SPECIAL FEATURE

Data rescue—collection of precious and laborious in situ observed data

Large-scale ecological field data for satellite validation in deciduous forests and grasslands

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Abstract

In situ accurate data sets of leaf area index (LAI), above-ground biomass (AGB), and fraction of absorbed photosynthetically active radiation (fAPAR) are indispensable to validate and improve ecological products obtained from satellites. In situ data for satellite validation must be created not from a single-point data but from areal data (such as multiple-points data) representing a satellite footprint. Using multiple-points data, the error of in situ data can be calculated statistically. The quantification of the error in the in situ data enables us to evaluate the discrepancy between the satellites' products and the in situ data as the error in the in situ data and the estimation error in the products separately. Besides, the accuracy of the in situ data is required to be much higher than the accuracy of the satellite products which was officially set. To obtain such in situ data, we have established observation sites for typical land cover types in East Asia, from temperate to cool ecosystems: deciduous needle-leaved forest (DNF), evergreen needle-leaved forest (ENF), deciduous broad-leaved forest (DBF), and grassland (GL). We conducted the observations in 500 m × 500 m areas, which is the footprint scale of the Global Change

Observation Mission-Climate satellite. In this paper, the data of LAI, AGB, and fAPAR observed at DNF, DBF, and GL (i.e., except at ENF) are reported. These data are useful even for the validation of other satellite products, especially with higher spatial resolution. Also, the long-term tree census data from 2005 to 2018 at DNF are reported.

The complete data set for this abstract published in the Data Paper section of the journal is available in electronic format in MetaCat in JaLTER at <http://db.cger.nies.go.jp/JaLTER/metacat/metacat/ERDP-2020-16.1/jalter-en>.

KEYWORDS

above-ground biomass, fAPAR, leaf area index, long-term tree census data, satellite validation data set

1 | INTRODUCTION

Validation by in situ data is essential for satellite remote sensing of ecosystems. However, it is not easy to obtain in situ data for satellite validation (e.g., Cohen et al., 2006; Fuster et al., 2020; Morisette et al., 2006; Wang et al., 2004). It is because the spatial resolution (i.e., pixel size) of satellite products, especially taken by global sensors such as the Moderate Resolution Imaging Spectroradiometer, is sometimes too high (such as $500\text{ m} \times 500\text{ m}$ or $250\text{ m} \times 250\text{ m}$) to conduct the in situ observation. It is especially true for ecological variables such as leaf area index (LAI), above-ground biomass (AGB), and fraction of absorbed photosynthetically active radiation (fAPAR), because of their spatial heterogeneity and microtopography. To challenge this issue, a project called “JAXA super sites 500” was initiated to make in situ observations of these variables covering areas of $500\text{ m} \times 500\text{ m}$ (Akitsu et al., 2015). Most of all validation projects have conducted the in situ observation in small areas at several points, and have expanded the areas by using an airborne/high-resolution-satellite optical observation to the target satellite footprint scale (e.g., Cohen et al., 2006; Sellers et al., 1995; Wang et al., 2004). Such approach is reasonable for the validation of spectral reflectance. Strictly speaking, for the validation of LAI, AGB, and fAPAR, such data in the expanded areas are based on the estimation, not on the in situ observation. Therefore, we have directly conducted the in situ observation at many points in a satellite footprint scale. The spatial scale ($500\text{ m} \times 500\text{ m}$) has been specifically chosen for validation of the official products of the Global Change Observation Mission-Climate (GCOM-C) satellite.

We had performed in situ observations of LAI and AGB in this scale at a deciduous needle-leaved forest (DNF), a deciduous broad-leaved forest (DBF), an evergreen needle-leaved forest (ENF), and dry/wet grassland

(DGL, WGL), and discussed the accuracy and the cost (required time and manpower) of several methods used in the observations (Akitsu et al., 2019). Since then, we have expanded our observation network. The observation sites have been established for typical land cover types in East Asia from temperate to cool ecosystems: DNF, ENF, DBF, evergreen broad-leaved forest, DGL, and WGL. The detailed datasets of LAI, AGB, and fAPAR at ENF can be obtained from Akitsu et al. (2020). In this paper, we report the detailed datasets of LAI, AGB, and fAPAR at six sites in deciduous forests and grasslands (GLs): Tomakomai Satellite validation site (TOS, DBF), Fujihokuroku Flux site (FHK, DNF), Watarase flood control basin (WTR, WGL), Baganuur (MBN, DGL), Delgertsogt (DGT, DGL), and Khar Yamaat (KYM, DGL). These datasets, which have been observed at many points (each attaches the data of latitude and longitude) at each site, are definitely unique and useful for validation even for other satellite products, especially with higher spatial resolution, such as the Sentinel-2 satellite.

In DNF, DBF, and GLs, the most accurate and reliable ways of in situ observation of LAI are the direct methods, such as litter-fall trap and leaf clipping. The disadvantages of the reliable clipping methods are generally known that the observations are destructive, thus cannot be repeated at fixed locations (e.g., Jonckheere et al., 2004). Besides, it is too laborious and time-consuming to conduct the litter-fall and leaf-clipping observations at a large number of points; although a large number of observation points are required to obtain the representative LAI in a satellite footprint scale. In contrast, the accuracy of indirect methods such as using an LAI-2200 (LI-COR Inc.), a digital camera, and a spectroradiometer is controversial (e.g., Jonckheere et al., 2004). Therefore, the LAI obtained using the indirect methods has to be calibrated by using the LAI obtained using a direct method. The advantages of the

indirect methods are that the observations are not destructive, thus they can be repeated even at fixed locations, and can be conducted easier even at a large number of observation points. To satisfy the accuracy and feasibility of the observation in a large area, we decided to use a combination of direct and indirect methods. First, we obtained the site- or region-specific relationship between the LAI observed by both direct and indirect methods in a limited area. Second, we conducted the observation using an indirect method at a large number of observation points in a large area and obtained the LAI using their relationship. As the combination method, the litter-fall and LAI-2200 methods were conducted in DBF and DNF. In the GLs and understory vegetation in the forests, the clipping method and the spectral observation were conducted. Besides, we investigated the leaf life span (LLS) of *Pinus densiflora*, which stands in FHK, in order to convert its litter-fall to LAI.

In forests and GLs, AGB was observed using a tree census method and a clipping method, respectively. Our basic sampling was designed to construct many small plots rather than a few large plots. It is because multiple measurements are necessary for accuracy assessment. According to the sampling design, for instance, AGB was observed at 25 plots in the 500 m × 500 m area at the TOM site. Each plot has a 1,000 m² area. However, such multiple tree census plots could not be installed at the FHK site due to the legal restraints of the Natural Parks Law. At the FHK site, instead of installing multiple tree census plots, AGB was observed in a large plot with a 200 m × 200 m area, where tree census had been conducted for the long term. In all tree census plots, we observed the tree height and the diameter at breast height (DBH) of each tree.

In summary, we report the following: (a) LAI and fAPAR at 105 points and AGB at 25 points of a 1,000 m² area at the TOS site; (b) LAI and fAPAR at 105 points and AGB in a 200 m × 200 m area at the FHK site; (c) LAI and AGB at 12 to 25 points and fAPAR at 12 points at the WTR site; (d) LAI and AGB at 105 points at the MBN site; (e) LAI and AGB at 51 points at the DGT site; (f) LAI and AGB at 52 points at the KYM site; (g) DBH and tree height for each tree in the tree census area at the TOS and FHK sites; (h) the mean of LAI and AGB in the 500 m × 500 m area at six observation sites; and (i) the mean of fAPAR in the 500 m × 500 m area at the TOS, FHK and WTR sites.

2 | DATA DESCRIPTION

2.1 | Identifier

ERDP-2020-16

2.2 | Contributor

2.2.1 | Dataset owner and contact person

(a) All data except for the following data:

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2.3 | Projects

2.3.1 | Title

(a) Validation of land ecology products of GCOM-C (April 2016–March 2019).

(b) Observation for the validation of terrestrial ecological products of GCOM-C (April 2019–March 2022).

2.3.2 | Personnel

(a) Principal investigator: Kenlo Nishida Nasahara (116).

(b) Principal investigator: Kenlo Nishida Nasahara (ER2GCF103).

