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# Mapping of strength reduction of particleboard subjected to various climatic conditions using a climate deterioration index

Hideaki Korai[1] · Ken Watanabe[1] · Katsuhiro Nakao[1] · Tetsuya Matsui[1] · Tomoyuki Hayashi[2]

**Abstract** The relationship between climatic factors and strength reduction of particleboard subjected to various climatic conditions at eight sites in Japan was investigated. Climatic factors such as mean temperature, sunshine duration, and precipitation were analyzed by principal component analysis. The first principal component score was introduced as a climate deterioration index (CDI). The particleboard strength reduced in high-CDI area. In this useful index for mapping deterioration zones, the CDI distribution was mapped. The strength reduction was predicted with multiple regression analysis using the CDI and exposure time, and the distribution of strength reduction after the outdoor exposure test was mapped as well. Strength reduced significantly in the southern area, particularly along the Pacific Ocean coast. The high-CDI area had high temperature and long sunshine duration. High temperature led to large strength reduction, and long sunshine duration accelerated the strength reduction process. Conversely, strength reduction in the northern area was smaller than that in the south. The mapping of CDI and strength reduction aided the understanding of the deterioration zone.

## 1 Introduction

Particleboards are typically used indoors only. To increase the demand for particleboards, their use must be extended outdoors. Therefore, the effect of outdoor exposure on particleboards must be investigated. Although outdoor exposure tests have been conducted on strength reduction of particleboards in North America (Hann et al. 1962; Gatchell et al. 1966; River 1994), very few tests were conducted in Japan until the early 2000s (Suzuki 2001). Therefore, sites that are representative of the Japanese climate were selected, and particleboards were subjected to various climatic conditions from 2004 to 2011 by the Research Working Group on Wood-based Panels of the Japan Wood Research Society. The sites were Asahikawa, Noshiro, Morioka, Tsukuba, Maniwa, Okayama, Shizuoka, and Miyakonojo, which are numbered 1–8, respectively, in Table 1. The authors' research group, Kojima et al. and Sekino et al. recently reported the results. (Korai et al. 2012, 2013, 2014a, b; Korai 2012; Korai and Hattori 2013; Korai and Saotome 2014; Korai and Watanabe 2015; Watanabe et al. 2015; Kojima et al. 2009, 2012; Kojima and Suzuki 2011a, b; Sekino et al. 2014).

With regard to the influence of climatic factors on the strength reduction of particleboard, Kojima et al. (2012) reported that temperature (cumulative temperature: $\Sigma T$), sunshine duration ($\Sigma S$), and precipitation ($\Sigma P$) are important factors. In a previous study (Korai and Watanabe 2015), these three climatic factors were combined into a first principal component (PC1) by principal component analysis. The PC1 score was closely related to strength reduction of particleboard. The strength of particleboard subjected to outdoor exposure in high-PC1-score area reduced significantly. The PC1 score was an effective index for predicting strength reduction

✉ Hideaki Korai
korai@ffpri.affrc.go.jp

[1] Forestry and Forest Products Research Institute, Tsukuba 305-8687, Japan

[2] Institute of Wood Technology, Akita Prefectural University, Noshiro 016-0876, Japan

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**Table 1** Site no., sites, north latitude, east longitude, third mesh code, and climatic factors at eight sites from the third mesh climate database

| Site no. | Sites | North latitude | East longitude | Third mesh code | Climatic factors from third mesh climate database | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $T$ (°C) | $S$ (h) | $P$ (mm) | CDI |
| 1 | Asahikawa | 43°41′ | 142°22′ | 65424330 | 6.2 | 1638 | 1065 | −2.22 |
| 2 | Noshiro | 40°11′ | 140°00′ | 60402020 | 11.0 | 1709 | 1476 | −0.664 |
| 3 | Morioka | 39°37′ | 141°05′ | 59413047 | 9.5 | 1731 | 1338 | −0.994 |
| 4 | Tsukuba | 36°02′ | 140°05′ | 54400048 | 13.6 | 1829 | 1217 | −0.048 |
| 5 | Maniwa | 35°05′ | 133°41′ | 52335505 | 12.6 | 1585 | 1529 | −0.785 |
| 6 | Okayama | 34°41′ | 133°46′ | 52330622 | 14.5 | 1892 | 1165 | 0.288 |
| 7 | Shizuoka | 34°57′ | 138°25′ | 52383354 | 15.9 | 2028 | 2214 | 2.18 |
| 8 | Miyakonojo | 31°43′ | 131°05′ | 47314076 | 16.1 | 1963 | 2449 | 2.24 |

Third mesh cord and third mesh climate database were shown in reference (Japan Meteorological Business Support Center 2002). The CDI was calculated by principal component analysis using the standardized T, S, and P

