FOREST MANAGEMENT METHOD FOR THE WATER RESOURCE CONSERVATION FUNCTION OF FORESTS: EXAMPLE FOR DETERMINING THE LOCATION AND AREA OF TREES CUT DOWN

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ABSTRACT
Forests are expected to exhibit various functions in addition to the functions of supplying timber and fuel. Particularly, expectations for the water resource conservation function of forests are increasing considerably because of widespread concerns about water resource shortages caused by climate change in recent years. Forest vegetation has a greater evapotranspiration rate than either agricultural land or grassland, and therefore has the effect of reducing the runoff volume. Consequently, a forest management method that appropriately adjusts the evapotranspiration rate by trees while preserving forest soil can be considered to exploit the water resource conservation function of forests. Moreover, a forest management regional plan must include appropriate locations and amounts of trees to be cut down. Therefore, in this report, a forest management method is reviewed to exert the water resource conservation function of forests and a model is developed to predict changes in the annual amount of available water resources caused by tree cut down. As results, the percentage of the annual amount of available water resources was found to be roughly proportional to the tree cut down ratio. Based on the points raised above, the method of calculating the number of trees to be cut down to achieve the required increase in the annual amount of available water resources is discussed using an example, particularly considering the case requiring an increase of 4,200 m^3 in the annual amount of available water resources in 10 ha of forest basins of 2,229 trees ha^{-1}in a region with annual precipitation of around 1,400 mm.
Keywords: available water resources, runoff delay effects by forest soil, reinforcing effect of slope stability by root system.

1 INTRODUCTION

Forests are expected to exhibit various functions in addition to the functions of supplying timber and fuel. Particularly, expectations for the water resource conservation function of forests are increasing considerably because of widespread concerns about water resource shortages caused by climate change in recent years. The water runoff delay effects of forest soil help to reduce the runoff volume during floods and help to increase it during droughts. However, forest trees have a greater evapotranspiration rate than either agricultural land or grassland, and therefore has the effect of reducing the runoff volume. Consequently, a forest management method that appropriately adjusts the evapotranspiration rate by trees while preserving forest soil can be considered to exploit the water resource conservation function of forests. Moreover, a forest management regional plan must include appropriate locations and amounts of trees to be cut down.

Therefore, in this report, Section 2 reviews a forest management method to exert the water resource conservation function of forests. Section 3 describes a method to predict changes in the annual amount of available water resources caused by tree cut down. Section 4 presents an example of prediction results. Section 5 presents discussion of how to calculate the number of trees to be cut down to obtain the expected annual amount of available water resources.

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2 THEORY

2.1 Water movement processes in the forest

Most rainwater that has fallen on a forest reaches the forest floor and penetrates into the forest soil. However, some rainwater adheres to the foliage and bark of trees and evaporates into the atmosphere after the rainfall ceases. This process, designated as “canopy interception” is unique to forests: it is not seen with other types of land use. Some water that has penetrated into the soil is absorbed by tree roots and subsequently “transpires” through the stomata of leaves, or “evaporates” from the forest floor (Fig. 1).

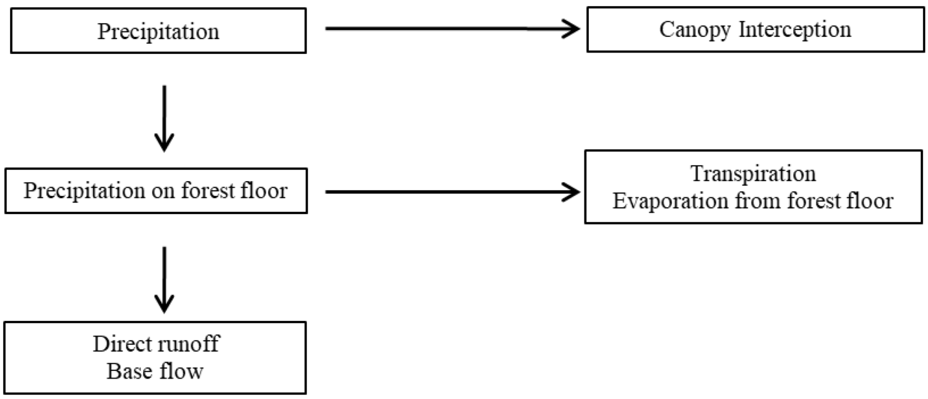

Figure 1: Simple processes of water movement in forest area [7].