2.3.3 | Funding

(a) GCOM: Sixth Research Announcement (April 2016–March 2019) of the Japan Aerospace Exploration Agency (JAXA).

(b) Research Announcement on the Earth Observations: EO-RA2 (April 2019–March 2022) of JAXA.

2.4 | Geographical coverage

Geographic coordinates and descriptions of the six observation sites are listed in Table 1 and Figure 1.

TABLE 1 Description of the study sites

Site ID	Site name	Country	Latitude	Longitude	Elevation (a.s.l.)	Vegetation type	Dominant species
TOS	Tomakomai	Japan	42°42'29.5"N	141°33'18.9"E	103 m	DBF	<i>Quercus crispula</i> , <i>Acer mono</i> , <i>Fraxinus mandshurica</i>
FHK	Fujihokuroku	Japan	35°26'36.9"N	138°45'56.9"E	1,100 m	DNF	<i>Larix kaempferi</i>
FJY	Fujiyoshida	Japan	35°27'16.3"N	138°45'44.1"E	1,030 m	ENF	<i>Pinus densiflora</i>
WTR	Watarase	Japan	36°15'56.9"N	139°40'59.0"E	16 m	WGL	<i>Phragmites australis</i> , <i>Miscanthus sacchariflorus</i>
MBN	Baganuur	Mongolia	47°47'53.3"N	108°19'51.5"E	1,396 m	DGL	<i>Agropyron cristatum</i> , <i>Cleistogenes squarrosa</i> , <i>Stipa krylovii</i> , <i>Artemisia</i> sp., <i>Chenopodium</i> sp.
DGT	Delgertsogt	Mongolia	46°14'56.0"N	106°29'42.9"E	1,380 m	DGL	<i>Artemisia</i> sp., <i>Allium</i> sp., <i>Salsora</i> sp., <i>Stipa</i> sp., <i>Curex</i> sp., <i>Caenopodium</i> sp.
KYM	Khar Yamaat	Mongolia	47°40'13.8"N	112°4'34.9"E	1,060 m	DGL	<i>Agropyron</i> sp., <i>Allium</i> sp., <i>Cleistogenes</i> sp., <i>S. krylovii</i> , <i>Artemisia</i> sp.

Abbreviations: a.s.l: above sea level; DBF, deciduous broad-leaved forest; DGL, dry grassland; DNF, deciduous needle-leaved forest; ENF, evergreen needle-leaved forest; WGL, wet grassland.

FIGURE 1 Location of the large-scale ecological observation sites: Tomakomai (TOS), Fujihokuroku (FHK), Watarase (WTR), Baganuur (MBN), Delgertsogt (DGT), and Khar Yamaat (KYM) sites [Color figure can be viewed at wileyonlinelibrary.com]

2.5 | Temporal coverage

From 2005 to 2019.

2.6 | Methods

2.6.1 | Study sites

Large-scale ecological observation was conducted at six observation sites (the TOS, FHK, WTR, MBN, DGT, and

KYM sites, see Table 1 and Figure 1). We selected the observation sites according to the criteria: flat topography, homogeneous vegetation cover over a 500 m × 500 m square, and accessibility. Furthermore, we conducted the observation of LLS of *P. densiflora* at the FJY site (Table 1 and Figure 2).

2.6.2 | Sampling design

(a) Forest sites:

Five parallel transects were placed at 100 m intervals, and each transect was 400 m long (Figure 3a,b). Along each transect, observation points of an LAI and an fAPAR were placed at 20 m intervals, and tree census points to observe AGB were placed at 100 m intervals. Furthermore, litter-fall traps were placed to obtain the representative LAI in the observation area (Figures 3a and 4). At the TOS site, tree census area was established in a 1,000 m² quadrat area centered on the point. At the FHK site, tree census was conducted in a 200 m × 200 m area (a hatched area in Figure 3b), where it has been conducted for a long term. It is because setting new quadrats for tree census is restricted due to the Natural Parks Law.

(b) WGL site:

Five parallel transects were placed at 100 m intervals, and each transect was 400 m long (Figure 3c). Along each transect, observation points of LAI and AGB using a clipping method were placed at 100 m intervals. fAPAR

FIGURE 2 Location of the Fujihokuroku (FHK) and Fujiyoshida (FJY) sites [Color figure can be viewed at wileyonlinelibrary.com]

observation points were selected using a random sampling method.

(c) DGL sites:

Five or three parallel transects were placed at 100 m or 200 m intervals, respectively, and each transect was 400 m long (Figure 3d–f). Along each transect, spectral observation points were placed at 20 m intervals. To obtain the relationship between LAI/AGB and spectral reflectance, 11 observation points for a clipping method were selected.

(d) Observation points' name (observation point ID):

The observation point ID was defined as ABCD, where A is a transect line ID, B is a direction from the center of the line or that from the tower (E or W meaning east or west, respectively), CD (10 m) is a distance from the center of the line or that from the tower (see Figure 3). For instance, the 3E12 indicates the observation point was located at 120 m east from the center/tower on line 3.

(e) Observation date, its method, and responsible person for each observation:

See Table 2.

2.6.3 | Observation methods

(a) Tree census:

At the FHK site, tree census has been conducted every year since 2005 (Table 2). The species name of each tree and its DBH, which was a 1.2 m height (a Japanese standard DBH), was observed (except for the shrub layer). The tree height of each tree and its position were additionally observed. The tree height was measured every 3 years using an ultrasonic height measuring instrument (Vertex IV, Haglöh Inc.). The position of each

tree was surveyed by distance (m) from the southwest corner of the tree census area.

At the TOS site, tree census was conducted in December 2017 (Table 2). The species name of each tree and its DBH, which was a 1.3 m height (a European standard DBH), were observed except for trees with less than 3 cm of DBH. Each tree height was estimated using the following allometric equation (Ogawa, 1969) calibrated by using the dataset of DBH and tree height obtained at the TOS site ($n = 76$, where n is the number of trees).

$$\frac{1}{H} = \frac{1}{aD^h} + \frac{1}{H_{\max}}, \quad (1)$$

where H (m) and D (cm) are tree height and DBH, respectively. The calibrated parameters a , h , and $H_{\max}$ (m) at the TOS site are 2.12, 0.75 and 51.75, respectively. Root mean squared error of the equation was 1.64.

(b) AGB:

AGB for *Larix kaempferi* (B_{Larix}) at the FHK site was calculated by:

$$B_{Larix} = B_{Larix_trunk} + B_{Larix_branches} + B_{Larix_leaves}, \quad (2)$$

$$B_{Larix_trunk} = 0.116680 \times (D^2)^{1.164}, \quad (3)$$

$$B_{Larix_branches} = 0.000289 \times (D^2)^{1.689}, \quad (4)$$

$$B_{Larix_leaves} = 0.001113 \times (D^2)^{1.231}, \quad (5)$$

where B_{Larix_trunk} , $B_{Larix_branches}$, and B_{Larix_leaves} are the mass of trunk, branches, and leaves for *L. kaempferi*, respectively. This equation was specifically made for *L. kaempferi* at the FHK site ($n = 10$).

Except for *L. kaempferi*, the AGB of each tree i (B_i ; kg) was calculated by the following two steps. First, the $\ln(B_i)$ was calculated using the tree census data as follows:

$$\ln(B_i) = a + b \times \ln(D) + c \times \ln(H) + d \times \ln(\rho), \quad (6)$$

where ρ (g cm^{-3}) is a wood specific gravity under oven-dry (Table 3), and a , b , c , and d are parameters depending on tree species (Table 4). When H was not measured for a deciduous broad-leaved tree, the following formula (Ishihara et al., 2015) was used instead:

$$\begin{aligned} \ln(B_i) = & -1.501 + 1.375 \times \ln(D) + 0.464 \\ & \times (\ln(D))^2 - 0.061 \times (\ln(D))^3 \quad (CF = 1.031), \end{aligned} \quad (7)$$

FIGURE 3 Sampling design of the leaf area index (LAI), the above-ground biomass (AGB) and the fraction of absorbed photosynthetically active radiation (fAPAR) at each site: (a) Tomakomai (TOS), (b) Fujihokuroku (FHK), (c) Watarase (WTR), (d) Baganuur (MBN), (e) Delgertsogt (DGT), and (f) Khar Yamaat (KYM) sites [Color figure can be viewed at wileyonlinelibrary.com]

where CF is a correction factor (Sprugel, 1983) described below. Second, to eliminate the bias

introduced by inverse logarithmic transformation, B_i was obtained as

FIGURE 4 Sampling design within the tree census area at the Fujihokuroku (FHK) site. The alphabets and numbers denote identification names of the observation zone

$$B_i = \exp(\ln(\widehat{B}_i)) \times CF, \quad (8)$$

where $\ln(\widehat{B}_i)$ is the natural logarithm value of the estimated AGB B_i using Equation (6) or (7). CF was calculated by

$$CF = \exp\left(\frac{SEE^2}{2}\right), \quad (9)$$

where SEE is the standard error of the estimate when the logarithm allometric equation was made. SEE was calculated by

$$SEE = \sqrt{\frac{\sum_{i=1}^n (\ln(b_i) - \ln(\widehat{B}_i))^2}{n-p}}, \quad (10)$$

where $\ln(b_i)$ is the natural logarithm value of the observed AGB b_i (kg) of a tree, n is the total number of trees which were cut and surveyed to make the allometric equation and p is the number of parameters in the allometric equation.

