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Models to predict changes in annual runoff with thinning and clearcutting of Japanese cedar and cypress plantations in Japan

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Abstract:

Forest management (thinning and clearcutting) can reduce evapotranspiration and increase catchment runoff. By summarizing data on the increase in annual runoff (ΔQ) due to forest management at various sites and analysing data using linear regression, traditional studies have reported large unexplained variability among data for different sites. To improve the predictability of ΔQ, it might be useful to model ΔQ for specific species and regions while considering underlying processes. This study performed such modelling for Japanese cedar and cypress plantations in Japan. Model 1 predicts ΔQ assuming that ΔQ equals the decrease in canopy interception loss (ΔE_i), which was further modelled by stem density using 46 data for interception loss. Model 2 predicts the potential maximum of ΔQ ($\Delta Q_{\max}$) assuming that $\Delta Q_{\max}$ equals the sum of ΔE_i and the decrease in canopy transpiration (ΔE_t). Here, ΔE_t was calculated using a model developed in our previous study. ΔQ predicted using Model 1 approximated ΔQ observed for seven catchments, and the errors in prediction were less than those derived from traditional linear-regression analysis. $\Delta Q_{\max}$ predicted using Model 2 was greater than the observed ΔQ for all catchments. Thus, Models 1 and 2 would be respectively useful in assessing the effectiveness and limitations of managing Japanese cedar and cypress plantations to secure water resources, which have been controversial in Japan. Furthermore, the concept of the models gives implications for studies on other species and regions, because the models have demonstrated how to improve predictability of ΔQ considering underlying processes with the input of commonly available data. © 2015 The Authors. *Hydrological Processes* published by John Wiley & Sons Ltd.

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INTRODUCTION

Forests consume more water by evapotranspiration than do other land-use categories (e.g. grasslands and crops), resulting in reduced catchment runoff and water resources (Farley *et al*., 2005; Sun *et al*., 2006). This negative impact of forests might be alleviated by forest management (e.g. thinning and clearcutting), because forest management could change the water cycle in the forest and thus catchment runoff (Sun *et al*., 2005; van Dijk and Keenan, 2007). Indeed, there are several regions where forest management has been conducted to increase catchment runoff and water resources (Komatsu *et al*., 2010). Furthermore, forest management is proposed as a possible measure to secure water resources under changing climate (Ford *et al*., 2011; Vose *et al*., 2011).

The effectiveness and limitations of forest management in increasing runoff have not been sufficiently evaluated. Numerous studies (Scott and Lesch, 1997; Cornish and Vertessy, 2001) have examined increases in annual runoff (ΔQ) induced by forest management for various sites around the world using the paired-catchment method or time-trend analysis. By synthesizing data from these site-specific studies and analysing data using linear regression, previous studies (Bosch and Hewlett, 1982; Brown *et al*., 2005; Komatsu *et al*., 2011) identified factors (e.g. annual precipitation, leaf phenology and seasonality of precipitation) affecting ΔQ induced by forest management. However, there is a large variability in ΔQ, which has not been explained by these factors (Brown *et al*., 2005; Adams and Fowler, 2006; Komatsu *et al*., 2011). It is still difficult to predict ΔQ induced by forest management accurately.

This problem might be alleviated by analysing data derived for specific species and regions and by considering underlying processes of ΔQ (e.g. changes in interception loss and transpiration induced by forest

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management). This study thus develops models that consider underlying processes and predict ΔQ induced by management of Japanese cedar (*Cryptomeria japonica*) and cypress (*Chamaecyparis obtusa*) plantations in Japan. Focusing on these species has practical importance. Japanese cedar and cypress plantations occupy 28% of the forested area in Japan or 19% of Japan's land surface (Japan Forestry Agency, 2014). These plantations had originally been thinned twice or three times before they were harvested at an age of ~50 years. However, such management has not been performed actively since the 1980s because of the stagnation of forestry in Japan. Several researchers in Japan (Tsukamoto, 1998; Kuraji, 2003) pointed out that plantations, not managed and therefore having dense canopies, can consume more water by evapotranspiration and therefore reduce water resources. Thirty-one of the 47 local governments in Japan have introduced taxes to aid the thinning of plantations mainly to secure water resources, and 11 of the 47 are planning to introduce similar taxes (Takai, 2012). However, there have been few attempts to assess the effectiveness and limitation of thinning in securing water resources owing to a lack of methods and models to predict ΔQ induced by forest management, specifically the thinning of Japanese cedar and cypress plantations (Komatsu, 2010). The models developed in this study allow assessments of the effectiveness and limitations of thinning these plantations in securing water resources.

The models are only applicable to Japanese cedar and cypress. However, this study gives implications for studies on modelling ΔQ for other species and regions. The models demonstrate how to improve the predictability of ΔQ considering the processes underlying ΔQ with the input of commonly available data, such as that of stem density and the mean diameter at breast height.

MODELS

General structure

The catchment water balance equation on a yearly time scale is written as

$$P = Q + E_i + E_t + E_g \tag{1}$$

where P is the precipitation, Q is the runoff, E_i is the interception loss from canopy trees, E_t is the transpiration from canopy trees and E_g is the evapotranspiration from understory vegetation and the ground surface. The change in catchment water storage is ignored because it is generally less than the other terms on this time scale. Thinning and clearcutting generally decrease E_i and E_t and increase E_g. Assuming no difference in P between before and after treatment (e.g. thinning and clearcutting), the increase in Q (ΔQ) induced by the treatment is thus written as

$$\Delta Q = \Delta E_i + \Delta E_t - \Delta E_g \tag{2}$$

where ΔE_i is the decrease in E_i, ΔE_t is the decrease in E_t and ΔE_g is the increase in E_g induced by the treatment. This equation shows that the prediction of ΔE_i, ΔE_t and ΔE_g for Japanese cedar and cypress plantations provides the value of ΔQ.

Modelling of ΔE_g is generally difficult, because only a few studies have reported E_g observed for Japanese cedar and cypress plantations (Hattori, 1983; Sun *et al.*, 2014). This study thus proposes two practical models that do not require modelling of E_g, as described in the succeeding discussions. Model 1 assumes that ΔE_t equals ΔE_g in Equation (2). ΔQ is therefore written as

$$\Delta Q = \Delta E_i \tag{3}$$

Model 2 assumes that ΔE_g is positive or zero in Equation (2). ΔQ therefore satisfies

$$\Delta Q \leq \Delta E_i + \Delta E_t \tag{4}$$

The right-hand side of Equation (4) represents the potential maximum of ΔQ, which is hereafter referred to as $\Delta Q_{\max}$. ΔE_i and ΔE_t need further modelling, as described in the next two subsections.

