Mapping of Japanese Cedar (*Cryptomeria japonica*) Forests Vulnerable to Global Warming in Japan

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Abstract

We evaluated the vulnerability of *Cryptomeria japonica* (Japanese cedar) forests to global warming in Japan, using two indexes of plant water balance. One was an index of the water supply available to plants: the effective water-holding capacity of forest soils. The other was an index of plant dryness: the ratio of the annual transpiration of *C. japonica* forests to annual precipitation (Tr/P ratio). The effective water-holding capacities of four types of soil were estimated from soil-water retention curves calculated from soils' physical properties. Tr/P ratios were calculated from the leaf gas exchange characteristics of *C. japonica* and climatic data. Both indexes were projected on nationwide maps using a grid-square system. Forestlands in areas with low effective water-holding capacity were found mainly in the Mikawa and Kinki regions, and in coastal areas of the Setouchi and Shikoku regions. We predict that the decline of *C. japonica* forests will accelerate if droughts occur frequently in these areas because of climate change. Under current climatic conditions, high Tr/P ratio areas were recognized around the Tone River in the Kanto Plain, in the Kou-shin region, and in coastal areas of the Kansai and Setouchi regions, where declines of *C. japonica* have been observed already. To evaluate future declines in *C. japonica* forests, we calculated Tr/P ratios using predicted climatic data (average of 2081-2100) based on a global warming scenario. The area of declining *C. japonica* forests may expand in the Kanto Plain and the eastern part of Aomori Prefecture in the future.

Key words: *Cryptomeria japonica*, global warming, Japanese cedar, soil water retention curve, transpiration, vulnerability prediction

1. Introduction

Cryptomeria japonica (L.) D. Don (Japanese cedar; '*sugi*' in Japanese) is indigenous to Japan and distributed in cool-temperate and warm-temperate zones from Aomori Prefecture to Yakushima Island (Hayashi, 1951; Forest Agency, 1964; Fig. 1). This species tolerates a wide range of temperatures and grows well in humid areas with abundant precipitation in both the cool-temperate and warm-temperate zones. The wood of *C. japonica* is widely used as material for houses, furniture, tools, ships, vehicles, civil engineering projects, and packing. *Cryptomeria japonica* has a very long history of cultivation (Katsuta, 2001). At present, *C. japonica* plantations cover approximately 4.5 million ha in Japan, comprising about 13% of the land area of Japan and 45% of forest plantations, although the coverage in Hokkaido and Okinawa prefectures is very small.

Cryptomeria japonica has large water vapor diffusion conductance and large hydraulic resistance according to the soil-plant-atmosphere continuum (SPAC) system concept (Matsumoto *et al*., 1992). This means that *C. japonica* has a tendency to consume large amounts of water, but has a low ability to transport water from the soil. Therefore, *C. japonica* is very susceptible to water stress during drought.

Declines in *C. japonica* have been observed in low and flat areas of the Kanto, Kansai, and Setouchi regions (Nashimoto & Takahashi, 1990; Matsumoto *et al*., 2002). Although some studies have reported that these declines may have been caused by acid rain, air

