The JapanFlux2024 dataset for eddy covariance observations covering Japan and East Asia from 1990 to 2023

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Abstract. Eddy covariance observations play a pivotal role in understanding the land−atmosphere exchange of energy, water, carbon dioxide (CO_2), and other trace gases, as well as the global carbon cycle and earth system. To promote the networking of individual measurements and the sharing of data, FLUXNET links regional networks of researchers studying land−atmosphere processes. JapanFlux was established in 2006 as a country branch of AsiaFlux. Despite the growing number of shared data globally, the availability in Asia is currently limited. In this study, we developed an open dataset of the eddy covariance observations for Japan and East Asia, called JapanFlux2024, that was conducted by researchers affiliated with Japanese research institutions. The dataset consists of data collected at 83 sites with 683 site-years from 1990 to 2023. The data is processed with the standard data processing methods employed by the FLUXNET community. Here, we present the data description and data processing and show the value of processed fluxes of sensible heat, latent heat, and CO_2. The dataset will facilitate important studies for Japan and East Asia, such as land-atmosphere interactions, improvement of process models, and upscaling fluxes using machine learning and remote sensing technology as well as bridge collaborations between Asia and FLUXNET.

1 Introduction

The global network of micrometeorological flux observations, FLUXNET (Delwiche et al., 2024; https://fluxnet.org/), plays a pivotal role in multi-disciplinary fields, such as land−atmosphere interactions, global biogeochemical cycles, and earth system science (Baldocchi et al., 2024; Bonan et al., 2012). FLUXNET started in 1997 as a global network of eddy covariance observations that provides data on land−atmosphere exchanges of energy, water, carbon dioxide (CO_2), methane (CH_4), and other trace gases by measuring direct turbulent transfer. The quasi-continuous eddy covariance observations revealed variations of land−atmosphere exchange at the diurnal, seasonal, interannual, and decadal scales, ranging from site (Takamura et al., 2023; Ueyama et al., 2024f) to global scales (Beer et al., 2010; Keenan et al., 2023; Ueyama et al., 2020a).

The eddy flux communities have developed publicly open databases to promote the multidisciplinary sciences. FLUXNET has periodically released the open datasets for eddy covariance observations: La Thuile Database (252 sites in 2007; Verma et al., 2014; https://fluxnet.org/data/la-thuile-dataset/), and FLUXNET2015 (212 sites in 2015; Pastorello et al., 2020). Together with the global carbon project (Friedlingstein et al., 2023; www.globalcarbonproject.org), FLUXNET also provided a topical dataset, FLUXNET-CH_4 (Delwiche et al., 2021), which promotes understanding of wetland CH_4 emissions across the globe (Knox et al., 2019; Ueyama et al., 2023). Multiple open databases for the environmental sciences have also been developed for understanding CO_2 fluxes in high-latitude ecosystems (Virkkala et al., 2021) and soil respiration (Bond-Lamberty et al., 2020).

Asia has ca. ~60% of the total world population, and thus humans have been intensively modifying forest land cover in this region for food and energy production. Such land use changes in combination with climate change are likely to impact the regional and global carbon and water cycling. These issues are the greatest environmental concerns for the survival of the human population. Flux studies using eddy covariance observations were conducted since the early 1990s for agricultural fields, wetlands, lakes, plantations, primary and secondary forests, disturbed ecosystems, and urban areas. In Asia, although private databases for eddy covariance measurements were developed (Hirata et al., 2008; Ichii et al., 2017; Saigusa et al., 2013), no open databases have yet been developed except the AsiaFlux database (https://asiaflux.net/), which does not provide consistent gap-filling and flux partitioning.

JapanFlux (https://www.japanflux.org/) was established in 2006 as a national branch of AsiaFlux (Kang and Cho, 2021; Mizoguchi et al., 2009) for the promotion of a network of micrometeorological measurements by researchers affiliated with Japanese research institutions. The mission of JapanFlux is to promote micrometeorological measurements and their collaborations with each other, researchers from other countries, and other research fields (e.g., remote sensing and modeling). Measurements by Japanese institutions have been conducted in Japan and other regions of East Asia (Mizoguchi et al., 2009; Saigusa et al., 2013) since the early 1990s for understanding energy, water, carbon, and greenhouse gas exchanges at various land surfaces.

In this study, we developed JapanFlux2024, the first publicly open dataset by JapanFlux that consists of micrometeorological data measured since the early 1990s. The data is processed with the standard data processing methods employed by the FLUXNET community. The dataset is prepared with consistent post−processing, such as gap-filling and flux partitioning, and provides data at various temporal resolutions of half-hourly/hourly, daily, weekly, monthly, and annual intervals. The dataset consists of data collected at 83 sites with 683 site-years. The dataset promotes collaborations between researchers in Japan and other countries and improves our understanding of land-atmosphere interactions.

2 Data and methods

The JapanFlux2024 dataset is processed with the standard data processing methods employed by FLUXNET (e.g., FLUXNET2015), although some modifications and simplifications were made. According to the processing strategy of Pastorello et al., (2020), the JapanFlux2024 dataset was developed in four steps: (1) data submission by site teams, (2) formatting data in a FLUXNET format, (3) gap-filling and flux partitioning, and (4) preparing subsets and complete datasets (Fig. 1). Meta data files, so-called Biological, Ancillary, Disturbance, and Metadata (BADM), were also prepared. The data are available from the data portal (https://ads.nipr.ac.jp/japan-flux2024/) under the data management system, Arctic and Antarctic Data archive System (ADS). Under the ADS, a digital object identifier (DOI) was provided for each site (Table 1). The processing pipeline mentioned in this data paper represent steps downstream of "Filling gaps in meteorology with ERA5"in Fig. 1.

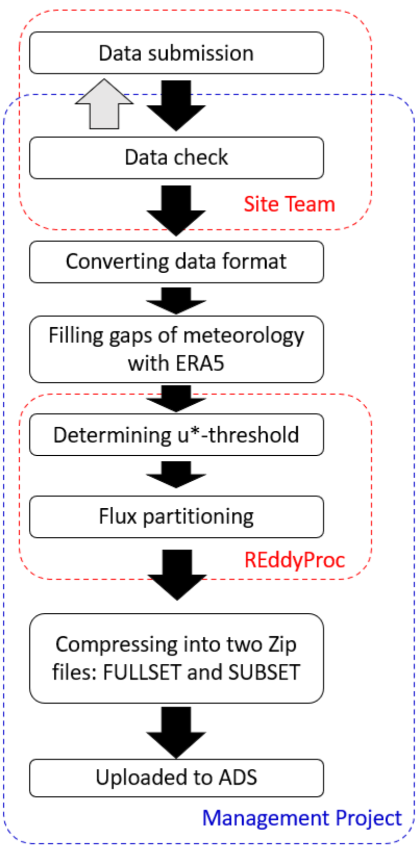

Figure 1. Flow chart of data processing in the JapanFlux2024 dataset. Details in each step and meaning of abbreviations are shown in the text.

Table 1. Information about sites included in the JapanFlux2024 dataset.

Site Code (BADM)	AsiaFlux ID	Country	Country ID	Site Name	Latitude (degree)	Longitude (degree)	Elevation (m)	Köppen climate	IGBP (land use)	Status	Years	Reference	doi
RU-Tur	TUR	Russia	RU	Tura	64.208888	100.463555	250	Dfc	DNF	Ongoing	04	Nakai et al. (2008)	Matsuura and Morishita (2025)
RU-NeB		Russia	RU	Neleger Burnt Forest	62.325937	129.487342	221	Dfd	GRA	Completed	99-00	Iwahana et al. (2005)	Machimura (2025a)
RU-NeF		Russia	RU	Neleger larch forest	62.315615	129.499964	223	Dfd	DNF	Completed	99-06	Iwahana et al. (2005)	Machimura (2025b)
RU-NeC		Russia	RU	Neleger Cutover	62.314844	129.500075	221	Dfd	OSH	Completed	01-06	Iwahana et al. (2005)	Machimura (2025c)
RU-SkP	YLF	Russia	RU	Yakutsk Spasskaya Pad larch	62.25471	129.618543	217	Dfc	DNF	Ongoing	04-14	Ohta et al. (2008)	Maximov et al. (2025b)
RU-Sk2	YPF	Russia	RU	Yakutsk Spasskaya Pad Pine	62.241291	129.651336	216	Dfc	ENF	Completed	04-08	Hamada et al. (2004)	Kotani et al. (2025)
RU-USk		Russia	RU	Ulakhan Sykkhan Alas	62.150995	130.527517	143		GRA	Completed	00	Yabuki et al. (2004)	Yabuki et al. (2025)

RU-Ege		Russia	RU	Elgeeii forest station	60.01551563	133.8240123	203	Dfd	DNF	Ongoing	10-18	Kotani et al. (2014)	Maximov et al. (2025a)
MN-Skt	SKT	Mongolia	MN	Southern Khentei Taiga	48.351861	108.654333	1630	Dwc	DNF	Completed	03-06	Li et al. (2005b)	Asanuma (2025b)
MN-Udg		Mongolia	MN	Udleg practice forest	48.25638888	106.8511111	1342	Dwc	DNF	Ongoing	10-12	Miyazaki et al. (2014)	Ishikawa (2025)
MN-Nkh		Mongolia	MN	Nalaikh grassland	47.693592	107.489342	1531	BSk	GRA	Completed	15-20	Wang et al. (2023)	Wang et al. (2025b)
MN-Hst		Mongolia	MN	Hustai grassland	47.594131	105.856439	1227	BSk	GRA	Completed	15-20	Wang et al. (2023)	Wang et al. (2025a)
MN-Kbu	KBU	Mongolia	MN	Kherlenbayan Ulaan	47.213972	108.737333	1235	Bsk	GRA	Completed	03-09	Li et al. (2005a)	Asanuma (2025a)
CN-Lsh	LSH	China	CN	Laoshan	45.279839	127.578206	340	Cfc	DNF	Ongoing	02-06	Wang et al. (2005)	Saigusa and Wang (2025)
JP-Sb1		Japan	JP	Sarobetsu Mire Moss	45.104722	141.688194	6	Dfb	WET	Completed	07-10	Hirano et al. (2016)	Hirano (2025a)
JP-Sb2		Japan	JP	Sarobetsu Mire Sasa	45.103611	141.680833	4	Dfb	WET	Completed	07-10	Hirano et al. (2016)	Hirano (2025b)
JP-Tef	TSE	Japan	JP	CC-LaG Teshio Experimental Forest	45.055808	142.107122	79.47	Dfb	DNF	Ongoing	01-23	Takagi et al. (2009)	Takagi and Takahashi (2025)