T annual mean temperature, S annual sunshine duration, P annual precipitation, CDI climate deterioration index (score of first principal component)
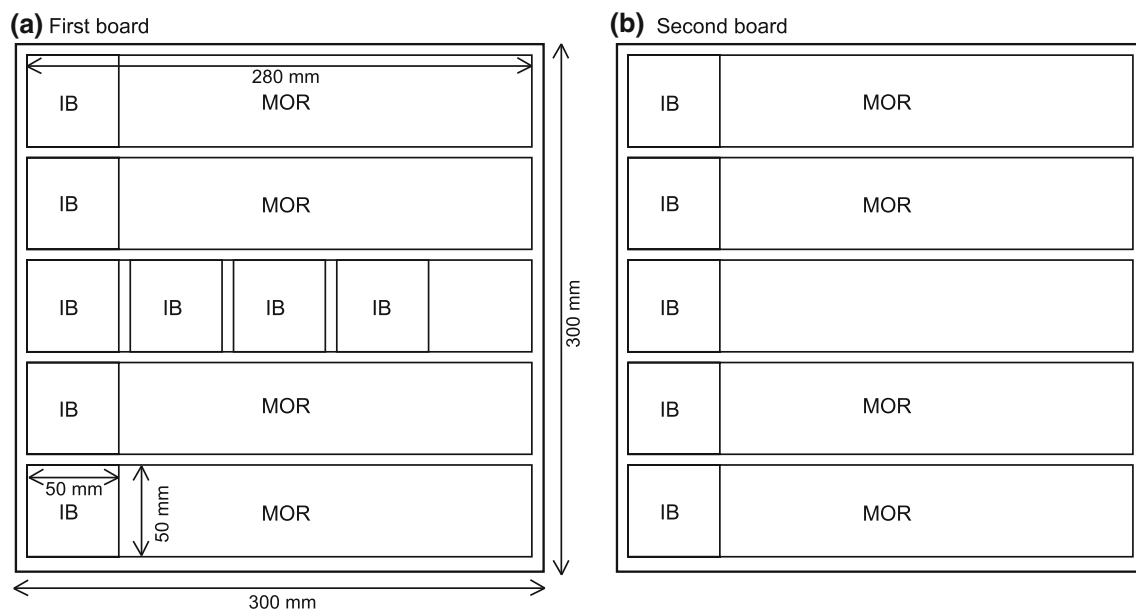


**Fig. 1** Trimming of specimens measuring 280 mm × 50 mm for modulus of rupture (MOR) and specimens measuring 50 mm × 50 mm for internal bond strength (IB) from specimens measuring 300 mm × 300-mm

resulting from outdoor exposure. In this study, the PC1 score was referred to as the "climate deterioration index (CDI)".

Kojima et al. (2012) also proposed "weathering intensity (WI)" as an index for predicting strength reduction of particleboard subjected to various climatic conditions. In their study, the WI was calculated using temperature and precipitation [WI = logΣ(T × P)]. In a previous study (Korai and Watanabe 2015), the CDI was found to be a more powerful index than the WI for predicting the

strength reduction of particleboard. Scheffer also proposed a climate index for predicting decay in solid wood (Scheffer 1971). This index, referred to as the "Scheffer index" in this study, was calculated using temperature and the number of days in the month with 0.01 inch or more of precipitation. Instead of using the Scheffer index, which was developed for biodeterioration of solid wood located at just 3 sites in the USA, the CDI was adopted as a more appropriate index of strength reduction of particleboard. Particleboard deteriorates in different ways to solid wood,

and the effects of the CDI on strength reduction of particleboard at the eight sites in Japan for 5 years were analyzed using much larger and location-specific databases for temperature, sunshine duration, precipitation. Rainwater commonly penetrates particleboard and results in swelling that ruptures resin bonding points to reduce strength. Even without biodeterioration, the particleboard strength reduces because of rupturing. Consequently, the rupturing results in the formation of large voids, thereby causing internal biodeterioration, which leads to further strength reduction. Furthermore, the CDI is more powerful than the WI, as described above. Therefore, in this study, the CDI was used as a climate index for predicting the strength reduction of particleboard.

Japan has a diverse climate, which may suggest a large variability in strength reduction (Hasegawa 1996). In this study, the strength reduction was predicted using multiple regression to examine the CDI and strength reduction at the eight sites. Strength reduction of particleboard subjected to outdoor exposure was mapped to aid the understanding of the deterioration zones.

## 2 Materials and methods

### 2.1 Outdoor exposure and strength tests

This study used data from outdoor exposure tests conducted at the eight sites from February 2004 to March 2009. The values of climatic factors at these sites, including annual mean temperature, annual sunshine duration, and annual precipitation, were obtained from the third mesh climate database (Japan Meteorological Business Support Center 2002). The third mesh is summarized on a 30″ latitude × 45″ longitude grid square (ca. 1 km × 1 km) using the small circle method. The climatic factors of 380,196 grid squares (nationwide area, ca. 380,196 km$^2$) were used for statistical analysis and mapping (Geographical Survey Institute 1992).

Commercially available phenol–formaldehyde resin-bonded particleboards were used for the outdoor exposure test. The density and thickness of the particleboard were 0.75 g/cm$^3$ and 12.2 mm, respectively. 30–40 particleboards measuring 910 mm × 1823 mm were cut into
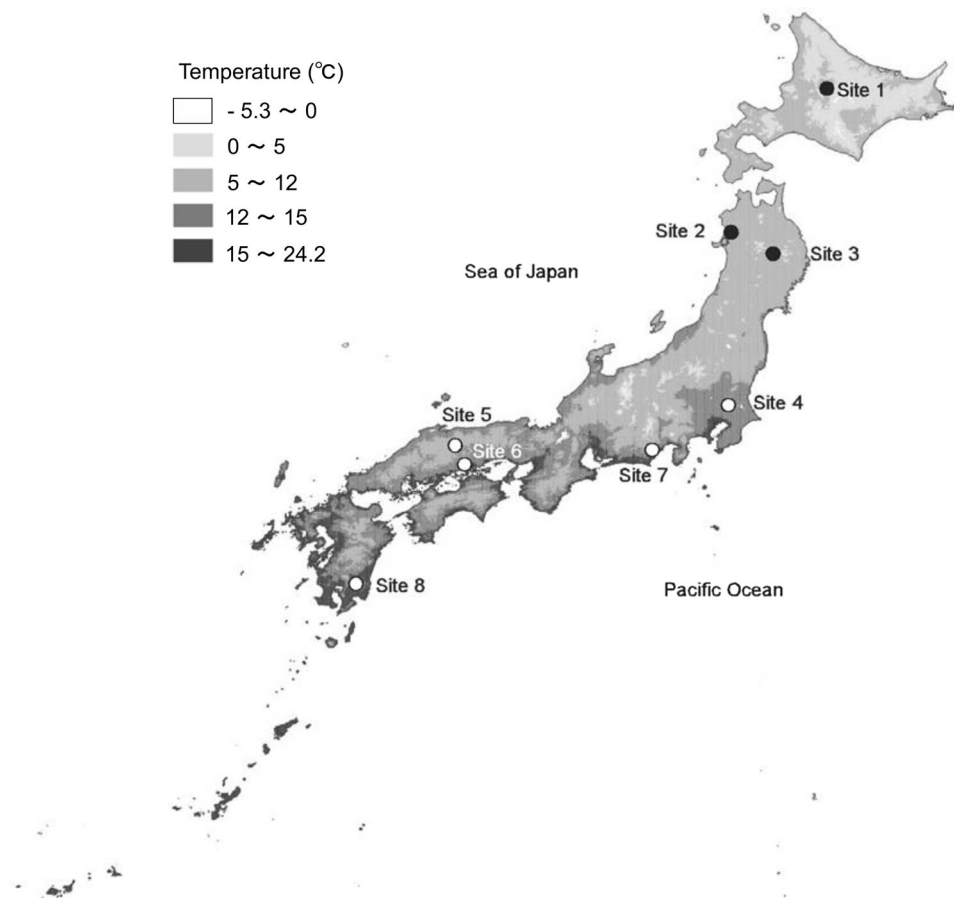