Model 1 assumes that the decrease in E_t induced by treatment (i.e. thinning and clearcutting) is cancelled by the increase in E_g. Previous studies (Fujieda *et al.*, 1996; Maita *et al.*, 2005; Sun, unpublished data) reported that the observed ΔQ induced by thinning and clearcutting of Japanese cypress and cedar plantations roughly equals ΔE_i. These results suggest that the decrease in E_t is comparable with the increase in E_g.

Submodel for predicting ΔE_i

The submodel for predicting ΔE_i is based on the relationship between the stem density (N) and the interception ratio (E_i^*, defined by E_i divided by precipitation). Previous studies by Komatsu (2007) and Komatsu *et al.* (2008a) synthesized E_i^* values on a yearly time scale for coniferous forests in Japan and reported a positive correlation between N and E_i^*. These studies observed no clear differences in E_i^* for a given N according to species, canopy height and incident precipitation. However, data for Japanese cedar and cypress were limited (i.e. the sample size was nine), and a number of values have been reported by recent studies (Shinohara *et al.*, 2010; Kato *et al.*, 2012; Saito *et al.*, 2013). Including these data would allow the development of a much more reliable relationship between N and E_i^*

(Methods of Analysis), which would be used as a submodel for predicting ΔE_i with the input of N before and after treatment and precipitation after treatment.

Submodel for predicting ΔE_t

The submodel for ΔE_t relates E_t to N, the mean diameter at breast height (d_m) and meteorological data. This submodel is identical to the model developed by Komatsu *et al.* (2014) on the basis of E_t data for 14 Japanese cedar and cypress sites. We briefly describe the structure of the model in the succeeding discussions, while a detailed description is available in Komatsu *et al.* (2014).

The model expresses daily E_t by the simplified Penman–Monteith equation (McNaughton and Black, 1973). Canopy conductance (G_c), the unknown parameter in the equation, is modelled as a product of the reference value of G_c (G_{cref}) and functions expressing responses of G_c to the vapour pressure deficit (D), solar radiation (R) and temperature (T):

$$G_c = G_{\mathrm{cref}} \cdot f(D) \cdot g(R) \cdot h(T) \tag{5}$$

where $f(D)$, $g(R)$ and $h(T)$ are the functions expressing the responses of G_c to D, R and T, respectively. Komatsu *et al.* (2014) found a relationship between the sapwood area on a stand scale (A) and the G_{cref} among the 14 sites. Regressing the relationship, G_{cref} in units of $\mathrm{m\,s^{-1}}$ is modelled as

$$G_{\mathrm{cref}} = 0.00157\,A \tag{6}$$

where A has units of $\mathrm{m^2\,ha^{-1}}$. A is calculated from N and d_m as (Komatsu *et al.*, 2014)

$$A = N \cdot a_{\mathrm{ref}} \cdot {d_m}^b \tag{7}$$

where a_{ref} and b are parameters. a_{ref} values for Japanese cedar and cypress are 1.40 and 1.96 $\mathrm{cm^2}$, respectively. b values for cedar and cypress were 1.55 and 1.42, respectively (Tsuruta *et al.*, 2011). $f(D)$, $g(R)$ and $h(T)$ are respectively modelled as (Oren *et al.*, 1999; Granier *et al.*, 2000)

$$f(D) = 1.00 - \beta \cdot \ln(D) \tag{8}$$

$$g(R) = \min\left\{\left(\frac{R}{600}\right)^{\delta}, 1.00\right\} \tag{9}$$

$$h(T) = \begin{cases} 1.00 & (T \geq \epsilon) \\ \dfrac{T-\zeta}{\epsilon-\zeta} & (\zeta < T < \epsilon) \\ 0.00 & (T \leq \zeta) \end{cases} \tag{10}$$

where β, δ, ε and ζ are parameters. These parameters were determined as 0.556 $\ln(\mathrm{kPa})^{-1}$, 0.284, 15.9 °C and −8.74 °C, respectively (Komatsu *et al.*, 2014). D, R and T in the aforementioned equations are in units of kPa, $\mathrm{W\,m^{-2}}$ and °C, respectively. These values of the parameters were the mean values for the 14 sites examined by Komatsu *et al.* (2014). Although the parameter values actually differed among the sites, the effect of the difference on the determination of E_t proved to be small.

ΔE_t induced by thinning predicted using the model described here is proportional to the change in A, because G_{cref} is proportional to A (Equation (6)) and $f(D)$, $g(R)$ and $h(T)$ do not change with thinning. This model prediction is supported by observation results. Komatsu *et al.* (2013) measured E_t before and after thinning of a Japanese cedar plantation. The ratio of ΔE_t to E_t before thinning approximated the ratio of the change in A relative to A before thinning. Komatsu *et al.* (2013) analysed data for E_t before and after thinning of a Japanese cypress plantation presented in Morikawa *et al.* (1986) and reported the same results.

METHODS OF ANALYSIS

Determination of the $N-E_i^*$ equation

This study comprises three parts: (1) determination of the $N-E_i^*$ equation, (2) comparison between predicted and observed ΔQ and (3) comparison between Model 1 and traditional analysis. These three parts are described in this subsection and in the following two subsections, respectively.

As for the first part, we summarized data for E_i from earlier publications using three criteria. Firstly, the measurement period must include at least 3 months during May–October (i.e. the typical rainy season in Japan), because E_i^* on a short time scale (e.g. 1 month) with a small amount of precipitation could differ greatly from E_i^* on a longer time scale. Note that when the measurement period was 2 years or longer and E_i^* for each year was available, we treated the data for the years separately. This treatment would enhance the detectability of the effect of annual precipitation on E_i^*, because of the difference in annual precipitation among the years. Secondly, the tree age of the site must be more than 15 years, or the canopy height must be more than 8 m. Thinning and clearcutting are not usually performed for such young and short forests. Additionally, interception loss for such forests might differ from that for mature and tall forests, because aerodynamic properties change with a change in canopy height (Jones, 1992; Kelliher *et al.*, 1993). Thirdly, the forest must not undergo uncommon management treatment, such as removing 50% of the tree crown by pruning (Wang *et al.*, 1991).

After confirming a correlation between N and E_i^* from the data summarized in this study, we regressed the relationship to determine the $N-E_i^*$ equation employing the least-squares method. Previous studies (Komatsu, 2007; Komatsu *et al*., 2008a) reported that including additional factors (i.e. species, canopy height and annual precipitation) did not improve the predictability of E_i^*. The present study also examined whether these results changed when using an extensive data set.

