Int J Biometeorol (2016) 60:615–627
DOI 10.1007/s00484-015-1053-3

REVIEW PAPER

Review: advances in in situ and satellite phenological observations in Japan

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Received: 5 June 2015 / Revised: 14 August 2015 / Accepted: 14 August 2015

Abstract To accurately evaluate the responses of spatial and temporal variation of ecosystem functioning (evapotranspiration and photosynthesis) and services (regulating and cultural services) to the rapid changes caused by global warming, we depend on long-term, continuous, near-surface, and satellite remote sensing of phenology over wide areas. Here, we review such phenological studies in Japan and discuss our current knowledge, problems, and future developments. In contrast with North America and Europe, Japan has been able to evaluate plant phenology along vertical and horizontal gradients within a narrow area because of the country's high topographic relief. Phenological observation networks that support scientific studies and outreach activities have used near-surface tools such as digital cameras and spectral radiometers. Differences in phenology among ecosystems and tree species have been detected by analyzing the seasonal variation of red, green, and blue digital numbers (RGB values) extracted from phenological images, as well as spectral reflectance and vegetation indices. The relationships between seasonal variations in RGB-derived indices or spectral characteristics and the ecological and CO_2 flux measurement data have been well validated. In contrast, insufficient satellite remote-sensing observations have been conducted because of the coarse spatial resolution of previous datasets, which could not detect the heterogeneous plant phenology that results from Japan's complex topography and vegetation. To improve Japanese phenological observations, multidisciplinary analysis and evaluation will be needed to link traditional phenological observations with "index trees," near-surface and satellite remote-sensing observations, "citizen science" (observations by citizens), and results published on the Internet.

Keywords Remote sensing · Phenology · Japan · Phenological observation network · Biometeorology

Introduction

To accurately evaluate changes in the spatial and temporal variation of ecosystem functioning (e.g., evapotranspiration, photosynthesis) and services (e.g., regulating, cultural) under the rapid climate changes that are occurring due to global warming, long-term, continuous, and broad-scale phenological observations are required (Richardson et al. 2013). The spatial and temporal variations of the timing of leaf flush and leaf fall affect biogeochemical processes such as CO_2 uptake during photosynthesis and the emission of biogenic volatile organic compounds (Peñuelas et al. 2009; Polgar and Primack 2011; Keenan et al. 2014) and carbon, water, and heat budgets through the effects on evapotranspiration and physical properties such as latent and sensible heat, albedo, and the aerodynamic roughness of the land surface (Peñuelas et al. 2009; Polgar and Primack 2011; Schwartz et al. 2013). A phenological mismatch between plants and their animal pollinators and consumers may increase the risk of losses of biodiversity and supporting services (SCBD 2010; Polgar and Primack 2011; Kudo 2014). Under the future warming that is predicted to occur, the time lag between the blossoming date of species such

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as cherry (*Prunus* spp.) and the dates of associated festivals may disrupt tourism activities. To prevent the loss of cultural services such as flower tourism, decision-makers must develop adaptation plans (Sparks 2014).

Many previous studies examined the spatial and temporal variation of phenology based on fixed-point visual observations of "index trees" by experts (Linderholm 2006; Ogawa-Onishi and Berry 2013). Such observations have the merit of permitting long-term detailed phenological records. However, this method is labor-intensive (Richardson et al. 2007), the detection of phenological stages is subjective, the numbers of species and individuals that can be surveyed are limited, the observations fail to cover the full range of the species (they are mainly distributed in cities and low-altitude areas), and the observations may be affected by urbanization (e.g., the heat island effect; Ohashi et al. 2012). To solve these problems, we can take advantage of in situ (near-surface) and satellite remote sensing, which permit more objective, long-term, continuous phenological observations of many individuals over a wide area (Linderholm 2006; Morisette et al. 2009).

Long-term continuous phenological observations with digital cameras and spectral radiometers have been conducted since around 2003 for a range of ecosystems, mainly by American and Japanese networks. In the USA, this has been done by the PhenoCam network (http://phenocam.sr.unh.edu/webcam/. Accessed 12 August 2015; Richardson et al. 2007); in Japan, it has been done by the Phenological Eyes Network (PEN; http://www.pheno-eye.org. Accessed 12 August 2015; Nasahara and Nagai 2015). However, these observations cover a limited area. Satellite remote sensing of vegetation indices, such as the data from the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard National Oceanic and Atmospheric Administration (NOAA) satellites since 1981, can detect the spatial and temporal variation of phenology at large scales (Delbart et al. 2006; Buitenwerf et al. 2015). Furthermore, the Moderate-resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua satellites have provided phenological data since 2000, and the VEGETATION sensor onboard the Satellite Pour l'Observation de la Terre (SPOT) have provided data since 1999 at point, regional, and continental scales, with a resolution of 500 to 1000 m (Delbart et al. 2006; Nagai et al. 2015b).

Japan includes subarctic to subtropical zones, and 70 % of the land is mountainous. The mountainous region in central Japan ranges widely in altitude (by 2000 to 3000 m) over relatively short distances (50 km). Japan's maritime climate is strongly influenced by global atmospheric patterns such as the El Niño–Southern Oscillation and the Arctic Oscillation (JMA 2014). These geographical characteristics create large regional differences and diversity and high spatial variation of vegetation (Natural Environmental Information GIS 1999). For this reason, we require not only phenological observations based on index trees but also quantitative satellite data that cover many ecosystems and plant species over a wide area, with low labor costs, to obtain and process the data.

In this review, we describe plant phenological observations in Japan based on remote sensing and discuss our current knowledge, problems, and future developments based on these studies. The geography of Japan allows for evaluation of the spatial and temporal variation of plant phenology along vertical (altitude) and horizontal (latitude) gradients over short distances (Doi and Takahashi 2008; Matsumoto 2010; Nagai et al. 2015b). Nagai et al. (2015b) found that the spatial and temporal variations of the timing of the start and end of the deciduous forest's growing season were strongly affected by both vertical and horizontal gradients. In addition, the Japanese Ministry of the Environment, Forestry Agency and other organizations have surveyed the vegetation cover and forest structure throughout the country for many years (Natural Environmental Information GIS 1999). This geographical and social background suggests the possibility of taking advantage of a large body of evidence to accurately evaluate the spatial and temporal variation of plant phenology. In this review, we will not discuss previous agricultural and horticultural studies because the effects of human manipulations may conceal the effects of climate change.