Fig. 2 Distribution of annual mean temperature in Japan. Site numbers are listed in Table 1

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specimens measuring 300 mm × 300 mm. The cut edges of the specimens were coated with enamel paint, which acted as a waterproofing agent. Twelve specimens that were selected randomly were subjected to outdoor exposure to the south at an angle of 90°. Two specimens were collected after 1-, 2-, 3-, 4-, and 5-year outdoor exposure. These specimens were then conditioned in a room at temperature of 20 °C and relative humidity of 65 % for approximately one month. After conditioning, the moisture content of the specimens was approximately 8–10 % (Korai et al. 2013). For the strength tests, internal bond strength (IB) and modulus of rupture (MOR), representing bending strength, were measured in compliance with Japanese Industrial Standards (2003). For the MOR test, specimens measuring 280 mm × 50 mm were removed from the specimens measuring 300 mm × 300 mm. After this test, specimens measuring 50 mm × 50 mm were removed from the MOR specimens to be used for the IB test. Prior to the IB test, all harsh surfaces of the specimens resulting from outdoor exposure were smoothed to a depth of approximately 3 mm using a sander to measure the bonding strength at the core of the particleboard. Figure 1

shows the trimming of the MOR and IB specimens. The MOR was calculated from specimen thickness after conditioning. From two specimens measuring 300 mm × 300 mm, eight and thirteen specimens were cut for the MOR and IB tests, respectively. The initial mean MOR and IB values of the particleboard were 20.3 (2.29) MPa and 0.833 (0.09) MPa, respectively, with the number in parentheses indicating standard deviation. Thirty specimens were used for measuring the initial mean MOR and IB values. The MOR retention and IB retention were calculated using below equation:

$$\text{MOR (or IB) retention}(\%) = \frac{\text{Value after outdoor exposure test}}{\text{Initial value before outdoor exposure test}} \times 100$$

## 2.2 Statistical analysis

Principal component analysis and multiple regression analysis were conducted using computer software "R. 3.0.2 (R Development Core Team 2013)". Standardized climatic factors at the eight sites listed in Table 1 were analyzed using
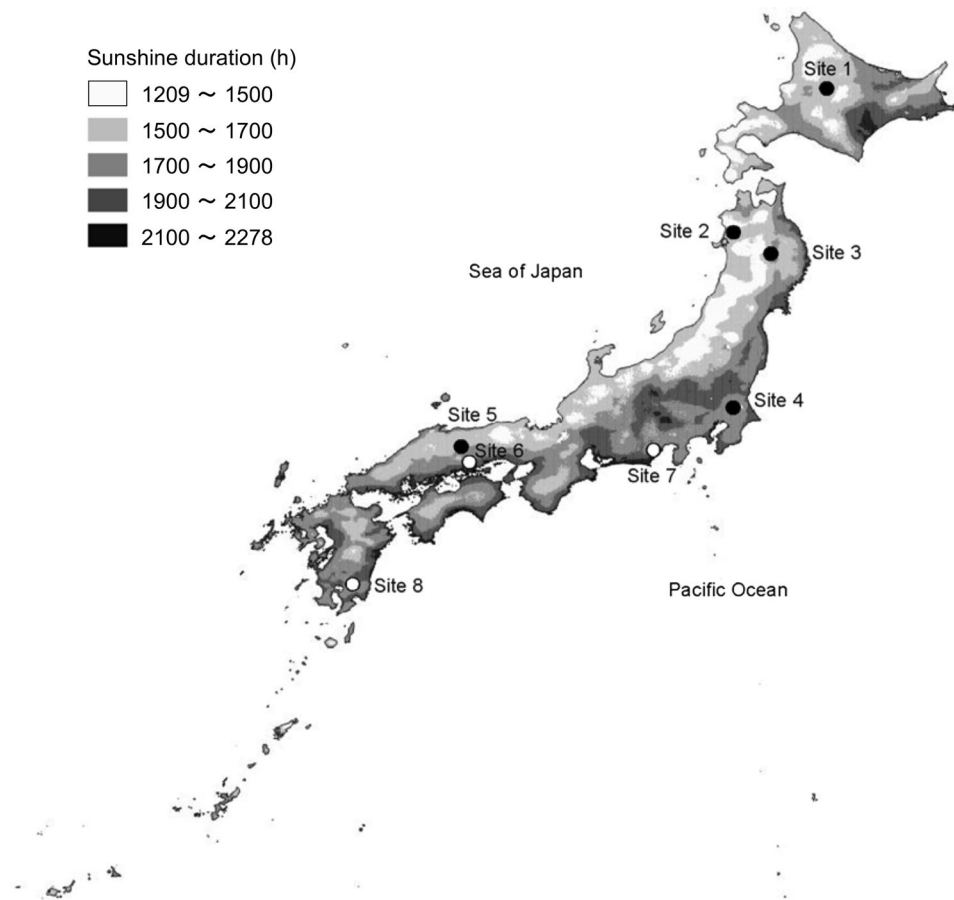