Comparison between predicted and observed ΔQ

There have been several studies (e.g. Maita *et al*., 2005; Dung *et al*., 2012) reporting ΔQ induced by clearcutting and thinning of Japanese cedar and cypress plantations employing the paired-catchments method or the time-trend analysis. We selected data for analysis on the basis of two criteria. Firstly, the site must not be located in regions with heavy snowfall (Hosoda and Murakami, 2007; Komatsu *et al*., 2008b). Processes of interception loss for snowfall differ from those for rainfall (Hedstrom and Pomeroy, 1998; Lundberg and Halldin, 2001). The submodel for predicting ΔE_i was developed using data for interception loss of rainfall. Secondly, if the ΔQ data were derived using time-trend analysis, data for at least 3 years excluding the first year after treatment (i.e. thinning or clearcutting) must be available. ΔQ derived employing time-trend analysis is not generally as accurate as that derived employing the paired-catchments method. Averaging ΔQ for several years would reduce the errors in ΔQ estimates obtained from time-trend analysis. In contrast, data for at least 1 year excluding the first year after treatment must be available if the data are derived employing the paired-catchments method. We did not use data for ΔQ in the first year after treatment. ΔQ in the first year often differs from that in succeeding years (Kubota *et al*., 2013), possibly because ΔQ in the first year would be affected by the transient change in catchment water storage induced by forest management (Tanakamaru *et al*., 2008). Note that we used data for afforestation as those for clearcutting to increase the sample size. The decrease in Q induced by afforestation was assumed to be the same as the increase in Q induced by clearcutting, as in previous studies (Bosch and Hewlett, 1982; Brown *et al*., 2005; Komatsu *et al*., 2011).

We calculated ΔQ (=ΔE_i) and $\Delta Q_{\max}$ (=$\Delta E_i + \Delta E_t$) using Models 1 and 2 for the years that ΔQ observations were available. We calculated E_i and E_t with the input of stem density (N) and the mean diameter at breast height (d_m) before and after treatment and meteorological data in the years. We then calculated ΔE_i and ΔE_t from the E_i and E_t data. We finally compared ΔQ calculated with Model 1 with the observed ΔQ and compared $\Delta Q_{\max}$ calculated with Model 2 with the observed ΔQ.

Calculations of E_i and E_t for the sites covered with a single species (e.g. Kubota *et al*., 2013) are straightforward. However, several sites included separate areas covered with cedar and cypress (e.g. Takeda *et al*., 2009). In such cases, E_i and E_t were calculated for each area, and E_i and E_t for the site were calculated as the area-weighted average values. When the ratio of the areas covered with cedar and cypress was unavailable, the ratio was arbitrarily assumed as 50%. We confirmed that our conclusions did not change when assuming that the whole catchment was covered with either of the species.

Models 1 and 2 require species, stem density (N), the mean diameter at breast height (d_m) and meteorological data as inputs. Although information of species was always available, the information of N and d_m was not (Forest Influences Unit Kyushu Branch Station, 1982; Shimizu *et al*., 2008). In such cases, we calculated N and d_m using Local Yield-table Construction System, which is the software used to predict changes in N and d_m with age for Japanese cedar and cypress and several other species in Japan (Matsumoto *et al*., 2011). Local Yield-table Construction System requires as inputs the location of the target site, the age and intensity of thinning, N at the initiation of the stand and the site index. Here, the site index is a parameter ranging between 1 and 3 (or between 1 and 5 for some cases) and expressing the difference in stand growth among different sites having the same age and management history. Information about the location of the target site and the age and intensity of thinning (i.e. reduction in N by thinning relative to N before thinning) was available. However, information about N at the initiation of the stand and the site index was not always available. In such cases, N at the initiation of the stand was assumed as 3000 stems per hectare, which is typical for Japanese cedar and cypress. The site index was assumed as 2 (i.e. moderate growth). We confirmed that changing N at the initiation of the stand in a possible range (i.e. between 2500 and 4000 stems per hectare) did not change our conclusions. Similarly, we confirmed that changing the site index between 1 and 3 did not change our conclusions.

Meteorological data required as model inputs were annual precipitation, and T, D and R on a daily time scale. Note that T, D and R were the mean values for the period 6 AM–6 PM. Although annual precipitation was available for all sites where ΔQ was measured, T, D and R were not available. T and D were thus estimated from daily maximum (T_x) and minimum temperatures (T_n) at the observatory nearest the target site (Japan Meteorological Agency, 2014), following Komatsu *et al*. (2014). T was approximated as $T = (T_x + T_n)/2 + (T_x - T_n)/(3\pi)$, where the diurnal trend in temperature was approximated using a sine function having a minimum at 6 AM and a maximum at 2 PM. D is thus approximated by $D = e_s(T) - e_s(T_n)$, where e_s is the saturation vapour pressure. We here assumed vapour pressure deficit at 6 AM to be zero and vapour pressure to be constant throughout daytime. In contrast with the case for T_x and T_n, R data were available only from the main meteorological observatories in Japan (Japan Meteorological Agency, 2014). We used data from the observatory located nearest the site among the main observatories. R in units of $\mathrm{W\,m^{-2}}$ was thus approximated as daily solar radiation in units of $\mathrm{MJ\,m^{-2}\,day^{-1}}$ multiplied by an index of 23.1, which converts the units.

Comparison between Model 1 and traditional analysis

In addition to employing Model 1, traditional analysis using linear regression (Bosch and Hewlett, 1982; Brown *et al.*, 2005) allows prediction of ΔQ. We thus compared the predictability of ΔQ using Model 1 with that using the regression line.

Two different methods are usually employed to predict ΔQ using a regression line. The first method uses the relationship between the intensity of treatment (such as the reduction in N induced by treatment relative to N before treatment) and ΔQ (Bosch and Hewlett, 1982; Sahin and Hall, 1996). We thus regressed the relationship between the intensity of treatment and the observed ΔQ using our data set. Here, we did not assume that the intercept of the regression line is zero, following previous studies (Bosch and Hewlett, 1982; Brown *et al.*, 2005). We predicted ΔQ for each site using this regression line. The second method uses the relationship between annual precipitation and converted ΔQ (ΔQ_c), the increase in Q corresponding to treatment at 100% intensity. ΔQ_c is calculated as ΔQ divided by the intensity of treatment. Variability observed in the relationship between the intensity of treatment and ΔQ is partly explained by variations in annual precipitation (Bosch and Hewlett, 1982; Brown *et al.*, 2005). To consider the effect of variations in annual precipitation on ΔQ, Brown *et al.* (2005) converted the observed ΔQ to ΔQ_c and detected a relationship between annual precipitation and ΔQ_c. We thus calculated ΔQ_c by dividing the observed ΔQ by the reduction in N relative to N before treatment and then regressed the relationship between annual precipitation and ΔQ_c. We predicted ΔQ_c using the regression line and reconverted ΔQ_c to ΔQ.