At the TOS site, AGB was calculated using two allometric equations (Table 4). The allometric equations

using an oven-dried ρ (ρ_{oven}) was basically applied (Tables 3 and 4). When ρ_{oven} was not available but an air-dried ρ (ρ_{air}) was available, it was estimated using the following relationship between ρ_{oven} and ρ_{air} created using the published data set (Kishima et al., 1962):

$$\rho_{\text{dried}} = 0.9454 \times \rho_{\text{air}} - 0.0107 \quad (n = 58, R^2 = 0.9788). \quad (11)$$

AGB (B ; Mg ha^{-1}) in each tree census area (A_{tree} ; m^2) was calculated by

$$B = \frac{\sum_i B_i}{A_{\text{tree}}} \times 10. \quad (12)$$

For understory vegetation at the TOS site, AGB (B_{clip} ; Mg ha^{-1}) was observed using a clipping method within nine quadrats. All understory vegetation was cut within each quadrat with a $1 \text{ m} \times 1 \text{ m}$ area. The cut vegetation was completely dried in an oven at 80°C for more than 24 hr, and their dry weights (W_{clip} ; g) were measured. B_{clip} in each clipping area (A_{clip} ; m^2) was calculated by

$$B_{\text{clip}} = \frac{W_{\text{clip}}}{A_{\text{clip}}} \times 10^{-2}. \quad (13)$$

At the FHK site, AGB for understory vegetation could not be observed because of the Natural Parks law.

For GL at the WTR site, B_{clip} was observed at 12 points selected using a random sampling method on June 6, 2018, at 25 points on July 23 and 24, 2018, and at 15 points on Lines 1, 3, and 5 on April 11, 2019. All vegetation was cut in a $50 \text{ cm} \times 50 \text{ cm}$ area at each observation point. The cut vegetation was completely dried in an oven at $70\text{--}80^\circ\text{C}$ for more than 24 hr, and the W_{clip} was measured. B_{clip} was calculated using Equation (13).

For GL in Mongolia (the MBN, DGT, and KYM sites), B_{clip} was observed in 11 quadrats in total (Figure 3d–f): 10 quadrats had a $50 \text{ cm} \times 50 \text{ cm}$ area, and 1 quadrat had a $25 \text{ cm} \times 25 \text{ cm}$ area. All vegetation was cut in each quadrat. The cut vegetation was completely dried in an oven at 60°C for more than 24 hr, and the W_{clip} was measured. B_{clip} was calculated using Equation (13). Moreover, to obtain AGB at many points, spectral reflectance was observed using the MS-720 spectral radiometer (EKO Instruments B.V.) attaching a 45° or 25° collimation tube at 11 quadrats before cutting vegetation (Figure 3d–f). The spectrum of sky-light ($L_{\text{sky}}(\lambda)$; $\text{W m}^{-2} \mu\text{m}^{-1}$) was observed twice before and after observing the spectrum of reflected light from the ground ($L_{\text{gr}}(\lambda)$; $\text{W m}^{-2} \mu\text{m}^{-1}$). At the MBN site, $L_{\text{sky}}(\lambda)$ was observed as reflected light from a calibrated whiteboard. It was calculated as follows:

TABLE 2 Date, method, and responsible persons for each observation

Site	Observation target	Method	Description	Observation date (sky condition)	Responsible person
TOS	LAI of canopy	LAI-2200	2.6.3 (d)	August 20 in 2015 (under near-perfect cloudy sky)	Akitsu T. K. and Nakaji T.
				August 29 in 2016	Nakaji T.
				April 28 in 2017	Nakaji T.
				April 11, May 25, June 19, August 7 and October 18 in 2018	Nakaji T.
				August 2 in 2019 (before sunrise)	Nakaji T.
	LAI of canopy	Litterfall	2.6.3 (d)	In 2018	Nakaji T.
	LAI of understory	LAI-2200	2.6.3 (d)	August 7, 2018 (under near-perfect cloudy sky)	Akitsu T. K.
	AGB for trees	Tree census	2.6.3 (a) and (b)	December 2017	Nakaji T.
	LAI and AGB for understory	Clipping method	2.6.3 (b)	August 18, 2015	Nakaji T.
	fAPAR	PAR sensors	2.6.3 (e)	August 7 in 2018	Akitsu T. K.
FHK	LAI of canopy	LAI-2000	2.6.3 (d)	August 28, 2014 (under near-perfect cloudy sky)	Akitsu T. K. and Honda Y.
		LAI-2000	2.6.3 (d)	Sep 21 in 2015 (under near-perfect cloudy sky)	Honda Y. and Akitsu T. K.
		LAI-2200	2.6.3 (d)	August 2, 2018 (under near-perfect cloudy sky)	Akitsu T. K.
	LAI of canopy	Litterfall	2.6.3 (d)	In 2018	Kobayashi H.
	LAI of understory	LAI-2200	2.6.3 (d)	August 2, 2018 (under near-perfect cloudy sky)	Akitsu T. K.
	AGB for trees	Tree census	2.6.3 (a) and (b)	In 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018	Okano T.
	fAPAR	PAR sensors	2.6.3 (e)	August 2, 2018	Akitsu T. K.
FJY	LLS	Counting leaf number	2.6.3 (c)	August 2, 2018	Akitsu T. K., Kobayashi H., Nakano T., and Nakano T.
WTR	LAI and AGB	Clipping method	2.6.3 (b) and (d)	June 6 and July 23–24, 2018	Akitsu T. K. and Terigele
				April 11, 2019	Akitsu T. K.
	fAPAR	PAR sensors	2.6.3 (e)	June 6, 2018	Akitsu T. K.
	Reflectance of PAR from the canopy	PAR sensors mounted on a drone	2.6.3 (e)	May 21, 2018	Honda Y. and Kajiwaru K.
MBN	LAI and AGB	Clipping method and MS-720	2.6.3 (b) and (d)	August 22–24, 2018	Akitsu T. K.
DGT	LAI and AGB	Clipping method and MS-720	2.6.3 (b) and (d)	August 8–9, 2018	Akitsu T. K. and Bayarsaikhan U.
KYM	LAI and AGB	Clipping method and MS-720	2.6.3 (b) and (d)	August 13, 2018	Akitsu T. K. and Bayarsaikhan U.

Note: The initials of the responsible persons' names are corresponding to the authors' names.

Abbreviations: AGB, above-ground biomass; fAPAR, fraction of absorbed photosynthetically active radiation; LAI, leaf area index; LLS, leaf life span.