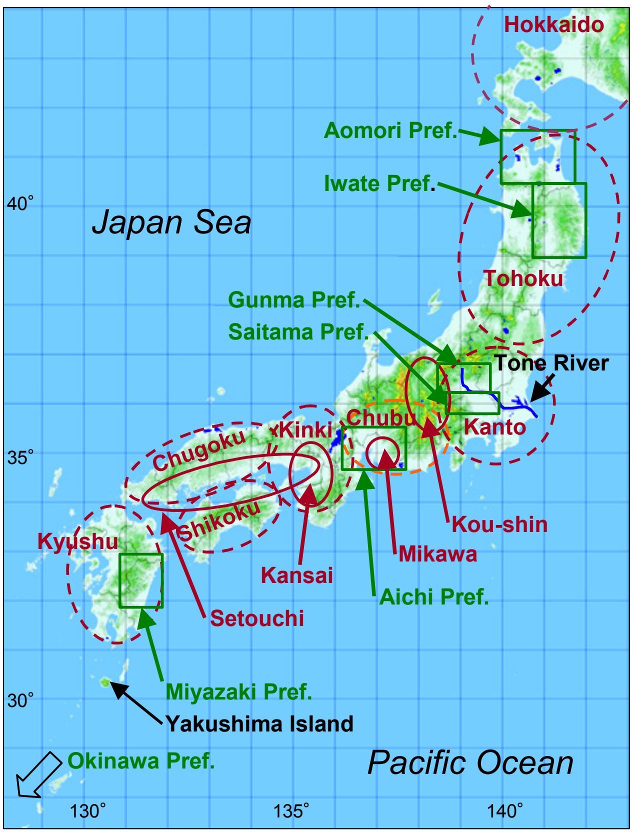

Fig. 1 Map of Japan.
Red and green text indicates regions and prefectures, respectively.

pollution, or both, this has not yet been demonstrated. Matsumoto *et al*. (1992) pointed out that the primary cause of *C. japonica* declines on the Kanto Plain is an increase in water stress due to dry air, and not acid rain or air pollution. Ito *et al.* (2002) suggested that low soil water-holding capacity may be a cause of *C. japonica* declines.

In addition, drought damage to *C. japonica* stands in southwestern Japan, mainly in Kyushu, has been reported since the 1960s (Ogawa, 1996). The drought damage recently observed in a *C. japonica* plantation in Miyazaki Prefecture may have been caused by increases in temperature and changes in precipitation patterns (Sanui, 1998).

According to the global warming scenario of the Intergovernmental Panel on Climate Change (IPCC, 2001), not only will average temperatures increase, but also the amounts of precipitation and rainfall intervals will also change in the future. These changes will result in changes in available soil water and air dryness. This will in turn affect the distribution and growth of plants, particularly for water-demanding species such as *C. japonica*, if the balance between water supply from precipitation and water consumption by transpiration is altered.

Because *C. japonica* is the primary coniferous plantation species in Japan, it is of concern whether *C. japonica* forests will decline due to increases in temperature and decreases in soil water availability. A nationwide assessment of the effects of climate change on *C. japonica* forests in Japan has not been performed. Thus, we estimated the vulnerability of *C. japonica* plantations to global warming in terms of the water-holding capacity of soil and the transpiration properties of *C. japonica*.

2. Regional Distribution of Soil Water-holding Capacity

Forest management experience has determined that *C. japonica* grows best at sites such as mountain slopes and valleys where abundant water is available. A national survey of forest soils began in Japan after World War II; thus, detailed analyses have been conducted on the relationships between environmental factors and the forest productivity of major conifer species in Japan. For *C. japonica*, soil type, geological conditions and parent materials, elevation (temperature), and local topography are the four most important factors affecting productivity. Among these, soil type was found to have the greatest effect on *C. japonica* growth (Mashimo, 1970). Based on this survey, *C. japonica* plantations were rapidly expanded throughout Japan under the policy of increasing coniferous plantations. However, at that time, it was not anticipated that climate change might suddenly change the productivity of *C. japonica*.

Generally, the soil-water characteristics of forest-land are not easily altered. However, the dramatic changes in precipitation that are anticipated as a result of global climate change may greatly alter water availability for *C. japonica*. When evaluating the effects of precipitation changes on the growth of *C. japonica*, soil water-holding capacity must also be considered. Soils have different water-holding capacities and can be divided into separate classes based on soil type. We applied index values of the water-holding capacity of each soil type to grid-square data of forest soils (Digital National Land Information database) to evaluate the regional distribution of soil water-holding capacity in Japan.

