Field experiments to test the use of the normalized-difference vegetation index for phenology detection

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Field experiments to test the use of the normalized difference vegetation index for phenology detection

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Abstract

Some previous studies have detected the timing of leaf expansion and defoliation using the normalized-difference vegetation index (NDVI), but to examine tree phenology using satellite data, NDVI results should be confirmed using ground-truthing. We examined the relationship between NDVI and tree phenology during leaf expansion and defoliation by simultaneously observing the spectral reflectance of the canopy surface and canopy surface images in a cool-temperate deciduous broadleaved forest. To define the timing of leaf expansion and defoliation using NDVI, the index should meet three criteria: (1) NDVI should exhibit a monotonous increase or decrease (monotonicity). (2) The relationship between NDVI and the forest canopy's status should be unique (uniqueness). (3) The method is robust against the systematic noise (bias) (robustness). In the spring, NDVI values of 0.2 to 0.3 (relative values: 0.15 to 0.28) and 0.6 to 0.7 (relative values: 0.65 to 0.78) satisfied all three criteria. NDVI values of 0.6 to 0.7 can serve as potential criteria for detecting the timing of leaf expansion. In autumn, no NDVI values satisfied all three criteria. Thus, NDVI does not appear to be useful for detecting the timing of defoliation. For an area where evergreen vegetation or snow covers the forest floor in winter, our results suggest that previous uses of NDVI to identify the timing of leaf expansion and defoliation on the basis of the date of the maximum rate of growth or reduction of NDVI and the date with a value midway between the year's maximum and minimum values are misleading.

Keywords: NDVI, criterion, leaf expansion, defoliation, deciduous broadleaved forest

1. Introduction

Some previous studies have used satellite-observed normalized-difference vegetation index (NDVI) values to detect extension of the growing season in terrestrial ecosystems as a result of global warming (Myneni et al., 1997; Tucker et al., 2001; Zhou et al., 2001; Shabanov et al., 2002; Stöckli and Vidale, 2004; Chen et al., 2005; Piao et al., 2006). In those studies, researchers generally detected the start and end of the growing season on the basis of the timings of leaf expansion and defoliation, using two criteria:

Criterion 1: They defined the day with the maximum rate of NDVI growth as the onset of leaf expansion, and the day with the maximum rate of NDVI reduction as the offset of defoliation (Tateishi and Ebata, 2004; Piao et al., 2006; Studer et al., 2007).

Criterion 2: They defined the date when a specific NDVI value (the reference NDVI value) was obtained as the onset of leaf expansion, and the day when the reference NDVI value was obtained as the offset of defoliation (White et al., 1997; Duchemin et al. 1999; Zhou et al., 2001; Schwartz et al., 2002; White et al., 2002; Suzuki et al., 2003; Chen et al., 2005; Delbart et al., 2005; Fisher and Mustard, 2007; Karlsen et al., 2008; Prasad et al., 2007).

In those studies, researchers examined these criteria by investigating the relationship between satellite-observed NDVI values and phenophase data for typical trees in the field (White et al., 1997; Schwartz et al., 2002; Chen et al., 2005; Delbart et al., 2005; Fisher and Mustard, 2007; Studer et al., 2007; Karlsen et al., 2008; Soudani et al., 2008).