Fig. 3 Distribution of annual sunshine duration in Japan. Site numbers are listed in Table 1
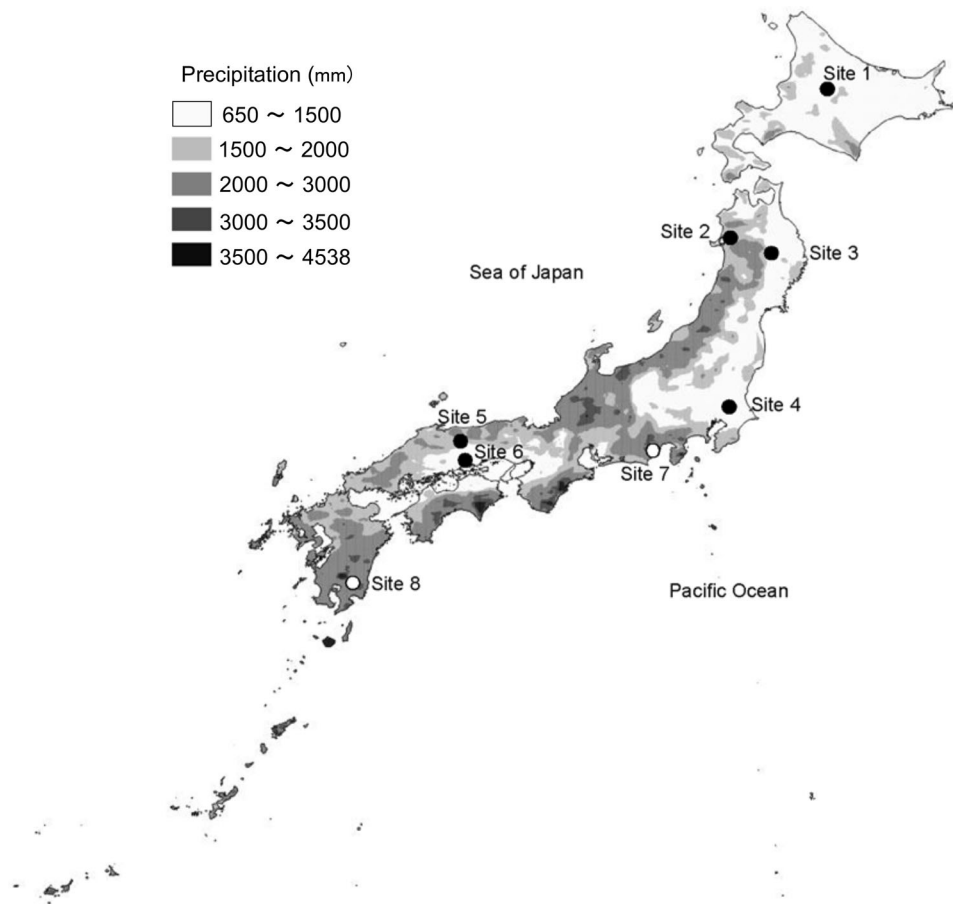
**Fig. 4** Distribution of annual precipitation in Japan. Site numbers are listed in Table 1

**Table 2** Eigenvalue, proportion, cumulative proportion, and eigenvector calculated using the principal component analysis of climatic factors

|                          | PC1   | PC2    | PC3    |
|--------------------------|-------|--------|--------|
| Eigenvalue               | 2.40  | 0.381  | 0.219  |
| Proportion (%)           | 80.0  | 12.7   | 7.30   |
| Cumulative proportion (%)| 80.0  | 92.7   | 100    |
| Eigenvector              |       |        |        |
| $T$                      | 0.593 | −0.294 | −0.749 |
| $S$                      | 0.584 | −0.483 | 0.652  |
| $P$                      | 0.554 | 0.824  | 0.115  |

Principal component analysis was conducted using the T, S, and P listed in Table 1. Prior to principal component analysis, the T, S and P were standardized

*PC1* first principal component, *PC2* second principal component, *PC3* third principal component, *T* annual mean temperature, *S* annual sunshine duration, *P* annual precipitation

**Table 3** Correlation coefficients among climatic factors

|       | Correlation coefficient | | | |
|-------|---------------------|---------------------|---------------------|-----|
|       | $T$                 | $S$                 | $P$                 | CDI |
| $T$   | 1                   |                     |                     |     |
| $S$   | 0.781[*]            | 1                   |                     |     |
| $P$   | 0.679[ns]           | 0.642[ns]           | 1                   |     |
| CDI   | 0.920[**]           | 0.905[**]           | 0.859[**]           | 1   |

CDI was calculated by principal component analysis using the T, S, and P listed in Table 1. The T, S and P were standardized. The correlation coefficients were calculated using the T, S, P, and CDI listed in Table 1

*T* annual mean temperature, *S* annual sunshine duration, *P* annual precipitation, *CDI* climate deterioration index (score of first principal component)

[*] Statistical significance at 5 % level

[**] Statistical significance at 1 % level

[ns] no statistical significance

principal component analysis, and the eigenvalues, proportion, cumulative proportion, eigenvectors, and PC1 score (CDI) were calculated. The CDI was predicted using the standardized climatic factors of the 380,196 grid squares.

