean soil loss, corresponding to 350.71 g/2m^2 followed by H with 205.89 g/2m^2. M corresponded to 95.53 g/2m^2 but L and VL did not have any significant difference.

Soil loss according to rainfall intensity classes on the treatments with different stand density

It was obvious that the more rainfall intensity increased, the more soil loss amount had been observed. In M, L, and VL intensities, the only difference of soil loss resides in those areas with high stand densities such as cypress with Ry 0.70–0.80 and Ry 0.80–0.90 and also in cedar with Ry 0.80–0.90 though this latter relative yield index showed lower values compared to the cypress species with the same *relative yield index* (Fig. 3).

In lower stand densities, soil loss amount recorded was in small quantity and did not significantly differ among species. However, VH and H intensities were the source of the highest soil loss in most of the areas, except in natural forest and in cedar with Ry 0.60–0.70. Cypress species hosted most soil loss especially in areas with high Ry. These results suggest that soil loss depended mainly on rainfall intensities and were the strongest in areas without or with insufficient forest thinning operations.

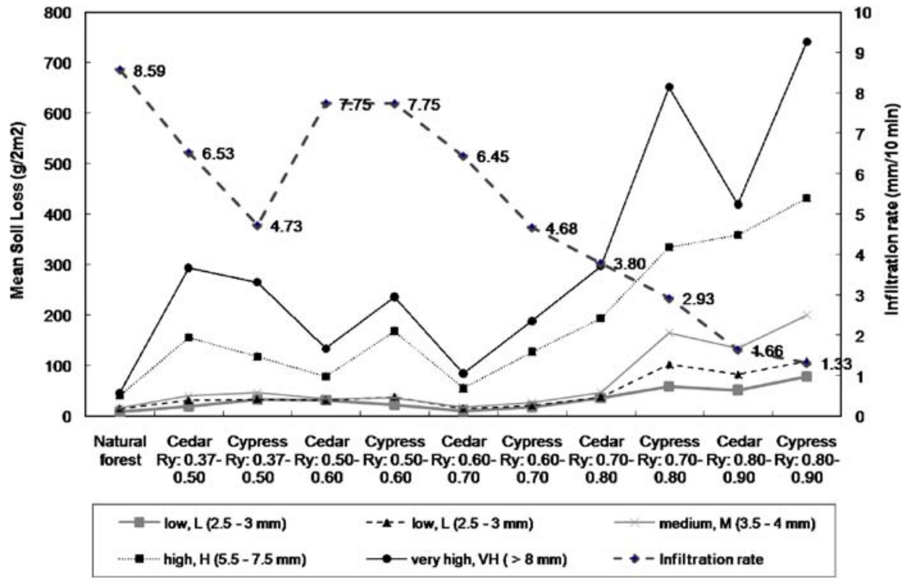

Fig. 3 Infiltration rate and average soil loss based on each rainfall intensity class

Average soil loss in each treatment regardless of slope class

Although soil erosion was found to be slightly different (0.05 level) for slopes above and below 40°, the trend was similar in terms of soil loss fluctuation. Table 3 shows the average soil loss in each treatment regardless of slope angle. The highest amount recorded was in Japanese cypress with Ry 0.80–0.90, followed by the same species with Ry 0.70–0.80. The four first highest values were found in all treatments without or with very few forest operations. Those having experienced forest operations (T6, T4, T7, T3, T5, T2) showed lower values of soil loss although moderately thinned plots had the lowest ones (T6, T4, T7) and were comparable to that of the natural forest.

Discussions

Forest floor conditions and stand density

Results showed that soil loss collected in Japanese cypress were the highest in comparison with

Table 3 Results of Tukey's HSD test for soil loss in all treatment regardless of slope class

Treatments	Characteristics	Number	Soil loss (g/2m^2)
T1	Natural forest	82	21.989 d
T6	Cedar Ry 0.60–0.70	82	29.821 d
T4	Cedar Ry 0.50–0.60	82	52.970 cd
T7	Cypress Ry 0.60–0.70	82	59.768 cd
T3	Cypress Ry 0.37–0.50	82	78.054 cd
T5	Cypress Ry 0.50–0.60	82	80.129 cd
T2	Cedar Ry 0.37–0.50	82	82.598 cd
T8	Cedar Ry 0.70–0.80	82	97.058 c
T10	Cedar Ry 0.80–0.90	82	169.567 b
T9	Cypress Ry 0.70–0.80	82	205.454 ab
T11	Cypress Ry 0.80–0.90	82	245.414 a
F-value			29.481
Sig.			0.000