TABLE 3 Above-ground biomass (AGB) estimation method and wood specific gravity (ρ) for each tree species

Species name	Air-dried wood specific gravity (ρ_{air} ; g cm ⁻³)	Oven-dried wood specific gravity (ρ_{oven} ; g cm ⁻³)	AGB estimation method	References
<i>Fraxinus lanuginosa</i>	0.71	0.66	grav_oven	K
<i>Picea glehnii</i>	0.46	0.42	grav_oven	K
<i>Ostrya japonica</i>	0.73	0.69	grav_oven	K
<i>Sorbus alnifolia</i>	0.68	0.63	grav_oven	K
<i>Acer pictum</i> Thunb. subsp. <i>mono</i>	0.65	0.61	grav_oven	K
<i>Betula maximowicziana</i>	0.67	0.63	grav_oven	K
<i>Picea jezoensis</i>	0.43	0.40	grav_oven	K
<i>Prunus sergentii</i> Rehder.	0.62	0.58	grav_other: <i>Cerasus jamasakura</i>	K
<i>Tilia maximowicziana</i>	0.54	0.50	grav_air	K
<i>Cercidiphyllum japonicum</i>	0.50	0.47	grav_oven	K
<i>Larix kaempferi</i>	0.50	0.48	grav_oven	K
<i>Magnolia kobus</i> var. <i>borealis</i> Sarg.	0.48	0.44	grav_air	O
<i>Phellodendron amurense</i>	0.48	0.44	grav_air	K
<i>Alnus hirsuta</i>	0.74	0.67	grav_other: <i>Alnus hirsuta</i>	K
<i>Actinidia arguta</i>	NA	NA	without_grav	NA
<i>Chengiopanax sciadophylloides</i>	0.45	0.41	grav_air	K
<i>Carpinus cordata</i>	0.73	0.69	grav_oven	K
<i>Prunus ssiori</i>	0.67	0.63	grav_oven	K
<i>Tilia japonica</i>	0.50	0.47	grav_oven	K
<i>Betula platyphylla</i>	0.64	0.60	grav_oven	K
<i>Betula ermanii</i>	0.68	0.64	grav_oven	K
<i>Toxicodendron orientale</i>	NA	NA	without_grav	NA
<i>Hydrangea petiolaris</i>	NA	NA	without_grav	NA
<i>Celastrus orbiculatus</i>	NA	NA	without_grav	NA
<i>Abies sachalinensis</i>	0.40	0.37	grav_oven	K
<i>Populus suaveolens</i>	0.42	0.40	grav_oven	K
<i>Sorbus commixta</i>	0.71	0.66	grav_air	K
<i>Picrasma quassioides</i>	0.58	0.54	grav_air	K
<i>Hydrangea paniculata</i>	NA	NA	without_grav	NA
<i>Acer japonicum</i>	0.67	0.59	grav_oven	K
<i>Styrax obassia</i>	0.70	0.65	grav_air	K
<i>Syringa reticulata</i>	0.63	0.58	grav_air	O
<i>Salix bakko</i>	0.45	0.41	grav_air	K
<i>Kalopanax septemlobus</i>	0.52	0.49	grav_oven	K
<i>Ulmus davidiana</i> var. <i>japonica</i>	0.63	0.61	grav_oven	K
<i>Magnolia obovata</i>	0.49	0.45	grav_oven	K
<i>Cornus controversa</i>	0.63	0.49	grav_oven	K
<i>Quercus crispula</i>	0.68	0.64	grav_oven	K
<i>Prunus maximowiczii</i>	0.66	0.62	grav_oven	K
<i>Fraxinus mandshurica</i>	0.55	0.52	grav_oven	K

(Continues)

TABLE 3 (Continued)

Species name	Air-dried wood specific gravity (ρ_{air} ; g cm ⁻³)	Oven-dried wood specific gravity (ρ_{oven} ; g cm ⁻³)	AGB estimation method	References
<i>Morus australis</i>	0.62	0.58	grav_oven	K
<i>Vitis coignetiae</i>	NA	NA	without_grav	NA
<i>Acre palmatum</i> var. <i>mastumurae</i>	0.64	0.59	grav_air	O

Note: “grav_oven” indicates that AGB was calculated using a ρ_{oven} , “grav_air” indicates that AGB was calculated using a ρ_{oven} estimated from a ρ_{air} and “without_grav” indicates that AGB was calculated without using ρ . “K” means Kishima, Okamoto, and Hayashi (1962) and “O” means a ρ_{air} was observed at the TOS site. “NA” means not available.

TABLE 4 Parameters, determination coefficient (R^2) and correction factor (CF) of allometric equations of above-ground biomass (AGB)

Site	Species name or plant type	a	b	c	d	R^2	CF	Literature for the AGB estimation model
FHK	Evergreen needle-leaved tree except for <i>Larix kaempferi</i>	-2.356	2.157	0.247	0	NA	1.033	Ishihara et al. (2015)
	Deciduous broad-leaved tree	-2.407	2.141	0.390	0	NA	1.033	Ishihara et al. (2015)
TOS	Most of all trees	-1.876	2.174	0.283	0.611	NA	1.031	Ishihara et al. (2015)
	Deciduous broad-leaved tree for which ρ was not available	-2.407	2.141	0.390	0	NA	1.033	Ishihara et al. (2015)

Abbreviation: NA, not available.

$$L_{\text{sky}}(\lambda) = \frac{L_{\text{sky}1}(\lambda) + L_{\text{sky}2}(\lambda)}{2}, \quad (14)$$

where $L_{\text{sky}1}(\lambda)$ and $L_{\text{sky}2}(\lambda)$ are $L_{\text{sky}}(\lambda)$ observed before and after observing $L_{\text{gr}}(\lambda)$, respectively. At the DGT and KYM site, $L_{\text{sky}}(\lambda)$ was observed as reflected light from four sheets of filter paper with a 300 mm diameter. It was calculated by

$$L_{\text{sky}}(\lambda) = \frac{L_{\text{sky}1}(\lambda) + L_{\text{sky}2}(\lambda)}{2 \times R_{4\text{paper}}(\lambda)}, \quad (15)$$

where $R_{4\text{paper}}(\lambda)$ (W m⁻² μ m⁻¹) is a spectral reflectance of four sheets of filter paper. $R_{4\text{paper}}(\lambda)$ was observed using the spectroradiometer FieldSpec 3 (ASD Inc.) and the integrating sphere LI-1800-12 (LI-COR Inc.).

To obtain the relationship between AGB and spectral reflectance, normalized difference vegetation index (NDVI) was calculated by

$$\text{NDVI} = \frac{R_{\text{NIR}} - R_{\text{red}}}{R_{\text{NIR}} + R_{\text{red}}}, \quad (16)$$

where R_{red} and R_{NIR} (W m⁻² μ m⁻¹) are a reflectance of red light and that of near-infrared (NIR) light, respectively. R_{red} and R_{NIR} were calculated as a band reflectance of the Second generation GLocal Imager (SGLI) mounted on the GCOM-C satellite as follows:

$$R_{\text{red}} = \frac{\int L_{\text{gr}}(\lambda) \times \text{RSR}_7(\lambda) d\lambda}{\int L_{\text{sky}}(\lambda) \times \text{RSR}_7(\lambda) d\lambda}, \quad (17)$$

$$R_{\text{NIR}} = \frac{\int L_{\text{gr}}(\lambda) \times \text{RSR}_{10}(\lambda) d\lambda}{\int L_{\text{sky}}(\lambda) \times \text{RSR}_{10}(\lambda) d\lambda}, \quad (18)$$

where RSR_7 and RSR_{10} are the relative spectral response of Bands 7 and 10 of the SGLI, respectively. AGB estimated using NDVI (B_{NDVI}) was calculated using the relationship between AGB and NDVI (Figure 5a) at many points by

$$B_{\text{NDVI}} = 0.1240 \times \exp(3.4062 \times \text{NDVI}). \quad (19)$$

(c) LLS of *P. densiflora*:

LLS of *P. densiflora*, which was needed to calculate LAI from litters collected at the FHK site, was observed at the Fujiyoshida forest meteorology research site (FJY) belonging to AsiaFlux and JaLTER networks (<http://asiaflux.net/> and <http://jalter.org/>, respectively) on August 2, 2018. The leaves of *P. densiflora* were accessible from the ecological observation tower at the FJY site, which is approximately 1.25 km away from the FHK site (see Figure 2).

FIGURE 5 Relationships (a) between the normalized difference vegetation index (NDVI) and the above-ground biomass (AGB) and (b) between NDVI and the leaf area index (LAI) in Mongolia. RMSE denotes the root mean squared error

Ten branches were cut from a sunny (upper) part. The other 10 branches were cut from a shaded (lower) part. The number of leaves on each branch was counted depending on leaf age. The age of current leaves was counted as 0 year. As a result, most of all sun leaves have been alive for two growing seasons (Figure 6). For the shade leaves, the number of leaves that were born and grown varies depending on the year; however, they have been alive at least for two growing seasons. Although additional studies might be needed to obtain the accurate LLS, we roughly estimated the leaves of *P. densiflora* might be alive for two growing seasons or more.