Background for Japanese phenological observations

The dramatic lifestyle changes since World War II (rapid urbanization) drastically reduced opportunities to experience nature. However, citizens continue to enjoy viewing of spring cherry blossoms (*hanami*; Aono and Kazui 2008), which has been recorded since the ninth century AD, and maple leaves (*Acer* spp.) in autumn (*momiji-gari*; Aono and Tani 2014), which has been recorded since the tenth century AD, because these activities are part of Japan's traditional culture. Recently, meteorological and tourist services, city offices, and tourist associations have published phenological information such as flowering and leaf coloring dates at scenic spots, resorts, temples, shrines, and parks on their Web sites. The Internet has dramatically increased the availability of such phenological information (Nagai et al. 2015a). Social networks such as Twitter and Facebook also let citizens share phenological information.

To find and experience these seasonal changes, citizens travel to scenic spots to view flowers and leaf coloring. Although technological crop cultivation (e.g., in greenhouses) and imported foods have undermined the sense of seasonality, citizens nonetheless receive nature's bounty (supporting ecosystem services) by purchasing seasonal vegetables and fruits. Seasonal events such as the timing of flowering and appearance of insects and birds have been important in Japanese literature, including classical poetry (*waka*) and *haiku*, since ancient times. Japanese citizen scientists have actively conducted phenological observations. “Ikimono Log,” managed by the Biodiversity Center of Japan, is a major system for collecting and sharing biological information (http://ikilog.biodic.go.jp. Accessed 12 August 2015). These cultural, historical, and social backgrounds have created favorable conditions for Japanese phenological observations.

Phenological observations using index trees

In this section, we will briefly summarize previous phenological studies based on observations of index trees. Ogawa-Onishi and Berry (2013) provide detailed descriptions of Japanese studies. Typical data include the timing of flowering, leaf flush, leaf coloring, and leaf fall that have been published by meteorological agencies (Matsumoto et al. 2003; Doi and Takahashi 2008; Ibáñez et al. 2010; Matsumoto 2010). This dataset has been compiled at weather stations throughout Japan since 1953 (JMA 1985). In addition, long-term continuous observations of these parameters have been conducted at research forests and agricultural experiment stations (Miller-Rushing et al. 2007; Fujisawa and Kobayashi 2010).

Japan stretches more than 3000 km, from 45° N to 20° N and from 123° E to 154° E, and comprises nine climatic divisions (Suzuki 1962). This allows mapping of the spatial characteristics of the timing of flowering, leaf flush, leaf coloring, and leaf fall in each season and examination of the changes in timing in response to climate change (JMA 1985). By way of example, Fig. 1 shows the spatial distribution of the first flowering date of cherry (*Prunus* × *yedoensis*; *somei-yoshino*) in 2014, and Table 1 provides details of these data. Global warming has advanced blooming of this cherry by 5 days from 1953 to 2013 (JMA 2014) and leaf coloring of *Ginkgo biloba* by 4 days from 1953 to 2000 (Matsumoto et al. 2003), but has delayed leaf coloring of *Acer palmatum* by 18 days from 1953 to 2013 (JMA 2014) and leaf fall of *G. biloba* by 8 days from 1953 to 2000 (Matsumoto et al. 2003). Unlike the case in North America and Europe, Japan’s delay in autumn phenology has been clearer than the advance in spring phenology (Matsumoto et al. 2003; Ibáñez et al. 2010; Matsumoto 2010).

Japanese phenological observation networks

Recently, automatic fixed-point phenological observations using near-surface remote-sensing techniques such as digital cameras and spectral radiometers have been conducted to support research and outreach activities. Typical networks include the Internet Nature Information System (INIS) in national parks across the country, managed by the Biodiversity Center of Japan (http://www.sizenken.biodic.go.jp. Accessed 12 August 2015; Ide and Oguma 2010), PEN at ecosystem study sites (http://www.pheno-eye.org. Accessed 12 August 2015; Nasahara and Nagai 2015), and Cyberforest, which mainly supports university forest research (http://landscape.nenv.k.u-tokyo.ac.jp/cyberforest/Welcome.html. Accessed 12 August 2015; Saito et al. 2004). These networks have published daily phenological images on their Web sites. In addition, PEN has conducted automatic fixed-point spectral measurements of the canopy surface in forests and grasslands to provide vegetation index data (Nasahara and Nagai 2015).

The main aims of these systems were to introduce national parks to citizens through outreach activities (Ide and Oguma 2010), permit ground truthing of satellite remote-sensing data (Nasahara and Nagai 2015), and improve environmental education (Saito et al. 2004). INIS targets the landscape scale (200 to 1000 m), whereas PEN and Cyberforest aim for coverage from shoot to landscape scales (20 cm to 200 m; Saito et al. 2004; Ide and Oguma 2010; Nasahara and Nagai 2015). Figure 2 summarizes the locations of the sites in each phenological observation network.

Phenological observations by digital cameras and spectral radiometers

Digital cameras

We can detect differences in plant phenological characteristics among ecosystems and tree species by analyzing the temporal variations in the red, green, and blue (RGB) digital numbers extracted from daily digital images (Richardson et al. 2007; Ide and Oguma 2010). These analyses have been conducted by INIS and PEN in various ecosystems (Ide and Oguma 2010; Nasahara and Nagai 2015). At some study sites, continuous daily phenological images exist for more than 10 years. Target ecosystems have been typical Japanese vegetated landscapes. Accordingly, the studies provide ground truthing data for phenological observations obtained by satellite remote sensing. However, some typical vegetation types such as oak (*Quercus serrata*) and mangrove (*Rhizophoraceae* spp.) forests have not yet been analyzed. In addition, Cyberforest has not conducted this analysis. Table 2 summarizes the previous studies that have been conducted in each Japanese ecosystem.