As for water that has penetrated into the soil, the deeper the water penetrates into the soil, the longer it takes eventually to run off into streams. The components which penetrate into the shallow soil layer and which contributes the increase the runoff in a few days after the rainfall called “direct runoff”, whereas components that penetrate deep into the soil and subsequently contributes the runoff, especially in drought time, are called “base flow” (Fig. 1).

2.2 Effects of forest trees and forest soil on the water resource

The evapotranspiration effect by forest trees releases the water from the forests into the atmosphere, thereby reducing the amount of water that runs off into streams. Furthermore, the evapotranspiration rate in forests is greater than that in other types of land use. Consequently, through evapotranspiration, forest trees have a negative effect on the water resource conservation function of forest.

Well-developed forest soil has numerous soil pores, allowing more water to penetrate deep into the soil. This quality helps to increase the base flow. In contrast, immature soil helps to increase the amount of direct runoff which flows down into the shallow part of the soil. In this way, forest soil with well-developed structure positively affects the water resource conservation function through the “runoff delay effects”, which reduce the direct runoff and which increase that of base flow.

2.3 Forest management method for the water resource conservation function of forests

As described in the preceding section, forest trees and forest soil act in opposition to the water resource conservation function of forests. Cutting down forest trees to control the evapotranspiration rate might be regarded as one option to enhance the water resource conservation function of forests. However, cutting down forest trees will reduce other functions of forests, especially the slope failure prevention function derived from the reinforce effect of slope stability by tree root system (Tamai [1]). Once a slope failure occurs, forest soil with well-developed structure, and therefore the runoff delay effects by the forest soil, will be lost. Consequently, the water resource conservation function of the forest will be impaired.

According to the discussion presented above, to be compatible with the slope failure prevention function of forests, a forest management method to exploit the water resource conservation function of forests should:

- adopt conservation of forest trees as a principle to "conserve forest soil",
- control the evapotranspiration rate by cutting down forest trees, as the next best option, in areas where water resources are chronically scarce, and
- follow the list of (a) to (c) below for determination of where to cut down forest trees and for determination of how many trees they should be cut down:
  - (a) Tree cutting should not be conducted in areas where the slope failure risk is high.
  - (b) When tree cutting is necessary in areas with a risk of slope failure, sites chosen for tree cutting should be in lower-risk areas or distant from residential areas to prevent damage if slope failure occurs.
  - (c) The degree and extent of tree cutting should be minimized. More root systems of trees should be left after cutting.

The list of items (a) to (c) above incorporates the reinforcing effect of slope stability by tree root system. It is also included in Tamai [1], which also reports on a method to judge the areas presenting a high risk of slope failure.

2.4 Necessity of predicting the increase in the amount of water resources attributable to cutting down trees

Along with determining where to cut down trees, it is also necessary to ascertain the number of trees to be cut down. When cutting down trees for timber production, the number of trees to be cut down should be estimated according to the amount of timber to be harvested. When cut down trees for improvement of the water resource conservation function, the number of trees to be cut down must be estimated similarly. At that time, one must predict the increasing amount of the water resources corresponding to the number of trees to be cut down.

Section 3 describes the method to predict the increasing amount of the water resources attributable to tree cut down. Section 4 presents an example of prediction results.