(d) LAI:

LAI was defined as the projected (one-sided) green leaf area divided by the ground surface area beneath those leaves. In DGL, LAI was defined as the projected green leaf and stem area divided by the ground surface area since the leaves and stems were too tiny to be divided into each part.

At the TOS and FHK sites, LAI of canopy (LAI_{c_2200} ; $m^2 m^{-2}$) and that of understory (LAI_{u_2200} ; $m^2 m^{-2}$) were observed using LAI-2200C (LI-COR Inc.) or LAI-2000 (LI-COR Inc.) under the near-perfect cloudy sky or before sunrise (Table 2). LAI_{c_2200} and LAI_{u_2200} were observed at 105 observation points. Since the LAI-2200C's data are a set of five light data obtained from five rings, if a set of the data contained one or more zero data, the set was excluded from the analysis.

At the TOS site, LAI_{c_2200} was calculated as follows:

$$LAI_{c_2200} = PAI_{c_2200} - PAI_{leafless}, \quad (20)$$

FIGURE 6 Total number of leaves for each age on 10 branches of *Pinus densiflora*

where $PAI_{leafless}$ and PAI_{c_2200} are plant area indices observed using the LAI-2200C during the leafless and leafy seasons, respectively. To obtain the accurate LAI, a correction factor (CF_c) of LAI_{c_2200} was obtained at litter-fall traps in 2016 (Figure 3a): LAI was observed from the litter-fall (LAI_{litter}). It was also observed using the LAI-2200C in the leafless and the leafiest seasons over each litter-fall trap (LAI_{2200_litter}). LAI_{2200_litter} was calculated by

$$LAI_{2200_litter} = PAI_{c_2200} - PAI_{leafless}. \quad (21)$$

The litters were collected several times during the growing season. The collected litters were dried in an oven at 80°C, and the weight (W_{litter} ; g) was measured. LAI_{litter} was estimated from the leaf mass area (LMA; g m⁻²) and basal area density of target trees around the litter-fall trap (Ishihara & Hiura, 2011). LAI_{litter} was calculated by

$$LAI_{litter} = \frac{W_{litter}}{LMA \times GA_{traps}}, \quad (22)$$

where GA_{traps} (m²) is a total ground area of litter-fall traps. Using the LAI_{litter} and LAI_{2200_litter} , CF_c was calculated by

$$CF_c = \frac{LAI_{litter}}{LAI_{2200_litter}}. \quad (23)$$

As a result, CF_c was 0.96 at the TOS site. Eventually, LAI of canopy (LAI_c) was obtained as

$$LAI_c = LAI_{c_2200} \times CF_c. \quad (24)$$

At the FHK site, Equation (20) could not be adopted because of the existence of evergreen needle-leaved trees. A correction factor (CF_c) of LAI_{c_2200} was obtained at litter-fall traps, where LAI_{litter} and LAI_{2200_litter} were observed (Figure 4). LAI_{litter} was calculated as follows:

$$LAI_{litter} = \frac{\left(\frac{W_{litter_larch}}{LMA_{larch}} + \frac{W_{litter_pine} \times 2}{LMA_{pine}} + \frac{W_{litter_other}}{LMA_{other}} \right)}{GA_{traps}}, \quad (25)$$

where W_{litter_larch} , W_{litter_pine} , and W_{litter_other} (g) are the dry weights of litters of *L. kaempferi*, *P. densiflora*, and the other trees, respectively. They were measured after drying them at 80°C for 48 hr in an oven. LMA_{larch} , LMA_{pine} , and LMA_{other} (g m⁻²) are LMA of *L. kaempferi* (66.81 g m⁻²), *P. densiflora* (64.47 g m⁻²), and the other trees (65.63 g m⁻², which is LMA of *Quercus crispula* as a representative value of the other trees), respectively. To obtain their LMA, dry weight for each species was measured, and the leaves' area was measured after infiltrating the leaves with water. CF_c was calculated using Equation (23). As a result, CF_c was 1.33 at the FHK site. In Equation (25), the leaves area of *P. densiflora* was doubled because of its LLS (see the previous subsection). LAI_c was calculated using Equation (24).

At the TOS site, LAI of understory (LAI_u) was obtained using LAI_{u_2200} and the correction factor of LAI_{u_2200} obtained at northern Hokkaido ($CF_u = 0.79$; Akitsu et al., 2020) as follows:

$$LAI_u = LAI_{u_2200} \times CF_u. \quad (26)$$

On the other hand, at the FHK site, LAI_{u_2200} was directly adopted as LAI_u .

In DGLs in Mongolia (i.e., the MBN, GDT, and KYM sites), LAI (LAI_{clip}) was observed in 11 quadrats in total (see the details at the subsection 2.6.3 (b)). All vegetation was cut within each quadrat, and the cut vegetation was divided into leaves and the others on sites. Fresh leaves area was observed using digital images captured by a digital camera or an image scanner. The images were taken including a coin. The pixel number of the leaf part (PN^{leaf}) was counted from the images using a threshold method. Leaves area in each quadrat (LA ; cm²) was calculated as follows:

$$LA = \sum_{i=1}^n \frac{PN_i^{leaf} \times CA}{PN_i^{coin}}, \quad (27)$$

where n is a total number of images at each quadrat, CA (cm²) is an already-known coin area and PN^{coin} is a pixel number of a coin part. LAI at each quadrat was calculated by

$$LAI = \frac{LA}{GA}, \quad (28)$$

where GA (cm²) is the ground area of a quadrat. Furthermore, to obtain LAI at many points, $R(\lambda)$ was additionally observed using the MS-720 (Figure 3d–f). Using the relationship between LAI and NDVI, which was calculated by Equation (16) (Figure 5b), LAI was estimated from the MS-720's data (LAI_{MS720}) by

$$LAI_{MS720} = 0.0504 \times \exp(3.7791 \times NDVI). \quad (29)$$

In a WGL (i.e., the WTR site), LAI was observed using a clipping method. The number of observation points was described in the subsection 2.6.3 (b). All vegetation was cut in a 50 cm × 50 cm area at each observation point. The cut vegetation was divided into leaves and the others. Fresh leaves area ($LA_{LAI-3100}$; cm²) was measured using an area meter LAI-3100C (LI-COR Inc.). On June 6, 2018, and April 11, 2019, all of the clipped leaves were measured. Leaves area within each quadrat (LA ; cm²) was calculated as follows:

$$LA = \frac{LAI_{LAI-3100} \times 10}{DA_{LAI-3100}}, \quad (30)$$

where $DA_{LAI-3100}$ (cm²) is a 10-cm² disk area measured using the LAI-3100C. In contrast, on July 23 and

FIGURE 7 Relationships between leaves area and dry weight of (a) *Phragmites australis* and (b) *Miscanthus sacchariflorus*

24, 2018, a part of the clipped leaves was not directly measured using the LAI-3100C. It is because there was more vegetation than we can handle the direct measurement for all. Therefore the relationships between leaves area and dry weight of dominant species (i.e., *Phragmites australis* and *Miscanthus sacchariflorus*) were obtained in the WTR site (Figure 7), and leaves areas of *P. australis* and *M. sacchariflorus* ($LA_{Phra.}$ and $LA_{Misc.}$; cm^2 , respectively) were estimated using the relationships. They were calculated as follows:

$$LA_{Phra.} = 15.677 \times DW_{Phra.} + 160.865 \quad (n = 16), \quad (31)$$

$$LA_{Misc.} = 13.315 \times DW_{Misc.} + 91.646 \quad (n = 17), \quad (32)$$

where $DW_{Phra.}$ and $DW_{Misc.}$ (g) are the dry weights of *P. australis* and *M. sacchariflorus* in each quadrat, respectively. For the other species, all of the leaves area (LA_{others} ; cm^2) was directly measured. LA was calculated by

$$LA = LA_{Phra.} + LA_{Misc.} + LA_{others}. \quad (33)$$

LAI in each quadrat was calculated by Equation (28).

(e) fAPAR:

Photosynthetically active radiation (PAR) was observed using the LI-190 (LI-COR Inc.), LI-190R (LI-COR Inc.), and the PAR-02D (Prede Co., Ltd.) at the TOS, FHK, and WTR sites (Figure 3a–c).