2.1 Categorization of soils according to water-holding capacity

According to the Digital National Land Information database (see Section 2.2), four major forest soil groups (Soil Division, 1976; Editorial Committee of Survey Methods for the Forest Environment, 1999) are found in Japan: brown forest soils (69% of the total forest area), black soils (13%), podzolic soils (4%), and red and yellow soils (2%). These four groups together comprise 88% of the forested area, with the remainder being immature soils or soils in other categories. Because *C. japonica* has been planted mainly in brown forest soils and black soils, we chose these forest soil groups for analysis. Data on soil physical characteristics from 112 profiles from *C. japonica* forests (Mashimo, 1960) and 131 profiles from Kyushu (Hotta, 1997) were converted into a database of soil water-retention curves. The slopes of the curves were generally gentle, at pF 1.0-3.2 (from – 0.98 to –155 kPa) in moderately moist brown forest soils and black soils. These soils showed relatively constant changes in soil matric potential in proportion to changes in soil moisture content. Conversely, in dry brown forest soils and slightly wet brown forest soils, sudden steep increases in moisture-characteristics' curves were observed, at pF 1.5-1.8 (from –3.1 to – 6.2 kPa). Most of these soils showed large changes in soil matric potential with small changes in soil moisture content. The soils were classified as follows based on the above analysis.

Brown forest soil-dry type:

Dry brown forest soil (loose granular structure; B_A), dry brown forest soil (granular and nutty structure; B_B), slightly dry brown forest soil (B_C), and moderately moist brown forest soil [drier subtype; B_D(d)].

Brown forest soil-moderately moist type:

Moderately moist brown forest soil (B_D).

Brown forest soil-wet type:

Moderately moist brown forest soil in which features of the wet type are present [B_D(w)], and slightly wet brown forest soil (B_E).

Black soil:

Black soils (Bl).

The soil water-holding capacity was defined using the following formula, taking into consideration the water available for plants:

$\theta e = \theta f - \theta r$,

where θe is the moisture content at the effective water-holding capacity, θf is the moisture content at field water capacity, and θr is the moisture content at the wilting point.

Experimental data having a high matric potential near θr were lacking in the data of Mashimo (1960). Therefore, soil water-retention curves were drawn using a lognormal distribution model (Kosugi, 1994) and θr was assumed. Four parameters for the lognormal distribution model are shown in Table 1, i.e., θs (water content at maximum water capacity), θr (moisture content at the wilting point, suitable pF 4.2 [–1,554 kPa]), Ψm (soil matric potential corresponding to the median pore size), and σ (width of the pore-size distribution), as well as the average value of θf (moisture content at field capacity) and $\theta f - \theta r$ (moisture content of effective water-holding capacity) for each soil type.

2.2 Mapping soils using grid-square data

Grid-square data of the geography, topography, and vegetation of Japan were obtained from the Digital National Land Information database (Ministry of Land, Infrastructure and Transport of Japan). Meteorological data from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency and changing climatic scenarios were both converted to databases using the grid-square system (Ministry of Internal Affairs and Communications of Japan). The advantage of the grid-square method is that it is easy to superimpose various factors to characterize specific properties at a regional scale. Here, we used the grid-square method for mapping, in which the area of a second-order grid square is approximately 100 km^2, delimited by every 5' in latitude and 7'30" in longitude. The area of a third-order grid square is approximately 1 km^2, obtained by dividing a second-order grid square into 10 segments in both latitude and longitude. A code is assigned to each grid square based on its latitude and longitude, and the position of this code is specified.

A nationwide map of forest water-holding ability was obtained at the level of second-order grid squares using the average moisture contents of effective water-holding capacity (see Table 1) for the 100 third-order grid squares within each second-order grid square. Attributes of the third-order grid squares were determined from analysis of the soil water retention curves based on soil types from the Digital National Land Information database (Ministry of Land, Infrastructure and Transport of Japan; natural topographic grid squares [G05-54M] and land-use grid squares [L03-62M]).