3 METHOD

3.1 Method for predicting changes in the annual amount of available water resources

The annual amount of available water resources is used as an index of the amount of water resources. The annual amount of available water resources is obtained by subtracting the annual evapotranspiration rate released into the atmosphere from the annual precipitation. In other words, it is equivalent to the total amount of water that is expected to flow out of the forested basin. Strictly speaking, excluding the amount of water that flows out during floods is preferred from the estimation for amount of available water resources. Because it is difficult to use the flow water during floods as a water resource. However, the increase in the runoff volume caused by thinning and clear cutting is readily apparent during droughts but it is not recognized during floods (Tamai [2]). Therefore, the annual amount of available water resources is used as an index in this report. We would like to make an evaluation of the amount of water resources by excluding the amount of flow water during floods as a future task.

It is necessary for calculation of the annual amount of available water resources to estimate the annual evapotranspiration rate. We used the model proposed in Tamai [3] with two improvements: (1) modification of the equation for determining the annual rate of canopy interception and (2) addition of a process for calculating the evaporation rate from the forest floor, to estimate the annual evapotranspiration rate.

Eqn (1) proposed by Komatsu et al. [4] was used instead of the equation used by Tamai [3] to ascertain the canopy interception rate (E_i; mm).

$$E_i = 0.308P \{1 - \exp(-0.000880\, Dense)\}, \tag{1}$$

where P represents the precipitation (mm); *Dense* denotes the timber density (trees ha^{-1}).

The method for ascertaining the transpiration rate (E_t; mm) is the same as that presented by Tamai [3]: the transpiration rate is calculated using the Penman–Monteith equation (Monteith [5]), which calculates E_t using meteorological data. At that time, as Tamai [3] did, we estimated the roughness length and surface replacement height, which are variables indicating the state of the forest in the Penman–Monteith equation from *Dense* and tree height (h; m) to make it possible to evaluate the effects of tree cut down with various tree cut down ratio.

The evaporation rate from forest floor (E_f; mm), which is the sum of the amount of evaporation from the litter (E_l; mm) and that from the soil (E_s; mm) covered by the litter, was calculated using eqns (2) and (3) developed by Tamai [6].

$$E_l = (1.02 \times 10^{-6}\theta - 1.3 \times 10^{-7})\, \alpha S \quad (\text{when } \theta < 1.8 \text{ g g}^{-1}) \tag{2}$$

$$= 1.7 \times 10^{-6}\, \alpha S \quad (\text{when } 1.8 \text{ g g}^{-1} \leq \theta),$$

$$E_s = 1.2 \times 10^{-6}\, \alpha S, \tag{3}$$

where θ denotes the water content rate (g g^{-1}) of the litter; α stands for the relative solar radiation rate (%). S represents solar radiation above the forest canopy (kJ m^{-2}), θ is calculated in the process of calculating E_l in the last calculation unit time (Tamai [6]).

α is an important parameter that strongly affects E_f, although it varies greatly depending on *Dense*. Therefore, it is particularly important among the parameters used in the model in this report. Tamai [6] reported that the combinations of observations of the *Dense* variable and α in forests were 2,229 trees ha^{-1} and 7%, 900 trees ha^{-1} and 13%, and 407 trees ha^{-1} and 43% shown as white diamonds in Fig. 2. Eqn (4), shown by a solid line in Fig. 2, was obtained as an approximate equation of these three white diamonds in Fig. 2. The correlation coefficient was 0.9759.

$$\alpha = 21960\, Dense^{-1.058} \tag{4}$$

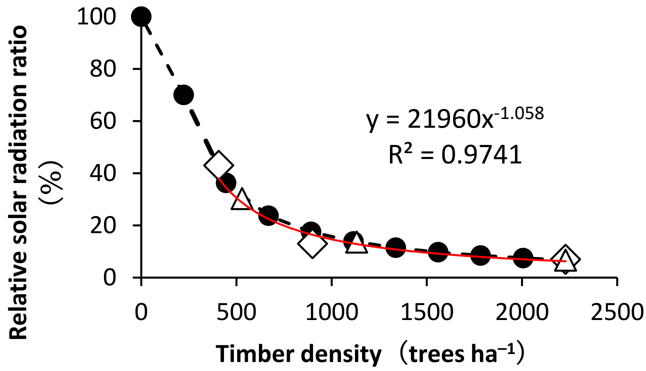

Figure 2: Relation between timber density (Dense) and relative solar radiation ratio (□). White diamond and solid red line: observed ratio and its approximate equation, White triangle: calculated ratio with eqn (4) shown in Table 1 for model verification in Fig. 3, Black circle and broken black line: estimated ratio for model calculation in Fig. 4 [6].