The year-to-year variation in the timing of flowering, leaf flush, and leaf fall for the whole canopy and for each tree species in deciduous forests can be detected by analyzing RGB time series (Ide and Oguma 2010; Nagai et al. 2011a; Inoue et al. 2014). The seasonal variation of these values correlates well with that of gross primary production (GPP) in this forest (Saitoh et al. 2012), deciduous coniferous forest (larch (*Larix kaempferi*) forest; Ide and Oguma 2011), and evergreen coniferous forest (Japanese cedar forest; Saitoh et al. 2012; Nagai et al. 2013a). Nagai et al. (2013a) examined differences between the seasonal variation in RGB-derived indices between a Japanese closed canopy evergreen

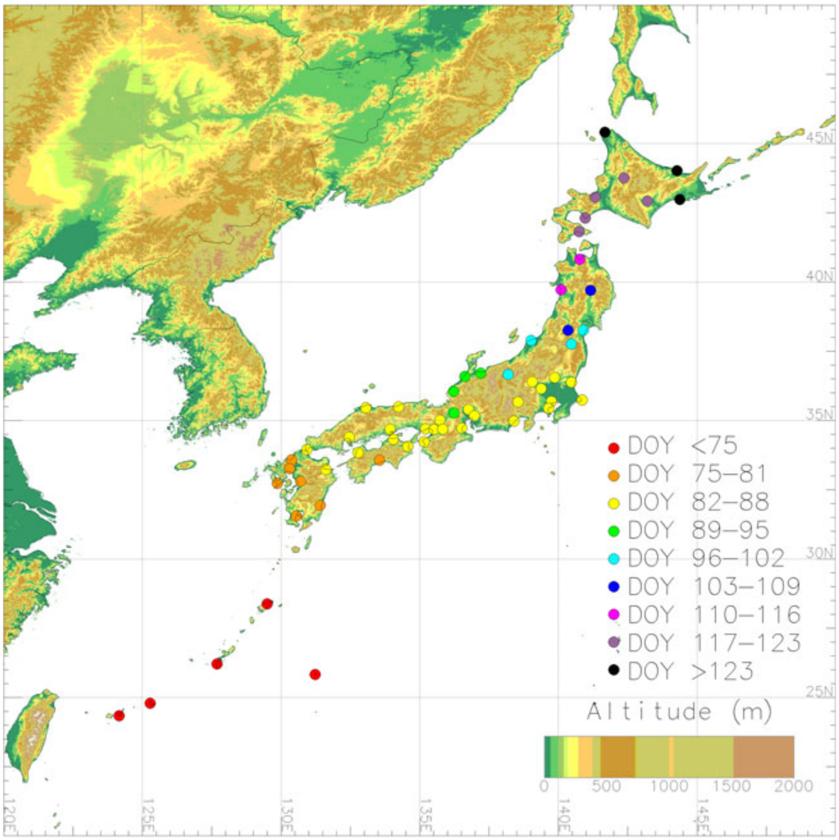

Fig. 1 Spatial distribution of the first flowering date (day of year) of cherry (*Prunus* × *yedoensis*) in 2014. Data obtained nearby the 58 weather stations conducted by the Japan Meteorological Agency were published on the Internet. See Table 1 for details. *DOY* day of year

coniferous forest (Japanese cedar, *Cryptomeria japonica*) and an Alaskan open canopy evergreen coniferous forest (black spruce, *Picea mariana*). However, insufficient comparative studies have been conducted in Japan.

Sonnentag et al. (2012) compared the RGB-derived indices extracted from images taken from several types of digital cameras. They found that the seasonal patterns of RGB-derived indices were likely to be more relevant to detecting changes in plant phenology than were particular RGB-derived indices values. This means that the seasonal patterns of the changes in RGB-derived indices could be used to detect phenological transitions without having to account for the characteristics of different types of digital cameras. However, additional examinations of the unique and common characteristics of the seasonal variation of RGB-derived indices are required for Japan and elsewhere.

Very steep terrain, with large altitude changes (e.g., 900 m) over short distances (e.g., 14 km), exists in the mountainous region of central Japan (Muraoka and Koizumi 2009). Nagai et al. (2015b) reported that along a vertical gradient in deciduous forests between 35° N and 46° N, leaf flush began 1 day later per 38.6 to 68.5 m increase in altitude and leaf fall began 1 day earlier per 78.1 to 142.9 m increase. This suggests the possibility that studying a small river basin in steep terrain would let researchers evaluate the sensitivity of plant phenology to climate change using a "space for time substitution," although more such studies are needed to confirm this. Studies conducted over a wide range of latitudes (horizontal distance) are also required to account for the spatial distribution of tree species and populations, genetic diversity, and phenological plasticity (Doi et al. 2010). However, studies over a wide range of latitudes include more uncertainties because of the greater variation in topographic and environmental characteristics.

In forest ecosystems, digital cameras have generally been installed at the top of CO_2 flux or ecosystem observation towers (Richardson et al. 2007; Nasahara and Nagai 2015). Nagai et al. (2013b) found that the seasonal patterns of RGB-derived indices extracted from upward images taken from the forest floor detected canopy phenology almost as well as downward images taken from the top of a tower in a closed canopy deciduous broad-leaved forest. Eliminating the requirement to install towers would allow such studies to be conducted at more sites for the same research budget.

Plant phenology is mainly affected by physiological events such as the onset of flowering or changes of leaf biomass and the amount of leaf pigments (Sims and Gamon 2002); Nagai et al. (2011a) found that RGB-derived indices can sensitively detect these changes based on changes of leaf color during leaf flush (from yellowish to dark green) and leaf coloring (from yellowish green to yellow or red). This seasonal variation can also be detected by spectral reflectance data and vegetation indices measured by spectral radiometers. In particular, the

Table 1 Summary of the first flowering date (day of year, DOY) of cherry (*Prunus* × *yedoensis*; *somei-yoshino*) near 58 weather stations based on data published on the Web site of the Japan Meteorological Agency