2.3 Regional distribution of soil effective water-holding capacity

A nationwide distribution of soil types was determined on a second-order grid-square level (Fig. 2). The dominant soil type of the third-order grid squares was shown if the type occupied at least 50% of the forest soil area of the second-order grid square. Brown forest soil-dry type was distributed widely along the seaboard from Aichi Prefecture westward. Brown forest soil-wet type was distributed only at the foot of valleys. Because of the limited distribution area of this soil type, it did not appear at the level of second-order grid squares (Fig. 2). This soil type rarely appeared at the level of third-order grid squares inland from Tohoku to Kanto and Chubu, or in Shikoku and the northern part of Kyushu. Black soil was widely distributed on the Pacific side from Aomori Prefecture to Iwate Prefecture, on the Kanto Plain, and in mountainous regions of Kyushu. Brown forest soil-moderately moist type was the most widely distributed in Japan, and tended to occur mainly in inland mountainous areas.

A nationwide map of soil water-holding capacity (moisture contents of effective water-holding capacity) was determined at the second-order grid-square level (Fig. 3). Low risk of water stress value (0.132) was used the mean of moisture content of effective water-holding capacity of the black soil (see Table 1) in this figure. And high risk of water stress value (0.104) in Fig. 3 was used the value that 30% value (0.012) of the difference in the brown forest soil-dry type and the black soil was added to the value of the brown forest soil-dry type (0.092).

Regions having a high risk of water stress for the growth of *C. japonica* were distributed in western Japan, in the Mikawa region, the coastal area of the Setouchi region, the Kinki region, the northwestern Kyushu region, and the coastal area of the Shikoku region (Fig. 3, in red). This was because brown forest soil-dry type has a low water-holding capacity and is distributed on the seaboard of western Japan, whereas brown forest soil-moderately moist type and black soil are predominantly distributed in the eastern part of Japan from the Kanto region to the Tohoku region and in the inland mountainous area of the Kyushu region.

Declines in *C. japonica* and *Chamaecyparis*

Table 1 Values of four parameters in the lognormal distribution model of soil water retention curve and average values at field capacity moisture content and water content of effective water-holding capacity by soil category.

Soil category	N	Water content at maximum moisture capacity θs (m^3/m^3)	Moisture content at wilting point θr (m^3/m^3)	Soil matric potential corresponding to median porosity size Ψm (cm H_2O)	Width of porosity distribution σ (mm)	Moisture content at field capacity θf (m^3/m^3)	Moisture content of effective water-holding capacity θf–θr (m^3/m^3)
Brown forest soil-dry type	47	0.752	0.317	– 43.6	1.21	0.409	0.092
Brown forest soil-moderately moist type	103	0.710	0.542	– 84.6	1.41	0.678	0.136
Brown forest soil-wet type	50	0.770	0.450	– 47.6	1.37	0.546	0.096
Black soil	78	0.722	0.578	– 59.6	1.17	0.710	0.132

Source: Mashimo (1960).
Forest soil types (Soil Division, 1976) are as follows. Brown forest soil-dry type; B_A, B_B, B_C, and B_D(d): brown forest soil-moderately moist type; B_D: brown forest soil-wet type; B_D(w) and B_E: black soil; Bl.