We compared errors in ΔQ prediction using Model 1 and that using each regression line. Here, the regression lines were determined using ΔQ observations, in contrast with Model 1. To compare the predictability of ΔQ using Model 1 with that using each regression, we calculated errors in ΔQ prediction for each regression line using the jackknife method (Tukey, 1958; Fujii, 2005), where the regression line was determined using six of the seven data and the error in prediction of the remaining datum was calculated. We calculated Glass's delta (Glass *et al.*, 1981; Ellis, 2010) to compare relative errors in ΔQ prediction using Model 1 with those using each regression line. Glass's delta was calculated as $(M_M - M_R)/SD_M$, where M_M and M_R were the mean relative errors in ΔQ prediction using Model 1 and the regression line, respectively, and SD_M was the standard deviation for the relative errors in ΔQ prediction using Model 1. We did not use Cohen's d (Cohen, 1988, 1992; Ellis, 2010) because the difference in the standard deviation for the relative errors in ΔQ prediction between Model 1 and each regression line was relatively large.

Throughout this study, we did not perform hypothesis testing to examine statistical significance of the relationships and the differences. Statistical significance is not always meaningful in a practical context. A very weak relationship or small difference can be found to be statistically significant, if we have a large number of samples. For example, a relationship having the correlation coefficient of 0.00620 is found to be statistically significant, if the sample size is 100 000. This problem was noted by several prominent statisticians many years ago (Berkson, 1938; Bakan, 1966; Deming, 1975; Carver, 1978) and by numerous researchers repeatedly (Cohen, 1990, 1994; Yoccuz, 1991; Suter, 1996; Thompson, 1996, 1998, 1999, 2002, 2007; Johnson, 1999; Fidler *et al.*, 2006; Armstrong, 2007; Hubbard and Lindsay, 2008; Lambdin, 2012; Nuzzo, 2014; White *et al.*, 2014). Many of the researchers recommend reporting confidence intervals and effect sizes (e.g. the correlation coefficient, Spearman's rho, Cohen's d and Glass's delta) instead of p values (Thompson, 1996, 1999, 2002; Johnson, 1999; Fidler *et al.*, 2006; Hubbard and Lindsay, 2008). Readers, who are interested in statistical significance of the relationships and differences examined in this study, may infer the significance on the basis of the confidence intervals and effect sizes reported in this study (Ellis, 2010).

RESULTS

Determination of the $N - E_i^*$ equation

We obtained 45 data for E_i^* (Table I). The sites covered most regions where Japanese cedar and cypress plantations were distributed (Figure 1). N tended to decrease with age (Figure 2). N for a given age class varied among data, suggesting that our data set would be useful in examining the relationship between N and E_i^*.

We observed a correlation between N and E_i^* (Figure 3). The correlation coefficient (r) was 0.644, and the lower and upper boundaries of the 95% bootstrapping confidence interval ($\mathrm{CI}_{95\%}$; Efron, 1979; Fox, 2008) were 0.491 and 0.749, respectively. Regressing the relationship between N and E_i^*, we obtained the following equation:

$$E_i^* = k_1\{1 - \exp(-k_2 N)\} \tag{11}$$

where k_1 and k_2 were 0.308 and 0.000880 ha, respectively. The normal probability plot for the difference between observed E_i^* and E_i^* predicted using this equation suggests

Table I. Data for the ratio of interception evaporation to precipitation (E_i^*) used in this study

Data code	Age (year)	Stem density (stems ha^{-1})	Diameter at breast height (cm)	Height (m)	Period (months)	Annual precipitation (mm)	E_i^*	References
Cedar								
1	67	513	39	27	12	1932	0.18	Tanaka *et al.* (2005)
2	68	513	39	27	12	2279	0.12	Tanaka *et al.* (2005)
3	69	513	39	27	12	2024	0.18	Tanaka *et al.* (2005)
4	41	1300			8	1218[a]	0.23	Kato *et al.* (2012)
5	10	3864	11	9	12	1520	0.28	Wang *et al.* (1991)
6	11	3864	11	9	12	1336	0.30	Wang *et al.* (1991)
7	12	3864	11	9	12	1260	0.30	Wang *et al.* (1991)
8	13	3864	11	9	12	1923	0.30	Wang *et al.* (1991)
9	18	3000	15	12	12	1650	0.25	Ohrui and Mitchell (1996)
10	71	750	29	25	12	1150	0.12	Haibara and Aiba (1982)
11	35	1000			30	2762	0.18[b]	Yasuda (1994)
12	30	1467	23	15	12	1584	0.26	Sato *et al.* (2003a,b)
13	41	1107	27	23	19	1930[a]	0.26	Saito *et al.* (2013)
14	42	553	27	23	8	1852[a]	0.22	Tateishi *et al.*, unpublished data
Cypress								
15	29	1750	18	14	12	1543	0.21	Hattori and Chikaarashi (1988)
16	29	2051	16	11	12	1543	0.21	Hattori *et al.* (1982)
17	30	1750	18	14	12	1336	0.23	Hattori and Chikaarashi (1988)
18	31	1325	18	14	12	1453	0.19	Hattori and Chikaarashi (1988)
19	73	783	32	18	12	1826	0.12	Murakami *et al.* (2000)
20	75	783	32	18	12	1642	0.15	Murakami *et al.* (2000)
21	67	923	34	19	12	1932	0.16	Tanaka *et al.* (2005)
22	68	923	34	19	12	2279	0.12	Tanaka *et al.* (2005)
23	32	2198	19	16	12	1445	0.29	Sun *et al.*, unpublished data
24	33	1099	19	16	12	1267	0.21	Sun *et al.*, unpublished data
25	40	1700			18	1367[a]	0.16	Hirata *et al.*, submitted; Kato *et al.* (2012)
26	41	800			17	1200[a]	0.12	Hirata *et al.*, submitted
27	40	1785	16	12	16	1355[a]	0.17	Fujii (1959)
28		675	23	20	12	1499	0.30	Gomyo *et al.* (2004)
29	24	2500	15	15	9	1846[a]	0.35	Dohi *et al.* (2012)
30	24	1250	18	16	9	1846[a]	0.26	Dohi *et al.* (2012)
31	65	3200	8	8	12	1793	0.26	Iwatsubo and Tsutsumi (1967)
32	43	2400	25	18	6	2803[a]	0.30	Nanko *et al.*, 2015
33	44	1200	25	18	8	3267[a]	0.13	Nanko *et al.*, 2015
34	50	1836	23	19	8	1388[a]	0.30	Sado and Kurita (2004); Komatsu (2008)
35	50	1440	22	17	8	1388[a]	0.30	Sado and Kurita (2004); Komatsu (2008)
36	50	1487	22	17	8	1388[a]	0.28	Sado and Kurita (2004); Komatsu (2008)
37	91	915	26	18	12	3011	0.16	Takagi (2013)
38	39	1300	31	26	6	1965	0.14	Shinohara *et al.*, submitted
39	40	600	31	26	9	2056	0.08	Shinohara *et al.*, submitted
40	41	1526	19	17	19	1930[a]	0.26	Saito *et al.* (2013)
41	42	848	19	17	9	1852[a]	0.21	Tateishi *et al.*, unpublished data
42	51	1700	21	14	12	1606	0.24	Shinohara *et al.* (2010)
43	52	1700	21	14	12	1606	0.24	Shinohara *et al.* (2010)
44	53	1700	21	14	12	2177	0.24	Shinohara *et al.* (2010)
45	54	1700	21	14	12	1483	0.28	Shinohara *et al.* (2010)