JP-MBF	MBF	Japan	JP	Moshiri Birch Forest Site	44.38416667	142.3186111	596	Af	DBF	Completed	03-11	Nakai et al. (2006)	Nakai et al (2025a)
JP-MMF	MMF	Japan	JP	Moshiri Mixd Forest Site	44.32194444	142.2613889	343	Af	MF	Completed	03-11	Nakai et al. (2006)	Nakai et al (2025b)
JP-BBY	BBY	Japan	JP	Bibai bog	43.32296	141.81079	17	Dfb	WET	Completed	12-21	Ueyama et al. (2020c)	Ueyama et al. (2025a)
JP-Km1		Japan	JP	Kushiro Mire: Onnenai Fen	43.107511	144.330906	4.9	Dfb	WET	Completed	94-96, 98	Miyata et al. (2001)	Harazono and Miyata (2025a)
JP-Km2		Japan	JP	Kushiro Mire: Akanuma Bog	43.1	144.35	7	Dfb	WET	Completed	98-99	Miyata et al. (2001)	Harazono and Miyata (2025b)
JP-Spp	SAP	Japan	JP	Sapporo forest meteorology research site	42.9868431	141.3853305	174	Dfb	DBF	Ongoing	00-18	Yamanoi et al. (2015)	Mizoguchi and Kitamura (2025)
CN-In4		China	CN	Inner Mongolia maize	42.94413333	120.7266222	354	Bsk	CRO	Completed	94	Li et al. (2000)	Harazono and Takagi (2025d)
CN-In2		China	CN	Inner Mongolia grassland	42.93396389	120.7109639	355	Bsk	GRA	Completed	91	Li et al. (2000)	Harazono and Takagi (2025b)
CN-In5		China	CN	Inner Mongolia no grazing	42.93396389	120.7109639	355	Bsk	GRA	Completed	92-94	Li et al. (2000)	Harazono and Takagi (2025e)

CN-In6		China	CN	Inner Mongolia heavy grazing	42.93396389	120.7109639	355	Bsk	GRA	Completed	92-94	Li et al. (2000)	Harazono and Takagi (2025f)
CN-In7		China	CN	Inner Mongolia light grazing	42.93396389	120.7109639	355	Bsk	GRA	Completed	92-94	Li et al. (2000)	Harazono and Takagi (2025g)
CN-In8		China	CN	Inner Mongolia medium grazing	42.93396389	120.7109639	355	Bsk	GRA	Completed	92, 94	Li et al. (2000)	Harazono and Takagi (2025h)
CN-In1		China	CN	Inner Mongolia dune	42.92970833	120.70735	356	Bsk	BSV	Completed	90-91	Li et al. (2000)	Harazono and Takagi (2025a)
CN-In3		China	CN	Inner Mongolia soybean	42.92557222	120.6990389	354	Bsk	CRO	Completed	91-93	Li et al. (2000)	Harazono and Takagi (2025c)
JP-Tmk	TMK	Japan	JP	Tomakomai Flux Research Site	42.736972	141.516944	140	Dfb	DNF	Completed	01-03	Hirano et al. (2003)	Hirata and Hirano (2025)
JP-Tmd	TMK	Japan	JP	Tomakomai Flux Research Site Disturbed	42.735911	141.523147	117	Dfb	DBF	Ongoing	05-23	Hirano et al. (2017)	Hirano and Hirata (2025)
JP-Toc		Japan	JP	Tomakomai Crane site	42.709727	141.565898	96	Dfb	DBF	Ongoing	10-14	Nakamura et al. (2014)	Nakaji et al. (2025)
JP-Tom	TOE	Japan	JP	Tomakomai Experimental Forest	42.698906	141.571488	90	Dfb	DBF	Completed	99-13	Shibata et al. (2005)	Nakaji (2025)

JP-Srk	SRK	Japan	JP	Shirakami Beech Forest Site	40.565485	140.127794	340	Dfa	DBF	Ongoing	10-16	Ishida et al. (2009)	Ishida (2025)
JP-Api	API	Japan	JP	Appi forest meteorology research site	40.0013585815243	140.9365859182 96	831	Dfa	DBF	Ongoing	00-22	Yasuda et al. (2012)	Yasuda (2025a)
JP-Mra	MRA	Japan	JP	Muramatsu Agricultural Field	37.690275	139.194429	43	Cfa	CRO	Ongoing	23	Boiarskii and Hasegawa (2019)	Nagano and Hasegawa (2025)
CN-HaM	QHB	China	CN	Qinghai Flux Research Site	37.607432	101.332	3250	BSk	GRA	Ongoing	01-14	Du et ak. (2021)	Du et al. (2025)
JP-NsM	NSS	Japan	JP	Nasu Research Station, Manure Application Plot	36.91583333	139.9358333	320	Cfa	GRA	Completed	04-15	Matsuura et al. (2023)	Matsuura (2025a)
JP-NsC	NSS	Japan	JP	Nasu Research Station, Chemical Fertilizer Plot	36.915	139.9366667	320	Cfa	GRA	Completed	04-15	Matsuura et al. (2023)	Matsuura (2025b)
JP-Kzw	KZW	Japan	JP	Karuizawa	36.406667	138.5725	1385	Dfb	DBF	Completed	01-08	Nakaya et al. (2006)	Nakaya et al. (2025)
JP-Tkb		Japan	JP	Tsukuba Experimental Watershed	36.173379	140.176634	341	Cfa	ENF	Ongoing	14, 18-21	Iida et al. (2020)	Shimizu et al. (2025b)
JP-Tak	TKY	Japan	JP	Takayama deciduous	36.14616667	137.4231111	1425	Dfb	DBF	Ongoing	98-21	Murayama et al.	Murayama et al.

				broadleaf forest site								(2024a)	(2025b)
JP-Ta2	TKC	Japan	JP	Takayama evergreen coniferous forest site	36.139722	137.370833	800	Dfb	ENF	Ongoing	05-22	Saitoh et al. (2010)	Saitoh and Tamagawa (2025)
JP-Tgf	TGF	Japan	JP	Terrestrial Environment Research Center, University of Tsukuba	36.11353	140.09488	27	Cfa	GRA	Completed	02-22	Shimoda et al. (2005)	Asanuma and Shimoda (2025)
JP-KaP		Japan		Kasumigaura lotus paddy	36.08	140.24	3	Cfa	CRO	Completed	97-98	Takagi et al. (2003)	Harazono et al. (2025)
JP-Mse	MSE	Japan	JP	Mase paddy flux site	36.05393	140.02693	11	Cfa	CRO	Ongoing	01-09	Saito et al. (2005)	Ono (2025)
JP-SwL	SWL	Japan	JP	Suwa Lake Site	36.0465722	138.1083528	758	Dfc	WAT	Ongoing	15-23	Iwata et al. (2018)	Iwata (2025b)
JP-KaL		Japan	JP	Koshin, Lake Kasumigaura	36.037778	140.404167	0.26(at the water level of Y.P.1.1 m)	Cfa	WAT	Ongoing	07-22	Sugita et al. (2020)	Sugita (2025)
JP-		Japan	JP	NIAES	36.0243	140.11	24	Cfa	CRO	Comp	90	Harazon	Harazono

Nsb				Soybean	03	4975				leted		o et al. (1992)	(2025a)
JP-Yrp		Japan	JP	Yawara Rice paddy	36.00766667	140.0301752	23	Cfa	CRO	Completed	93-95	NA	Harazono (2025b)
JP-Kwg	KWG	Japan	JP	Kawagoe forest meteorology research site	35.8725	139.4869	41	Cfa	DBF	Completed	97-02	Yasuda et al. (1998)	Yasuda (2025b)
JP-Shn		Japan	JP	Shinshu University Experimental Forest Site	35.865755	137.932563	775	Dfa	MF	Ongoing	14-19	NA	Iwata and Suzuki (2025)
JP-Nkm	NKM	Japan	JP	Nishikoma Site	35.808064	137.833883	2641	Dfb	ENF	Ongoing	18-23	NA	Iwata (2025a)
JP-Fmt		Japan	JP	Field Museum Tama Hills	35.638745	139.379748	168	Cfa	MF	Ongoing	13-23	Matsuda et al. (2015)	Takagi and Matsuda (2025)
JP-Kgu		Japan	JP	Kugahara urban residensial area	35.582859	139.693543	18.5	Cfa	URB	Completed	01-02	Moriwaki and Kanda (2004)	Kanda and Moriwaki (2025)
JP-Fjy	FJY	Japan	JP	Fujiyoshida forest meteorology research site	35.45454	138.76225	1043	Cfa	ENF	Ongoing	00-21	Mizoguchi et al. (2012)	Takanashi et al. (2025a)
JP-Fhk	FHK	Japan	JP	Fuji Hokuroku Flux Observation Site	35.44355577	138.7646931	1100	Cfa	DNF	Ongoing	06-23	Takahashi et al. (2015)	Takahashi et al (2025)

JP-Hrt		Japan	JP	Hiratsuka Rice Paddy	35.362778	139.338056	6.98	Cfa	CRO	Completed	13	Komiya (2015)	Komiya (2025a)
JP-SMF	SMF	Japan	JP	Seto Mixed Forest Site	35.261528	137.07875	212	Cfa	MF	Completed	02-16	Matsumoto et al. (2008)	Kotani and Ohta (2025)
JP-Nuf		Japan	JP	Nagoya University Forest	35.15241667	136.9718889	66	Cfa	DBF	Completed	00-01	Hiyama et al. (2005)	Awal and Ohta (2025a)
JP-Tdf		Japan	JP	Toyota Deciduous Forest	35.0358889	137.1857778	104	Cfa	DBF	Completed	02-04	Awal et al. (2010)	Awal and Ohta (2025b)
JP-Yms	YMS	Japan	JP	Yamashiro forest meteorology research site	34.790278	135.840939	220	Cfa	DBF	Ongoing	00-23	Kominami et al. (2008)	Takanashi et al. (2025b)
JP-Nap		Japan	JP	Nunoike Agricultural Pond	34.77485	134.892442	40	Cfa	WAT	Completed	21-23	NA	Sakabe and Itoh (2025)
JP-Ako	AKO	Japan	JP	Akou green belt	34.735192	134.374798	10.5	Cfa	EBF	Completed	00-03	Kosugi et al. (2005)	Kosugi and Takanashi (2025)
JP-Sac	SAC	Japan	JP	Sakai City Office	34.5739 1389	135.4828889	17	Cfa	URB	Ongoing	08-23	Ueyama and Takano (2022)	Ueyama (2025d)
JP-Ozm	IZM	Japan	JP	Oizumi Urban Park	34.563469	135.533483	22	Cfa	URB	Completed	15-16	Ueyama and Ando	Ueyama (2025a)