Multiple regression analysis was conducted using the CDI of the eight sites and the exposure time as the explanatory variables. Particleboard strength (MOR or IB)

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**Table 4** Mean internal bond strength (IB) and mean modulus of rupture (MOR) of particleboard subjected to outdoor exposure at eight sites for 5 years, climate deterioration index (CDI) at eight sites, and correlation coefficient between IB (or MOR) and CDI for 1 to 5 years

| Exposure time (year) | IB (MPa) | | | | | MOR (MPa) | | | | | CDI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | |
| Site 1 | 0.812 | 0.626 | 0.666 | 0.596 | 0.360 | 14.9 | 13.7 | 12.8 | 11.8 | 6.34 | −2.22 |
| Site 2 | 0.630 | 0.540 | 0.464 | 0.287 | 0.377 | 14.9 | 14.1 | 9.63 | 9.41 | 10.3 | −0.664 |
| Site 3 | 0.639 | 0.458 | 0.521 | 0.480 | 0.193 | 13.2 | 11.5 | 10.6 | 8.69 | 4.01 | −0.994 |
| Site 4 | 0.605 | 0.573 | 0.318 | 0.320 | 0.140 | 14.1 | 12.5 | 9.85 | 7.70 | 9.44 | −0.048 |
| Site 5 | 0.551 | 0.434 | 0.323 | 0.186 | 0.119 | 12.9 | 9.90 | 7.05 | 6.28 | 4.69 | −0.785 |
| Site 6 | 0.556 | 0.324 | 0.185 | 0.208 | 0.186 | 14.0 | 8.33 | 7.65 | 4.77 | 5.22 | 0.288 |
| Site 7 | 0.337 | 0.212 | 0.152 | 0.07 | 0.05 | 11.9 | 8.90 | 6.67 | 5.79 | 5.07 | 2.18 |
| Site 8 | 0.229 | 0.125 | 0.09 | 0.06 | 0.06 | 7.90 | 7.17 | 5.86 | 5.14 | 4.88 | 2.24 |
| Correlation coefficient | −0.961[***] | −0.900[**] | −0.919[**] | −0.885[**] | −0.776[*] | −0.778[*] | −0.773[*] | −0.842[**] | −0.793[*] | −0.217[ns] | |

Site nos. are listed in Table 1. CDI was calculated by principal component analysis using the T, S, and P listed in Table 1 (score of first principal component). Prior to principal component analysis, the T, S and P were standardized. Correlation coefficients were calculated between IB (or MOR) and CDI for one to 5 years

[*] Statistical significance at 5 % level

[**] Statistical significance at 1 % level

[***] Statistical significance at 0.1 % level
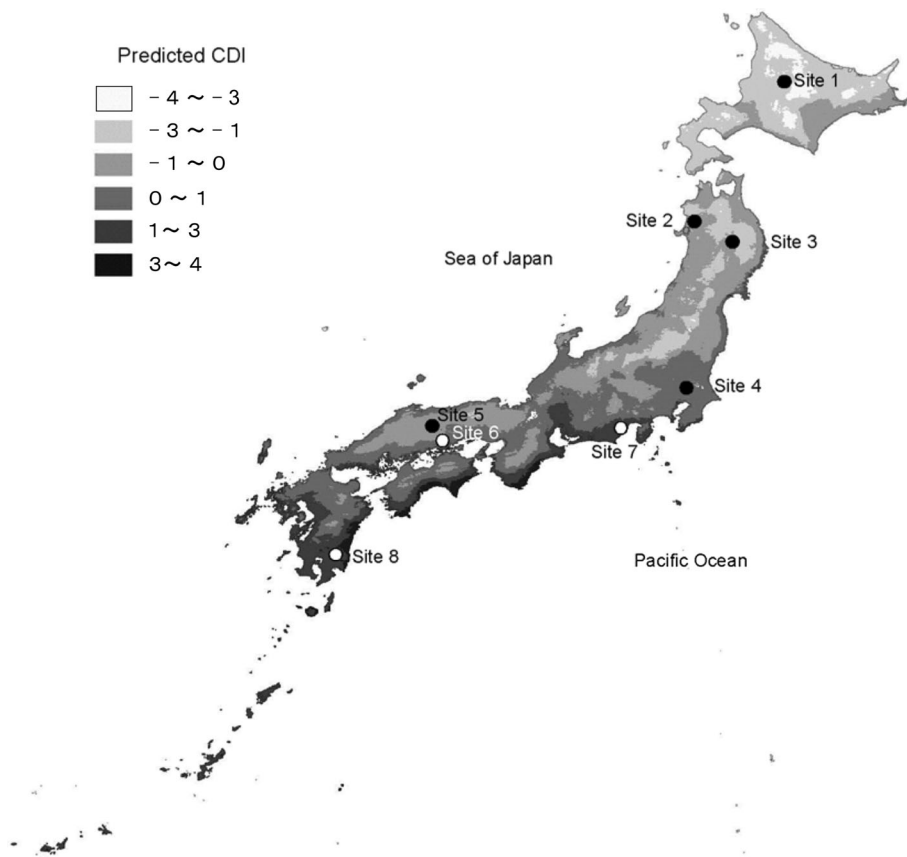
[ns] no statistical significance



**Fig. 5** Distribution of predicted CDI in Japan. Site numbers are listed in Table 1. *CDI* climate deterioration index (score of first principal component). CDI was predicted by principal component analysis using the standardized T, S, and P

was the criterion variable. The IB and MOR of hypothetical particleboards subjected to outdoor exposure at the 380,196 grid squares for 5 years were predicted using a multiple regression equation. In addition, the MOR for 4 years was predicted.