Typical studies have used satellite data with a spatial resolution of 250 m (Karlsen et al., 2008; Soudani et al., 2008), 500 m (Fisher and Mustard, 2007), 1000 m (White et al., 1997; Schwartz et al., 2002), 8000 m (Chen et al., 2005; Delbart et al., 2006), and about 12000 m (Studer et al., 2007). However, it appears possible that tree phenology detected using resolutions within this range does not coincide with that of typical trees because, for instance, about 40 tree species may be present in a typical cool-temperate deciduous broadleaved forest in Japan (Ohtsuka et al., 2005), and each species may have a different phenology. Moreover, these previous studies have used composite NDVI data collected over periods of 8 days (Fisher and Mustard, 2007), 10 days (Chen et al., 2005; Delbart et al., 2006; Studer et al., 2007), and biweekly (Schwartz et al., 2002; Karlsen et al., 2008) to remove noise resulting from contamination of the data by clouds or atmospheric effects. These studies also used phenophase data obtained in the field at intervals of 3 to 7 days (White et al., 1997; Fisher and Mustard, 2007; Karlsen et al., 2008; Soudani et al., 2008). Unfortunately, it appears likely that data with this temporal resolution cannot detect rapid growth or reduction of leaf area during the periods of leaf expansion or defoliation (Muraoka and Koizumi, 2005; Nasahara et al., 2008). Therefore, to examine the relationship between NDVI and tree phenology, it is important to obtain NDVI values and information on the status of the forest canopy for the same stand more frequently (e.g., daily).

For NDVI to be useful in detecting the timing of leaf expansion and defoliation, it should satisfy the following three criteria: (1) NDVI should be measured during a period of monotonous increase or decrease. If NDVI values are obtained during a period with considerable fluctuation, the timing of leaf expansion and defoliation may be detected many times within a short period. We describe this criterion as “monotonicity”. (2) The relationship between NDVI and the status of the forest canopy should be unique; that is, the same relationship should not be obtained for periods with different phenology.

If this criterion is not met, we cannot discuss differences in the timing of leaf expansion and defoliation between years. We describe this criterion as “uniqueness”. (3) The method is robust against the systematic noise (bias). If we increase or decrease the criterion of NDVI value in some degree, differences in the timing of leaf expansion and defoliation between years should not be changed. We describe this criterion as “robustness”.

We examined the use of NDVI data to detect the dates of leaf expansion and defoliation by performing a field study in a cool-temperate deciduous broadleaved forest in Japan. To obtain daily NDVI values and tree phenology data for the same stand, we installed a spectroradiometer and a digital camera above the canopy surface and simultaneously obtained spectral reflectance data for the canopy surface and canopy surface images. Using these data, we investigated the monotonicity, uniqueness, and robustness of the relationship between NDVI and phenology in the spring and autumn.

Our goal was to test the fundamental concept of the phenology detection algorithm. For this purpose, we decided to rely on long-term, noise-free, continuous time-series data observed in a ground experiment and clearly indicative of the NDVI–phenology relationship. Therefore, the results may not be directly relevant to satellite-based phenology studies, because time-series satellite data usually contain noise and deficits due to the presence of, for example, clouds, atmospheric particles, and directional reflectance. This potential gap between the applicabilities of the ground experiment and satellite study data needs to be mitigated by correction and interpolation of the satellite data—actions that are beyond the scope of this study.

2. Material and Methods

2.1 Study site and period

Our study site, which is part of the AsiaFlux network (http://asiaflux.net/), is located in a cool-temperate deciduous broadleaved forest at Takayama in Japan (36°08'N, 137°25'E, 1420 m a.s.l.). CO_2 and sensible heat fluxes and meteorological parameters have been observed continuously at this site from a 25-m tall tower (Yamamoto et al., 1999, Saigusa et al., 2002), and soil respiration has been observed continuously above the ground under the tower (Mo et al., 2005). Tree physiology data (leaf photosynthesis and respiration; Muraoka and Koizumi, 2005) and leaf area (Nasahara et al., 2008) have also been observed periodically from an 18-m-tall tower (the “eco-tower”) located 100 m from the 25-m tower. From 1980 to 2002, the annual mean air temperature and annual rainfall at the nearby site (about 500 m south of the eco-tower) averaged 7.2°C and 2275 mm, respectively. The snow season begins in December and ends in April, with a maximum snow depth of 100 to 180 cm (Mo et al., 2005). Dominant canopy species are *Quercus crispula* and *Betula ermanii*. The forest floor is covered by an evergreen dwarf bamboo, *Sasa senanensis* (Ohtsuka et al., 2005). The height of the tree canopy ranges from 13 to 20 m (Nasahara et al., 2008).

The present study was conducted from 1 October 2003 to 31 December 2007.