Site name	Latitude (°N)	Longitude (°E)	Annual mean air temperature (°)[a]	Mean annual precipitation (mm)[a]	DOY						Substitute species
					2011	2012	2013	2014	2015	Normal[a]	
Wakkanai	45.4150	141.6783	6.8	1062.8	139	135	146	131	123	134	*Prunus sargentii*
Asahikawa	43.7567	142.3717	6.8	1042.1	129	123	138	122	117	125	*Prunus sargentii*
Abashiri	44.0167	144.2783	6.5	787.5	136	124	145	127	120	131	*Prunus sargentii*
Sapporo	43.0600	141.3283	8.9	1106.6	127	122	133	119	112	123	
Obihiro	42.9217	143.2117	6.8	887.8	123	126	130	117	116	124	*Prunus sargentii*
Kushiro	42.9850	144.3767	6.2	1042.9	138	138	143	132	126	137	*Prunus sargentii*
Muroran	42.3117	140.9750	8.6	1184.9	126	130	136	119	118	126	
Hakodate	41.8167	140.7533	9.1	1151.9	122	123	128	118	111	120	
Aomori	40.8217	140.7683	10.4	1300.2	115	120	119	112	104	114	
Akita	39.7167	140.0983	11.7	1686.6	113	115	113	110	101	108	
Morioka	39.6983	141.1650	10.2	1266.2	110	115	113	103	99	111	
Yamagata	38.2550	140.3450	11.7	1163.2	108	114	105	104	100	105	
Sendai	38.2617	140.8967	12.4	1254.2	102	109	99	97	93	101	
Fukushima	37.7583	140.4700	13.0	1166.1	102	107	95	98	92	99	
Nigata	37.8933	139.0183	13.9	1821.0	104	107	97	97	92	99	
Kanazawa	36.5883	136.6333	14.6	2398.9	97	101	89	91	90	94	
Toyama	36.7083	137.2017	14.1	2300.1	98	103	88	92	91	95	
Nagano	36.6617	138.1917	11.9	932.7	105	109	96	101	94	103	
Utsunomiya	36.5483	139.8683	13.8	1493.1	96	99	80	88	89	91	
Fukui	36.0550	136.2217	14.5	2237.7	97	101	87	90	90	93	
Maebashi	36.4050	139.0600	14.6	1248.5	93	99	81	88	87	90	
Kumagaya	36.1500	139.3800	15.0	1286.4	91	95	78	87	86	88	
Mito	36.3800	140.4667	13.6	1353.8	96	97	80	88	89	92	
Gifu	35.4000	136.7617	15.8	1827.6	87	90	80	83	82	85	
Nagoya	35.1667	136.9650	15.8	1535.4	86	90	78	83	80	85	
Kofu	35.6667	138.5533	14.7	1135.3	88	92	78	87	84	86	
Chōshi	35.7383	140.8567	15.4	1660.0	94	93	80	88	89	90	
Tsu	34.7333	136.5183	15.9	1581.3	91	95	84	86	88	89	
Shizuoka	34.9750	138.4033	16.6	2325.0	79	84	76	83	81	84	
Tokyo	35.6917	139.7500	15.4	1528.8	87	91	75	84	82	85	
Yokohama	35.4383	139.6517	15.8	1688.8	89	93	77	84	82	85	
Matsue	35.4567	133.0650	14.9	1787.2	96	97	82	86	88	90	
Tottori	35.4867	134.2383	14.9	1914.0	92	94	79	86	87	90	
Kyoto	35.0133	135.7317	15.9	1491.3	87	94	81	86	86	87	
Hikone	35.2750	136.2433	14.7	1570.9	91	99	89	92	90	92	
Hiroshima	34.3983	132.4617	16.3	1537.6	91	93	81	84	83	86	
Okayama	34.6850	133.9250	16.2	1106.2	90	94	83	87	87	88	
Kobe	34.6967	135.2117	16.7	1216.3	90	93	80	86	86	87	
Osaka	34.6817	135.5183	16.9	1279.1	90	93	80	86	85	87	
Wakayama	34.2283	135.1633	16.6	1317.0	86	90	77	85	82	85	
Nara	34.6933	135.8267	14.9	1316.1	90	94	81	86	86	88	
Matsuyama	33.8433	132.7767	16.5	1314.9	84	90	76	83	86	84	
Takamatsu	34.3167	134.0533	16.3	1082.4	90	93	81	85	83	87	
Kochi	33.5667	133.5483	16.9	2547.6	81	81	74	77	81	81	
Tokushima	34.0667	134.5733	16.6	1453.9	90	92	83	88	87	87	
Shimonoseki	33.9483	130.9250	16.7	1684.5	89	90	78	84	84	86	
Fukuoka	33.5817	130.3750	17.0	1612.5	81	87	72	78	81	82	
Saga	33.2650	130.3050	16.5	1870.2	81	88	77	78	81	83	

Table 1 (continued)

Site name	Latitude (°N)	Longitude (°E)	Annual mean air temperature (°)[a]	Mean annual precipitation (mm)[a]	DOY						Substitute species
					2011	2012	2013	2014	2015	Normal[a]	
Oita	33.2350	131.6183	16.4	1644.7	82	87	73	84	85	83	
Nagasaki	32.7333	129.8667	17.2	1857.7	82	86	75	79	81	83	
Kumamoto	32.8133	130.7067	16.9	1985.9	80	85	75	79	80	82	
Kagoshima	31.5550	130.5467	18.6	2265.7	82	86	74	79	80	85	
Miyazaki	31.9383	131.4133	17.4	2508.7	82	84	72	78	81	83	
Naze	28.3783	129.4950	21.7	2837.7	30	20	14	16	20	19	*Prunus campanulata*
Ishigaki-jima	24.3367	124.1633	24.3	2106.8	17	359[b]	22	16	6	16	*Prunus campanulata*
Miyako-jima	24.7933	125.2783	23.6	2021.1	17	18	19	16	22	16	*Prunus campanulata*
Naha	26.2067	127.6867	23.0	2040.9	7	22	362[b]	15	15	18	*Prunus campanulata*
Minami-Daito-jima	25.8283	131.2283	23.3	1591.6	24	17	7	7	15	20	*Prunus campanulata*

The data in this table was obtained from the biometeorological and meteorological observations conducted by the Japan Meteorological Agency (http://www.data.jma.go.jp/sakura/data/sakura003_06.html and http://www.jma.go.jp/jma/menu/menureport.html; in Japanese. Accessed 12 August 2015)

[a] Average from 1981 to 2010

[b] Observed in the preceding year

green–red vegetation index (GRVI), which is based on the visible red and green reflectance bands, was better able to detect the canopy surface color changes than the normalized-difference vegetation index (NDVI) and the enhanced vegetation index (EVI), which are based on the visible red and blue and near-infrared reflectance bands (Motohka et al. 2010; Ide and Oguma 2011; Nagai et al. 2014a).