At the TOS and FHK sites, above the canopy, we observed incoming PAR ($PAR_{above\downarrow}$) using an LI-190 encased in a weather-proof external housing with a glass dome (Hukseflux), which we call Encased LI-190. The Encased LI-190 was installed on the top of the tower. Reflecting PAR from the canopy ($PAR_{above\uparrow}$) was observed

using the PAR-02D and the Encased LI-190 installed on the top of the tower at the TOS and FHK sites, respectively. Under the canopy, we observed downward and upward PAR ($PAR_{middle\downarrow}$ and $PAR_{middle\uparrow}$, respectively) using the LI-190R equipped with the LAI-2200C. Furthermore, downward and upward PAR ($PAR_{under\downarrow}$ and $PAR_{under\uparrow}$, respectively) were observed under the understory vegetation. The PAR observation was conducted at each observation point as the following sequences: (a) $PAR_{middle\downarrow}$ and $PAR_{middle\uparrow}$ in synchronization with the observation of $PAR_{above\downarrow}$ and $PAR_{above\uparrow}$, (b) $PAR_{middle\downarrow}$ and $PAR_{middle\uparrow}$ over the target understory, (c) $PAR_{under\downarrow}$ and $PAR_{under\uparrow}$ under the target understory, and (d) $PAR_{middle\downarrow}$ and $PAR_{middle\uparrow}$ over the target understory.

All of the used PAR sensors were calibrated with the accurate PAR which was observed using two spectroradiometers (MS-700, EKO instruments B.V.) applying the direct and diffuse separate observation method (Akitsu, Nasahara, Hirose, Ijima, & Kume, 2017).

An fAPAR was calculated at each observation point. fAPAR of the canopy ($fAPAR_{canopy}$; unitless) was calculated by

$$fAPAR_{canopy} = \frac{PAR_{above\downarrow} - PAR_{above\uparrow} - PAR_{middle\downarrow} + PAR_{middle\uparrow}}{PAR_{above\downarrow}}. \quad (34)$$

Here, fAPAR of the understory ($fAPAR_{under}$; unitless) at each observation point was calculated by

$$fAPAR_{under} = \frac{PAR_{middle\downarrow} - PAR_{middle\uparrow} - PAR_{under\downarrow} + PAR_{under\uparrow}}{PAR_{middle\downarrow}}. \quad (35)$$

TABLE 5 Names of data files and their descriptions

Data file names	Descriptions
2017_tree_census_TOS_Nakaji.csv	Tree census data in 2017 at TOS site.
2017_AGB_TOS_Akitsu.csv	AGB observed in 2017 at each observation point at TOS site.
2015_LAI-2200_canopy_TOS_Akitsu.csv	LAI of canopy obtained using the LAI-2200 on August 20, 2015 at TOS site.
2016_LAI-2200_canopy_TOS_Nakaji.csv	LAI of canopy obtained using the LAI-2200 on August 29, 2016 at TOS site.
2018_LAI-2200_canopy_TOS_Nakaji.csv	LAI of canopy obtained using the LAI-2200 on April 11, May 25, June 19, August 7, and October 18, 2018 at TOS site.
2019_LAI-2200_canopy_TOS_Nakaji.csv	LAI of canopy obtained using the LAI-2200 on August 2, 2019 at TOS site.
2015_LAI_AGB_understory_clipping_TOS_Nakaji.csv	AGB and LAI of understory observed using a clipping method on August 20, 2015 at TOS site.
2018_LAI-2200_understory_TOS_Akitsu.csv	LAI of understory obtained using the LAI-2200 on August 7, 2018 at TOS site.
2018_fAPAR_TOS_Akitsu.csv	fAPAR observed on August 7, 2018 at TOS site.
2005_2018_tree_census_FHK_Okano.csv	Tree census data with tree location from 2005 to 2018 at FHK site.
2018_AGB_FHK_Akitsu.csv	AGB observed in 2018 at each observation zone at FHK site.
2014_LAI-2000_canopy_FHK_Akitsu.csv	LAI of canopy obtained using the LAI-2000 on August 28, 2014 at FHK site.
2015_LAI-2000_canopy_FHK_Akitsu.csv	LAI of canopy obtained using the LAI-2000 on September 21, 2015 at FHK site.
2018_LAI-2200_canopy_FHK_Akitsu.csv	LAI of canopy obtained using the LAI-2200 on August 2, 2018 at FHK site.
2018_LAI-2200_understory_FHK_Akitsu.csv	LAI of understory obtained using the LAI-2200 on August 2, 2018 at FHK site.
2018_fAPAR_FHK_Akitsu.csv	fAPAR observed on August 2, 2018 at FHK site.
2018_2019_LAI_AGB_WTR_Akitsu.csv	LAI and AGB observed in 2018 and 2019 at WTR site.
2018_fAPAR_WTR_Akitsu.csv	fAPAR observed on June 6, 2018 at WTR site.
2018_LAI_AGB_MBN_Akitsu.csv	AGB and LAI data observed on August 23 and 24, 2018 at MBN site.
2019_LAI_AGB_DGT_Akitsu.csv	AGB and LAI data observed on August 8 and 9, 2019 at DGT site.
2019_LAI_AGB_KYM_Akitsu.csv	AGB and LAI data observed on August 13, 2019 at KYN site.
lat_lon_XXX.csv	Latitude and longitude at each observation point at XXX site, where XXX means the site name.
2015_2019_mean_AGB_all_sites.csv	Mean and standard error of AGB in the 500 m × 500 m area from 2015 to 2019 at all sites.
2014_2019_mean_LAI_all_sites.csv	Mean and standard error of LAI in the 500 m × 500 m area from 2014 to 2019 at all sites.
2018_mean_fAPAR_all_sites.csv	Mean and standard error of LAI in the 500 m × 500 m area in 2018 at all sites.

Abbreviations: AGB, above-ground biomass; fAPAR, fraction of absorbed photosynthetically active radiation; LAI, leaf area index.

TABLE 6 Description of columns in the 2017_tree_census_TOS_Nakaji.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification (ID).
tree_ID	—	Tree ID.
species	—	Tree species name.
DBH_2017	cm	DBH (1.3 m) measured in November 2017.
height_2017	m	Estimated tree height using a DBH measured in November 2017.
gravity	g cm ⁻³	Wood specific gravity (ρ).
AGB_2017	kg	AGB for each tree.
method	—	AGB estimation method.

Note: “NA” means not available. “grav_oven” means AGB was calculated using an oven-dried ρ , “grav_air” means AGB was calculated using an oven-dried ρ estimated from air-dried ρ , “grav_other” means AGB was calculated using an oven-dried ρ of the other species and “without_grav” means AGB was calculated using the equation without using ρ .

Abbreviations: AGB, above-ground biomass; DBH, diameter at breast height.

TABLE 7 Description of columns in the 2017_AGB_TOS_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
AGB_2017	Mg ha ⁻¹	AGB observed in a 1,000-m ² area in 2017.

Abbreviation: AGB, above-ground biomass.

Total fAPAR ($fAPAR_{total}$; unitless) at each observation point was calculated by

$$fAPAR_{total} = \frac{PAR_{above \downarrow} - PAR_{above \uparrow} - PAR_{under \downarrow} + PAR_{under \uparrow}}{PAR_{above \downarrow}} \quad (36)$$

At the WTR site, $PAR_{above \downarrow}$ was observed using the Encased LI-190 fixed on a tripod stand on the embankment near the observation point. A reflectance of PAR from the canopy (R_{PAR}^{canopy}) was observed using two PAR-02Ds mounted on a drone which has gimbals to keep the sensors level. It is because $PAR_{above \uparrow}$ could not be observed on the ground due to the plant height which was 4 m or more and no observation tower at the WTR site. $PAR_{under \downarrow}$ and $PAR_{under \uparrow}$ were observed under the canopy using the LI-190R equipped with the LAI-2200C

TABLE 8 Description of columns in the 2015_LAI-2200_canopy_TOS_Akitsu.csv, 2016_LAI-2200_canopy_TOS_Nakaji.csv, and 2019_LAI-2200_canopy_TOS_Nakaji.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
YYYY_MMDD_PA1	m ² m ⁻²	PA1 observed using LAI-2200 on MM DD, YYYY ($PA1_{leafless}$).
YYYY_MMDD_PA1	m ² m ⁻²	PA1 observed using LAI-2200 on MM DD, YYYY ($PA1_{c-LAI-2200}$).
YYYY_MMDD_LAI_2200	m ² m ⁻²	LAI observed using LAI-2200 on MM DD, YYYY (LAI_{c-2200}).
YYYY_MMDD_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on MM DD, YYYY (LAI_c).