2.2 Data

To monitor tree phenology, we installed an automatic digital fisheye camera system composed of a Coolpix 4500 digital camera (Nikon, Japan), FC-E8 fisheye lens (Nikon), and SPC31A controller (Hayasaka Rikoh, Japan), as described by Tsuchida et al.

(2005) and Nishida (2007). The system contains a camera pointed downwards at the top of the eco-tower to capture images of the forest canopy. During the daytime, the camera system captured hemispherical images of the forest canopy every 90 min. To measure the NDVI of the canopy, we installed a hemispherical spectroradiometer system based on an MS-700 spectroradiometer (Eko Instruments Co. Ltd., Japan) with a spectral range of 300 to 1100 nm, a spectral interval of 3.3 nm, and a half-bandwidth of 10 nm, which was mounted on a CHS-AR reversible stage (Hayasaka Rikoh). The spectroradiometer system was installed at the top of the eco-tower (Nishida, 2007), which is beside the camera system. Under automatic control by a personal computer, the reversible stage changes the direction (upwards and downwards) of the spectroradiometer every 10 min. During the daytime, the spectroradiometer system obtained five measurements in succession every 10 min: the spectral radiance of the sky (upwards) twice, the spectral radiance of the canopy surface (downwards) once, and the spectral radiance of the sky (upwards) twice. Thus, we calculated the spectral reflectance of the canopy surface every 10 min using the spectral radiance of the sky and the canopy surface. However, from 1 October 2003 to 10 April 2004, we installed two spectroradiometers, with one pointing upwards and the other pointing downwards. During the daytime, we used the two spectroradiometers to simultaneously measure the spectral radiance of the sky (upwards) and the canopy surface (downwards) every 30 min.

Using the diurnal average (from 10:00 to 14:00) of the reflectance in the red (red_{ave}) and near-infrared (NIR_{ave}) bands, we calculated NDVI at a daily time step using the following equation:

$$\mathrm{NDVI} = (NIR_{\mathrm{ave}} - red_{\mathrm{ave}}) / (NIR_{\mathrm{ave}} + red_{\mathrm{ave}}) \qquad (1).$$

We used data from 620 to 670 nm and from 841 to 876 nm as the reflectance in the red_{ave} and NIR_{ave} bands, respectively. If our data were obtained on rainy, snowy, or foggy days, we removed the NDVI values from them by examining the canopy surface images, because we could not precisely measure the spectral reflectance of the canopy surface on such days. We also removed data from days from October 2003 to April 2004 on which some of the band reflectance values were greater than 0.5, because these were spike noises that appeared much bigger than the neighbouring values. This may have been due to the presence of snowpack on the spectroradiometer. We then interpolated the missing data linearly. Moreover, we reduced the impact of short-term random noise by using a moving average (n = 3 data points). However, we did not interpolate missing data for a period longer than 10 days in a row.

The combined camera and spectroradiometer observations were among the activities conducted under the phenological eyes network (PEN; Tsuchida et al., 2005; Nishida, 2007). The data obtained by PEN, including the data from our present study, are publicly available on the Internet (http://www.pheno-eye.org).

2.3 Evaluation of the three criteria

To investigate the monotonicity criterion for the NDVI–phenology relationship, we examined the seasonal patterns in NDVI in each year of the study. To investigate the uniqueness criterion, we compared canopy surface images taken at the beginning of day, when we obtained the reference values in each spring. For this image, we captured both the canopy surface and the forest-floor vegetation or snow cover. We selected NDVI values of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 as our spring reference values. In the same way, we compared canopy surface images taken on the last day when we obtained reference NDVI values in each autumn. We selected NDVI values of 0.7, 0.6, 0.5, 0.4, 0.3, and 0.2 as the autumn reference values. Finally, to investigate the robustness criterion, we examined the deviation between the date when a given NDVI reference value was obtained and the mean date when that value was obtained in each spring and autumn. To do so, we calculated the average number of days from 2003 to 2007 (Julian dates) before each reference value was attained. We then subtracted this average date from the actual date when the reference value was attained in each year to obtain the date anomaly for that year. Days when a reference value was attained earlier than the average date thus became a negative anomaly, whereas days when the reference value was attained later than the average date became a positive anomaly. The absolute NDVI value may be unique for the study site because it may be affected by the observation conditions, including the specifications of the sensor and its location. Therefore, we also calculated a relative NDVI value that would facilitate comparisons between our results and those of previous studies by expressing calculated values relative to a baseline value, thereby normalizing the resulting values. We calculated the relative NDVI value by using the following equation:

$$\text{relative NDVI value} = (\text{NDVI} - \text{NDVI}_{\text{min}}) / (\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}) \qquad (2)$$

where NDVI_{max} represents the mean of the annual maximum NDVI values over the study period. Similarly, NDVI_{min} represents the mean of the annual minimum NDVI values.

3. Results

3.1 Seasonal patterns in NDVI

We divided the seasonal patterns in NDVI for each year into seven phases based on the pattern of change in NDVI (Fig. 1):

Phase 1: NDVI showed nearly constant values near the year’s minimum value (0.08) until day of year (DOY) 90 to 110. This minimum showed little difference between years (standard deviation: 0.02). Images of the canopy surface during this period showed that the forest canopy had no leaves yet, and that the forest floor was fully covered by snow.

Phase 2: Next, NDVI increased rapidly and monotonically for about 2 weeks. The timing of the increase was earliest in 2007 and latest in 2006. The difference in the start dates was about 20 days. The images of the canopy surface during this period showed that the canopy had no leaves yet and that the forest floor remained partly covered by snow (i.e., the snowmelt period).

Phase 3: NDVI again increased gradually and monotonically until about DOY 140 (about DOY 130 in 2004). Images of the canopy surface during this period showed that the forest canopy had no leaves yet and that the forest floor, which had no snow, was covered by *Sasa senanensis*.

Phase 4: NDVI again increased rapidly and monotonically for about 2 weeks. The timing of the increase in 2004 was about 1 week earlier than that in other years. Images of the canopy surface during this period showed that leaves in the forest canopy were expanding (i.e., the leaf expansion period).

Phase 5: NDVI showed nearly constant values that ranged between 0.75 and the year’s maximum (0.88) until about DOY 270. The year’s maximum differed little between years (standard deviation: 0.01). Images of the canopy surface during this period showed that all canopy leaves were green.

Phase 6: NDVI then gradually decreased to about 0.5, with small fluctuations, by about DOY 300 to 310. NDVI reached this value about 10 days later in 2005 than in the other years. Images of the canopy surface showed that leaves were falling during this period (i.e., the defoliation period).

Phase 7: In the final phase, NDVI decreased again to the year’s minimum value, but with wide fluctuations that differed among the years. Images of the canopy surface during this period showed that the forest canopy had no leaves and that the forest floor was covered by either *Sasa senanensis* or snow.

[Insert Figure 1 here]

3.2 Relationship between spring phenology and NDVI

Figure 2 shows the canopy surface images taken at the beginning of day, when we observed NDVI reference values of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 (corresponding relative values: 0.15, 0.28, 0.40, 0.53, 0.65, 0.78, and 0.90) in each spring and the corresponding date anomaly. The status of the forest canopy or forest floor, which corresponded to the reference value, was the same in each year for a given reference value:

NDVI = 0.2 (relative value = 0.15; phase 2): About 80% of the forest floor was covered by snow.

NDVI = 0. 3 (relative value = 0.28; phase 2): About 30% of the forest floor was covered by snow.

NDVI = 0.4 (relative value = 0.40; phase 2): About 90% of the forest floor was covered by exposed *Sasa senanensis*.

NDVI = 0.5 (relative value = 0.53; phase 3): Some tree species had started leaf expansion.

NDVI = 0.6 (relative value = 0.65; phase 4): All tree species had started leaf expansion.