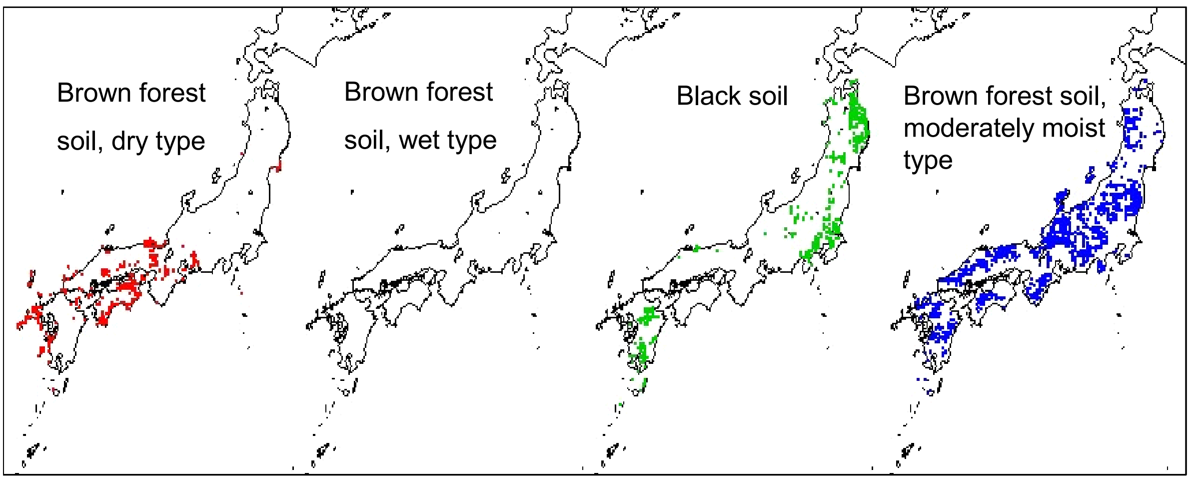

Fig. 2 Distribution map of second-order grid squares in which third-order grid squares dominated by a particular soil pattern that comprised at least 50% of the second-order grid squares of the forested area.
Brown forest soil-wet type does not appear here substantially; it can be seen only at the level of third-order grid squares.

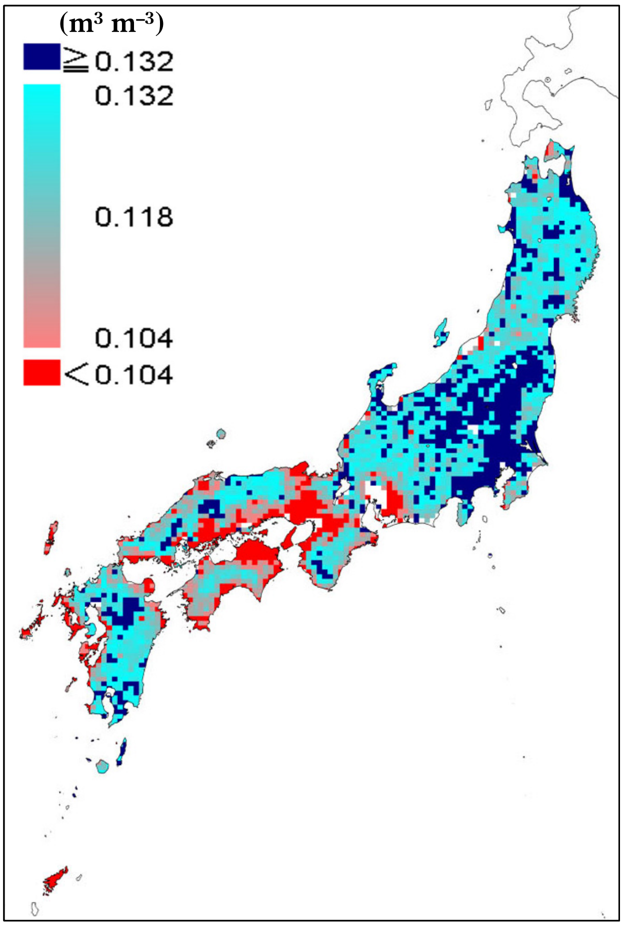

Fig. 3 Map of the soil water-holding capacity (SWC), i.e., moisture content of effective water-holding capacity (MCC).
Darker blues indicate higher SWC; darker reds indicate lower SWC.
MCC (m^3 H_2O / m^3 soil) = Moisture content at field capacity – Moisture content at wilting point

obtusa Sieb. *et* Zucc. (Japanese cypress; '*hinoki*' in Japanese) forests in the Mikawa region (Nagoya Branch Forest Office, 1997) and declines in *C. japonica* forests in the Setouchi region (Nashimoto & Takahashi, 1990) have been reported. The soil water-holding capacities in these regions are low (Fig. 3). In contrast, although declines in *C. japonica* forests have been documented in the Kanto region (Nashimoto & Takahashi, 1990; Matsumoto *et al.*, 1992, 2002; Ito *et al.*, 2002), a low soil water-holding capacity was not indicated in this area. Therefore, insufficient soil water-holding capacity alone cannot explain the cause of the decline in *C. japonica* forests on the Kanto Plain.