For the case in which the value of *Dense* is 407 trees ha^{-1} or more, the value of α given by eqn (4) was used. For the case in which *Dense* is 407 trees ha^{-1} or fewer, the value on the line connecting the two points of (*Dense*, α) = (407 trees ha^{-1}, 43%) and (0 trees ha^{-1}, 100%) was taken.

3.2 Forest and meteorological data used to model verification

To demonstrate the reliability of the values calculated using the method above, we shall compare the calculated values with the model described herein and the observed values (the difference between observed precipitation and observed runoff from the forest basin), covering three time periods of different timber densities, tree heights, and relative solar radiation ratios (Table 1), in a forest located in Ibaraki Prefecture, Japan (36°34’N, 140°35’E) for a total of nine years. Relative solar radiation ratios in Table 1 are shown as white triangles in Fig. 2. To obtain the calculated values with the model, we used weather data observed at the Onahama Local Meteorological Station (36°57’N, 140°54’E), and the Mito Local Meteorological Observatory (36°23’N, 140°28’E), which are the two closest observation places by Japan Meteorology Agency to the target forest in Ibaraki Prefecture.

Table 1: Forest conditions for which available water resource were calculated for model verification [8].

Period	Tree density (tree ha^{-1})	Tree height (m)	Relative solar radiation (%)
1981–1984	530	24	30.3
2006–2008	2,229	11.1	6.7
2010–2011	1,132	13.3	13.6

3.3 Forest and meteorological data used to predict changes in the amount of water resources

We predicted changes in the annual amount of available water resources assuming the forest in the state of 2006–2008, which is shown in Table 1, were cut down at a ratio of 10% to 100%. Whereas the values of *h* and *Dense* before cutting down trees were 11.1 m and 2,229 trees ha^{-1}, respectively, we assumed that *h* would not change even after tree cut down, but that *Dense* would change depending on the tree cut down ratio. For the value of α, the value denoted by black circle in Fig. 2 was used. The annual amount of available water resources varies greatly from year to year depending on the annual precipitation. Therefore, it is desirable to predict the changes under various weather patterns. We used data for a total of 54 years observed at the Onahama Local Meteorological Station, during 1988–2011, and the Mito Local Meteorological Observatory during 1988–2017. The average annual precipitation for the data for 54 years was 1,414 mm.

4 RESULTS

4.1 Model verification

Fig. 3 represents results of comparing the calculated values with the model described herein and the observed values (the difference between observed precipitation and observed runoff from the forest basin). Calculated values in Tamai [3] with the previous model had been much smaller than the observed values. However, dots located along with 1:1 line in Fig. 3. The improvements of the model in this report can be judged to allow the accurate estimation of the amount of available water resources. This concludes that the model described in Section 3 has the ability to estimate the amount of available water resources from the basins covered by forests with different tree density.

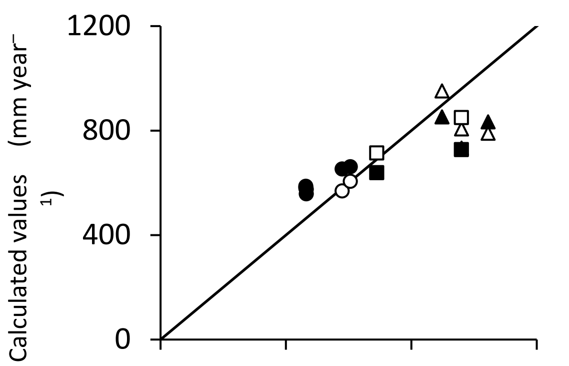

Figure 3: Model verification with the comparison between calculated values with model and verified values of available water resource (the difference between observed precipitation and observed runoff from the forest basin). Circle: 1981–1984, Triangle: 2006–2008, Square: 2010–2011, Black dots: calculated values with Onahama Local Meteorological Station data, White dots: calculated values with Mito Local Meteorological Observatory data, Solid line: 1:1 line.