NDVI = 0.7 (relative value = 0.78; phase 4): About 50% of the canopy leaves had expanded.

NDVI = 0.8 (relative value = 0.90; phase 5): All of the canopy leaves had expanded.

These results revealed two groups based on the values of the date anomaly: NDVI values of 0.2, 0.3, and 0.4 (relative values of 0.15, 0.28, and 0.40), which correspond to phase 2, and NDVI values of 0.6 and 0.7 (relative values of 0.65 and 0.78), which correspond to phase 4. Both groups showed a common trend in the date anomaly in each year. However, we found different trends in the date anomaly between the two groups. For instance, in 2006, phase 2 showed a positive anomaly of about 10 days, whereas phase 4 showed a positive anomaly of about 2 days. In contrast, phase 2 in 2007 (NDVI = 0.2) showed a negative anomaly of about 10 days. Phase 4 showed little difference in the date anomaly between years.

[Insert Figure 2 here]

3.3 Relationship between autumn phenology and NDVI

Figure 3 shows the canopy surface images taken on the last day when we observed NDVI reference values of 0.7, 0.6, 0.5, 0.4, 0.3, and 0.2 (with corresponding relative values of 0.78, 0.65, 0.53, 0.40, 0.28, and 0.15) in each autumn, and the corresponding date anomaly. The status of the forest canopy or forest floor that corresponded to the reference value differed among the years, as follows:

NDVI = 0.7 (relative value = 0.78; phase 6): All canopy leaves were green (2004) or had turned red (all other years).

NDVI = 0.6 (relative value = 0.65; phase 6): From about 30% (2004 and 2007) to 50% (2005 and 2006) of the canopy leaves had fallen.

NDVI = 0.5 (relative value = 0.53; phase 6): From about 70% (2007) to 90% (2005) of the canopy leaves had fallen.

NDVI = 0.4 (relative value = 0.40; phase 7): About 90% of the canopy leaves had fallen (2007). In all other years, the forest canopy had no leaves and the forest floor was covered by *Sasa senanensis*.

NDVI = 0.3 and 0.2 (relative values = 0.28 and 0.15; phase 7): The forest canopy had no leaves and the forest floor was covered by snow (2003, 2005, and 2006) or by *Sasa senanensis* (2004 and 2007).

Only NDVI values of 0.3 and 0.2 (relative values of 0.28 and 0.15, respectively; phase 7) showed a common trend in the date anomaly in each year.

[Insert Figure 3 here]

4. Discussion

4.1 Using NDVI to detect spring leaf expansion

Our simultaneous observations of NDVI and canopy surface conditions revealed the following results in the spring:

NDVI values of 0.2 to 0.3 (relative values of 0.15 to 0.28; phase 2) satisfied the criteria of monotonicity, uniqueness, and robustness (Fig. 1, 2). This may result from the fact that these values represented a period of rapid exposure of the ground surface at the end of the snowmelt in each year, when the increase in NDVI was rapid.

NDVI values of 0.4 to 0.5 (relative values of 0.40–0.53; phases 2 and 3) did not satisfy the robustness criterion (Fig. 2). This may result from the fact that these values represented a period of gradual change in tree phenology before overall leaf expansion of the forest canopy in each year, so that the increase in NDVI was gradual.

NDVI values of 0.6 to 0.7 (relative values of 0.65 to 0.78; phase 4) satisfied the criteria of monotonicity, uniqueness, and robustness (Fig. 1, 2). This may result from the fact that these values represented a period of rapid growth in overall leaf area of the forest canopy in each year, so that the increase in NDVI was rapid. When we compare these values with the ground-measured canopy LAI in 2006 (Nasahara et al., 2008), the NDVI values are equivalent to LAI values of about 1.3 to 2.3, indicating that about one-third of leaf expansion is complete.

An NDVI value of 0.8 (relative value of 0.90; phase 5) did not satisfy the monotonicity and robustness criteria (Fig. 1, 2). This may result from the fact that this value represented the end of the period of overall leaf expansion in the forest canopy in each year, when the change in NDVI was small because NDVI had already become saturated (i.e., reached the annual maximum).