												(2016)	
JP-Om1	OM1	Japan	JP	B11 building in Osaka Metropolitan University	34.547177	135.502861	27	Cfa	URB	Ongoing	14-23	Ueyama and Ando (2016)	Ueyama (2025b)
JP-Om2	OM2	Japan	JP	Farm field in Osaka Metropolitan University	34.542452	135.508227	50	Cfa	GRA	Ongoing	22-23	NA	Ueyama (2025c)
JP-Hc3		Japan	JP	Hachihama Experimental Farm: Double Crop	34.539672	133.911731	-0.25	Cfa	CRO	Completed	05-09	Takimoto et al. (2010)	Takimoto and Iwata (2025b)
JP-Hc1		Japan	JP	Hachihama Experimental Farm	34.53789167	133.9267972	0	Cfa	CRO	Completed	96	Harazono et al. (1998)	Harazono (2025i)
JP-Hc2	HCH	Japan	JP	Hachihama Experimental Farm	34.537518	133.927545	-1	Cfa	CRO	Completed	99-08	Ohtaki (1984)	Takimoto and Iwata (2025a)
JP-Khw	KHW	Japan	JP	Kahoku Experiment watershed	33.13658	130.70834	196	Cfa	ENF	Ongoing	00-03, 07-21	Shimizu et al. (2015)	Kitamura et al (2025)
JP-Ynf	YNF	Japan	JP	Yona-Field Tower Site	26.751	128.212667	213	Cfa	EBF	Ongoing	13-22	Matsumoto et al. (2023)	Matsumoto et al. (2025)
TH-		Thailan	TH	Kog-Ma	18.8	98.9	1265	Af	EBF	Comp	05-	Kume et	Kumagai

Kog		d		Wateshed						leted	13	al. (2007)	and Takamura (2025a)
TH-Mae		Thailand	TH	Mae Moh plantation	18.38333333	99.71666667	380	Aw	DBF	Completed	05-16	Igarashi et al. (2015)	Kumagai and Takamura (2025b)
TH-Kms		Thailand	TH	Kamphaeng Saen Rice Paddy	14.009167	99.984167	4.74	Aw	CRO	Completed	14	Komiya (2015)	Komiya (2025b)
KH-Kmp		Cambodia	KH	Kampong Thom Lowland Dry Evergreen Forest	12.74457978	105.4785661	95	Am	EBF	Ongoing	11-14	Kabeya et al. (2021)	Shimizu et al. (2025a)
MY-LHP	LHP	Malaysia	MY	Lambir Hills National Park	4.201007	114.039079	140	Af	EBF	Completed	09-19	Takamura et al. (2023)	Kumagai et al. (2025)
ID-Pag		Indonesia	ID	Palangkaraya Undrained Forest	-2.323916667	113.9043917	22	Am	EBF	Ongoing	04-19	Hirano et al. (2024)	Hirano and Ohkubo (2025c)
ID-PaB		Indonesia	ID	Palangkaraya Drained Burnt forest	-2.340796	114.0379	14	Am	OSH	Completed	04-17	Ohkubo et al. (2021)	Hirano and Ohkubo (2025a)
ID-PaD	PDF	Indonesia	ID	Palangkaraya Drained forest	-2.346070697	114.036408	26	Am	EBF	Completed	01-17	Hirano et al. (2024)	Hirano and Ohkubo (2025b)

2.1 Data collections

We collected the micrometeorological measurement data from the site teams, which were identified using the web pages for AsiaFlux (https://www.asiaflux.net/, last access: 11 July 2024) and JapanFlux (https://www.japanflux.org/, last access: 11 July 2024). We also collected information on previous studies that reported micrometeorological measurements from domestic researcher connections and literature surveys. The collected data were from eddy covariance observations that were operated by the site teams affiliated with Japanese research institutes and universities. By this criterion, the dataset covers not only Japan but also other countries, such as Russia, China, Mongolia, Cambodia, Thailand, Malaysia, and Indonesia. Most of the sites were established for long-term monitoring of CO_2 fluxes, but intensive observations for about a week in the 1990s were also included in the dataset. Since the data format differed in each team, we reformatted the file to the FLUXNET format (https://ameriflux.lbl.gov/data/aboutdata/data-variables/, last access: 11 July 2024) after consultation with each site team. Generally, non-gap-filled data were provided by the site teams, but some teams provided gap-filled meteorological and flux data in addition to the non-gap-filled data.

The dataset consists of data from 83 sites with 683 site-years, of which 52 sites are located in Japan (Fig. 2; Table 1). The dataset includes 43 forest sites, 15 grassland sites, 5 wetland sites, 10 cropland sites, 3 lake and pond sites, and 4 sites in urban landscapes. Sites that suffered from various types of disturbance are also included: wind damage by typhoon (JP-Tmd, JP-Spp), fire (RU-NeB, ID-PaB), harvesting (RU-NeC, JP-Tef), thinning (JP-Fhk), insect outbreak (JP-Api), drainage (ID-Pag), and mowing (JP-NsC, JP-NsM, JP-Tgf, JP-Om2). The data records started in 1990 at a soybean cropland in Japan (Harazono et al., 1992), their number increased in the early 2000s, and peaked at 34 sites in 2008 and 2015 (Fig. 3). More recently, the number of data records gradually declined owing to site closured or the fact that the data have not been processed yet. The longest record was 24 years (JP-Tak and JP-Yms; both deciduous broadleaf forests) (Fig. 4). There are 26 sites with observation records of CO_2 flux for more than 10 years and 6 sites with those for more than 20 years (JP-Tef, JP-Tmk/JP-Tmd, JP-Api, JP-Fjy, JP-Tak, JP-Yms). Note that JP-Tmk and JP-Tmd represent a continuous observation series, although they are assigned different site IDs. At 12 sites, data records are available for less than one year. Data for CH_4 flux are available at six sites (JP-BBY, JP-SwL, JP-Nap, JP-Hrt, JP-Sac, JP-Om1).

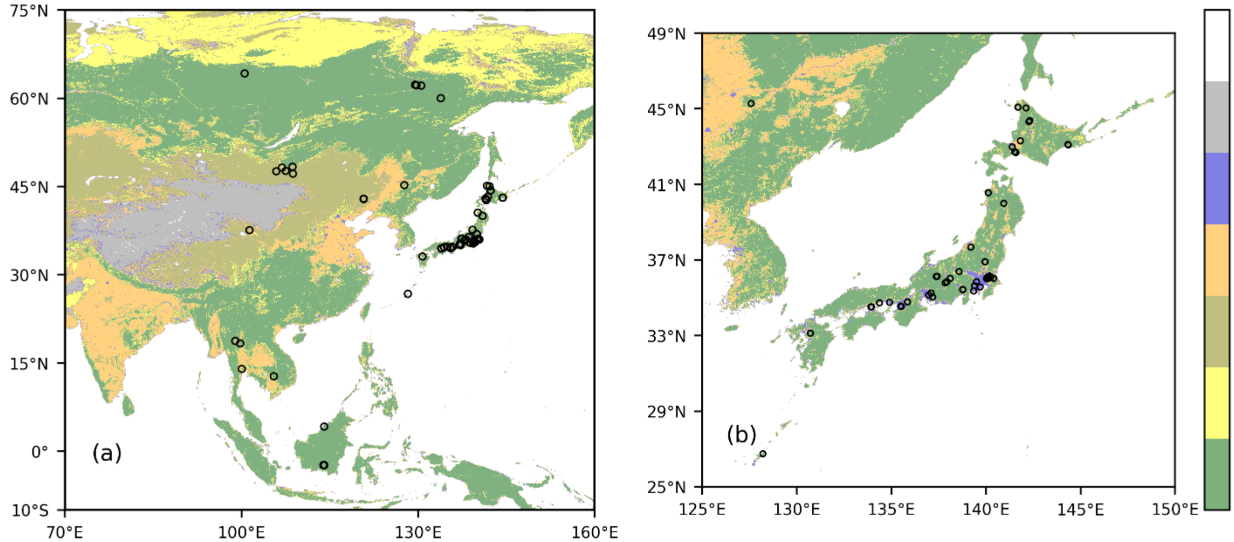

Figure 2. Distributions of the sites that constitute the JapanFlux2024 database on a land cover map provided by the MOD12 product (version 6.1; Sulla-Menashe et al., 2019): a map of Asia region (a) and an enlarged map showing Japan (b).

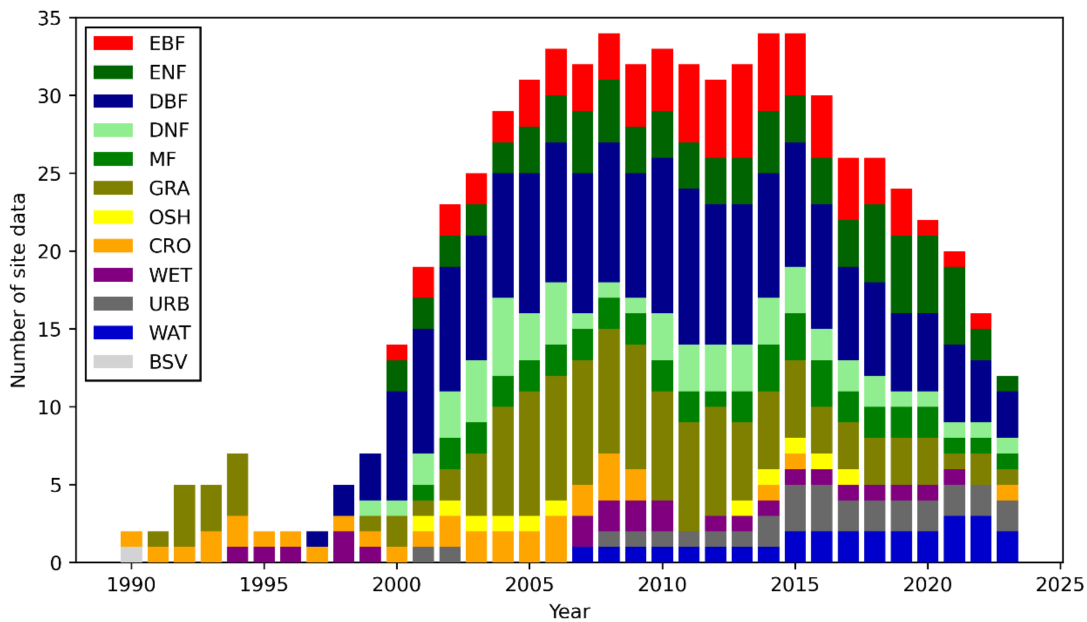

Figure 3. Number of site data records in each year. Land cover types: evergreen broadleaf forest (EBF), evergreen needleleaf forest (ENF), deciduous broadleaf forest (DBF), deciduous needleleaf forest (DNF), mixed forest (MF), grassland (GRA), open shrubland (OSH), cropland (CRO), wetland (WET), urban (URB), lake (WAT), and barren sparse vegetation (BSV).