4.2 Prediction of changes in water resource amounts

Fig. 4 shows the changes of annual rates of E_t, E_i and E_f attributable to changes in the tree cut down ratio using the average of calculated values for 54 years. The calculation results show that, as the cut down ratio increased, the E_t and E_i decreased and E_f increased.

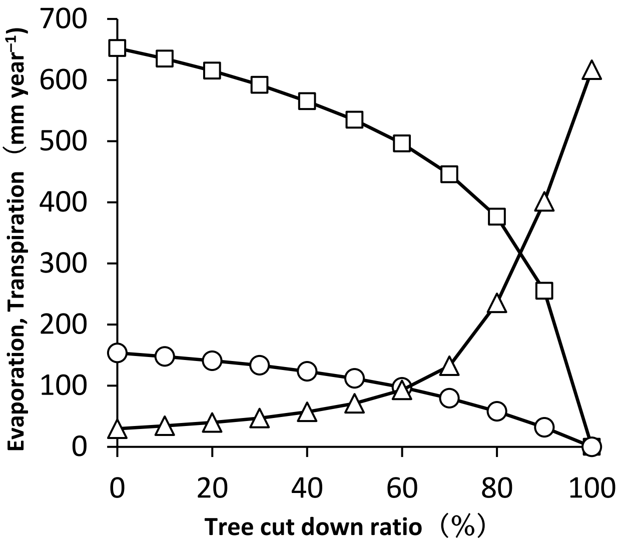

Figure 4: Changes of calculated transpiration (square; E_t), canopy interception (circle; E_i) and evaporation from forest floor (triangle; E_f) according to tree cut down ratio [6].

Fig. 5 shows changes in the shares of E_t, E_i, E_f and the available water resources in annual precipitation according to changes in the cut down ratio. The share of the amount of available water resources to the precipitation was about 40% before tree cut down, and about 55% after clear cutting. Roughly speaking, the percentage of the annual amount of available water resources increased in proportion to the increase in the cut down ratio.

Looking at it in detail, the shares of available water resources showed a maximum value at a tree cut down ratio of 70% and a minimum value at 90%. However, the difference in the share was only 2.2%. Although the value of α is a factor that greatly fluctuates the calculated value of forest floor evaporation, only three data were used in this study to obtain eqn (4). Therefore, the maximum and minimum values due to the difference of 2.2% that appeared in the calculation results of this report may not occur when eqn (7) is updated due to future data accumulation. I want to make it a future issue.

However, the ratio of the annual amount of available water resources to the amount of precipitation is an example of that in Ibaraki Prefecture. When predicting the increase in the annual amount of available water resources using the method described herein, it is fundamentally important to obtain prediction results similar to those shown in Fig. 5 for each area using meteorological data and data indicating the status of forests in the target area.