Note: “NA” means missing or anomalous value. YYYY means the year, MM means the month, DD means the day.

Abbreviations: LAI, leaf area index; PA1, plant area index.

in synchronization with the observation of $PAR_{above \downarrow}$. $fAPAR_{total}$ was calculated at each observation point by

$$fAPAR_{canopy} = 1 - R_{PAR}^{canopy} + \frac{PAR_{under \uparrow} - PAR_{under \downarrow}}{PAR_{above \downarrow}}, \quad (37)$$

where R_{PAR}^{canopy} is 0.0566056 which was the mean observed using a drone at the WTR site.

(f) Location survey:

The location of the observation points was surveyed using the A-325 (Hemisphere GNSS Inc.) at the TOS site. At the FHK site, it was surveyed using the Trimble M5 2" ST (Trimble Inc.) and the GPSmap 60CSx (Garmin Ltd.). At the MBN, DGT, and KYM sites, it was surveyed using the GPSmap 60CSx.

(g) Sample mean and standard error of the mean (SEM) within the 500 m × 500 m area:

The sample means of LAI, AGB, and fAPAR were calculated by

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n}, \quad (38)$$

TABLE 9 Description of columns in the 2018_LAI-2200_canopy_TOS_Nakaji.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_0411_PAI	m ² m ⁻²	PAI observed using LAI-2200 on April 11, 2018 (PAI_{leafless}).
2018_0525_PAI	m ² m ⁻²	PAI observed using LAI-2200 on May 25, 2018 ($PAI_{\text{c_LAI-2200}}$).
2018_0525_LAI-2200	m ² m ⁻²	LAI observed using LAI-2200 on May 25, 2018 ($LAI_{\text{c_2200}}$).
2018_0525_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on May 25, 2018 (LAI_{c}).
2018_0619_PAI	m ² m ⁻²	PAI observed using LAI-2200 on June 19, 2018 ($PAI_{\text{c_LAI-2200}}$).
2018_0619_LAI-2200	m ² m ⁻²	LAI observed using LAI-2200 on June 19, 2018 ($LAI_{\text{c_2200}}$).
2018_0619_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on June 19, 2018 (LAI_{c}).
2018_0807_PAI	m ² m ⁻²	PAI observed using LAI-2200 on August 7, 2018 ($PAI_{\text{c_LAI-2200}}$).
2018_0807_LAI-2200	m ² m ⁻²	LAI observed using LAI-2200 on August 7, 2018 ($LAI_{\text{c_2200}}$).
2018_0807_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on August 7, 2018 (LAI_{c}).
2018_1018_PAI	m ² m ⁻²	PAI observed using LAI-2200 on October 18, 2018 ($PAI_{\text{c_LAI-2200}}$).
2018_1018_LAI-2200	m ² m ⁻²	LAI observed using LAI-2200 on October 18, 2018 ($LAI_{\text{c_2200}}$).
2018_1018_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on October 18, 2018 (LAI_{c}).

Note: “NA” means missing or anomalous value. For the 5E14 observation point, the value of 2017_0428_PAI was used instead of the anomalous value of 2018_0411_PAI.

Abbreviations: LAI, leaf area index; PAI, plant area index.

TABLE 10 Description of columns in the 2018_LAI-2200_understory_TOS_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_0807_LAIu	m ² m ⁻²	LAI observed using LAI-2200 on August 7, 2018 (LAI_{u}).

Note: “NA” means missing or anomalous value.

Abbreviation: LAI, leaf area index.

where $\bar{x}$ is the sample mean, x_i is each sample data and n is the number of the sample. The *SEM* indicates how far the sample mean of the data may be from the true population mean. It was calculated as follows:

$$SEM = \frac{s}{\sqrt{n}}, \quad (39)$$

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}, \quad (40)$$

where s is the standard deviation.

2.7 | Data structure

2.7.1 | Data files

The names of the data files are described in Table 5.

TABLE 11 Description of columns in the 2015_LAI_AGB_understory_clipping_TOS_Nakaji.csv

Variable name	Unit	Variable definition
ID	—	Observation group identification.
veg	—	Vegetation type.
num	—	Number of quadrats installed at the observation point.
LA	cm ²	Area of clipped and measured leaves.
W_leaf1	g	Dry weight of clipped and measured leaves.
W_leaf2	g	Dry weight of leaves without measuring leaves area.
W_stem	g	Dry weight of stems and the others.
LAI	m ² m ⁻²	LAI of understory.
AGB	Mg ha ⁻¹	AGB.

Abbreviations: AGB, above-ground biomass; LAI, leaf area index.

2.7.2 | File format

The data files are formatted in comma-separated values (csv) format with the UTF-8 encoding.

TABLE 12 Description of columns in the 2018_fAPAR_TOS_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_fAPAR_canopy	Unitless	fAPAR of canopy observed on August 7, 2018 ($fAPAR_{canopy}$).
2018_fAPAR_understory	Unitless	fAPAR of understory observed on August 7, 2018 ($fAPAR_{under}$).
2018_fAPAR_total	Unitless	Total fAPAR observed on August 7, 2018 ($fAPAR_{total}$).

Abbreviation: fAPAR, fraction of absorbed photosynthetically active radiation.

2.7.3 | Variable definitions

(a) Tree census data including AGB for each tree at the TOS site:

The columns in the 2017_tree_census_TOS_Nakaji.csv include the following data (Table 6). The columns in the 2017_AGB_TOS_Akitsu.csv include the following data (Table 7).

(b) LAI data using LAI-2200 at the TOS site:

There are four files for canopy LAI: 2015_LAI-2200_canopy_TOS_Akitsu.csv, 2016_LAI-2200_canopy_TOS_Nakaji.csv, 2018_LAI-2200_canopy_TOS_Nakaji.csv, and 2019_LAI-2200_canopy_TOS_Nakaji.csv. Moreover, there is a file for understory LAI: 2018_LAI-2200_understory_TOS_Akitsu.csv. The columns in the 2015_LAI-2200_canopy_TOS_Akitsu.csv, 2016_LAI-

TABLE 13 Description of columns in the 2005_2018_tree_census_FHK_Okano.csv

Variable name	Unit	Variable definition
tree_ID	—	Tree identification.
species	—	Tree species name.
x_WE	m	X coordinate from the southwest corner of the tree census area to the east.
y_SN	m	Y coordinate from the southwest corner of the tree census area to the north.
DBH_2005	cm	DBH (1.2 m) measured in December 2005.
DBH_2006	cm	DBH (1.2 m) measured in December 2006.
DBH_2007	cm	DBH (1.2 m) measured in December 2007.
DBH_2008	cm	DBH (1.2 m) measured in December 2008.
DBH_2009	cm	DBH (1.2 m) measured in December 2009.
DBH_2010	cm	DBH (1.2 m) measured in December 2010.
DBH_2011	cm	DBH (1.2 m) measured in December 2011.
DBH_2012	cm	DBH (1.2 m) measured in December 2012.
DBH_2013	cm	DBH (1.2 m) measured in December 2013.
DBH_2014	cm	DBH (1.2 m) measured in December 2014.
DBH_2015	cm	DBH (1.2 m) measured in December 2015.
DBH_2016	cm	DBH (1.2 m) measured in December 2016.
DBH_2017	cm	DBH (1.2 m) measured in December 2017.
DBH_2018	cm	DBH (1.2 m) measured in December 2018.
height_2005	m	Tree height measured in December 2005.
height_2007	m	Tree height measured in December 2007.
height_2009	m	Tree height measured in December 2009.
height_2011	m	Tree height measured in December 2011.
height_2013	m	Tree height measured in December 2013.
height_2016	m	Tree height measured in December 2016.
AGB_2018	kg	AGB.
remarks	—	Remarks.

Abbreviations: AGB, above-ground biomass; DBH, diameter at breast height; NA, not available.