3. Transpiration/Precipitation (Tr/P) Ratio as an Index of Vulnerability for *C. japonica* Forests, and Projections of Unsuitable Areas for their Growth under Global Warming

Temperature is an important environmental factor that influences the amount of water consumed by forest trees. Precipitation is the source of available water. Thus, specific combinations of air temperature and precipitation, i.e., climatic conditions, should determine the water environment of forest trees.

Mashimo (1983) indicated that the site index for *C. japonica* forests is low if the ratio of annual precipitation to annual average temperature is less than 130-140 mm/mm. For *C. japonica*, which generally favors humid locations, the climate-related water environment is considered to be a factor affecting its growth in Japan. Increases in temperature and increases or decreases in precipitation due to global warming would alter the water environment, which might have adverse effects on the *C. japonica* planted in certain areas.

Our purpose was to estimate the areas unsuitable for *C. japonica* growth using the water environment predicted from changes in the environment due to global warming. We used the transpiration/precipitation (Tr/P) ratio as an index of the vulnerability of *C. japonica* forests with regard to the water environment. First, we established the regionality of the Tr/P ratio under current climate conditions and compared areas with high Tr/P ratios to areas of current *C. japonica* decline. We then determined the areas predicted to be unsuitable for *C. japonica* growth in the future from predicted changes in the Tr/P ratio under a global warming scenario.

3.1 Calculation and mapping of the Tr/P ratio

Plantation forests of *C. japonica* with fixed needle weights were assumed. The annual transpiration rates were calculated from the needle gas-exchange characteristics and monthly second-order grid square climate characteristics. We used the methods of Shigenaga *et al*. (2005) to calculate the transpiration rate and the Tr/P ratio. Two types of grid square climatic data were used: current climate (1981-2000, annual mean) and future climate (2081-2100). The future climate data were converted (Nishimori, personal communication) from the second version of the standard climate scenario provided by the Japan Meteorological Agency.

In mapping the parameters, areas where no *C. japonica* forests occurred and where Kira's warmth index (Kira, 1977) was less than 65°C month, which is the lower limit for the afforestation of *C. japonica* (Mashimo, 1983), were excluded from the analysis. The area of *C. japonica* forests in each second-order grid square was calculated from forestry census data (Statistics and Information Department, Ministry of Agriculture, Forestry and Fisheries, 1992). Warmth indices were obtained from third-order grid square climatic values (Japan Meteorological Agency 2002), which were derived from the 30-year average for the period 1971-2000.

3.2 Regionality of the Tr/P ratio and the decline of *C. japonica* forests

The annual transpiration rates of *C. japonica* forest calculated from current climatic data were within the 400 to 800 mm range and were higher in southern than in northern Japan (Fig. 4). Kondo *et al.* (1992) estimated the annual transpiration of a hypothetical forest at 300-800 mm/year, using the heat-budget method and climatic data from meteorological stations throughout Japan. The annual transpiration of *C. japonica* forest in central Japan was estimated at approximately 610-760 mm/year using heat-pulse methods (Tange, 1987). Our calculated values were similar to these previous results.

The Tr/P ratios were within the 0.14 to 0.67 mm/mm range (Fig. 5). A particularly high incidence of grid squares with high Tr/P ratios was observed in the Kanto-Kou-shin and Kansai-Setouchi regions. Recent declines in *C. japonica* have been reported in both areas (Nashimoto & Takahashi, 1990; Matsumoto *et al*., 2002). For the Kanto Plain, the Tr/P ratio was highest in areas along the Tone River in Gunma and Saitama prefectures, where signifi-cant declines in *C. japonica* have been reported (Matsumoto *et al*., 2002). Although the primary cause of these declines has not been determined, the climatic conditions suggest that these areas are unsuitable for *C. japonica* growth. The Tr/P ratio appears to be an effective index to determine the vulnerability of *C. japonica* forest to climatic factors.