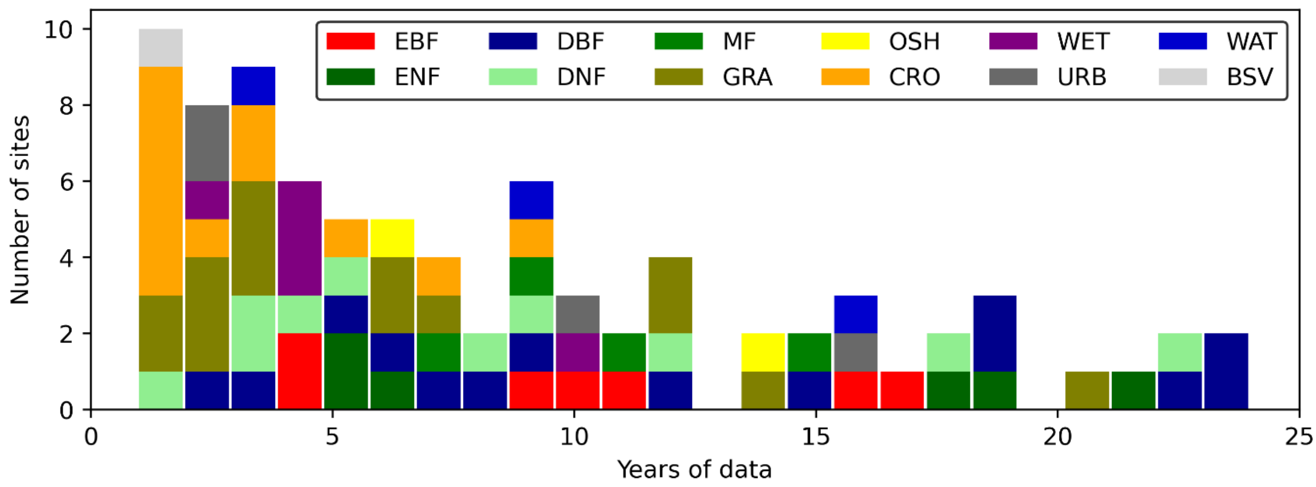

Fig. 4. The number of site records with different durations of data records. Sites affected by disturbance that changed the vegetation type during the observational period were classified according to the dominant land cover type: JP-Tef as DNF, JP-Tmd as DBF, and ID-PaB as OSH. Land cover type abbreviations are as in Fig. 3.

2.2 Gap-filling meteorological variables

As with the FLUXNET2015 dataset (Pastorello et al., 2020; Vuichard and Papale, 2015), the meteorological variables were filled using the European Center for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) data (Hersbach et al., 2020). Instead of using ERA5, we used the gap-filled meteorology if the site teams had filled the gaps. If meteorological variables for multiple sensors or positions were available, these variables were prioritized and aggregated; if data were missing in the highest priority dataset, they were filled with values from the second-highest priority dataset, or, if that were also unavailable, based on the priority order. The gaps in the aggregated meteorological variables were then filled with ERA5 data because measured variables were less biased than ERA5, even when measured at different locations within a site. Air temperature, relative humidity, wind speed, downward shortwave radiation, downward longwave radiation, precipitation, and barometric pressure were filled using ERA5 after correcting biases at each site each year. Linear regression for meteorological variables (except precipitation) between observations and ERA5 was determined and then applied to correct site-specific biases in ERA5 to fill the data gaps. Water vapor pressure was calculated from the relative humidity, and the gaps in relative humidity were filled using the gap-filled water vapor pressure and air temperature, rather than directly filling the relative humidity. If all meteorological variables were missing in some years when constructing the linear regression, the bias was corrected using a regression for the entire multi-year data record. For precipitation (denoting rainfall plus snowfall), we determined the ratio of the annual precipitation between observations and ERA5 during the period when observed precipitation were available, and then filled hourly or half-hourly precipitation after multiplying the ratio to ERA5-based precipitation. If only the rainfall was measured, the correction ratio was determined using liquid precipitation which was defined as precipitation when relative humidity was below the critical relative humidity (RH_{cri}; %): $RH_{cri} = 92.5 - 7.5T$, where T is the air temperature (Matsuo and Sasyo, 1981).

2.3 Gap-filling and flux partitioning

Gap-filling and flux partitioning were conducted based on REddyProc (version 1.3.2; Wutzler et al., 2018). First, the friction velocity (u*) threshold was determined for the identified low-turbulence conditions during the nighttime using the moving-point method (Papale et al., 2006). The u* threshold was determined from the temperature sensitivity of nighttime net ecosystem exchange (NEE) by seasonal clustering, an approach that is widely used in the FLUXNET community. In the moving point method, the u* threshold was first determined for each of the four seasons, and the maximum value among them was used for the entire year. Thus, the determined u* threshold was conservative (Papale et al., 2006). In this dataset, we determined the u* threshold each year to consider its potential shift over the years, which is termed as a Variable u* Threshold (vUT). The vUT differs slightly from the definition of the Variable u* Threshold (VUT) in FLUXNET2015 (Pastorello et al., 2020) (Table 2), where VUT in FLUXNET2015 was determined by pooling data from each year along with data from the immediately preceding and following years (if available). The u* threshold was determined with 100 bootstrap replicates, where reference (original data obtained without using a bootstrapped sample), the 5th, 50th, and 95th percentiles of the estimated u* threshold were used for subsequent data filtering, gap-filling, and flux partitioning. Here, the nighttime was defined as downward shortwave radiation < than 10 W m^{-2}, and was further confirmed using exact solar time at the site location. On the basis of the estimated u* threshold, nighttime CO_2 fluxes and/or NEE were eliminated. For urban sites, the threshold was generally not used for two reasons (e.g., Liu et al., 2012; Ueyama and Ando, 2016): 1) nighttime CO_2 fluxes were not expected to correlate with air temperature, making it difficult to evaluate the correct u* threshold, and 2) the surface layer was often unstable even at night. Consequently, the u* filtering was not applied for highly urbanized sites (JP-Sac and JP-Kgu).

Table 2 List of variable basenames not used in FLUXNET2015, along with their descriptions and related sites.

Basename	Description	Sites
pre-processing variables		
SW_IN_SLOPE_PI	Slope-normal incoming shortwave radiation	JP-Nkm
NETRAD_SLOPE_PI	Slope- normal net radiation	JP-Nkm
USTAR_QC_FP	Friction velocity qualified with footprint	JP-Ozm
H_QC_FP	Sensible heat flux qualified with footprint	JP-Ozm, JP-Khw

LE_QC_FP	Latent heat flux qualified with footprint	JP-Ozm, JP-Khw
FC_QC_FP	CO_2 flux qualified with footprint	JP-Ozm, JP-Khw, JP-Sac
NEE_QC_FP	NEE flux qualified with footprint	JP-Khw
post-processing variables		
TA_multiple	Air temperature by multiple sensors or positions	CN-In1, CN-In2, CN-In3, CN-In4, CN-In5, CN-In6, CN-In7, CN-In8, CN-Lsh, JP-BBY, JP-Fhk, JP-Fjy, JP-Hc1, JP-Ozm, JP-Khw, JP-KaP, JP-Km1, JP-Km2, JP-Kzw, JP-MBF, JP-MMF, JP-Nsb, JP-Nuf, JP-Spp, JP-Tgf, JP-Tak, JP-Tmk, JP-Tef, JP-Ynf, JP-Yrp, MN-Udg, MY-LHP, RU-Ege, RU-SkP, RU-Sk2, TH-Kog, TH-Mae, RU-USk
RH_multiple	Relative humidity by multiple sensors or positions	CN-In1, CN-In2, CN-In3, CN-In4, CN-In5, CN-In6, CN-In7, CN-In8, CN-Lsh, JP-BBY, JP-Fhk, JP-Fjy, JP-Hc1, JP-KaP, JP-Km1, JP-Km2, JP-Kzw, JP-MBF, JP-MMF, JP-Nsb, JP-Nuf, JP-Spp, JP-Tgf, JP-Tak, JP-Tmk, JP-Tef, JP-Ynf, JP-Yrp, MN-Udg, MY-LHP, RU-Ege, RU-SkP, RU-Sk2, TH-Mae, RU-USk
SW_IN_multiple	Incoming shortwave radiation by multiple sensors or positions	JP-Fhk, JP-Spp, JP-Tgf, JP-Tmk, JP-Tef, JP-Ynf
P_multiple	Precipitation by multiple sensors or positions	JP-BBY, JP-Khw
WS_IN_multiple	Wind speed by multiple sensors or positions	CN-In1, CN-In2, CN-In3, CN-In4, CN-In5, CN-In6, CN-In7, CN-In8, CN-HaM, JP-Fhk, JP-Hc1, JP-KaP, JP-Km1, JP-Km2, JP-Kzw, JP-MBF, JP-MMF, JP-Nsb, JP-Spp, JP-SMF, JP-Tgf, JP-Tef, JP-Yms, JP-Ynf, JP-Yrp, MN-Udg, TH-Kog, TH-Mae, RU-USk
G_multiple	Ground heat flux by multiple sensors or positions	JP-Sac, JP-Spp, JP-Ynf, MN-Udg
NETRAD_F_MDS	Net radiation filled with MDS	JP-Tef

PPFD_IN_F_MDS	PPFD filled with MDS	CN-Lsh, CN-HaM, JP-Km2, JP-MBF, JP-MMF, JP-Nkm, JP-Tgf, RU-SkP, TH-Kog
NEE_vUT	Gap-filled NEE with the variable u* threshold	ALL sites
RECO_NT_vUT	RECO with the variable u* threshold based on the nighttime approach	ALL sites
GPP_NT_vUT	GPP with the variable u* threshold based on the nighttime approach	ALL sites
RECO_DT_vUT	RECO with the variable u* threshold based on the daytime approach	ALL sites
GPP_DT_vUT	GPP with the variable u* threshold based on the daytime approach	ALL sites

Gaps in sensible heat flux (H), latent heat flux (LE), and NEE were filled using marginal distribution sampling (MDS) based on REddyProc. In MDS, a look-up-table (LUT) with air temperature, downward shortwave radiation, and vapor pressure deficit (VPD) was created for a 7-day window. When data gaps could not be filled with this window, they were filled in the following order: (1) LUT was applied with a 14-day window, (2) the mean diurnal variation method (Falge et al., 2001) was applied with a 1- or 2-day window, and (3) LUT was applied with a 21-day window, which was increased with a 7-day step until 70-day window if not enough data points were available. NEE were filled using MDS with the four different u* thresholds (reference, 5th, 50th, and 90th percentiles values), whereas H and LE were filled without applying the u* threshold. In addition to the fluxes, net radiation, soil temperature, ground heat flux, and photosynthetically photon flux density (PPFD) were also filled using MDS. In the data collected from the site teams, energy imbalance correction (Twine et al., 2000) was not applied for H and LE at any sites; thus, the gap-filled H and LE were not corrected for the energy balance closure.