Means are presented. Means with the same letter did not differ significantly ($P < 0.05$)

Japanese cedar and natural forest, regardless of rainfall intensity. Also, regression analysis with dummy variables showed that cedar species recorded less soil loss compared to the cypress plantation; this may be due to the difference in forest floor condition between the two species. Sakai and Inoue (1988) reported that the form of the leaf litter in cedar and cypress differed markedly; cypress leaf litter breaks down into flakes within 2 or 3 months of falling and is readily transported on slopes, whereas cedar litter does not move easily because it remains attached to branches for long periods while on the forest floor (Tsukamoto 1991). This explains the differing properties in leaf litter leading to different forest floor litter conditions. In addition, although having almost the same stand density in T10 (Japanese cedar Ry 0.80–0.90) and T11 (Japanese cypress Ry 0.80–0.90), cedar species showed lower values of soil loss than in cypress. The same case happened for T8 and T9.

On the other hand, results showed that soil erosion differed according to forest species as well as forest stand density. Soil loss was found higher in areas having high *relative yield index*, in both cedar and cypress plantations. This could be due to forest floor conditions. Although forest cover dynamics under various densities (different Ry) was not conducted, direct observation showed that fewer understory vegetation was found in plantations with high Ry (especially those close to 1.0). Light intensity in the plots could be one of the reasons since areas having experienced no thinning operations are too dense, not allowing for development of understory vegetation. Shiozaki (1977) explained the development of understory plant growth due to the increase in sunlight penetration to the forest floor. Miura et al. (2003) also found that transport rates in young Japanese cedar and cypress increased abruptly after cover removal although the floor cover conditions in the experimental plots differed markedly. This indicates that, in our case, the high amount of sediments collected in T11, T9, and T10 may have originated from the floor cover conditions where, due to the absence of forest thinning operations thus less sunlight penetration, there were fewer floor cover and understory vegetation compared to other areas.

Beside the difference in soil loss due to forest species (cedar and cypress), *relative yield index* has an important role in soil erosion control. If Ry was earlier used as an indicator of forest management for an objective of timber production (Ando 1982), it can also be an important tool for stand density control as well as soil erosion control, as our study shows. For timber production, a *relative yield index* of 0.70 is encouraged in Japan (Ando 1982). Based on our findings, a stand density control with Ry between 0.60 and 0.70 could reduce soil loss in forested slopes. This concept is not only valid for cedar plantations but especially for cypress plantations where stand density control is a primary goal since these plantations are more subject to soil erosion. As our results showed, keeping cypress with Ry between 0.60 and 0.70 reduced soil loss up to five or six orders of magnitude (Table 3).

Based on our results, forest floor cover also appears to be an important factor controlling erosion. If the effect of understory vegetation was mentioned in previous sections, alone, it is not enough to influence soil erosion as reported by Miura et al. (2003) who suggested the development of a method of predicting temporal changes in floor cover conditions. Kiyono (1990) proposed a dynamic understory model estimating the height and coverage of the understory in cypress plantations. However, the understory in cypress plantations quickly decreases as the cypress trees grow, and subsequently the floor cover is mainly dependent on the cover formed from litter (Miura 2000). Thus, the development of a predictive model that estimates floor cover percentage from both floor litter and understory is required (Miura et al. 2003). Therefore, although we found that Ry was crucial in the soil erosion control in our results, further studies on Ry and related floor cover conditions, based on both floor litter and understory vegetation, appear to be necessary to be able to suggest the most appropriate decision for soil conservation based on *relative yield index*.

Soil physical properties contributed to the difference in soil erosion amount

Physical properties of soil under different species and densities especially soil texture and infiltration rate seem to affect the intensity of soil erosion. Previous research conducted in the same study area showed that in topsoil the highest infiltration rate and macroporosity among forest plantations were found in Japanese cedar and cypress having *relative yield index* between 0.50 and 0.60 and comparable to that of natural forests, followed by cedar with Ry 0.60–0.70. Areas without forest operations and having a high stand density (Ry above 0.70) showed the lowest values (Razafindrabe 2006a, c). This explains that most areas having better soil physical properties also appear to show low soil loss recorded. Areas with high Ry having poorer physical properties showed the highest amount of soil erosion. These results indicate that soil physical properties, in particular infiltration rate and macroporosity, might have indirectly affected the amount of soil loss.