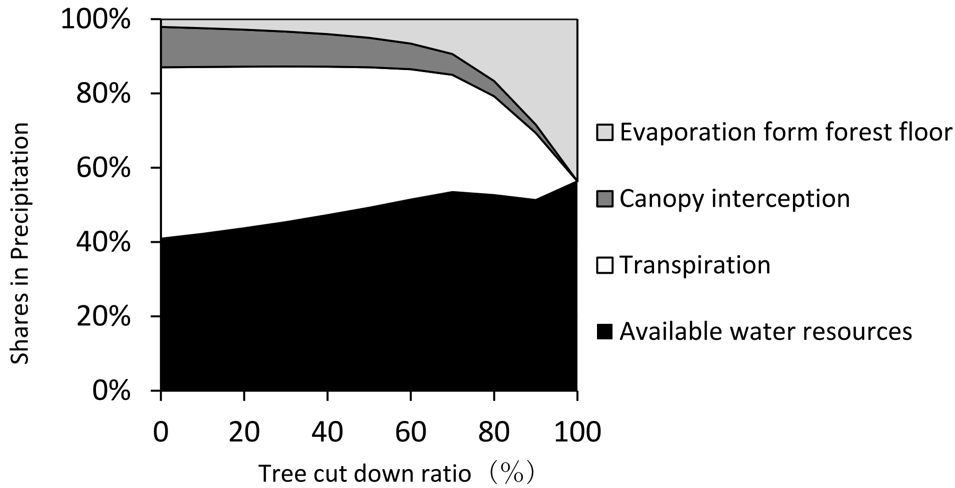

Figure 5: Changes in the shares in precipitation of available water resources and three types of evapotranspiration according to tree cut down ratio [6].

5 DISCUSSION

5.1 How to calculate the number of trees cut down to increase the annual amount of available water resources to the target amount

Section 4 presented a prediction example in which clear cutting of a forest of 2,229 trees ha^{-1} would increase the ratio of the annual amount of available water resources to the amount of precipitation by about 15%. In addition, the percentage of the annual amount of available water resources was found to be roughly proportional to the tree cut down ratio. Based on the points raised above, the method of calculating the number of trees to be cut down to achieve the required increase in the annual amount of available water resources is discussed below using an example, particularly considering the case requiring an increase of 4,200 m^3 in the annual amount of available water resources in 10 ha of forest basins of 2,229 trees ha^{-1}in a region with annual precipitation of around 1,400 mm in Ibaraki Prefecture, Japan.

Because the annual precipitation is 1,400 mm, the expected increase in the amount of water resources when a forest of 2,229 trees ha^{-1} is cleared is 1,400 mm × 15% = 210 mm. Converting this amount of water into volume, the volume is 210 mm × 1 ha = 0.21 m × 100 m × 100 m = 2,100 m^3. Therefore, if 2 ha of the 10 ha basin area are cleared, the annual amount of available water resources is expected to increase by 4,200 m^3.

However, the percentage of the annual amount of available water resources is roughly proportional to the tree cut down ratio as shown in Fig. 5. Therefore, the same result can be obtained even if 50% tree cut down is performed at 4ha. In other words, if 4,458 trees are cut down throughout the entire basin with 10ha area, the annual amount of available water resources can be expected to increase by 4,200 m^3.

Where to cut down those trees and the tree cut down ratio should be ascertained appropriately following the list of (a) to (c) described in Section 3

5.2 How to determine the location of trees cut down and forest management strategy to increase the annual amount of available water resources to the target amount

Section 5 presented an example of calculating the number of trees to be cut down to obtain the increasing amount of annual available water resources to the target amount. However, this is an example based on results presented in Fig. 5, which predicts changes in water resource amounts based on meteorological data of Ibaraki Prefecture and target forest data. To apply a similar method to other areas, one must use the following processes:

At first, the prediction results are obtained similar to those in Fig. 5 by application of the method described in Section 3 and by Tamai [3] to meteorological data and data indicating the status of forests in the target area.

Second, the number of trees to be cut down is ascertained, as described in Section 5 to obtain the increasing amount of annual available water resources to the target amount.

Third, the location is determined where to cut down trees and the tree cut down ratio based on the list presented in Section 2 and by Tamai [1].

And last, the management method is determined for each forest and reflected in the forest management regional plan.

The description of Fig. 5, showing that "the ratio of the annual amount of available water resources to the amount of precipitation was about 40% before tree cut down, and about 55% after clear cutting", is intended specifically for the case examined for this study: Ibaraki Prefecture, Japan.

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