Using REddyProc, NEE was partitioned into gross primary productivity (GPP) and ecosystem respiration (RECO) using two methods: nighttime flux partitioning and daytime flux partitioning. In the nighttime partitioning method, nighttime NEE was parameterized on the basis of the temperature response function (Lloyd and Taylor, 1994) with a 7-day window, and then this function was used to calculate daytime and nighttime RECO. GPP was determined by subtracting RECO from NEE. In the daytime partitioning method (Lasslop et al., 2010), the common rectangular hyperbolic light-response curve was determined with a 4-day window, where the function accounted for the VPD effect on the initial slope of the light-response curve and the temperature effect of respiration. GPP and RECO using the daytime partitioning method were calculated based on a fitted model that combines a light-response curve and a temperature-dependent respiration model; thus, the daytime method did not directly add up observed NEE (Wutzler et al., 2018). Using the two methods, fluxes were partitioned for NEE with different u* thresholds.

2.4 Site-specific considerations

For the sites with heterogeneous land surfaces─JP-Khw and JP-Ozm— the dominant land surface fluxes were extracted using wind sectors. JP-Khw is an evergreen needleleaf plantation forest consisting of *Cryptomeria japonica* (sugi) and *Chamaecyparis obtusa* (hinoki), but evergreen or deciduous broadleaf trees grow in gaps in some wind sectors. The H, LE, and CO_2 fluxes for sugi, which occupies the dominant wind sector area (the right-bank side), were extracted as quality control with footprint, "_QC_FP" (Table 2). To extract these flux data, daytime fluxes for a wind sector on the right bank were selected, but nighttime fluxes for all wind sectors were used to increase data availability because there were no clear differences in nighttime fluxes among wind sectors. Gap-filling and flux partitioning were done only for the extracted data. JP-Ozm is located at the edge of an urban park; thus, measured flux representing this park (Ueyama and Ando, 2016) were selected and designated "_QC_FP" in addition to the variables for measured fluxes representing both sectors of the urban park and other land covers. Gap-filling and flux partitioning were done only for the extracted data, which represented the urban park. These extracted flux data ("_QC_FP") were included in the FULLSET files (described in section 2.5) in addition to measured fluxes for all sectors, and the gap-filled extracted fluxes were included in the SUBSET files (described in section 2.5).

Flux partitioning and gap-filling for JP-Nkm, located on a complex mountainous terrain, were conducted using slope-normal shortwave radiation instead of downward shortwave radiation. Horizontally observed incident shortwave radiation was converted to radiation normal to the slope on the basis of the tilt and azimuth angles of the slope and the solar altitude and azimuth angles (Hammerle et al., 2007; Nie et al., 1992) as follows. Horizontally observed incident shortwave radiation was partitioned into direct and diffuse components using observed diffuse fraction (BF5, Delta-T Devices, UK), and the direct component was converted to that normal to the slope surface. The diffuse component was assumed to be isotropic. The total incident shortwave radiation normal to the slope surface was calculated as the sum of the direct component converted as above and the original diffuse component. When diffuse fraction was not observed, it was estimated from the relationship between the diffuse fraction and cloudiness; the latter was defined as the ratio of observed incident shortwave radiation to extraterrestrial radiation (Wang et al., 2018). The slope-normal shortwave radiation was included as a variable, SW_IN_SLOPE_PI_1_1_1, in FULLSET.

For tropical ecosystems (TH-Kms, TH-Kog, TH-Mae, ML-LHP, ID-PaB), nighttime-based flux partitioning failed because little seasonality in temperature hampered the determination of a significant relationship between nighttime CO_2 flux and temperature. For these sites, only daytime partitioning was provided in the dataset. In a subtropical forest (KH-Kmp), the determination of the u* threshold failed; thus, the u* threshold was estimated using gap-filled u* by the site team instead of measured u* with data gaps. Since the data quality of u* for KH-Kmp seemed reasonable, we were unable to find out why REddyProc failed to determine the u* thresholds with measured u* in KH-Kmp. The u* threshold for ID-Pag and ID-PaD could not be determined for several years; so, constant u* thresholds across these years were determined with REddyProc and applied for the subsequent data processing.

Low availability of nighttime data due to the limited fetch in JP-Ako (Kosugi et al., 2005) hampered determination of the u* threshold, gap-filling flux for CO_2 flux, and flux partitioning with REddyProc. Consequently, no aggregated fluxes longer than half-hourly data for CO_2 flux, GPP, and RECO were provided in the dataset.

Fluxes were not partitioned for lakes and a pond (JP-SwL, JP-KaL, JP-Nap) and an urban center (JP-Sac). For the lakes and pond, gap-filling H, LE, and CO_2 flux was based on MDS. For JP-Sac, gap-filling for H and LE was also based on MDS, but MDS was not applied to CO_2 flux because it was controlled by traffic volume and air temperature (Ueyama and Takano, 2022). Gap-filling for CO_2 flux at JP-Sac was conducted by the site team on the basis of random forest regression (Ueyama and Takano, 2022), and was included as FCO2_F_PI in SUBSET and FULLSET. The u* threshold was not applied for JP-Nap, because the moving point method (Papale et al., 2006) developed for terrestrial ecosystems was not applicable to the pond.

In this dataset, CH_4 fluxes were not gap-filled, because (1) consistent gap-filling was not possible because of missing important variables, such as water table depth, and (2) inconsistent processes control CH_4 emissions on different land surfaces, such as a rice paddy (JP-Hrt), bog (JP-BBY; Ueyama et al., 2020c, 2022b), lake (JP-SwL; Iwata et al., 2018), pond (JP-Nap), and urban landscapes (JP-Sac, JP-Om1; Takano and Ueyama, 2021). If the gap-filled CH_4 fluxes were provided by the site team (i.e., JP-BBY), the data were included as FCH4_F_PI in SUBSET; otherwise, non-gap-filled data were included in FULLSET.

2.5 Data format

The dataset was prepared in a format partially compatible with FLUXNET format, although the content and split of variables between FULLSET and SUBSET were slightly different to FLUXNET2015 (Pastorello et al., 2020) (Table 2), which consists of files separated by sites, temporal aggregation (i.e., half-hourly/hourly, daily, weekly, monthly, and annual), and data product, i.e., FULLSET and SUBSET, as described later. The separated files for FULLSET and SUBSET were combined into two zip files for each site.

The following file naming rules (Pastorello et al., 2020) were followed.

[SITE_ID]_JapanFlux2024_[DATA_PRODUCT]_[RESOLUTION]_[FIRST_YEAR]-[LAST_YEAR]_[SITE_VERSION]-[CODE_VERSION].csv

[SITE_ID] is the site ID, the CC-SSS format: CC is a two-letter country code, and SSS is the three-character site code. [Data_PRODUCT] represents the data types: FULLSET, SUBSET, AUXMETEO, AUXNEE, or ERA5. SUBSET is the data type representing selected data variables, including basic micrometeorological data and fluxes, and quality information flags. FULLSET is a data file representing all variables of data products, including variables listed in SUBSET, original data before the processing pipeline, and internal variables. AUXMETEO includes auxiliary variables related to the meteorological downscaling of ERA5. ERA5 includes the meteorological data from ERA5 for 1990−2024. [RESOLUTION] is the temporal resolution of the data products: HH (half-hourly time step), HR (hourly time step), DD (daily time step), WW (weekly time step), MM (monthly time step), and YY (annual time step). [FIRST_YEAR] is the first year in the file, and [LAST_YEAR] is the last year in the file. The first and last years are based on the years in which the micrometeorological measurements are conducted, except for ERA5, where the first year is 1990 and the last year is 2024 for all sites. [SITE_VERSION] is the version of the original dataset, and [CODE_VERSION] is the code of the data processing pipeline used to process the dataset.

The SUBSET file included variables for basic meteorology and turbulent fluxes. The gap-filled meteorological variables of air temperature, incoming shortwave radiation, incoming longwave radiation, relative humidity, VPD, atmospheric pressure, precipitation, wind speed, net radiation, ground heat flux, soil temperature, PPFD, CO_2 concentration, and soil water content were included. If the original data provided by a site team included wind direction, outgoing shortwave radiation, outgoing longwave radiation, outgoing PPFD, u*, and shortwave radiation, incoming, potential (top of atmosphere), non-gap-filled data for these variables were included. Gap-filled soil temperature and soil water content were measured at the shallowest depth, while CO_2 concentration was gap-filled for the highest altitude. A quality information flag was assigned for gap-filled variables, where 0 is the original data, 1 is a gap-filled value of the most reliable quality (calculated using a 14-day window), 2 is a gap-filled value of the medium quality (calculated using a 14- to 56-day window), and 3 is the gap-filled value of the least reliable quality (calculated using a window longer than 56 days) (Wutzler et al., 2018). If gap-filled CH_4 flux data were provided by the site team (i.e., at JP-BBY), they were included in SUBSET. The SUBSET file was provided with five temporal resolutions (half-hourly/hourly, daily, weekly, monthly, and annual aggregations).

The FULLSET file includes original unprocessed data, internal variables (aggregated meteorological variables measured at different locations or with different sensors), and meteorological data from ERA5, in addition to processed variables included in SUBSET. The FULLSET file is provided with the five temporal resolutions listed above.

For NEE, GPP, and RECO, the unit was μmol m^{-2} s^{-1} for half-hourly and hourly timescales, g C m^{-2} d^{-1} for the daily, weekly, and monthly timescales, and g C m^{-2} yr^{-1} for the annual timescale. For CH_4 flux, the unit for the half-hourly and hourly timescales was nmol m^{-2} s^{-1}, whereas the units for the other timescales were as the same as those for CO_2 fluxes. The units of precipitation were mm for the half-hourly and hourly timescales, mm d^{-1} for the daily, weekly, and monthly timescales, and mm yr^{-1} for the annual timescale. The units of other variables followed FLUXNET format (https://ameriflux.lbl.gov/data/aboutdata/data-variables/), which did not change with the timescales.