Table 4 shows the difference of soil organic matter content and observed soil color among the treatments. Although areas having experienced thinning operations did not have any significant difference among them, areas with high stand density (without thinning) showed significantly lower organic matter content ($p < 0.05$). These areas are also showing lighter-colored soil which is also reflected from lower moisture content (Persson 2005). Brady (2001) reported that soils high in organic matter are darker in color (such as the case of thinned plots) and have greater water holding capacity and higher infiltration rate than do soils low in organic matter. This could affect the stability of aggregates and in turn will affect soil erosion since soil organic matter is a key attribute of soil quality that impacts soil aggregation and water infiltration (Franzluebbers 2002). In addition, soils with available moisture may be subjected to more microbial activities and influence macroporosity and water infiltration (Lee and Foster 1991).

It has been reported that organic matter had been easily mineralized in cypress species compared to that of the cedar species (Ichikawa et al. 2003; Nakane 1995). Also, decomposition rates appeared to increase in thinned plots where soil organic matter was more abundant (similar findings in Tang et al. 2005; Misson et al. 2005). The available moisture added with light penetration may have been creating more understory plants which added with leaf litter, gave birth to more abundant organic materials, especially in those areas with moderate thinning operations. This abundance of organic materials as substrate favors higher microbial activity and organic matter decomposition (Fisher and Binkley 2000). According to Franzluebbers (2002), the enhancement of organic matter decomposition contributes to the improvement of the formation of stable aggregates and soil structures thus improving the overall aeration of the soil. This appears to have reduced the amount of soil erosion in lower stand density plantations (Ry 0.50 to 0.70). The opposite process occurred in areas with high stand density (above 0.70) where more erosion occurred and led to the disappearance of A_0 horizon of the soil surface.

Table 4 Soil organic matter and soil color distribution in each treatment (0–25-cm depth)

Treatments	Characteristics	C/N[a]	Color[b]	Color chart[b]
T01	Natural forest	14.66a	Brownish black	7.5 YR 1.7/1
T02	Japanese cedar Ry 0.37–0.50	12.06ab	Dark yellowish brown	7.5 YR 2/3
T03	Japanese cypress Ry 0.37–0.50	12.50ab	Dark yellowish brown	7.5 YR 3/3
T04	Japanese cedar Ry 0.50–0.60	11.56bc	Dark grayish brown	7.5 YR 2/1
T05	Japanese cypress Ry 0.50–0.60	12.35ab	Dark yellowish brown	7.5 YR 3/1
T06	Japanese cedar Ry 0.60–0.70	12.59ab	Dark grayish brown	7.5 YR 2/1
T07	Japanese cypress Ry 0.60–0.70	12.72ab	Dark grayish brown	7.5 YR 3/1
T08	Japanese cedar Ry 0.70–0.80	12.11ab	Dark yellowish brown	7.5 YR 2/3
T09	Japanese cypress Ry 0.70–0.80	9.26cd	Light yellowish brown	10 YR 6/4
T10	Japanese cedar Ry 0.80–0.90	11.01bcd	Light yellowish brown	10 YR 6/4
T11	Japanese cypress Ry 0.80–0.90	8.68d	Light yellowish brown	7.5 YR 6/6

[a]Means are presented. Means with the same letter did not differ significantly ($P < 0.05$)
[b]Based on the Munsell Soil Color Charts (Japan Color Research Institute 2002)

Rainfall intensity as a main factor leading to soil loss

Although factors related to forest conditions alone affected soil loss, its intensity was regulated by rainfall intensity. Soil loss was recorded though its amount was less in areas where soil infiltration rate was found less than rainfall intensity (Fig. 3), showing that raindrop impact was important. However, although soil loss was recorded from rainfall intensities of 1.5 mm/10 min and above, its amount was minimal for rainfall intensities of up to 3 mm/10 min. Already, at that level, the difference of soil loss amount was palpable especially in cypress plantations without thinning operations having high Ry. This difference is at its maximum when rainfall intensity exceeded 5.5 mm/10 min. Since infiltration rate for areas with lower Ry were from 4.6 to 7.7 mm/10 min, runoff was still prevented in those areas unlike the case of cedar and cypress plantations with Ry above 0.70 where infiltration rate was less than 4 mm/10 min.