[a] Annual precipitation for the measurement year of the site was unavailable in the original paper. Annual precipitation recorded at the meteorological observatory nearest the site (Japan Meteorological Agency, 2014) was thus substituted.
[b] Data for seasons without snowfall (April–September) were used.

that none of the data were apparent outliers. We here used a saturation curve for regression, not the linear equation used in our previous studies (Komatsu, 2007; Komatsu *et al.*, 2008a), for two reasons. Firstly, the determinant coefficient (r^2) for the saturation curve (0.547) was higher than that for the linear equation (0.445). Secondly, the number of parameters for the saturation curve was the same as that for the linear equation.

We did not observe differences in E_i^* according to species, canopy height and annual precipitation (Figure 4a–c). Data

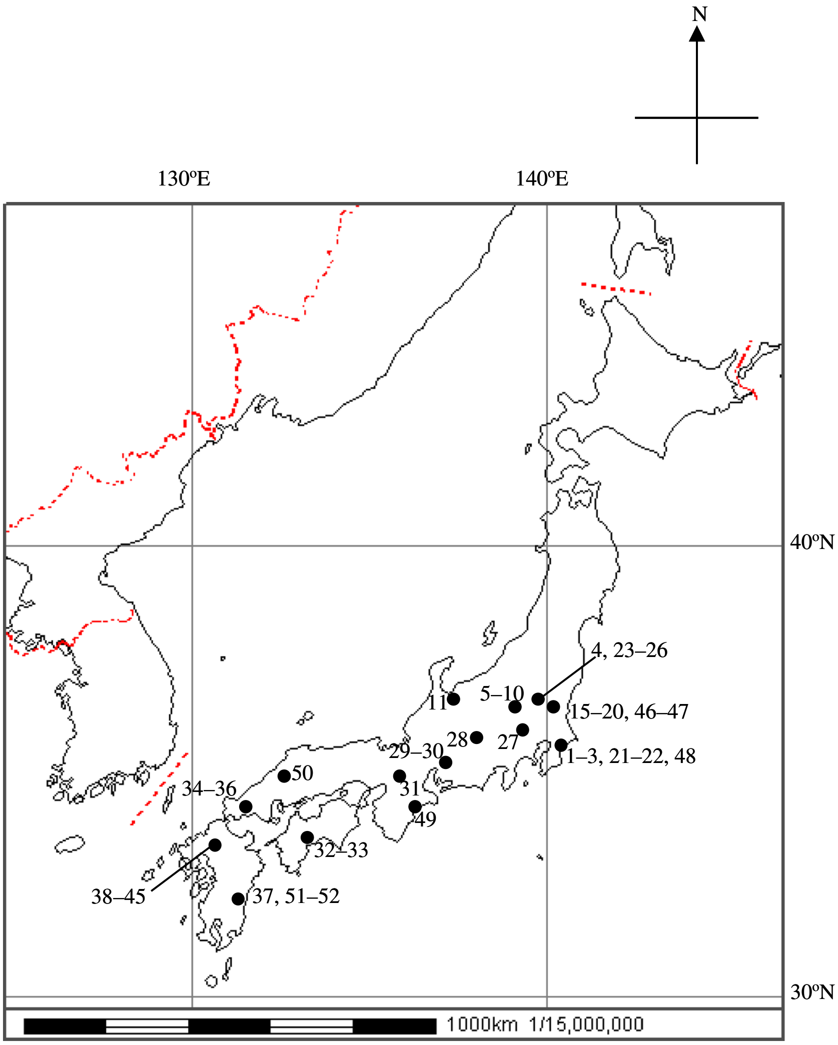

Figure 1. Location of the sites. A numeral in this figure indicates the code of the data, which was recorded there. Data codes are described in Tables I and II

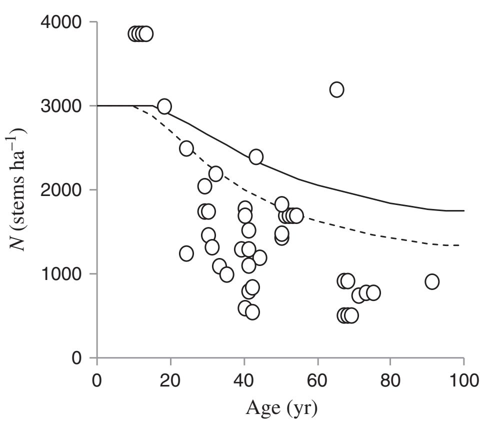

Figure 2. Relationship between age and stem density (N). The solid and dotted curves indicate typical changes in N with age for cedar and cypress, respectively, calculated using Local Yield-table Construction System. The calculations assumed that the target site was located in the Kanto region, that N at the initiation of the site was 3000 stems per hectare, that the site index was 2 and that no thinning treatment was performed

for different categories were generally located along the regression line in all cases. The difference between observed E_i^* and E_i^* predicted by Equation (11) did not show clear correlations with species, canopy height and annual precipitation (the r values were 0.178, 0.215 and 0.123, respectively). These results suggest that including these factors would not improve the reproducibility of E_i^*. Indeed, adding these factors to Equation (11) did not increase the adjusted r^2 value of the equation considerably (data not shown). There were several data recorded just after thinning (#14, 18, 24, 26, 30, 33, 35, 36, 39 and 41). We did not observe systematic differences between these data and other data (Figure 4d).

Comparison between predicted and observed ΔQ

We obtained seven data for ΔQ (Table II and Figure 1). Four of the seven were for clearcutting and the other three were for thinning. The intensity of treatment (the ratio of

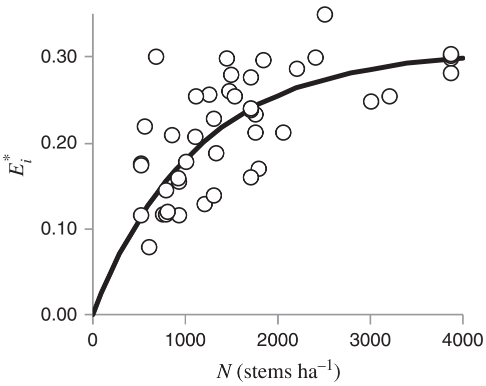

Figure 3. Relationship between stem density (N) and the ratio of interception loss to precipitation (E_i^*). The solid curve indicates Equation (11): $E_i^* = 0.308\ \{1 - \exp(-0.000880\,N)\}$

the reduction in N induced by treatment relative to N before treatment) for #46 and #49 was 50% and 58%, respectively. These values were typical for intensive thinning conducted to enhance ecological services including securing water resources (Forestry and Forest Products Research Institute, 2010). The intensity of treatment for #50 was 24%, which was typical for traditional commercial thinning in Japan.