These results indicate that spring NDVI values of 0.6 to 0.7 (relative values of 0.65 to 0.78) can potentially be used to detect tree phenology. This range corresponds to the period of rapid leaf expansion. However, because the elapsed time between budburst and the completion of leaf elongation varies among years, it is important that we evaluate leaf expansion as more than just a discrete “event”, and instead evaluate the trajectory of leaf expansion (i.e., the green-up trajectory).

The root-mean-square error of the difference between the observed data and the 3-day moving average values for all data was quite low (0.02). This result indicates that it is possible to remove most of the random noise by using a 3-day moving average.

4.2 Using NDVI to detect autumn defoliation

In autumn, no NDVI values satisfied all three (monotonicity, uniqueness, and robustness) criteria (Fig. 1, 3). This may result from the fact that the timing of defoliation varies widely, possibly because of species differences and heterogeneity from leaf-scale to branch-scale in leaf biochemical properties (pigments) and leaf numbers (Nasahara et al., 2008); this variation leads to a gradual decrease in NDVI and undetectable fluctuations.

This result suggests that the autumn NDVI values do not provide a suitable indicator for the timing of leaf defoliation. Instead, we are currently attempting to identify the timing of autumn defoliation from an ecophysiological viewpoint by using ground-observed data such as leaf area, chlorophyll content, and leaf spectral reflectance.

4.3 Validation of previous studies

4.3.1 Validation of criterion 1 (using the maximum rate of NDVI growth or that of NDVI reduction)

Previously published values for studies that used criterion 1 (Yu et al., 2003; Tateishi and Ebata, 2004; Piao et al., 2006; Studer et al., 2007) suggest that the criteria for the timing of leaf expansion in 2004, 2005, 2006, and 2007 in the present study should be

NDVI = 0.43 (relative value of 0.44; phase 2), NDVI = 0.70 (relative value of 0.78; phase 4), NDVI = 0.71 (relative value of 0.79; phase 4), and NDVI = 0.44 (relative value of 0.45; phase 2), respectively. Similarly, the criteria for the timing of defoliation in 2004, 2005, 2006, and 2007 should be NDVI = 0.29 (relative value of 0.26; phase 7), NDVI = 0.19 (relative value of 0.14; phase 7), NDVI = 0.29 (relative value of 0.26; phase 7), and NDVI = 0.30 (relative value of 0.28; phase 7), respectively. In the spring, we detected differences in the status of the forest canopy that corresponded to these NDVI values in each year. In 2004 and 2007, the forest canopy had no leaves and the forest floor was covered by *Sasa senanensis*. In 2005 and 2006, the forest canopy showed expanding leaves (Fig. 4). In contrast, in autumn, despite the fact that the forest canopy had no leaves in all years, the status of the forest floor differed among the years. For example, the forest floor was covered by *Sasa senanensis* in 2004 and 2007 and by snow in 2005 and 2006 (Fig. 4).

These results show that evaluating tree phenology at the present study site on the basis of only criterion 1 is misleading. In particular, the fact that there are two periods when NDVI increases rapidly (during the snowmelt and leaf-expansion periods; Fig. 1) can lead to a significant misunderstanding of the meaning of the NDVI changes. If there is a correlation between the timing of snowmelt and that of leaf expansion, we can use the timing of snowmelt as a substitute for that of leaf expansion to evaluate the date anomaly. However, there was no correlation between the timing of snowmelt and that of leaf expansion (Fig. 2). If the day with the maximum rate of NDVI growth always occurs during the snowmelt period, we can at least evaluate the date anomaly in the timing of snowmelt. However, the day with the maximum rate of NDVI growth occurred in the snowmelt period in some years and in the leaf expansion period in other years (Fig. 4). Moreover, the time lags between snowmelt and leaf expansion were about 2 to 4 weeks, depending on the year (Fig. 1).