In addition, Fig. 4 shows that an important part of soil loss recorded originated from rain splash. Nanko et al. (2004) reported that throughfall raindrops were fewer in number and larger in size than open rainfall drops and total raindrop impact energy from throughfall was over twice than that of open rainfall in Japanese cypress plantations. There may be in our result a possibility that throughfall raindrops did not always have a uniform distribution between different events as in the findings of Nanko et al. (2004). This finding is in contrast to those of Tsukamoto (1966), Mosley (1982), and Brandt (1989) where throughfall raindrops had the same distribution independently of open rainfall intensity. Marshall and Palmer (1948) also reported that open raindrop distribution correlates with rain intensity. This explains the result that, even when rainfall intensity did not exceed infiltration rate, an important amount of rain-splash-induced erosion may take place. Moreover, Mihara (1951) argued that maximum infiltration per unit does not vary in relation to the angle of inclination and to the rainfall duration. The same author reported that, even when the rainfall intensity is the same, if the raindrop is larger, the decrease of infiltration is more rapid and the final value will be smaller.

One of the crucial questions to be answered is how the open canopy should be managed to overcome these problems. Ry parameter helps characterize stand density and simultaneously canopy cover. Results showed that high Ry dense forest plantations (close to 1) registered high soil loss amounts.

Considering that throughfall raindrops are one of the soil-loss-influencing factors, soil loss amount may not have differed that much among treatments with similar tree heights and close Ry values (reflected through Ry calculation (Ando 1982)). Thus, other parameters such as understory vegetation, which were developed according to the canopy characteristics as well as leaf litter originating from the trees themselves, appear to have strongly affected soil erosion. Previous studies (Razafindrabe 2004) showed that forest age and

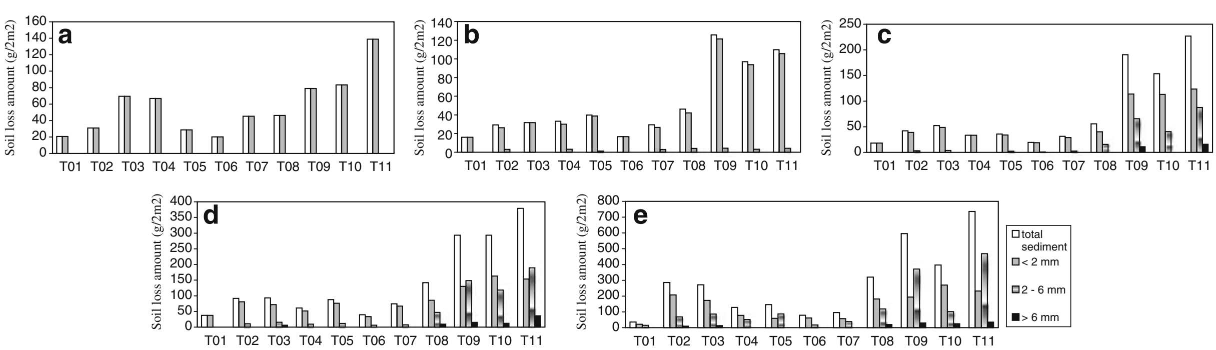

Fig. 4 Average soil loss from 01 July to 31 July 2006 showing sediments particle size class according to rainfall intensity (**a** $r_i = 2$ mm; **b** $r_i = 3$ mm; **c** $r_i = 4$ mm; **d** $r_i = 5.5$ mm; **e** $r_i = 8.5$ mm)

slope aspect did not significantly affect soil physical properties ($p < 0.05$). Based on our results, though forest age parameter was important as a forest condition indicator, Ry seemed to have a better explanation as far as soil physical properties and soil effects are concerned. One of the reasons for this is that, in unknown plantation age or in uneven growth of trees of the same age, based on the degree of management, its soil environment can be determined through the use of *relative yield index* (Ando 1982), a tool recognized by the Japanese authorities.

To illustrate the effect of rainfall intensity on soil loss, soil particle size of collected transported sediments were investigated for 1 month July 2006 results are shown in Fig. 4. A clear difference on the collected sediment particle size is visible for each class of rainfall intensity and for each treatment. In the case of very low rainfall intensity, particle size of deposited sediments did not exceed 2-mm diameter even in unmanaged plantations (T10 and T11). The more the rainfall intensity increased, the bigger particle size became (especially in Fig. 4c–e with rainfall intensity of more than 4 mm/10 min). Mihara (1951) reported that the impulse of raindrops is the main cause of the sheet erosion, which appears to be the case in this site. However, in the case of rainfall intensity above 4 mm/10 min, sediments with particle sizes up to 6 mm in diameter or more were registered. This suggests that the particles that have been dispersed by raindrops were added to those transported by runoff. Mihara (1951) found that, when raindrops strike the ground, the surface layer of particles will be mixed and at the same time pressed tightly so that an impermeable layer will be formed; this phenomenon will decrease infiltration rate and cause a great increase of surface runoff. This finding was added by that of Chapman (1948) reporting that the canopy produces large raindrops and promotes the erosive potential of the raindrops by increasing their kinetic energy. Magarisawa et al. (1992) reported that weak penetration of sunlight into the Japanese cypress forest results in poor growth of forest undergrowth. This seems to be the case in cypress plantations with high *relative yield index* close to 1 where most soil erosion have occurred.