E_i and E_t before and after treatment were predicted as summarized in Table III. From E_i and E_t before and after treatment, ΔQ ($=\Delta E_i$) and $\Delta Q_{\max}$ ($=\Delta E_i + \Delta E_t$) were predicted as in Figure 5. ΔQ and $\Delta Q_{\max}$ differed among the sites. For example, ΔQ and $\Delta Q_{\max}$ for #51 were respectively greater than ΔQ and $\Delta Q_{\max}$ for #47 by a factor of 2.5 or more, even though the treatment was the same for #51 and #47. ΔQ for #47 was approximately twice of that for #46, even though these data were recorded under nearly the same meteorological conditions but for different treatments. These results suggest the effects of meteorological conditions and treatment on the determination of ΔQ and $\Delta Q_{\max}$. ΔQ predicted using Model 1 approximated the observed ΔQ (Figure 6a). Data were located around the 1 : 1 line. The mean relative error for the seven data was 0.277. $\Delta Q_{\max}$ predicted using Model 2 exceeded the observed ΔQ in all cases (Figure 6b).

Comparison between Model 1 and traditional analysis

The observed ΔQ tended to be greater for a higher intensity of treatment (Figure 7a). The r value was 0.725, and the lower and upper boundaries of $CI_{95\%}$ were 0.345 and 0.988, respectively. This r value was slightly higher

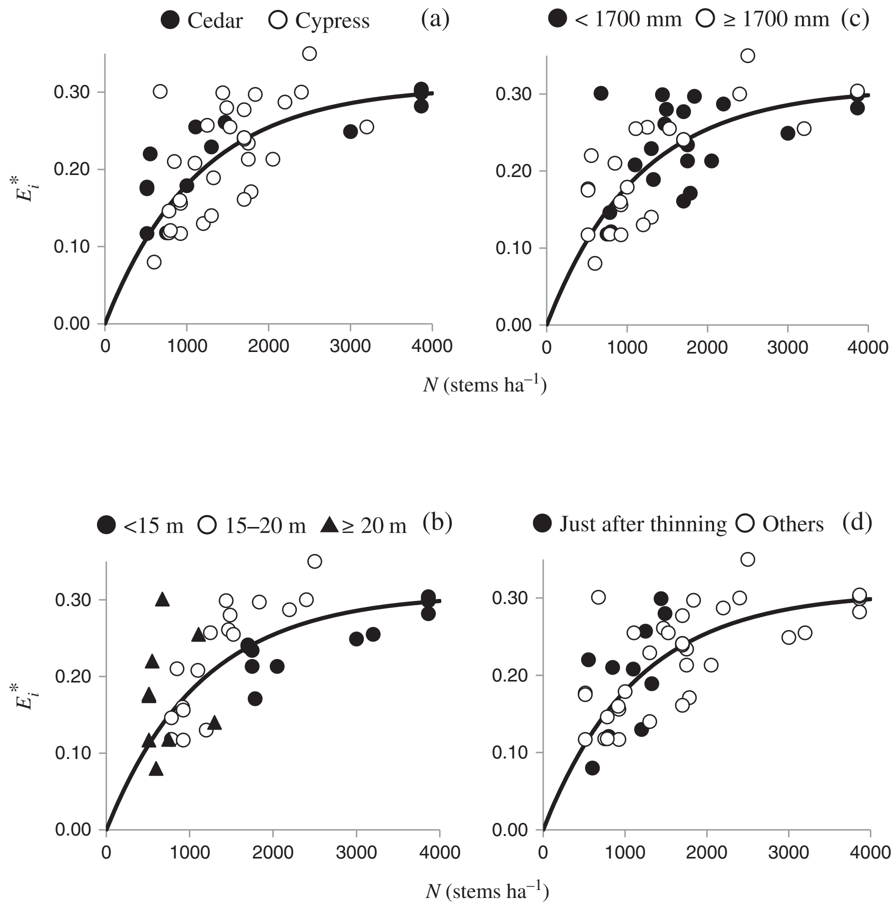

Figure 4. The same as Figure 3 but classified according to (a) species, (b) canopy height, (c) annual precipitation and (d) thinning history

Table II. Data for the increase in annual runoff (ΔQ) used in this study

Data code	Site name	Before treatment				After treatment				Precipitation (mm)	ΔQ (mm)	References
		Period	Vegetation	N (stems ha^{-1})	d_m (cm)	Period	Vegetation	N (stems ha^{-1})	d_m (cm)			
46	Hitachi-Ohta	2006–2008	Cypress (1986–1988)[a]	2229	13.6	2011	Cypress (1986–1988)	1125	13.6	1499	161	Kubota *et al.* (2013)
47	Hitachi-Ohta	1981–1985	Cypress/cedar[b] (1925)	783	32	1988–1990	Clearcut[c]	0	—	1792	167	Fujieda *et al.* (1996)
48	Fukuroyamasawa	1993–1998	Cedar/cypress (1928–1931)	673	29.3/21.5[d]	2001–2002	Clearcut	0	—	2384	308	Maita *et al.* (2005)
49	Mie #5	2004–2006	Cypress (early 1960s)	3475	14.0[e]	2008	Cypress (early 1960s)	1450	14.0[e]	1551	160	Dung *et al.* (2012)
50	Shimane #2	1999–2001	Cypress/cedar[f] (1988/1948)	2500/1300	10.5/19.5	2004–2006	Cypress/cedar (1988/1948)	2000/1000	10.5/19.5	1665	56[g]	Takeda *et al.* (2009)
51	Sarukawa #1	1993–2000	Cypress (1967)	2540[h]	14.7[g]	1968–1970	Clearcut	0	—	2488	438[g]	Forest Influences Unit Kyushu Branch Station (1982); Shimizu *et al.* (2008)
52	Sarukawa #3	1993–2000	Cedar/cypress[i] (1967)	2357/2540[h]	15.8/14.7[h]	1968–1970	Clearcut	0	—	2488	602[g]	Forest Influences Unit Kyushu Branch Station (1982); Shimizu *et al.* (2008)

[a] A numeral in parentheses indicates the year when trees were planted.
[b] Cypress and cedar trees were planted separately in the catchment. Cypress and cedar occupy 77% and 23% of the catchment area, respectively.
[c] Sixteen percent of the catchment area remained uncut.
[d] Tanaka *et al.* (2005).
[e] Estimated from the basal area reported by Dung *et al.* (2012).
[f] Cypress and cedar trees were planted separately in the area. Cypress and cedar occupy 60% and 13% of the catchment area, respectively. The remaining area was covered with broadleaf–pine forests. Thinning was also performed in this area. Changes in interception evaporation and transpiration for the area were assumed the same as the area-weighted average of the values for cedar and cypress areas
[g] Calculated by the authors of this paper using data presented in the original papers.
[h] Calculated using Local Yield-table Construction System (Matsumoto *et al.*, 2011).
[i] Cedar and cypress trees were planted separately in the area. Cedar and cypress occupy 67% and 33% of the catchment area, respectively.