These findings suggest that the evaluation of tree phenology on the basis of the rate of NDVI growth can provide misleading results in areas where snow covers the ground during the winter and parts of the autumn and spring. The rates of NDVI growth and decrease may be greatly changed by the correction methods used (e.g., noise removal) or by temporal resolution of the data.

In consequence, our findings indicate that the timing of leaf expansion and defoliation solely on the basis of criterion 1 and the use of satellite-observed NDVI values is not reliable and may lead to significant misunderstandings in deciduous broad-leaved forests where there are periods in which snow covers the ground.

[Insert Figure 4 here]

4.3.2 Validation of criterion 2 (using the reference NDVI value)

The previously published values for studies that used criterion 2 (White et al., 1997, 2002; Schwartz et al., 2002; White and Nemani, 2006; Fisher and Mustard, 2007) suggest that, in the present study, NDVI = 0.48 (the midpoint value between the year's maximum and minimum NDVI values) corresponds to the criterion for the timing of leaf expansion and defoliation. However, this value corresponded to periods in the present study when the forest canopy had no leaves and the forest floor was covered by *Sasa senanensis* in the spring, and periods when 70% (2007) to 95% (2005) of the canopy leaves had fallen in the autumn (Fig. 5). Moreover, this value did not satisfy the robustness criterion.

These results suggest that detection of the timing of leaf expansion and defoliation solely on the basis of criterion 2 is also misleading in areas where evergreen vegetation covers the forest floor. In particular, the midpoint value in spring is more misleading than that in autumn because there is a high possibility that the spectral data reflect the forest floor phenology rather than the timing of leaf expansion in the forest canopy. If the forest floor is covered by deciduous vegetation, the status of the forest floor leaf expansion may provide a more accurate reflection of the timing of leaf expansion in the forest canopy. However, in areas where the forest floor is covered by snow in winter, we cannot evaluate whether the forest floor is covered by deciduous vegetation on the basis of the seasonal pattern in NDVI. To solve this problem, it is important to define a relative NDVI value (for instance, values such as about 0.65 to 0.78 in the present study, which are higher than the midpoint value) as the reference NDVI value for detecting the timing of leaf expansion.

However, the failure of a method in one area does not guarantee that the method will fail elsewhere (White et al., 2009). We also cannot guarantee that the reference NDVI value will apply to all deciduous broad-leaved forests. Therefore, to detect the timing of leaf expansion and defoliation over wide areas using satellite-observed NDVI, the approach should be calibrated for a range of ecosystems and sites.

[Insert Figure 5 here]

4.4 Another vegetation index

We performed an analysis similar to that of NDVI for another vegetation index, namely, the enhanced vegetation index (EVI) (Huete et al., 2002), because this index has recently become as popular as NDVI (Zhang et al., 2003; Sakamoto et al., 2005).

Among EVI values of 0.2, 0.3, 0.4, 0.5, and 0.6, only 0.4 and 0.5 in spring (relative values of 0.55 and 0.73) satisfied all three criteria (monotonicity, uniqueness, and robustness). These values corresponded to the period of leaf expansion. In autumn, no EVI values satisfied all three criteria (Fig. 6).

In the case of criterion 1 (using the maximum rate of EVI growth or that of EVI reduction), we detected inconsistent status of the forest canopy among the years. This indicates that evaluating tree phenology on the basis of criterion 1 and EVI is misleading.

In the case of criterion 2 (using the midpoint value between the year's maximum and minimum NDVI values; EVI = 0.37), we consistently detected the period of leaf expansion in spring in each year. This value satisfied all three criteria. This may result from the fact that EVI was not sensitive to the snowmelt and forest floor phenology (Fig. 6). In contrast, we detected inconsistent status of the forest canopy in autumn among the years. This indicates that detection of the timing of leaf expansion on the basis of criterion 2 and EVI is reliable, but that of defoliation is misleading.