The ERA5 file contains the data for air temperature (TA_ERA5; °C), relative humidity (RH_ERA5; %), VPD (VPD_ERA5; hPa), vapor pressure (e_ERA5; hPa), saturation vapor pressure (e_sat_ERA5; hPa), wind speed (WS_ERA5; m s^{-1}), atmospheric pressure (PA_ERA5; kPa), incoming shortwave radiation (SW_ERA5; W m^{-2}), incoming longwave radiation (LW_ERA5; W m^{-2}), and precipitation (P_ERA5; mm). The ERA5 file is provided with the five temporal resolutions listed above. The variables in the ERA5 file were not corrected for the bias in comparison to the site data.

Two auxiliary files—for meteorology and u*-threshold—are provided. The AUXMETEO file includes the following statistics for downscaling ERA5 to the site scale: the linear slope between the measured data and ERA5 (ERA_SLOPE), intercept (ERA_INTERCEPT), root mean square error (ERA_RMSE), and correlation coefficient (ERA_CORRELATION). These statistics are included for each year and for all years when measurements were conducted. The TIMESTAMP column in the AUXMETEO file represents the year for the statistics, where -9999 represents the statistics for the entire year. The AUXNEE file includes the u* threshold in each year, with the reference threshold and the 5th, 50th, and 95th percentiles of the estimated u* threshold.

The dataset also includes the BADM files, which are used in the FLUXNET community. Six BADM files are provided: (1) general information, (2) instrument, (3) instrument operations, (4) vegetation cover, (5) soil, and (6) disturbance and management.

3 Database summary

3.1 CO_2 flux

Based on the dataset constructed, mean seasonalities in NEE, GPP, and RECO were as expected from the biomes and mean climatology (Figs. 5, 6). In northern boreal forests in Siberia (RU-Tur, RU-NeF, RU-SkP, RU-Sk2), the magnitude of the flux was generally low, and growing seasons when GPP was not negligible were short. In the southern Eurasian boreal forests in Siberia and Mongolia (RU-Ege, MN-Udg, MN-Skt), the magnitudes of CO_2 fluxes were greater than those in the above northern boreal forests. Inland grasslands in Mongolia (MN-Nkh, MN-Hst, MN-Kbu) had smaller CO_2 flux magnitudes than the nearby forests (MN-Udg, MN-Skt). For temperate forest and grassland sites, the dataset showed known seasonality with spring onset, summer peak, and autumn senescence with low fluxes in winter. Among forest sites, seasonal variations became smaller in the subtropics (JP-Ynf), and clear seasonality disappeared in the tropics (KH-Kmp, MY-LHP, ID, Pag, ID-PaD, ID-PaB) as the climate became warmer. Among rice paddies, single-cropping sites had a single peak (JP-Mse, JP-Hc2), but a double cropping site had two peaks (JP-Hc3) in GPP, RECO, and NEE (Fig. 6). For lakes (JP-SwL, JP-KaL), a pond (JP-Nap), and an urban center (JP-Sac), CO_2 fluxes showed smaller seasonality than those at vegetation surfaces.

Some data for CO_2 fluxes raise suspicions. First, markedly negative NEE values in harsh winters were estimated for MN-Skt and MN-Kbu (Figs. 5, 6), which could be caused by an artifact known for the open path sensor (Burba et al., 2008). The artificially negative NEE caused a considerable positive GPP in winter. Data users should be cautious about the data for MN-Skt and MN-Kbu. Second, the daytime partitioning method extrapolated the relationship obtained during the growing season to winters when NEE was not measured. The result was erroneous estimation of GPP and RECO (e.g., JP-Nkm in Fig. 5). Using the nighttime approach, GPP and RECO were not estimated for the period when NEE was not measured. Despite these suspicious data, the fluxes partitioned using the nighttime and daytime methods were generally consistent across the sites.

The spatial variabilities in annual NEE, GPP, and RECO were also consistent with earlier reports for Asian ecosystems (Fig. 7; Table 3). In Asia, the spatial variabilities in GPP and RECO are explained mostly by mean annual air temperature (Hirata et al., 2008; Kato and Tang, 2008; Saigusa et al., 2013; Yu et al., 2013). Except in disturbed forests and croplands, GPP and RECO increased linearly with mean annual air temperature (Fig. 7). Correlations of GPP and RECO with the annual sum of precipitation were lower than with mean annual air temperature. No clear correlation was found between annual NEE and mean annual air temperature or annual sum of precipitation, but the maximum CO_2 sink (i.e., negative NEE) with each temperature range appeared to be increased by temperature up to the annual mean temperature range until approximately 10°C (Fig. 7a). Except for disturbed forests and urban sites, most ecosystems were estimated to be a CO_2 sink of up to 1.0 kg C m^{-2} yr^{-1}.

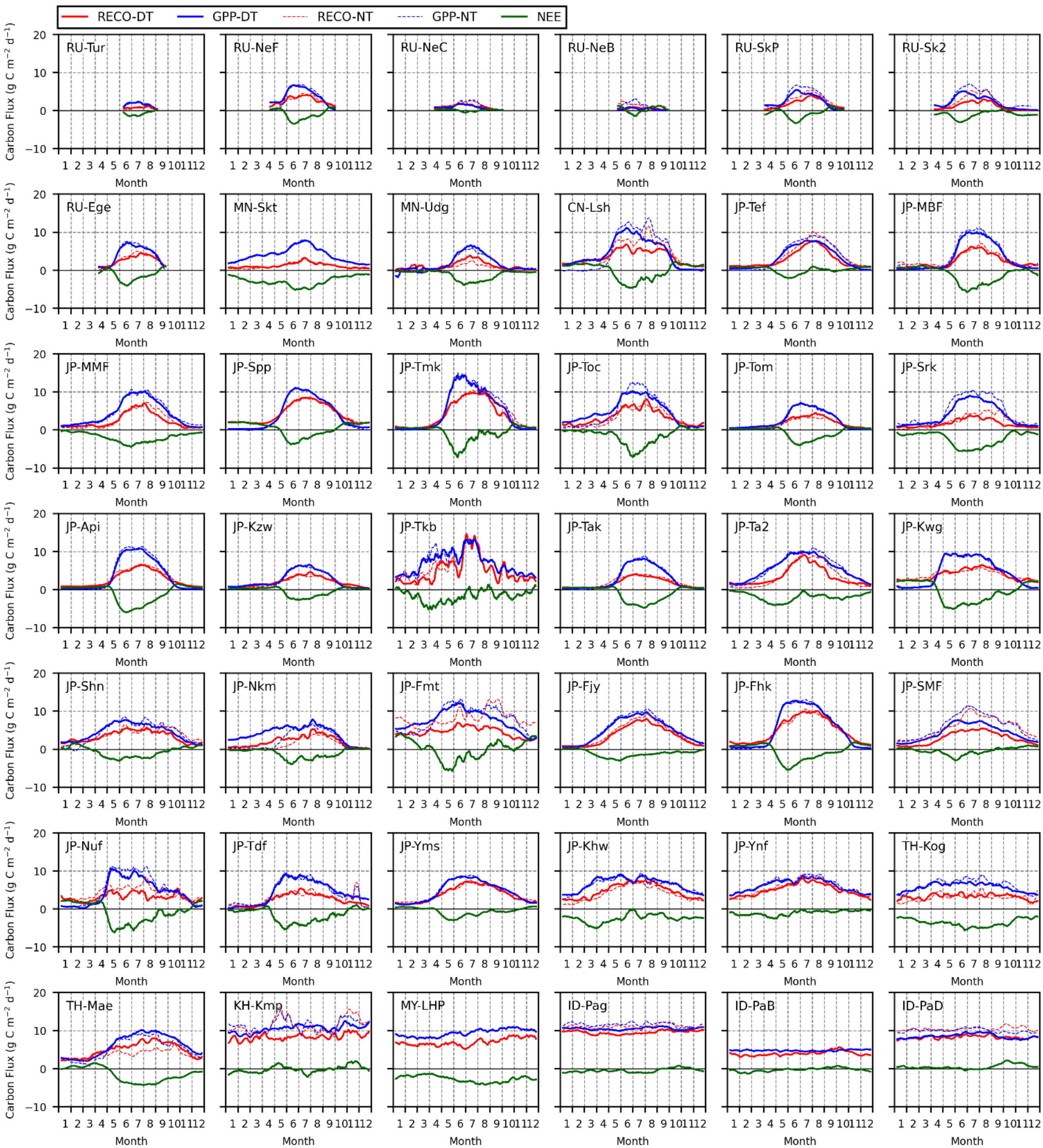

Figure 5. Mean seasonality of GPP, RECO, and NEE across forest sites. GPP and RECO were partitioned using the daytime method (DT, solid lines) or the nighttime method (NT, dashed lines). The seasonality is shown when NEE was measured,

and those for GPP and RECO are shown when the partitioning was successful. The seasonality is the ensemble mean of the daily fluxes with for each day of year for all years. The sites are ordered according to latitude from high to low. The mean seasonality is shown for sites having the data at least one growing season.