Table III. Ratio of interception evaporation (E_i^*), interception evaporation (E_i), sapwood area (A) and transpiration (E_t) predicted using our models

Data code	Site name	Before treatment					After treatment				
		Vegetation	E_i^*	E_i (mm)	A (m^2 ha^{-1})	E_t (mm)	Vegetation	E_i^*	E_i (mm)	A (m^2 ha^{-1})	E_t (mm)
46	Hitachi-Ohta	Cypress	0.265	440	17.8	146	Cypress	0.194	322	8.97	73.7
47	Hitachi-Ohta	Cypress/cedar	0.153/0.153	231	21.1/22.0	137	Clearcut	0	0	0	0
48	Fukuroyamasawa	Cedar/cypress	0.138/0.138	328	16.5/10.3	122	Clearcut	0	0	0	0
49	Mie #5	Cypress	0.294	546	28.9	287	Cypress	0.222	413	12.1	120
50	Shimane #2	Cypress/cedar	0.274/0.210	437	13.8/17.1	137	Cypress/cedar	0.255/0.180	300	11.1/13.2	125
51	Sarukawa #1	Cypress	0.275	684	22.6	237	Clearcut	0	0	0	0
52	Sarukawa #3	Cedar/cypress	0.269/0.275	674	22.5/22.6	237	Clearcut	0	0	0	0

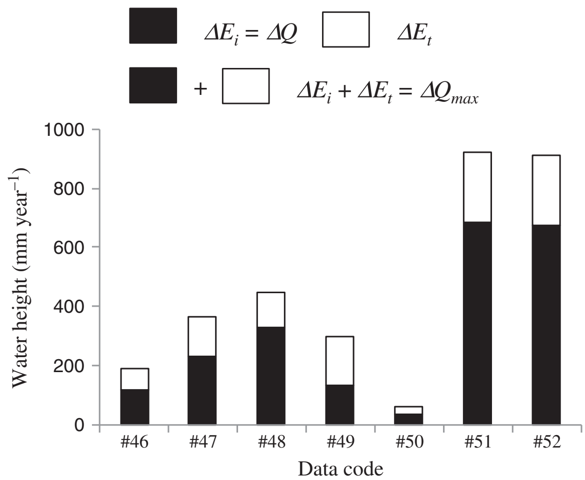

Figure 5. Results of model prediction for each site. ΔE_i and ΔE_t are the increases in interception loss and transpiration, respectively. ΔQ and $\Delta Q_{\max}$ are the increase and the maximum increase in annual runoff, respectively. Data codes for the catchments are described in Table II

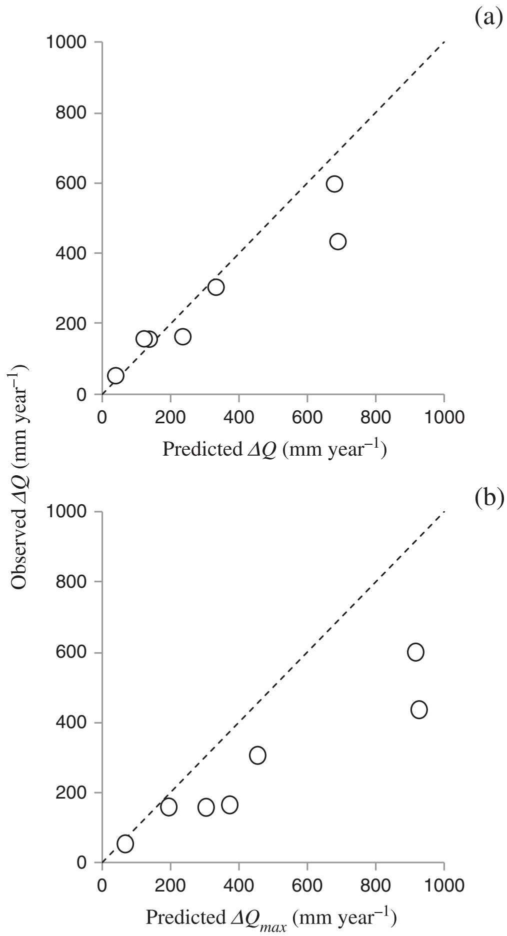

Figure 6. Comparison between model prediction and observations. ΔQ and $\Delta Q_{\max}$ are the increase and the maximum increase in annual runoff, respectively. A dotted line indicates a 1 : 1 relationship

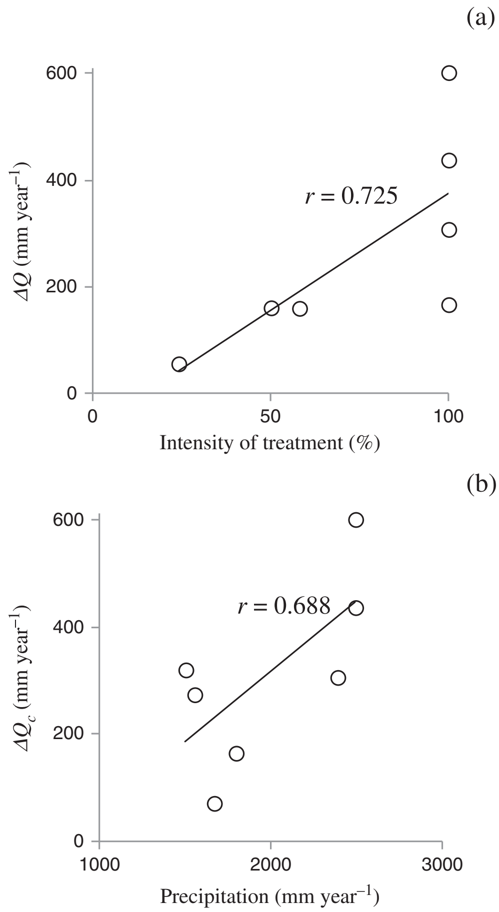

Figure 7. (a) Relationship between the intensity of treatment and the increase in annual runoff (ΔQ). (b) Relationship between annual precipitation and the increase in annual runoff corresponding to 100% treatment (ΔQ_c). A solid line indicates the regression line determined using the least-squares method and all data

than that reported by Bosch and Hewlett (1982). Employing the jackknife method, the mean relative error in ΔQ prediction using the regression line was determined as 0.502.