3.3 Estimation of vulnerable areas of *C. japonica* forest under changing climatic conditions

According to the future climatic scenario (2081-2100), the annual mean temperature of areas currently containing *C. japonica* forests will increase by 2.2°C to 3.2°C. Annual precipitation is anticipated to increase by approximately 150 mm/year on average, although some areas are expected to have increases of at least 700 mm/year, and others decreases of 200 mm/year. Under this scenario, the annual transpiration rate is calculated to increase from 50 mm/year to 100 mm/year compared to current conditions because of increases in temperature. On the Setouchi side of the Chugoku region and in northern Kyushu, the Tr/P ratio is predicted to decrease compared to current values (Figs. 5 & 6) because of increases in precipitation. In contrast, the Tr/P ratio is predicted to increase on the Kanto Plain and in northern Tohoku.

Under current climate conditions, grid squares with Tr/P ratios of 0.5 mm/mm or more occur in the Setouchi region and along the Tone River in Gunma and Saitama prefectures (Fig. 5), where declines in *C. japonica* have been reported. Assuming this value as the threshold of vulnerability in terms of climatic conditions, grid squares with a Tr/P ratio greater than 0.5 mm/mm are anticipated to expand outward on

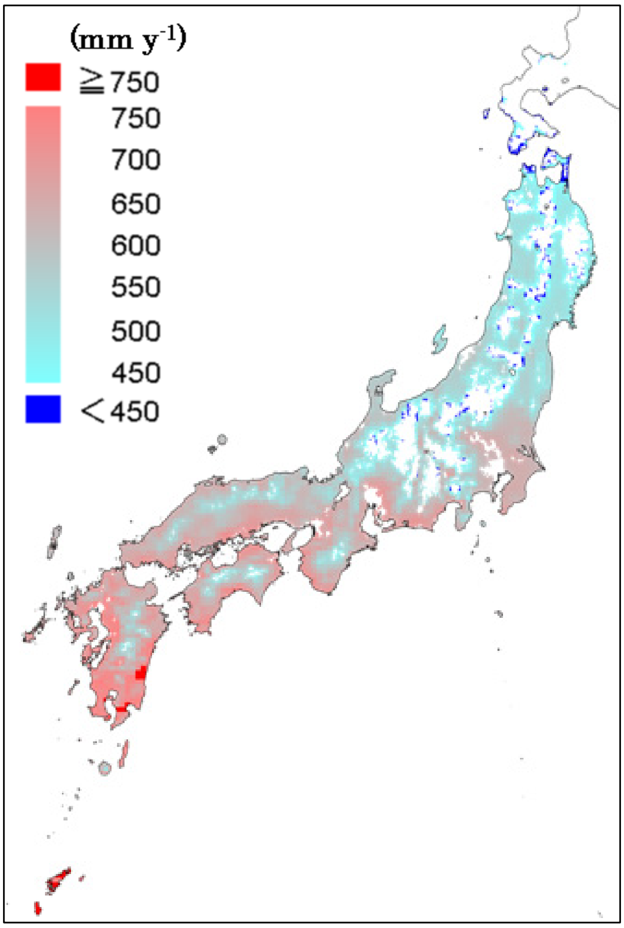

Fig. 4 Map of the annual transpiration of *Cryptomeria japonica* (Japanese cedar) forests calculated using current climate data (1981–2000).
Darker reds indicate higher annual transpiration rates.