However, automatic fixed-point observations that target the whole canopy using spectral radiometers cannot detect differences in the seasonal changes among tree species. Nakaji et al. (2011) found that the seasonal variation in phenology of each deciduous broad-leaved tree species could be detected by measurements with a three-band multispectral camera. Saitoh et al. (2012) found that the seasonal variation in whole canopy

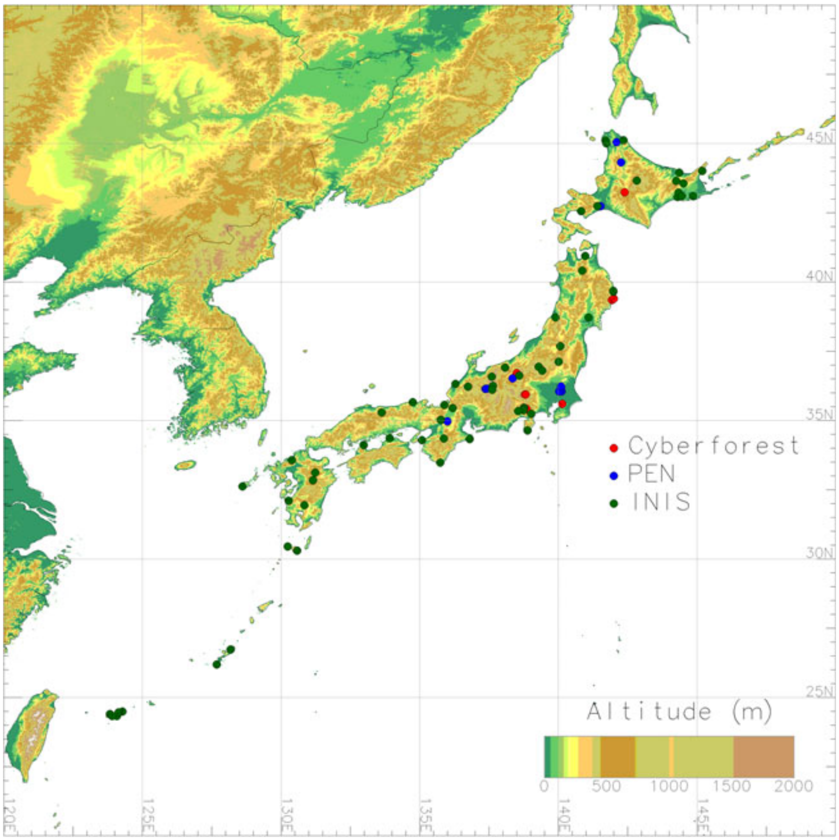

Fig. 2 Summary of the locations of the sites in each phenological observation network discussed in the text. The locations of the sites were determined by using Google Maps (http://maps.google.com/. Accessed 12 August 2015), information from each network's Web site (INIS, http://www.sizenken.biodic.go.jp. Accessed 12 August 2015; PEN, http://www.pheno-eye.org. Accessed 12 August 2015; Cyberforest, http://landscape.nenv.k.u-tokyo.ac.jp/cyberforest/Welcome.html. Accessed 12 August 2015), and the literature (Ueta et al. 2012). *INIS* Internet Nature Information System, *PEN* Phenological Eyes Network

Table 2 Summary of Japanese studies that analyzed RGB values obtained from phenological images

Ecosystem type	Phenological network	Scale of image target (m)	Camera direction	References
Deciduous broad-leaved forest	PEN, INIS	0.5 to 1000	Downward from towers; sideways from buildings; upward from the ground	Ide and Oguma (2010); Nagai et al. (2011a, 2013a, 2013b, 2014b); Inoue et al. (2014)
Deciduous coniferous forest	PEN	20 to 200	Downward from towers	Ide et al. (2011)
Evergreen broad-leaved forest	INIS	1000	Sideways from buildings	Ide and Oguma (2010)
Evergreen coniferous forest	PEN	20	Downward from tower; upward from the ground	Nagai et al. (2013a)
Mixed forests	PEN	20	Sideways from building	Mizunuma et al. (2011)
Grassland	PEN	20	Downward from tower	Akitsu et al. (2011)
Wetland	INIS	200	Sideways from buildings	Ide and Oguma (2010)

PEN Phenological Eyes Network (Nasahara and Nagai 2015), *INIS* Internet Nature Information System (http://www.sizenken.biodic.go.jp. Accessed 12 August 2015)

RGB-derived indices was well correlated with that of spectral reflectance and the associated vegetation indices in deciduous broad-leaved and evergreen coniferous (Japanese cedar) forests. This suggests that RGB-derived indices for each tree or species may be a proxy for spectral reflectance values and vegetation indices (Ide and Oguma 2011). Noda et al. (2015a) measured the spectral reflectance values of various deciduous and evergreen tree species at the scale of individual leaves. However, it would be prohibitively difficult to perform such observations for multiple tree species and individuals at multiple points because of the high cost of the instruments and the labor-intensive analysis. Further examinations of the relationship between RGB-derived indices and spectral characteristics for a range of tree species will be required to confirm that RGB-derived indices can be used as proxies for spectral reflectance and vegetation indices. In addition, examination of the relationships between seasonal variation of RGB-derived indices, leaf traits, and ecophysiological parameters for various tree species (Noda et al. 2015b) would provide useful direct evidence for analysis of GPP values (Ide and Oguma 2011).

Digital cameras can capture phenological observations at shoot, canopy, and landscape scales. However, the long distance between the camera and the target vegetation that is required to cover larger areas may prevent detailed phenological observations. Nagai et al. (2014b) found that the year-to-year variation in the timing of full blooming of *Prunus sargentii* could be detected at a canopy scale, but detailed continuous flowering phenology could not. Inoue et al. (2014) reported that the threshold RGB-derived index values for detection of the timing of leaf flush and leaf fall could not be defined uniquely by analyzing phenological images taken with a fisheye lens. The problem resulted from the different conditions of target individuals; the center of the images captured the canopy surface of a tree, whereas the perimeter captured the side of the canopy. These results suggest that it may be necessary to install multiple digital cameras at a study site to capture enough usable images at different spatial scales. In addition, the problem resulted from a requirement to identify particular RGB-derived index values (i.e., thresholds) for determining phenological transitions. Curve fitting approaches that can detect the inflection point for RGB-derived indices during a phenological change may help to solve this problem (Ide and Oguma 2013; Henneken et al. 2014; Klosterman et al. 2014). To continuously observe detailed flowering, fruiting, leaf flush, leaf coloring, and leaf fall phenology, it will be necessary to improve phenological observations at the shoot scale, as has been done by Cyberforest (Saito et al. 2004), and comparative analyses of phenological images acquired at different spatial scales will be required.