## 2.3 Mapping

The distributions of temperature, sunshine duration, precipitation, predicted CDI, predicted IB, and predicted MOR of the 380,196 grid squares were mapped using QGIS

**Table 5** Standardized regression coefficient, coefficient of determination, and adjusted coefficient of determination of the IB and MOR multiple regression equations

|  | Standardized regression coefficient | | $R^2$ | Adjusted $R^2$ |
|---|---|---|---|---|
|  | CDI | Exposure time |  |  |
| IB | $-0.712$*** | $-0.588$*** | 0.853 | 0.845 |
| MOR | $-0.467$*** | $-0.722$*** | 0.740 | 0.726 |

*IB* internal bond strength, *MOR* modulus of rupture, *CDI* climate deterioration index (score of first principal component), $R^2$ coefficient of determination, *Adjusted $R^2$* adjusted coefficient of determination

*** Statistical significance at 0.1 % level

version 2.2.0 (Geographic Information System). The CDI that ranged from −2.22 to 2.24 (Table 1) involved 324,948 grid squares. The predicted CDI of the 380,196 grid squares (nationwide area) ranged from −4.19 to 3.87. Although the former range was smaller than the latter range, the former was representative of most of Japan, covering 85.5 % of the 380,196 grid squares. The multiple regression equations were applicable within the predicted CDI range of the 380,196 grid squares and were thus used to map the distributions of the predicted IB and MOR.

## 3 Results and discussion

### 3.1 Distributions of climatic factors

Figures 2, 3, 4 show the distributions of mean temperature, sunshine duration, and precipitation on a map of Japan. The temperature in the southern area was higher than that in the northern area, and the temperature in the inland area was lower than that in the coastal area. Not all areas with high temperature had long sunshine duration. For example, the sunshine duration along the Sea of Japan was short, but the temperature in that region was



**Fig. 6** Distribution of predicted IB retention for 5-year outdoor exposure in Japan. Site numbers are listed in Table 1. *IB* internal bond strength. IB retention was predicted by multiple regression analysis using predicted CDI and exposure time. *CDI* climate deterioration index
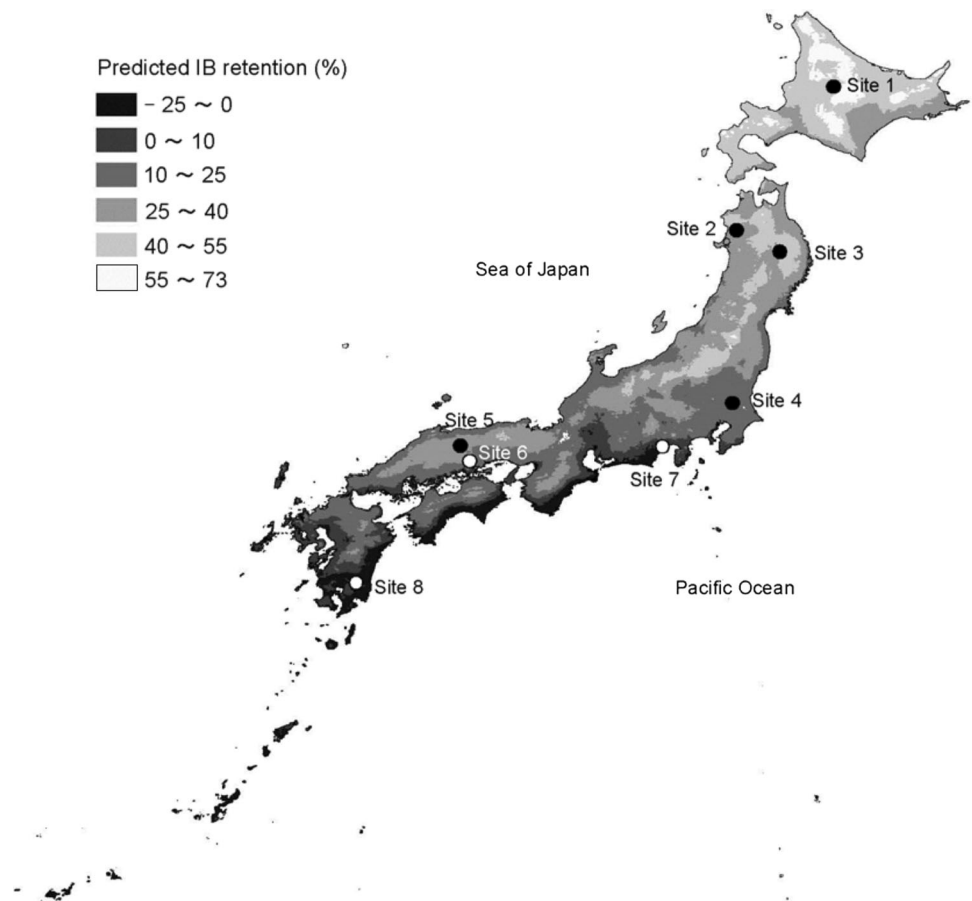
relatively high. Moreover, the northern area along the Pacific Ocean had low temperature but long sunshine duration.

## 3.2 CDI calculated by principal component analysis

Table 1 lists the climatic factors at the eight sites, and Table 2 lists the eigenvalues, proportion, cumulative proportion, and eigenvectors. For PC1, the eigenvalue was 2.40, and the proportion was 80.0 %. These values indicated that 80.0 % of the information resulting from temperature, sunshine duration, and precipitation were combined into PC1. Eigenvector was used as a coefficient in calculating the PC score. All eigenvectors of PC1 had positive values for each climatic factor, thus indicating that the PC1 score increased with increasing temperature, sunshine duration, and precipitation. All eigenvectors of PC1 were almost equal, approximately 0.6, indicating that the PC1 score was affected equally by temperature, sunshine duration, and precipitation. In contrast, the eigenvalues and proportions of PC2 and

PC3 were significantly lower than those of PC1, suggesting that PC1 accounted for the majority of the variability due to climatic factors. Consequently, PC2 and PC3 were not used for analytical purposes in this study. PC1 score, referred to as the climate deterioration index (CDI), combined temperature, sunshine duration, and precipitation into one explanatory variable (Korai and Watanabe 2015).