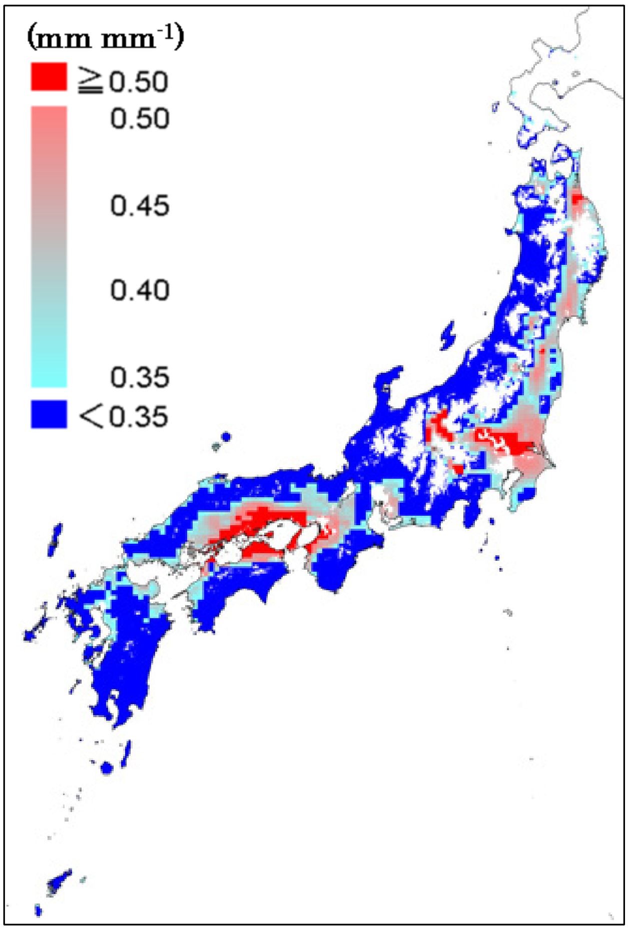

Fig. 5 Map of annual transpiration/precipitation (Tr/P) ratios calculated using current climate data (1981–2000).

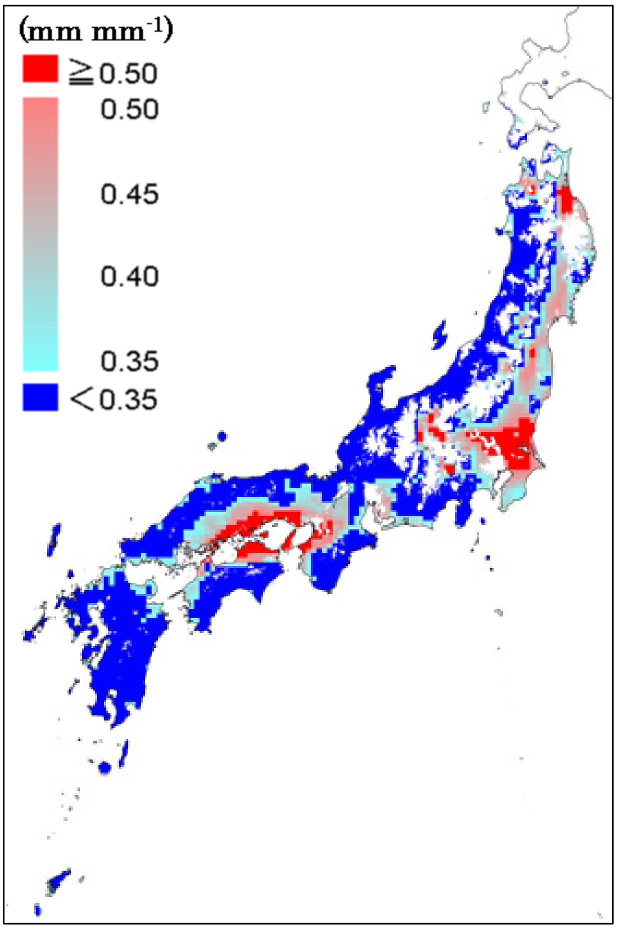

Fig. 6 Map of annual transpiration/precipitation (Tr/P) ratios calculated using future climate scenario data (2081–2100).

the Kanto Plain (Fig. 6). Our analysis predicts that *C. japonica* trees planted in such regions will be weakened by the anticipated climate changes. If this analysis is extrapolated throughout Japan, the area of *C. japonica* plantation forests that are predicted to be above the threshold of Tr/P greater than 0.5 mm/mm is approximately 24,000 ha under current climate conditions, but will increase to approximately 43,000 ha under the global warming scenario.

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