To conserve biodiversity, the Japanese government developed and revised the national biodiversity strategy in 2012 (MEJ 2012). This strategy has actively encouraged learning by students through hands-on experience with environmental studies. Such learning is now included in the course of study developed by Japan's Ministry of Education, Culture, Sports, Science and Technology (http://www.mext.go.jp). For instance, phenological observations of plants such as morning glory (*Ipomoea* spp.) are a valued part of science education at Japanese primary schools. To encourage learning through environmental studies, the online phenological data published on the Web site of Cyberforest may be helpful. Phenological observations by digital cameras are also helpful because they can replace or complement labor-intensive phenological observations using index trees conducted in university research forests and exhibition gardens (Fujimoto 2007; Sato 2014; the tree phenological observation network conducted by the Research Forests Council of Japanese universities, http://www.forest.kyushu-u.ac.jp/phenology/. Accessed 12 August 2015). Ide and Oguma (2013) demonstrated the usefulness of phenological observations by digital cameras in alpine ecosystems, where accessibility is difficult but remarkable environmental changes are occurring (Kudo 2014). These phenological observations by digital cameras may encourage students to pursue their interests through both university education and lifelong environmental learning. Strengthening cooperation with citizen scientists in a project such as the "Monitoring Sites 1000 Project," conducted by the Ministry of the Environment's Biodiversity Center of Japan (Kudo 2014; http://www.biodic.go.jp/moni1000/. Accessed 12 August 2015), may also develop environmental studies by encouraging activities related to phenological observation networks implemented using digital cameras.

Spectral radiometers

Spectral reflectance and vegetation indices measured by fixed-point spectral radiometers can detect the characteristics of plant phenology in secondary deciduous broad-leaved forest (Motohka et al. 2010; Nagai et al. 2010a), deciduous coniferous larch forest (Motohka et al. 2010), evergreen coniferous cypress (*Chamaecyparis obtusa*) forest (Nakaji et al. 2008) and Japanese cedar forest (Nagai et al. 2012), and grassland (Motohka et al. 2010). However, fewer ecosystems and study sites have been used for measurements with fixed-point spectral radiometers than for fixed-point digital cameras. Nasahara and Nagai (2015) used spectral radiometers to detect the mean tree phenology within 2 to 10 m of the device. To support ground truthing for satellite remote-sensing data is problematic because the footprint of the in situ spectral measurement is much smaller than that of the satellite data (typically ≥30 m and as great as 1000 m).

NDVI, EVI, and GRVI values in deciduous forests and grasslands increase rapidly during leaf flush and then become saturated before the vegetation achieves its maximum leaf area; they then decrease gradually during the leaf coloring and leaf fall periods (Nagai et al. 2010a; Motohka et al. 2010). Nagai et al. (2010a) examined the relationship between NDVI and EVI values observed by a spectral radiometer and the corresponding phenological images in a deciduous broad-leaved forest. NDVI values of 0.6 to 0.7 and EVI values of 0.4 to 0.5 potentially detected the onset of leaf flush, but neither index could detect the timing of leaf fall. This problem resulted from differences in the characteristics of the pattern and timing of leaf coloring and leaf fall among tree species (Nagai et al. 2014a). Nagai et al. (2014a) examined the relationship between seasonal variation of spectral reflectance and vegetation indices and spatial and temporal variations of leaf litter in a deciduous broad-leaved forest. GRVI, which observes only the seasonal color variation of the canopy surface, detected the timing of leaf fall more accurately than NDVI and EVI. Motohka et al. (2010) examined the relationship between seasonal variation of spectral reflectance and vegetation indices and daily phenological images in several deciduous forests and a grassland. The first date on which GRVI was greater than zero in the spring and the first date on which GRVI was less than zero in the autumn corresponded to the start and end of the growing season, respectively. This ground truthing information indicated a general ability to detect the start and end of the growing season in deciduous forests and a grassland by threshold-based analysis using GRVI (Motohka et al. 2010).

The seasonality of NDVI and EVI in evergreen coniferous forests was much smaller than that in deciduous forests (Nakaji et al. 2008; Nagai et al. 2012). In contrast, GRVI could detect the seasonal variation of leaf coloring at the canopy surface of a Japanese cedar forest in winter (winter reddening; Nagai et al. 2012). The seasonal variation of leaf color at the canopy surface in Japanese cedar forests was caused by changes in leaf pigments (Han et al. 2003). This seasonality correlated well with the seasonal variation in leaf photosynthetic capacity (Nagai et al. 2012). Detecting such changes is important because evergreen coniferous forests account for 30 % of Japan's total forested area (Japan FAO Association 1997).

Many previous studies indicated that seasonal variation of satellite EVI values was correlated with that of GPP in various ecosystems (Rahman et al. 2005; Huete et al. 2006). These reports suggest that GPP could be directly evaluated by satellite EVI. To test this possibility, Nagai et al. (2010b) and Muraoka et al. (2013) examined the relationships between EVI values observed with a spectral radiometer and GPP obtained from CO_2 flux tower measurements and between various vegetation indices (including EVI) observed with a spectral radiometer and photosynthetic capacity estimated by ecophysiological measurements and ecosystem modeling in the same deciduous broad-leaved forest. GPP increased exponentially with increasing EVI in spring; in contrast, GPP showed a linear decrease with decreasing EVI in autumn.

Previous studies used 8-, 10-, and 16-day composite satellite EVI data that comprised the best-quality data, with no effects of cloud contamination or atmospheric noise within these periods (Rahman et al. 2005; Huete et al. 2006). Estimated GPP values based on the composite satellite data were closer to the potential GPP values (i.e., the GPP under ideal conditions) observed under clear skies than to estimates of the actual GPP values under clear skies or rainy and cloudy conditions (Nagai et al. 2010b). During the leaf flush and leaf fall periods, high-quality Terra/MODIS NDVI data with no effects of cloud contamination or atmospheric noise were available in Japan for only 3 to 7 days per month (Nagai et al. 2011b). For this reason, GPP values estimated from satellite Japanese EVI data may overestimate the real values.