The CDI values calculated for the eight sites are listed in Table 1. As previously described, the CDI increased with increasing temperature, sunshine duration, and precipitation. Table 3 lists the correlation coefficients among the climatic factors, including the CDI. The correlation coefficient between temperature and sunshine duration was as strong as 0.781. The correlation coefficients between CDI and each climatic factor were stronger than that between temperature and sunshine duration. From the perspective of comprehensive climate evaluation, the CDI was thus more useful than the individual climatic factors.
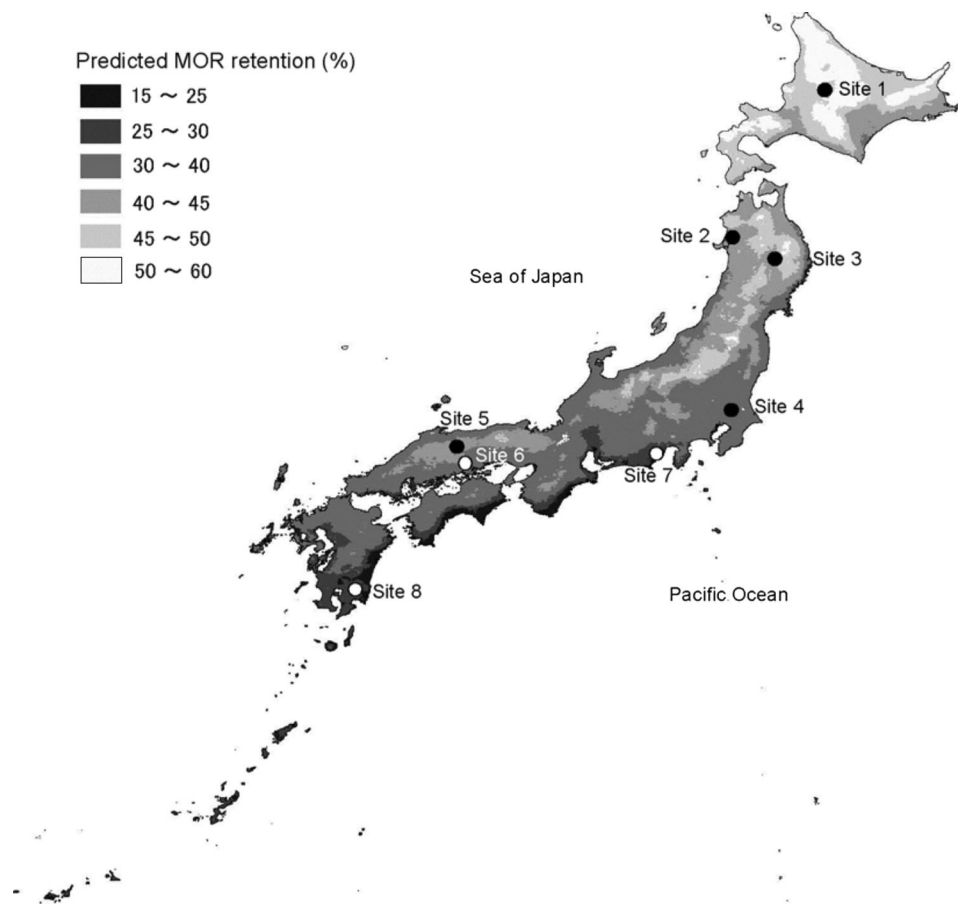


**Fig. 7** Distribution of predicted MOR retention for 4-year outdoor exposure in Japan. Site numbers are listed in Table 1. *MOR* modulus of rupture. MOR retention was predicted by multiple regression analysis using predicted CDI and exposure time. *CDI* climate deterioration index
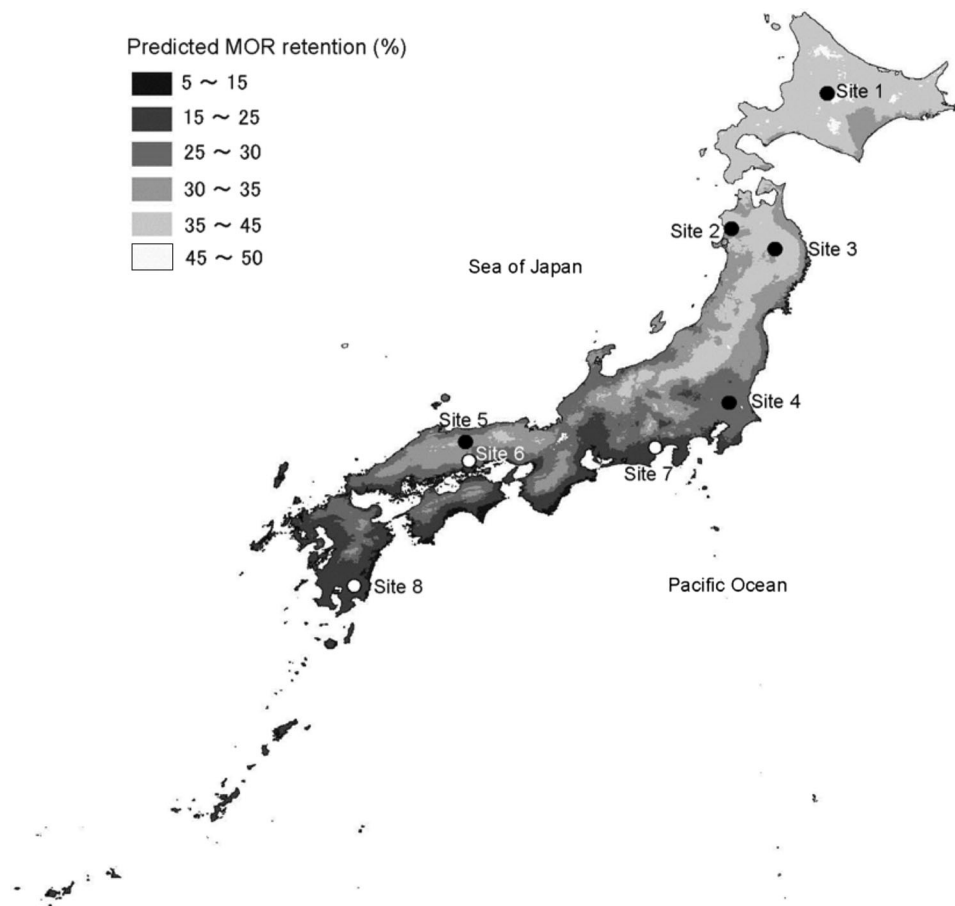
**Fig. 8** Distribution of predicted MOR retention for 5-year outdoor exposure in Japan. Site numbers are listed in Table 1. *MOR* modulus of rupture. MOR retention was predicted by multiple regression analysis using predicted CDI and exposure time. *CDI* climate deterioration index