Moreover, since sandy loam and sandy clay loam soils were dominant in this study area, erosion occurred immediately after forest cover decreased. Coarse sand loams present in areas without thinning operations were the impact of the deterioration of soil physical properties due to the local environmental conditions and which in turn led to more erosion in the area.

Forest management is capital

Although findings in this study revealed that soil loss differed significantly from a forest type to another—either between artificial and natural forest or between cedar and cypress plantations—the importance of forest management was reaffirmed. Forest plantations that experienced an appropriate thinning operation, leading to a less vulnerable stand density, showed lower values of soil loss during rainfall events.

The fact that cypress plantations are more prone to soil erosion if they are poorly managed was long debated by many researchers (Sakai and Inoue 1988; Tsukamoto 1991); however, to which extent forest management should be conducted remained unanswered. In the present study, even those fragile cypress plantations showed a better result (less soil loss), after their stand density was corrected to some extent, with a *relative yield index* Ry comprised between 0.5 and 0.7.

Therefore, returning to the key questions previously asked in the beginning of this paper, both forest characteristics and forest management influenced soil loss in the present study. However, stand density control as ensured by thinning operations could reduce the vulnerability of plantations to soil erosion and may play a major role in future works to combat sediment-related disasters in Japan.

Conclusion and policy implications

The effect of different forest conditions on soil erosion by measuring soil loss was investigated in this study. Results showed that most effects on soil loss came from rainfall intensity followed by *relative yield index*. Findings in this study demonstrated that less or no thinning operations led to higher amounts of soil loss and stand density control is necessary in order to achieve soil and water conservation. This study also mentioned the importance of forest floor cover and the understory in their influence on soil erosion. Although some indicators of forest floor conditions (such as soil color and soil organic matter) are presented, a direct investigation of forest litter composition and its amount have not been realized. The knowledge of this information would fill some gaps in this study. Therefore, we suggest the development of a method for forest floor analysis coupled with soil erosion assessment in the area. It should consider spatial dimensions to cover various forest conditions, especially stand density and species and topography, as well as in temporal dimension to be able to identify the variations in different periods.

Nonetheless, the present study plays a major role in clarifying technical processes related to soil erosion while it helps linking these matters to current Japanese Forestry issues and contributing to reduce sediment-related disasters in Japan at policy and operational levels. These technical inputs related to the extent of forest thinning operations for a better soil conservation can feed the current efforts on Forest Planning and Policy in Japan. In addition to the consideration of the stand density relative to $Ry = 0.7$ currently conducted for timber production (Ando 1982), further adjustment of stand density, gradually up to $Ry = 0.5 \sim 0.7$ for both cypress and cedar species, is needed for a more stable forest soil environment according to the present study. More attentions need to be taken as far as forest density control is concerned, especially for cypress plantations which are more prone to erosion. Therefore, such new