Phenological observations by satellite remote sensing

In this section, we will briefly summarize previous phenological research based on satellite remote sensing. Our previous research found fewer phenological studies in Japan than in

North America, Europe, and mainland Asia (Nagai et al. 2015b). This may be because the 8-km spatial resolution of the Global Inventory Modeling and Mapping Studies data (http://staff.glcf.umd.edu/sns/branch/htdocs.sns/data/gimms/. Accessed 12 August 2015) is too coarse to account for the heterogeneous Japanese plant phenology that results from the complex topography and vegetation cover. In contrast, the Terra and Aqua/MODIS GRVI, with 500-m spatial resolution, could detect the spatial variation in the timing of the start and end of the growing season along both vertical and horizontal gradients in Japan (Nagai et al. 2015b). Figure 3 shows the resulting spatial distribution of the timing of the start and end of the growing season in 2014.

To accurately evaluate the sensitivity of plant phenology to climate change, it is necessary to evaluate the year-to-year spatial variation of the timing of leaf flush and leaf fall over a wide area and a long time period. Although Nagai et al. (2015b) performed a decadal-scale analysis for Japan, they only showed the mean spatial and temporal timing of the start and end of the growing season during the study period for horizontal zones (2° latitude intervals) and vertical zones (200-m intervals). Previous research suggests that in a temperate climate, the sensitivity of plant phenology to climate change is clearer in southern parts of the region than in northern parts (Shen et al. 2014; Wang et al. 2015). In Japan, many river basins are divided by mountain ranges, creating small climatic zones close to each other but with different geographical characteristics. These divisions often occur at the boundaries between local authorities that are responsible for tracking phenological data. As a result, obtaining a detailed evaluation of the sensitivity of plant phenology to climate change would require the participation of Japan's 47 prefectural and city governments.

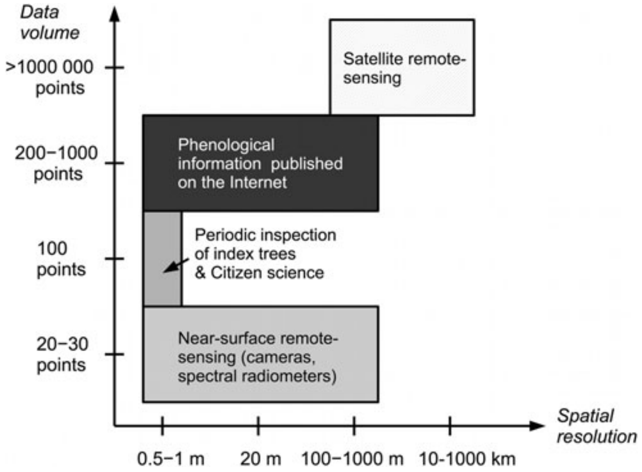

Fig. 4 Summary of the relationship between the amount and spatial resolution of the available datasets for phenological observations. Data obtained by citizen scientists tends to be openly published on the Internet

Hadano et al. (2013) calibrated a phenological model for prediction of the timing of leaf flush by using both spatial variation of this timing detected from MODIS GRVI data with a 500-m spatial resolution and meteorological data at weather stations throughout Japan. They predicted the spatial and temporal variation of the timing of leaf flush under future climate change. Previous phenological models were based on in situ

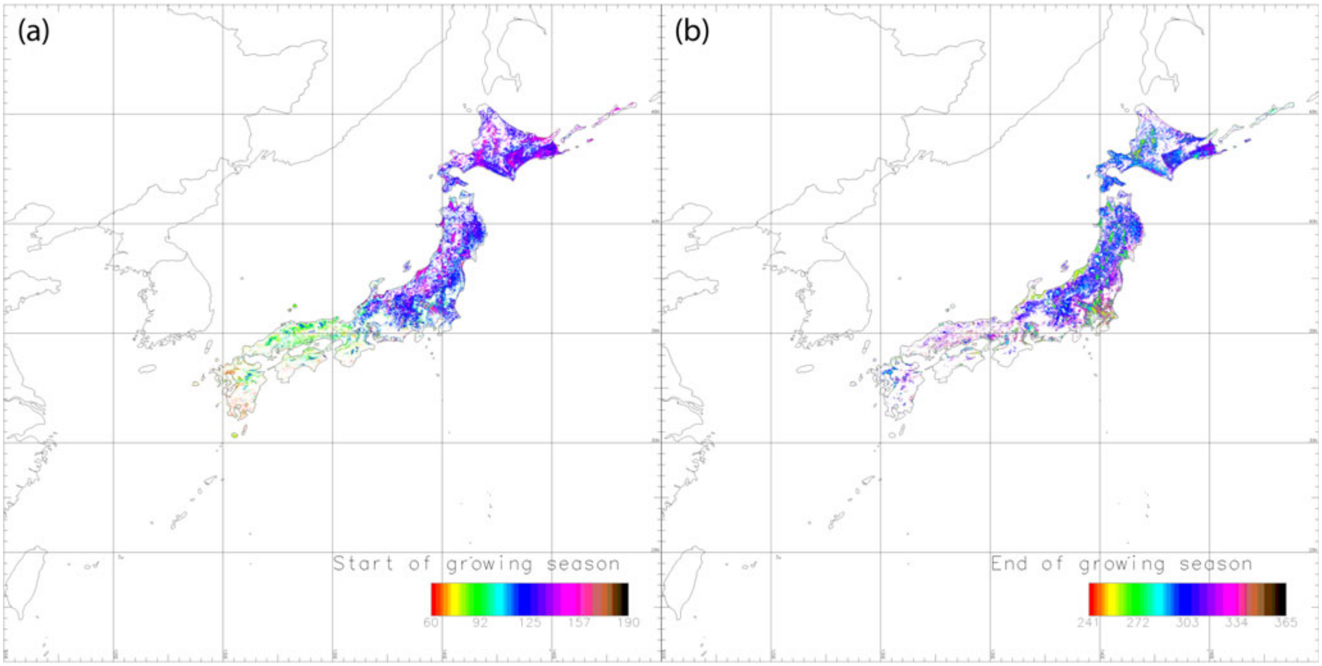

Fig. 3 Spatial distribution of **a** the start and **b** the end of the growing season (day of year) in 2014, detected by analyzing the daily Terra and Aqua MODIS GRVI observations with 500-m spatial resolution. *White* shows evergreen forests or points where we could not evaluate the timing of start or end of the growing season. For details of the method, see Nagai et al. (2015b)

Table 3 Summary of the advantages and limitations of different types of phenological observations