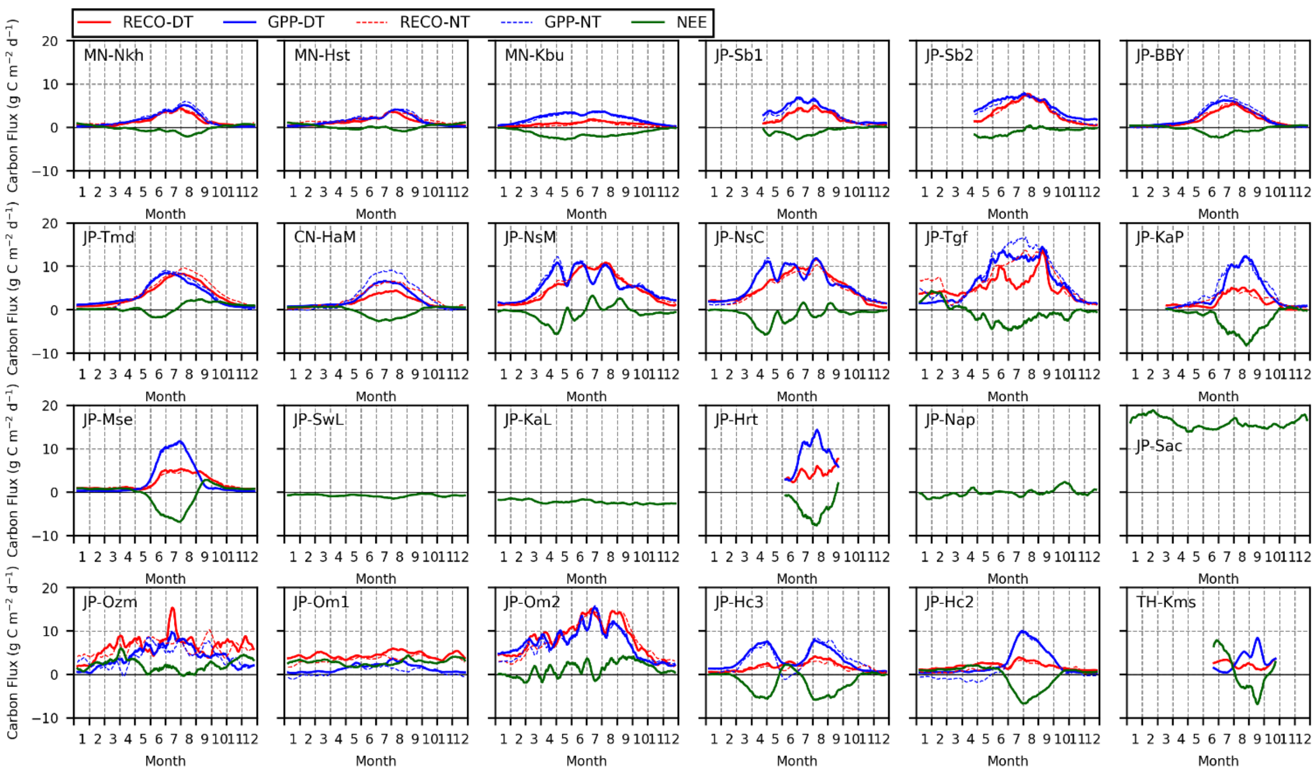

Figure 6. Mean seasonality of GPP, RECO, and NEE across sites other than forests. Designations are as in Fig. 5.

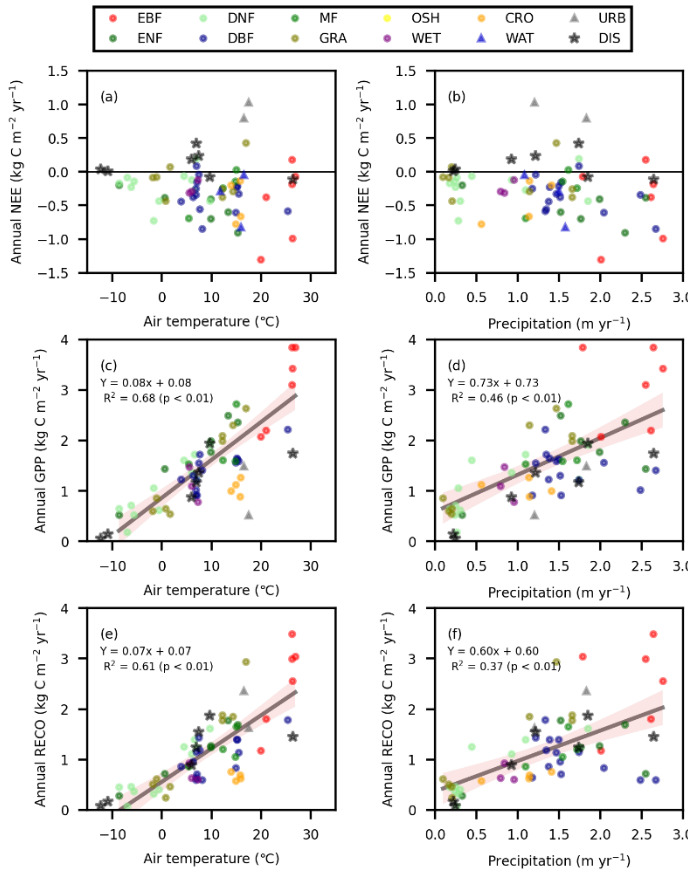

Fig. 7. Relationships of annual NEE (a, b), GPP (c, d), and RECO (e, f) to mean climate of annual mean air temperature (a, c, e) and annual sum of precipitation (b, d, f). GPP and RECO were estimated using the daytime method. The stars represent fluxes obtained at disturbed forests, where a disturbed forest was defined as a forest that experienced disturbance within the last 10 years. The annual fluxes were calculated based on the sum of mean seasonality shown in Figs. 5 and 6; missing measurements during the winter in high-latitudes were gap-filled as zero. Since sites of JP-Spp, JP-Tmd, and JP-Tef experienced significant disturbance (windthrow or clearcut) during the measurement period, data obtained within 10 years after a disturbance were classified as disturbed forests (DIS). The lines represent linear regressions with shading showing the confidence intervals ($p < 0.05$), that was determined excluding the DIS data. The annual CO_2 flux for JP-Sac (5.8 kg C m^{-2} yr^{-1}) is not shown due to the totally different carbon budget in the urban center compared to those in ecosystems. The values are shown in Table 3. Land cover type abbreviations are in Fig. 3.

Table 3. Summary of mean annual air temperature (TA), annual sum of precipitation (PREC), mean annual downward shortwave radiation (Rsd), mean annual carbon fluxes (NEE, GPP, RECO), and mean annual latent heat flux (LE), mean annual sensible heat flux (H), evapotranspiration (ET), and land cover. The statistics were calculated for observation years; for disturbed sites, the data were considered separately for the periods before, during, and after disturbance. Disturbed ecosystems were defined as those that experienced disturbance within the last 10 years. GPP, RECO, NEE, LE, and ET for boreal forests in Russia that lacked winter measurements (RU-Tur, RU-NeB, RU-NeC, RU-NeF, RU-SkP, RU-Ege, RU-Sk2) were considered zero. GPP, RECO, and NEE at MN-Skt and MN-Kbu were also considered zero during winter, when daily mean air temperature was below -5 ^{o}C (indicated by asterisks in the table), to mitigate the influence of the negative values of CO_2 fluxes caused by an artifact associated with an open-path sensor. The N/A values were listed because missing observations, even after gap-filled fluxes, prevented the calculation of annual fluxes or because the standard flux partitioning was not available for pond, lakes, and urban landscapes.

Site ID	disturbance	Land cover	TA	PREC	Rsd	NEE	GPP	RECO	LE	H	ET
			°C	mm yr^{-1}	W m^{-2}	g C m^{-2} yr^{-1}	g C m^{-2} yr^{-1}	g C m^{-2} yr^{-1}	W m^{-2}	W m^{-2}	mm yr^{-1}
RU-Tur		DNF	-7.0	264	93	-83	180	76	N/A	N/A	N/A
RU-NeB	fire	GRA	-12.3	244	117	37	57	85	N/A	N/A	N/A
RU-NeF		OSH	-8.6	175	117	-166	653	455	10	N/A	132
RU-NeC	clearcut	DIS	-10.9	224	112	12	147	170	13	N/A	162
RU-SkP		DNF	-5.7	238	118	-139	523	375	21	N/A	265
RU-Sk2		ENF	-8.7	328	117	-194	522	283	16	N/A	203
RU-USk		GRA	-11.6	289	110	N/A	N/A	N/A	15	N/A	193
RU-Ege		DNF	-6.3	248	122	-225	715	466	20	N/A	259
MN-Skt		DNF	-1.7	279	169	-722 *	1058 *	324 *	15	45	189
MN-Udg		DNF	-0.6	303	157	-431	617	413	19	29	246
MN-Nkh		GRA	-1.9	163	171	-83	603	516	20	25	253
MN-Hst		GRA	1.6	197	181	76	541	468	18	27	228
MN-Kbu		GRA	0.7	204	183	-433	647 *	248 *	9 *	30	116
CN-Lsh		DNF	4.4	443	144	-60	1606	1255	25	36	324
JP-Sb1		WET	6.0	794	145	-288	1098	638	N/A	N/A	N/A
JP-Sb2		WET	5.5	840	140	-313	1476	935	N/A	N/A	N/A

JP-Tef	before	DIS	5.9	926	125	192	882	898	18	10	232
	clearcut	GRA	5.9	926	125	-118	1363	1114	27	13	343
	after	MIX	5.9	926	125	-26	1238	1034	21	17	268
JP-MBF		DBF	3.9	1373	134	-442	1233	862	37	20	472
JP-MMF		MF	5.4	1092	134	-689	1537	861	43	21	537
JP-BBY		WET	7.2	953	143	-118	785	610	41	12	524
JP-Spp	before	DIS	7.4	1215	145	235	1366	1554	35	16	444
	windthow	DBF	7.4	1215	145	-42	1557	1432	40	15	500
JP-Tmk		DNF	6.6	1092	133	-270	1727	1401	45	31	568
JP-Tmd	windthow	GRA	7.0	1738	139	421	1176	1249	N/A	N/A	N/A
	after	DBF	7.0	1738	139	89	1225	1147	34	21	427
JP-Toc		DBF	7.6	1342	137	-556	1729	1189	33	30	418
JP-Tom		DBF	6.9	1173	128	-249	916	642	N/A	40	N/A
JP-Srk		DBF	8.1	2669	129	-847	1408	600	41	-1	509
JP-Api		DBF	6.3	1509	150	-375	1307	958	18	14	235
CN-HaM		GRA	-1.1	97	200	-77	862	618	31	23	389
JP-NsM		GRA	12.2	1658	150	-251	1989	1779	55	6	704
JP-NsC		GRA	12.2	1658	150	-376	2098	1880	53	7	674
JP-Kzw		DBF	7.0	1524	165	-155	919	709	15	32	187
JP-Tkb		ENF	13.3	1514	159	-599	2490	1781	45	-7	579
JP-Tak		DBF	6.8	2483	146	-342	1024	597	11	26	135
JP-Ta2		ENF	9.8	1760	148	-695	1990	1247	43	16	546
JP-Tgf		GRA	14.3	1141	153	-291	2307	1851	53	19	681
JP-KaP		CRO	14.9	561	155	-774	1127	584	70	7	894
JP-Mse		CRO	13.9	1407	154	-197	1004	763	67	6	858
JP-SwL		WAT	11.8	1499	178	-287	N/A	N/A	80	18	1021
JP-KaL		WAT	16.0	1575	163	-826	N/A	N/A	59	21	759
JP-Kwg		DBF	15.2	1492	151	-214	1631	1393	N/A	18	N/A
JP-Shn		MF	12.3	1713	167	-242	1612	1211	53	43	675
JP-Nkm		ENF	0.5	2544	162	-381	1442	725	36	-3	445