TABLE 14 Description of columns in the 2018_AGB_FHK_Akitsu.csv

Variable name	Unit	Variable definition
zone_ID	—	Identification of observation zone.
AGB_2018	Mg ha ⁻¹	AGB observed in a 100-m ² area in 2018.

Abbreviation: AGB, above-ground biomass.

TABLE 15 Description of columns in the 2014_LAI-2000_canopy_FHK_Akitsu.csv, 2015_LAI-2000_canopy_FHK_Akitsu.csv, and 2018_LAI-2200_canopy_FHK_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
YYYY_MMDD_LAI_2200	m ² m ⁻²	LAI observed using LAI-2200/LAI-2000 on MM DD, YYYY (LAI_{c-2200}).
YYYY_MMDD_LAI	m ² m ⁻²	LAI calibrated using a litter-fall LAI on MM DD, YYYY (LAI_c).

Note: YYYY means the year, MM means the month, DD means the day.

Abbreviation: LAI, leaf area index.

2200_canopy_TOS_Nakaji.csv, and 2019_LAI-2200_canopy_TOS_Nakaji.csv include the following data (Table 8). The columns in the 2018_LAI-2200_canopy_TOS_Nakaji.csv include the following data (Table 9). The columns in the 2018_LAI-2200_understory_TOS_Akitsu.csv include the following data (Table 10). (c) LAI and AGB data for understory vegetation using a clipping method at the TOS site:

The columns in the 2015_LAI_AGB_understory_clipping_TOS_Nakaji.csv include the following data (Table 11).

(d) fAPAR data at the TOS site:

The columns in the 2018_fAPAR_TOS_Akitsu.csv include the following data (Table 12).

(e) Tree census data including AGB for each tree at the FHK site:

The columns in the 2005_2018_tree_census_FHK_Okano.csv include the following data (Table 13). The columns in the 2018_AGB_FHK_Akitsu.csv include the following data (Table 14).

(f) LAI data at the FHK site:

There are four files for canopy LAI: 2014_LAI-2000_canopy_FHK_Akitsu.csv, 2015_LAI-2000_canopy_FHK_Akitsu.csv, and 2018_LAI-2200_canopy_FHK_Akitsu.csv.

TABLE 16 Description of columns in the 2018_LAI-2200_understory_FHK_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_0802_LAIu	m ² m ⁻²	LAI observed using LAI-2200 on August 2, 2018 (LAI_u).

Abbreviation: LAI, leaf area index.

TABLE 17 Description of columns in the 2018_fAPAR_FHK_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_fAPAR_canopy	Unitless	fAPAR of canopy observed on August 2, 2018 ($fAPAR_{canopy}$).
2018_fAPAR_understory	Unitless	fAPAR of understory observed on August 2, 2018 ($fAPAR_{under}$).
2018_fAPAR_total	Unitless	Total fAPAR observed on August 2, 2018 ($fAPAR_{total}$).

Abbreviation: fAPAR, fraction of absorbed photosynthetically active radiation.

The columns in the files include the following data (Table 15). Moreover, there is a file for understory LAI: 2018_LAI-2200_understory_FHK_Akitsu.csv. The columns in the file include the following data (Table 16).

(g) fAPAR data at the FHK site:

The columns in the 2018_fAPAR_FHK_Akitsu.csv include the following data (Table 17).

(h) LAI and AGB data at the WTR site:

The columns in the 2018_2019_LAI_AGB_WTR_Akitsu.csv include the following data (Table 18).

(i) fAPAR data at the WTR site:

The columns in the 2018_fAPAR_WTR_Akitsu.csv include the following data (Table 19).

(j) LAI and AGB data at Mongolian sites:

There are three files at Mongolian sites: 2018_LAI_AGB_MBN_Akitsu.csv, 2019_LAI_AGB_DGT_Akitsu.csv, and 2019_LAI_AGB_KYM_Akitsu.csv.

The columns in the files include the following data (Table 20).

(k) Latitude and longitude at each observation point:

There are six files about latitude and longitude at each observation site: lat_lon_TOS.csv, lat_lon_FHK.csv, lat_lon_WTR.csv, lat_lon_MBN.csv, lat_lon_DGT.csv,

TABLE 18 Description of columns in the 2018_2019_LAI_AGB_WTR_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
LAI_2018_0606	m ² m ⁻²	LAI observed on June 6, 2018.
AGB_2018_0606	Mg ha ⁻¹	AGB observed on June 6, 2018.
LAI_2018_0723	m ² m ⁻²	LAI observed on July 23 and 24, 2018.
AGB_2018_0723	Mg ha ⁻¹	AGB observed on July 23 and 24, 2018.
LAI_2019_0411	m ² m ⁻²	LAI observed on April 11, 2019.
AGB_2019_0411	Mg ha ⁻¹	AGB observed on April 11, 2019.

Abbreviations: AGB, above-ground biomass; LAI, leaf area index; NA, not available.

TABLE 19 Description of columns in the 2018_fAPAR_WTR_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
2018_fAPAR_total	Unitless	Total fAPAR observed on June 6, 2018 (fAPAR _{canopy}).

Abbreviation: fAPAR, fraction of absorbed photosynthetically active radiation.

TABLE 20 Description of columns in the 2018_LAI_AGB_MBN_Akitsu.csv, 2019_LAI_AGB_DGT_Akitsu.csv and 2019_LAI_AGB_KYM_Akitsu.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
LAI	m ² m ⁻²	LAI.
AGB	Mg ha ⁻¹	AGB.

Abbreviations: AGB, aboveground biomass; LAI, leaf area index.

and lat_lon_KYM.csv. The columns in the files include the following data (Table 21).

(l) The mean LAI and AGB in a 500 m × 500 m area at each site:

There are three files: 2014_2019_mean_LAI_all_sites.csv, 2015_2019_mean_AGB_all_sites.csv, and 2018_mean_fAPAR_all_sites.csv. The columns in the 2014_2019_mean_LAI_all_sites.csv include the following data (Table 22). The columns in the 2015_2019_mean_AGB_all_sites.csv include the following data (Table 23). The columns in the 2018_mean_fAPAR_all_sites.csv include the following data (Table 24).

TABLE 21 Description of columns in the lat_lon_TOS.csv, lat_lon_FHK.csv, lat_lon_WTR.csv, lat_lon_MBN.csv, lat_lon_DGT.csv, and lat_lon_KYM.csv

Variable name	Unit	Variable definition
point_ID	—	Observation point identification.
Latitude	Degrees, minutes, seconds	Latitude.
Longitude	Degrees, minutes, seconds	Longitude.

TABLE 22 Description of columns in the 2014_2019_mean_LAI_all_sites.csv

Variable name	Unit	Variable definition
site	—	Observation site.
layer	—	Canopy or understory.
date	—	Observation date.
num	—	Number of observed points.
mean_LAI	m ² m ⁻²	Mean of LAI.
std	m ² m ⁻²	Standard deviation.
ste	m ² m ⁻²	Standard error of the mean.

Abbreviation: LAI, leaf area index.

TABLE 23 Description of columns in the 2015_2019_mean_AGB_all_sites.csv

Variable name	Unit	Variable definition
site	—	Observation site.
layer	—	Canopy or understory.
date	—	Observation date.
num	—	Number of observed points.
mean_AGB	Mg ha ⁻¹	Mean of AGB.
std	Mg ha ⁻¹	Standard deviation.
ste	Mg ha ⁻¹	Standard error of the mean.

Abbreviation: AGB, above-ground biomass.

TABLE 24 Description of columns in the 2018_mean_fAPAR_all_sites

Variable name	Unit	Variable definition
site	—	Observation site.
layer	—	Canopy or understory.
date	—	Observation date.
num	—	Number of observed points.
mean_fAPAR	Unitless	Mean of fAPAR.
std	Unitless	Standard deviation.
ste	Unitless	Standard error of the mean.

Abbreviation: fAPAR, fraction of absorbed photosynthetically active radiation.

2.8 | Accessibility

2.8.1 | License

This dataset is provided under a Creative Commons Attribution 4.0 International license (CC-BY 4.0) (<https://creativecommons.org/licenses/by/4.0/>).

2.8.2 | Location of storage

<http://db.cger.nies.go.jp/JaLTER/metacat/metacat/ERDP-2020-16.1/jalter-en>.

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