Method	Observation period	Observation points	Spatial resolution	Spatial representativeness of the data	Labor	Cost
Periodic visual inspection of index trees by experts	1953 to the present[a]	Multiple weather stations	1 to 100 cm	Low	High	High personnel cost
Fixed-point observations by time-lapse digital photography	2003 to the present[b]	Multiple sites and different ecosystems	0.5 to 200 m	Low	Low	High capital investment (e.g., tower, power supply)
Analysis of near-surface remotely sensed spectral reflectance and vegetation indices	2003 to the present[b]	Multiple sites and different ecosystems	10 m	Low	Low	High observation instrument cost and capital investment (e.g., spectral radiometer, tower, power supply)
Analysis of satellite remotely sensed spectral reflectance and vegetation indices	2000 to the present[c]	Global scale	500 m	High	Low	Free for end users
Phenological information published on the Internet	Around 2010 to the present	Multiple points	0.5 to 1000 m	Low to high	Low	Free for end users

This table is a revised version of Table 1 in Nagai et al. (2015a)

[a] By the Japan Meteorological Agency (JMA)

[b] By the Phenological Eyes Network (Nasahara and Nagai 2015)

[c] By the MODIS spectral radiometer sensor aboard the Terra satellite

phenological datasets at multiple points (Xu and Chen 2013), and Hadano et al. (2013) suggested that it may be possible to accurately detect the sensitivity of plant phenology to climate change by integrating an analysis of satellite data with such a phenological model. In a temperate zone, the timing of flowering and leaf flush was estimated based on the number of chilling hours in winter and on the number of warming hours before bud burst in spring (Kim et al. 2012; Luedeling et al. 2013). Examining the relationship between the spatial variation of the timing of flowering and leaf flush predicted by phenological models and the timing of leaf flush detected by satellite observations may improve our understanding of the sensitivity of plant phenology to climate change at regional to continental scales.

Nagai et al. (2015a) examined the relationship between the spatial variation of Landsat-8 GRVI values with a 30-m spatial resolution and leaf coloring information published on Web sites on 1 day during the leaf coloring period in 2014. Ground truthing information for plant phenology obtained from weather stations, research forests, agricultural experiment stations, and phenological observation sites with digital cameras is not sufficient because of the scale mismatch between the satellite and in situ data. Further examination of the relationship between satellite-detected plant phenology and phenological information published on the Internet is required to account for the footprint of the satellite data.

Sekizawa et al. (2015) detected the evacuation-induced land cover changes following the Fukushima Daiichi nuclear power plant disaster in 2011 by analyzing seasonal patterns of vegetation indices derived from MODIS data with a 250-m spatial resolution. Plant phenology may change significantly in response to changes in land cover or land use, ecological succession, and invasion by nonnative species. In Japan, progressive abandonment of cultivation and succession to bamboo forests has occurred in mid- to low-elevation mountains and suburban regions (MEJ 2012). Further studies will be required to accurately evaluate the relationship between the spatial and temporal variability of satellite-observed vegetation indices and those of vegetation cover at scales ranging from individual sites to whole landscapes.

Conclusions and future developments

In the many previous studies described in this review, phenological observations were obtained using index trees for a few tree species, near-surface remote-sensing observations for a few ecosystems or tree species, and satellite remote sensing at a regional scale. The differences in these approaches resulted from the different goals of the studies and differences in the available data. Suzuki (2015) noted that many previous studies of remote-sensing data were mainly from a technical perspective and that the ecological meaning of the signals was not sufficiently considered. In addition, many previous studies only used the limited datasets observed by scientists and other experts rather than the larger amount of data provided by citizen scientists. This may have prevented researchers from obtaining phenological data at a synoptic scale that covered multiple species over wide areas.

To solve these problems, researchers should attempt a multidisciplinary analysis that links index trees, near-surface remote sensing, satellite remote sensing, citizen science, and open-access information published on the Internet. Figure 4 illustrates the relationship between the amounts and spatial resolutions of the available phenological datasets. Japanese citizens are very interested in plant phenology, and their interest provides data at a small personal scale that can be linked with the abundant data at wider regional and national scales. Establishing this link will require the development of databases of phenological observations that will reveal ecosystem changes from the leaf scale to national scales (Muraoka and Koizumi 2009). Each source of data has advantages and problems (Table 3), but because these differ among the data sources, the advantages of one dataset may compensate for another dataset's limitations.

Two studies from outside Japan provide examples of successful multidisciplinary studies that linked remote-sensing observations with index tree observations or citizen science. Delbart et al. (2015) examined the relationship between the start of the growing season in Canada, detected by SPOT/VEGETATION vegetation index data, and the timing of flowering and leaf flush reported by citizen scientists. The phenological information observed by the citizen scientists provided useful ground truthing for the satellite data. Kim et al. (2012) examined the relationships among the timing of cherry blooming at multiple locations in Korea, the start of the growing period detected from a MODIS vegetation index, and a model for prediction of the timing of leaf flush. Phenological information from index tree observations provided useful data for a multidisciplinary phenological study in both cases.

Phenological studies tend to be local because of the specific and diverse goals of the researchers. Unfortunately, this also means that there have been no direct comparisons between Japanese plant phenology and that in other countries. On the other hand, many Japanese studies were conducted both before and after World War II. However, those studies were published in Japanese. As a result, insufficient Japanese phenological information has been made available to the international research community (Ogawa-Onishi and Berry 2013). Recently, huge amounts of phenological information have become available on the Internet in Japanese, which means that it remains unavailable to researchers who cannot read Japanese. By way of example, Table 1 summarizes the first flowering date of cherry near 58 weather stations in Japan published by the Japan Meteorological Agency. To solve these issues, we propose the following challenging but important tasks: (1) We should conduct more multidisciplinary phenological studies in Japan through collaboration among researchers with different goals and between researchers and citizen scientists, with the aim of improving our understanding of phenology and permitting comparisons among observation networks. (2) We should evaluate both the unique characteristics of Japanese phenology and the characteristics shared with vegetation in other regions through international collaborations and through comparisons with results from foreign observation networks. (3) We should publicize Japanese language phenological data in the international research literature so that the data will be more accessible to the international research community. Of course, to accomplish this it will be necessary to obtain the necessary legal permissions to share this data, and it will also be necessary to find volunteers willing to translate the information into English and other languages. By implementing these recommendations, Japanese phenological studies will become increasingly powerful.

Acknowledgments We thank the editor and two anonymous reviewers for their kind and constructive comments. This study was supported by the Environment Research and Technology Development Fund (S-9) of the Ministry of the Environment of Japan.

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