JP-Fmt		MF	15.0	1611	158	35	2720	1652	71	35	913
JP-Kgu	urbanization	URB	16.5	1400	149	N/A	N/A	N/A	27	41	344
JP-Fjy		ENF	9.9	1989	165	-404	1772	1270	39	20	501
JP-Fhk	before	DIS	9.6	1846	168	-74	1945	1873	43	43	554
	thinning	DNF	9.6	1846	168	-433	1914	1619	40	40	510
JP-SMF		MF	14.8	1543	165	-142	1587	1059	51	23	658
JP-Nuf		DBF	15.4	1465	156	-327	1590	1139	22	16	277
JP-Tdf		DBF	14.8	2039	155	-601	1559	840	45	19	584
JP-Yms		DBF	15.0	1384	159	-223	1644	1400	63	30	805
JP-Nap		WAT	16.5	1083	176	-48	N/A	N/A	60	9	773
JP-Ako		EBF	15.3	739	169	N/A	N/A	N/A	27	47	347
JP-Sac	urbanization	URB	16.4	1594	159	5807	N/A	N/A	28	43	354
JP-Ozm	urbanization	URB	16.5	1828	150	793	1485	2353	52	23	673
JP-Om1	urbanization	URB	17.5	1202	165	1032	515	1622	23	39	294
JP-Om2	mowing	GRA	16.9	1466	166	430	2634	2937	71	9	908
JP-Hc3		CRO	15.8	1136	175	-663	1265	625	51	10	659
JP-Hc2		CRO	15.7	1141	161	-132	890	697	60	10	772
JP-Khw		ENF	15.2	2294	158	-906	2359	1689	81	20	1044
JP-Ynf		EBF	20.9	2611	159	-374	2200	1808	65	5	834
TH-Kog		EBF	19.9	2004	183	-1301	2078	1178	73	23	935
TH-Mae		DBF	25.3	1333	205	-579	2215	1783	69	36	888
KH-Kmp		EBF	26.9	1786	206	-72	3842	3044	106	19	1368
MY-LHP		EBF	26.2	2752	184	-989	3431	2552	89	28	1157
ID-Pag		EBF	26.1	2639	200	-183	3840	3486	111	29	1430
ID-PaB	fire	OSH	26.4	2642	197	-110	1746	1450	90	27	1164
ID-PaD		EBF	26.2	2543	197	179	3100	2997	94	29	1215

In the developed dataset, annual CO_2 fluxes tended to differ by land cover type (Fig. 8). Forest ecosystems included in the datasets had, on average, similar CO_2 sinks. Among the forest ecosystems, the mean CO_2 sink tended to be highest in ENF. GPP and RECO in temperate managed grasslands were higher than those in natural grasslands in Mongolia and Russia. The annual CO_2 sink also tended to be greater in managed grasslands compared to natural grasslands, except for a frequently mowed site (JP-Om2), which exhibited net annual CO_2 emissions. Disturbed forests, on average, acted as a small CO_2 source. CO_2 emissions in urban centers (JP-Sac; 5.8 kg C m^{-2} yr^{-1}; not included in Fig. 8a) were considerably higher than those from natural or agricultural ecosystems. The annual GPP was highest in EBF among forest ecosystems, followed by ENF, DBF, and DNF. RECO was highest in EBF, whereas those in ENF, DBF, and DNF were similar to each other. Annual GPP and RECO varied greatly among grasslands because they included inland dry grasslands and Japan's weedy grasslands (Fig. 8b, c).

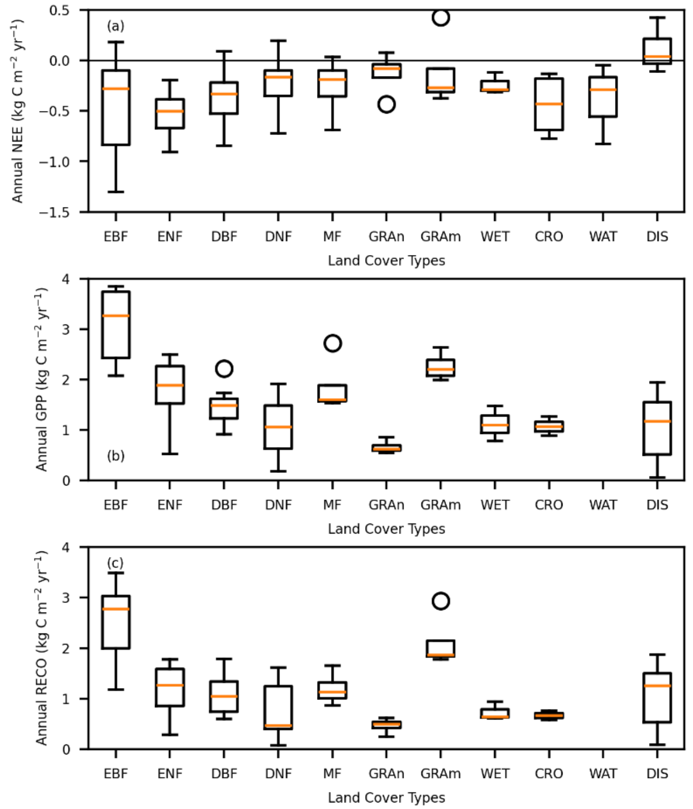

Figure 8. Boxplots for annual NEE, GPP, and RECO by land cover type. GPP and RECO were estimated using the daytime method. Fluxes at urban sites are not shown because the range of urban CO_2 emissions was totally different from those for vegetation or lakes. Since flux partitioning was not conducted for lakes, partitioned fluxes for lakes were not shown. Land cover type abbreviations are in Fig. 3, although the grassland category was separated into natural grassland (GRAn) and

managed grassland (GRAm). The definition of DIS was the same as in Fig. 7, where all data from RU-NeC, RU-NeB, and ID-PaB are also classified as DIS. The box represents the interquartile range (25th to 75th percentiles), the whiskers represent the maximum and minimum values, excluding outliers shown by circles, and the orange bar represents the median value.

3.2 Energy fluxes

Mean annual energy fluxes represented in the dataset were explained better by air temperature than precipitation (Fig. 9; Table 3). The mean annual LE increased with the mean annual air temperature; their strong linear correlation could be explained by a close coupling between transpiration and photosynthesis (Medlyn et al., 2011), where spatial variations in annual GPP were strongly correlated with annual air temperature (Fig. 7c). Evaporation could also be enhanced under high air temperature and resulting high VPD conditions (Zhang et al., 2015). The dataset included mostly ecosystems around the Pacific Ocean, which were especially densely distributed in Japan, whereas water-limited inland ecosystems were scarce. Consequently, the correlation between LE and precipitation was weaker than those reported in a literature survey for Asia (Kang and Cho, 2021). Under similar climate conditions, LE was lower and H was higher in urban landscapes in comparison with vegetation surfaces, in agreement with a previous report (Ueyama et al., 2021). Mean annual H did not change with air temperature or precipitation, possibly be caused by missing high-latitude observations owing to missing winter data (e.g., RU-Tur, RU-SkP, Ru-Ege) (Fig. 5). Negative H values in high-latitude ecosystems were observed owing to decreased available energy associated with snow albedo (Nakai et al., 2013; Ueyama et al., 2020b).

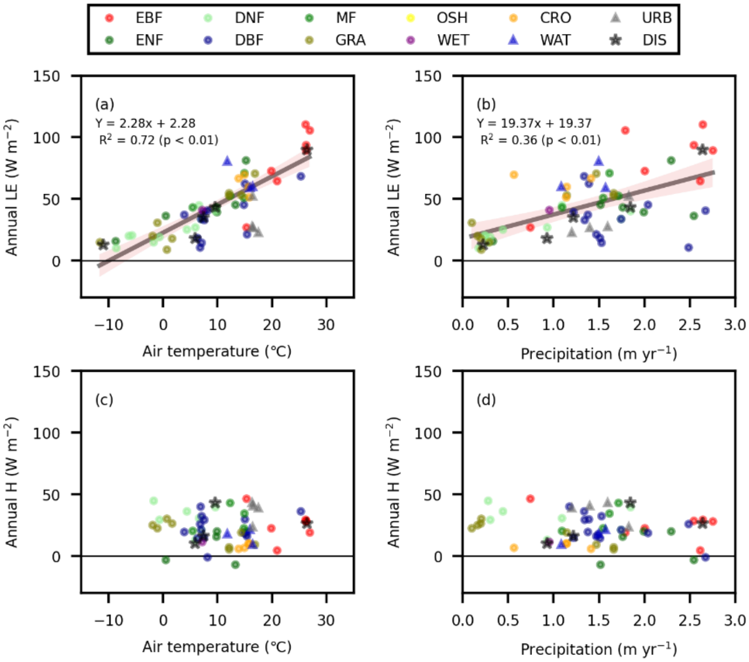

Figure 9. Relationships of annual energy fluxes of latent heat flux (LE) (a, b) and sensible heat flux (H) (c, d) to mean climate of annual mean air temperature (a, c) and annual sum of precipitation (b, d). The classification of the disturbed forest (DIS) is as in Fig. 8. Annual H were only calculated for the case where there were no missing data in the mean seasonality, whereas the missing LE data during the winter were considered to be zero for boreal forests in Russia. The lines represent linear regressions, with shading showing the confidence intervals ($p < 0.05$), that was determined excluding the data from DIS, urban areas (URB), and lakes and ponds (WAT). The values are shown in Table 3. Land cover type abbreviations are in Fig. 3.

4 Data availability and data use guidelines

The dataset associated with this publication can be found at the ADS website (https://ads.nipr.ac.jp/japan-flux2024/), where individual site data have their own DOIs. All data are available under the CC BY 4.0 copyright policy with appropriate citations of this paper. We suggest that researchers planning to use this dataset as a core dataset for their analysis contact and collaborate with database developers and relevant site teams. As in the data policy of FLUXNET2015, in case of a synthesis using both CC BY 4.0 and other private data, all data should be treated as Tier Two of the FLUXNET data policy (data producers must have opportunities to collaborate and consult with data users).

5 Conclusions

The JapanFlux2024 dataset is the first public dataset that includes as much data as possible, both old and new, as an activity of JapanFlux. The dataset is consistent with previous synthesis studies in Asia in terms of seasonalities in CO_2 and energy fluxes across Japan and East Asia, but substantially increased the number of the data, 83 sites with 683 site-years from 1990 to 2023. The dataset will facilitate important studies in East Asia including Japan, such as those on land−atmosphere interactions, improvement of process models, and upscaling fluxes using machine learning. Since the dataset is processed in line with the standard dataset provided by FLUXNET, the JapanFlux2024 dataset will bridge collaborations between researchers from Asia and FLUXNET.

Competing interests

The authors declare that they have no conflict of interest.

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