ΔQ_c tended to be greater for higher annual precipitation (Figure 7b). The r value was 0.688, and the lower and upper boundaries of $CI_{95\%}$ were −0.0622 and 0.963, respectively. The wide range of $CI_{95\%}$ can be attributed to the small sample size of this study. Indeed, the lower limit of $CI_{95\%}$ became positive (data not shown) if we included ΔQ data for sites located in western Japan and comprising other species (Komatsu *et al.*, 2011). Employing the jackknife method, the mean relative error in ΔQ_c prediction using the regression line was determined as 0.766. The mean relative error in ΔQ prediction was 0.402.

The mean relative error in ΔQ prediction using Model 1 (0.277) was less than that using the regression lines (0.502 and 0.402, respectively). Glass's delta was 1.28 for the former regression line and 0.715 for the latter regression line, which were respectively assessed as large and medium differences according to Cohen's effect size benchmarks (Cohen, 1988; Ellis, 2010). When considering that Model 1 did not require additional inputs other than those required by prediction using regression lines, Model 1 would be more useful in predicting ΔQ than the regression lines.

DISCUSSION

Relationship between N and E_i^*

We obtained a relationship between N and interception loss (Figure 3). Although the underlying processes of this relationship are unclear, results of Teklehaimanot *et al.* (1991) are useful in speculating the underlying processes of the relationship. Teklehaimanot *et al.* (1991) measured the interception loss for the four Sitka spruce stands having different N. They observed a relationship between N and interception loss, similar to this study. Teklehaimanot *et al.* (1991), on the basis of heat budget theory, inferred that the relationship between N and interception loss was derived from the following two conditions. Firstly, evaporation during precipitation, not after the cease of precipitation, is the main component of interception loss. Secondly, aerodynamic conductance is high for stands having high N (Figure 5 of Teklehaimanot *et al.*, 1991), resulting in a higher rate of evaporation for such stands (Figure 8 of Teklehaimanot *et al.*, 1991).

The aforementioned inference made by Teklehaimanot *et al.* (1991) could be a possible hypothesis for the underlying processes of the relationship between N and interception loss obtained in this study. As for the first condition, Murakami (2012) and Saito *et al.* (2013) pointed out, using the observation data for interception loss of Japanese cedar and cypress plantations, that the total interception loss was much greater than that expected from the canopy storage capacity. This suggests that evaporation during precipitation is the main component. Furthermore, a correlation between the leaf area index and the interception loss is not observed for our data (data not shown). As the leaf area index often relates to the canopy water storage capacity of the stand (Herwitz, 1985; Deguchi *et al.*, 2006) and therefore to the total amount of evaporation after the cease of precipitation, the absence of the correlation implies that evaporation after the cease of precipitation is not the main component.

As for the second condition, there have been very few studies (Yamanoi and Ohtani, 1992; Tanaka *et al.*, 1996) measuring aerodynamic conductance for Japanese cedar and cypress plantations. There is thus a need to accumulate data for aerodynamic conductance at various sites comprising Japanese cedar and cypress and to examine the relationship between N and interception loss. Here, aerodynamic conductance must be estimated by employing micrometeorological methods (e.g. Kumagai *et al.*, 2005), not by making inverse calculations using the heat budget equation (e.g. Teklehaimanot *et al.*, 1991). This is because several studies (Murakami, 2006, 2007; Dunkerley, 2009; Saito *et al.*, 2013) have recently noted that interception loss might not be fully explained by heat budget theory. If we do not find a relationship between N and aerodynamic conductance using data collected in the future, we might need to reconsider the use of heat budget theory to explain variations in interception loss among different cedar and cypress sites.

Practical implications

Models 1 and 2 respectively allow the prediction of ΔQ and ΔQ_{max} induced by the thinning and clearcutting of Japanese cedar and cypress under various meteorological conditions in Japan. Model 1 can be used by decision-makers to assess the effectiveness of forest management conducted in Japan to secure water resources in a given size of watershed. On the other hand, Model 2 can be used in assessing the limitations of forest management in securing water resources. The increase in E_g due to thinning (or clearcutting) might be reduced by cutting understory vegetation after thinning, because the efficiency of evapotranspiration could differ according to aerodynamic and physiological properties of the evaporative plane. Regardless of such treatment of understory vegetation, ΔQ would not exceed ΔQ_{max} predicted using Model 2. Thus, Model 2 allows the assessment of the potential maximum of controllability of Q by forest management.

The models are also useful to researchers in the field of forest hydrology, because the models allow hypothetical calculations to be used for developing a hypothesis for an effective method of forest management to increase Q. For example, intensive thinning in a limited area in a catchment could be more effective than light thinning of the whole catchment according to the models. Suppose the following two cases: (1) thinning by 20% in N for the whole catchment and (2) thinning by 60% in N for one third of the catchment. When assuming that N before thinning is 3000 stems per hectare, that there are no spatial variations in N before thinning in the catchment and that annual precipitation is 2000 mm, ΔQ values predicted using Model 1 are 30.6 and 56.8 mm for these cases, respectively. ΔQ for the latter case is higher than that for the former case, even though the number of trees removed from the catchments is the same. This suggests that intensive thinning in a limited area is more effective. ΔQ_{max} predicted using Model 2 is generally greater for the latter case than for the former case (data not shown), because ΔE_i is the main component of ΔQ_{max} under most conditions in Japan (Figure 5). Researchers may make field observations to examine the validity of such a hypothesis developed from hypothetical calculations using the models. The models would be thus useful tools in designing scientific research. If researchers succeed in validating the hypothesis, they would be able to propose to decision-makers a more effective way of forest management to secure water resources.

The models developed in this study give implications for studies examining ΔQ for other species and regions. The models predict ΔQ more accurately than traditional regression lines do (Bosch and Hewlett, 1982; Brown *et al.*, 2005), although the models require only readily available data (N, d_m and meteorological data) as inputs. Thus, the models have demonstrated how to improve the predictability of ΔQ considering the underlying processes without requiring additional input data. Although the models are not directly applicable to other species and regions, the concept of the models would be useful in developing similar models applicable to other species and regions. The method of forest management differs among species and regions (Fujimori, 2000; Mead, 2013). Similarly, the demand of water resources and the vulnerability of water resources to changing climate differ among regions (Vörösmarty *et al.*, 2000; Arnell, 2004). Development of similar models applicable to each species and region would contribute to the proposal of a forest management approach suited to indigenous conditions and to an understanding of the similarities and differences in the effectiveness of forest management in securing water resources among species and regions.

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