### 3.3 Mapping of predicted CDI for deterioration zone

Table 4 lists mean IB and MOR of particleboards subjected to outdoor exposure at the eight sites for 5 years (Korai and Watanabe 2015), CDI at eight sites, and the correlation coefficients between IB/MOR and CDI for 5 years. The correlation was strong, except for a MOR value of −0.217 for 5-year outdoor exposure (Korai and Watanabe 2015). In particular, the correlation of IB was stronger than that of MOR. Strength reduced with an increase in the CDI. Hence, the CDI is an effective index for predicting strength reduction of particleboards subjected to various climatic conditions.

Figure 5 shows the distribution of predicted CDI from the climatic factors of the 380,196 grid squares. The CDI was high in the southern area, particularly along the Pacific Ocean, whereas the value was low for the northern area. The CDI inland was lower than that along the coastline. The high-CDI area had high temperature and long sunshine duration. High temperature reduced strength, and long sunshine duration accelerated the strength reduction

process. Therefore, the CDI is a useful index for mapping deterioration zones.

### 3.4 Mapping of predicted strength reduction for deterioration zone

Multiple regression analysis was conducted using the CDI and exposure time to predict strength reduction. Table 5 lists the standardized regression coefficients of the developed equations. For IB, the standardized regression coefficients of the CDI and exposure time were −0.712 and −0.588, respectively, indicating that the degree of the IB reduction caused by the CDI was larger than that by the exposure time. Conversely, for MOR, the standardized regression coefficients of the CDI and exposure time were −0.467 and −0.722, respectively, indicating that the degree of MOR reduction caused by the exposure time was larger than that by the CDI. A difference is noted in the standardized regression coefficients between MOR and IB. The IB is related to bonding strength in the core layer of particleboard (Kawai et al. 1987), whereas the MOR is

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related to the strength in the face layer of particleboard (Wong et al. 1998). When particleboard was subjected to outdoor exposure, biodeterioration was greater in the core layer than that in the face layer. Moreover, this biodeterioration was greater in high-CDI area than that in low-CDI area. The core layer at high-CDI area was deteriorated more than that at low-CDI area. Therefore, the IB reduction caused by the CDI was larger than that by the exposure time, resulting in higher standardized regression coefficients of the CDI. On the contrary, the surface layer deteriorated due to the rupture of bonding points rather than biodeterioration. As for the deterioration of surface layer, the difference between low- and high-CDI areas is small. Therefore, the degree of MOR reduction caused by exposure time was larger than that by the CDI, resulting in higher standardized regression coefficients of the exposure time for the MOR.

Table 5 lists the coefficients of determination ($R^2$) and the adjusted coefficients of determination (adjusted $R^2$) for CDI and exposure time vs IB/MOR. $R^2$ and adjusted $R^2$ were high, indicating good predictive power of CDI and exposure time for IB and MOR of particleboard subjected to various climatic conditions.

Figure 6 shows the distribution of predicted IB retention for 5-year outdoor exposure in Japan. Figures 7 and 8 show the distributions of predicted MOR retention for 4- and 5-year outdoor exposure in Japan, respectively. As listed in Table 4, the correlation between CDI and MOR for 5-year outdoor exposure was low, and the distribution for 5-year outdoor exposure was expected to differ from that for 4-year outdoor exposure. However, the distribution for 5-year outdoor exposure was almost the same as that for 4-year outdoor exposure. This result is attributed to the high adjusted $R^2$, as listed in Table 5. The weak correlation of MOR for 5-year outdoor exposure did not influence the predicted MOR distribution.

Although the actual IB retention values were positive or zero, the predicted IB retention showed negative values in high-CDI area, as shown in Fig. 6, and was considered null when the exposure time increased further. The assumption of linearity in multiple regression analysis may be invalid in extreme climatic conditions. In a separate study (Watanabe et al. 2015), an artificial neural network was used to solve this issue.

Reduction in MOR and IB is symptomatic of other deterioration processes in particleboard due to outdoor exposure. Rupture of bonding points due to outdoor exposure leads to strength reduction of the particleboard, and biodeterioration accelerates the strength reduction. In future work, the effects of the rupture of bonding points and biodeterioration on the strength reduction of particleboards subjected to various climatic conditions in Japan will be analyzed.

## 4 Conclusion

Climatic factors of mean temperature, sunshine duration, and precipitation were analyzed using principal component analysis, and the CDI was developed to combine these factors. Multiple regression analysis using the CDI and exposure time was conducted to predict the strength reduction for 5-year outdoor exposure to map deterioration zones in Japan. High CDI values in the southern part of the country, particularly along the Pacific Ocean, were associated with larger strength reduction of particleboard. The strength did not reduce greatly in the northern sites. High temperature reduced the strength, and long sunshine duration accelerated the strength reduction. Such mapping facilitated better understanding of deterioration zones for strength reduction of particleboard subjected to various climatic conditions in Japan.

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