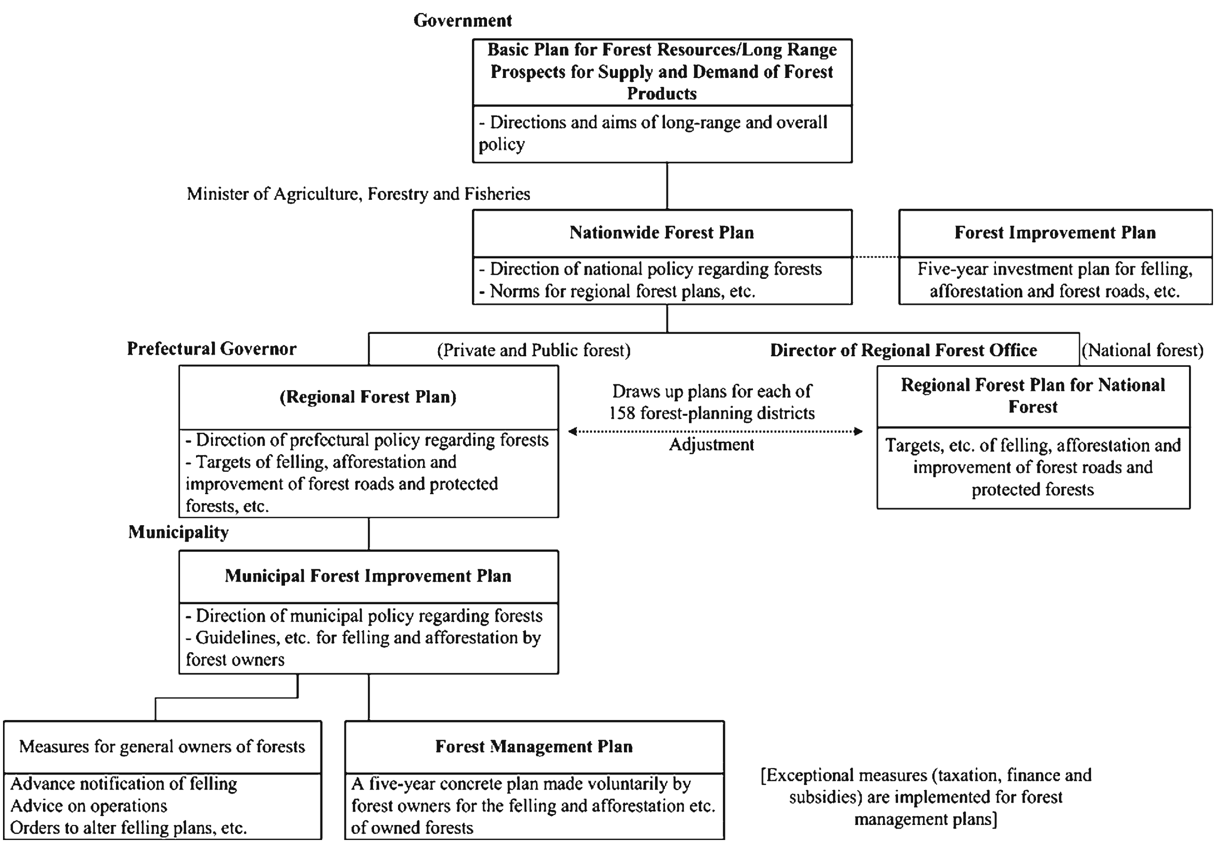

Fig. 5 Forest planning system in Japan (extracted from the 1998 Forest Law; Imaizumi 2001b)

inputs should be reevaluated and considered for the improvement of Forest Policy in Japan.

The implication of this study to the current forest policy concerns directly the 3-year program on the promotion of thinning, the implementation of efficient thinning, and the usage of thinned materials, having been promoted since 2005, and especially the newly implemented "Forests and Forestry Basic Plan" by the Ministry of Agriculture, Forestry, and Fisheries of Japan (Japanese Forestry Agency 2006). Forest thinning operations play an important role in the Japanese System of Forest Planning as illustrated in Fig. 5 (Imaizumi 2001b) from local, prefectural, and national levels. Focus should be also put on local communities and especially on private forest owners since they occupy more than a third of Japanese forests (Japanese Forestry Agency 2004). These actors need to be updated on the need of as well as the appropriate forest management in general and forest thinning operations in particular because they will be in charge of their 5-year Forest Management Plan. The next actor is the Municipality which is responsible for the Municipal Forest Improvement Plan followed by the Prefectural Governor, in charge of the Regional Forest Plan. At national level, focus is put on the Nationwide Forest Improvement Plan by the Ministry of Agriculture, Forestry, and Fisheries of Japan (Imaizumi 2001b).

Moreover, it is of prime importance to review the local government perspective as far as forest sediment-related disaster risk management is concern. The role played by national government and that of municipal governments should be clarified to avoid responsibility gaps in this process. A certain dilemma might occur due to local responsibilities of local governments on forest resources but which are controlled by national governments; mainly because local residents are the first victims of such disasters. Also, the collaboration between the bodies that are concerned with forest resource, production (Ministry of Agriculture, Forestry, and Fisheries with the Forests and Forestry Basic Plan), and soil conservation (Ministry of Land, Infrastructure, Transport, and Tourism with the Sediment-Related Disaster Prevention Plan) should be further enacted to ensure a healthy and stable forest and soil environment, from local to national level.

Therefore, outputs from the present study both help to target a healthy forest and a stable forest soil, which are the guarantees to ensure less damage in sediment-related disasters, often occurring in Japan. Approaches as well as steps to reach those goals merit to be further developed toward a better understanding of and a proactive fight against sediment-related disasters in Japan.

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