[Insert Figure 6 here]

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Figures and caption

Figure 1. Seasonal patterns in the ground-observed NDVI value: (a) day of year (DOY) from 1 to 365; (b) DOY from 91 to 160; (c) DOY from 271 to 330. Typical images of the canopy surface are presented at the top of the figure. The relative NDVI values are shown in parentheses on the vertical axis. We calculated the relative NDVI value by using the following equation:

relative NDVI = $(NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$, where $NDVI_{max}$ represents the mean of the annual maximum NDVI values over the study period. Similarly, $NDVI_{min}$ represents the mean of the annual minimum NDVI values.

Figure 2. Images of the canopy surface taken at the beginning of the period when we observed NDVI reference values of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 in each spring, and the corresponding date anomalies. The day of year for each canopy surface image is shown in parentheses. The corresponding relative NDVI values are shown at the bottom of the figure, in parentheses. We calculated the average number of Julian days from 2003 to 2007 for the date when each reference value was obtained. We then subtracted this average date from the observation date to calculate the date anomaly. When a reference value is reached earlier than the average date, this represents a negative anomaly; conversely, when a reference value is reached later than the average date, this represents a positive anomaly. We substituted the canopy surface images on 3 May 2006 and 17 April 2007 for the foggy images obtained on 2 May 2006 and 16 April 2007, respectively.

Figure 3. Images of the canopy surface taken on the last days when we observed NDVI reference values of 0.7, 0.6, 0.5, 0.4, 0.3, and 0.2 in each autumn, and their corresponding date anomalies. The day of year for each canopy surface image is shown in parentheses. The corresponding relative NDVI values are shown at the bottom of the figure, in parentheses. We calculated the average number of Julian days from 2003 to 2007 for the date when each reference value was obtained. We then subtracted this average date from the observation date to calculate the date anomaly. When a reference value is reached

earlier than the average date, this represents a negative anomaly; conversely, when a reference value is reached later than the average date, this represents a positive anomaly. We substituted the canopy surface images on 16 October 2005 and 11 November 2007 for the foggy images that we obtained on 15 October 2005 and 10 November 2007, respectively.

Figure 4. Images of the canopy surface taken on the days with the maximum rate of NDVI growth in the spring and the days with the maximum rate of NDVI reduction in the autumn in each year. The day of year for each image is shown in parentheses.

Figure 5. Images of the canopy surface taken on the days when we observed NDVI = 0.48, which was the midpoint value between the year's maximum and minimum NDVI values, in each spring and autumn. The day of year for each image is shown in parentheses.

Figure 6. Seasonal patterns in the ground-observed EVI value: (a) day of year (DOY) from 1 to 365; (b) DOY from 91 to 160; (c) DOY from 271 to 330. Typical images of the canopy surface are presented at the top of the figure. Using the diurnal average (from 10:00 to 14:00) of the reflectance in the red (red_{ave}), near-infrared (NIR_{ave}), and blue ($blue_{\mathrm{ave}}$) bands, we calculated EVI at a daily time step by using the following equation: $\mathrm{EVI} = G \times \{(NIR_{\mathrm{ave}} - red_{\mathrm{ave}}) / [NIR_{\mathrm{ave}} + (C_1 \times red_{\mathrm{ave}}) - (C_2 \times blue_{\mathrm{ave}}) + L]\}$, where $G = 2.5$,

$C_1 = 6$, $C_2 = 7.5$, and $L = 1$ are constants. We used data from 620 to 670 nm, from 841 to 876 nm, and from 459 to 479 nm as the reflectance in the red_{ave}, NIR_{ave} and $blue_{\mathrm{ave}}$ bands, respectively. Relative EVI values are shown in parentheses on the vertical axis. We calculated the relative EVI value by using the following equation: relative EVI = $(\mathrm{EVI} - \mathrm{EVI}_{\mathrm{min}}) / (\mathrm{EVI}_{\mathrm{max}} - \mathrm{EVI}_{\mathrm{min}})$, where $\mathrm{EVI}_{\mathrm{max}}$ represents the mean of the annual maximum EVI values over the study period. Similarly, $\mathrm{EVI}_{\mathrm{min}}$ represents the mean of the annual minimum EVI values.