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ASSESSING SATELLITE-DERIVED START-OF-SEASON MEASURES IN THE CONTERMINOUS USA

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ABSTRACT

National Oceanic and Atmospheric Administration (NOAA)-series satellites, carrying advanced very high-resolution radiometer (AVHRR) sensors, have allowed moderate resolution (1 km) measurements of the normalized difference vegetation index (NDVI) to be collected from the Earth's land surfaces for over 20 years. Across the conterminous USA, a readily accessible and decade-long data set is now available to study many aspects of vegetation activity in this region. One feature, the onset of deciduous plant growth at the start of the spring season (SOS) is of special interest, as it appears to be crucial for accurate computation of several important biospheric processes, and a sensitive measure of the impacts of global change.

In this study, satellite-derived SOS dates produced by the delayed moving average (DMA) and seasonal midpoint NDVI (SMN) methods, and modelled surface phenology (spring indices, SI) were compared at widespread deciduous forest and mixed woodland sites during 1990–93 and 1995–99, and these three measures were also matched to native species bud-break data collected at the Harvard Forest (Massachusetts) over the same time period. The results show that both SOS methods are doing a modestly accurate job of tracking the general pattern of surface phenology, but highlight the temporal limitations of biweekly satellite data. Specifically, at deciduous forest sites: (1) SMN SOS dates are close in time to SI first bloom dates (average bias of +0.74 days), whereas DMA SOS dates are considerably earlier (average bias of −41.24 days) and also systematically earlier in late spring than in early spring; (2) SMN SOS tracks overall yearly trends in deciduous forests somewhat better than DMA SOS, but with larger average error (MAEs 8.64 days and 7.37 days respectively); and (3) error in both SOS techniques varies considerably by year.

1. INTRODUCTION

National Oceanic and Atmospheric Administration (NOAA)-series satellites, carrying advanced very high-resolution radiometer (AVHRR) sensors were first launched in 1979 (Goward, 1989). These platforms have subsequently provided moderate spatial resolution (1 km) measurements of several reflectance bands from the Earth's land surfaces for more than 20 years. In particular, normalized difference vegetation index (NDVI) values, calculated from the red-visible and near-infrared bands, provide a general measure of the intensity of vegetation activity that can be compared among sites and over time (Justice *et al.*, 1985). Across the conterminous USA, these NDVI data have been further processed into biweekly maximum-value composites and consistently georegistered since 1990 (Eidenshink, 1992). Thus, a spatially registered and decade-long data set is now readily available to study many aspects of annual vegetation activity in this region.

One feature, the onset of deciduous plant growth at the start of the spring season (SOS), is of special interest in mid-latitudes, as it appears to be crucial for accurate computation of net primary productivity (Running

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and Nemani, 1991; Goetz and Prince, 1996; White *et al*., 1999a), a sensitive measure of the impacts of global change (Schwartz and Reiter, 2000; Chuine and Beaubien, 2001; Menzel *et al*., 2001; Penuelas and Filella, 2001; Chmielewski and Rötzer, 2002), and intimately connected with springtime changes in net ecosystem exchange, sensible heat and latent heat fluxes (Wilson and Baldocchi, 2000; Schwartz and Crawford, 2001). Multiple techniques have been developed (and continue to be refined) to measure the SOS from satellite-derived data (Reed *et al*., 1994; Moulin *et al*., 1997; White *et al*., 1997; Zhou *et al*., 2001). These remotely sensed measurements have tremendous advantages for terrestrial vegetation monitoring, including: (1) full spatial coverage of land surfaces; (2) regular temporal coverage; and (3) integration of multiple species data into a combined ecosystem-scale signal. However, difficulties such as (1) cloud cover data loss, (2) calibration mismatches between specific satellites and within-sensor calibration drift, and (3) complex data interpretation may limit their application to the full range of desired biospheric studies (Reed *et al*., 1994; Schwartz and Reed, 1999; Botta *et al*., 2000; Zhou *et al*., 2001).

Fortunately, the onset of spring vegetation activity can also be monitored in other complementary ways. A second approach is to use conventional native plant phenological data, which are observations of specific events in individual species at selected sites, such as bud-burst or first flower bloom. These events offer improved temporal resolution, and detailed information on interspecies dynamics at specific sites, but have limited spatial coverage (Menzel and Fabian, 1999; White *et al*., 1999b; Rötzer and Chmielewski, 2001). A third approach is to develop climate data-driven phenological models based on cloned (genetically identical) plant event data for a few 'indicator' species that are adaptable to a wide range of climates. Such model output can extend the availability of phenologically compatible simulated data to all sites that have daily temperature data, and can serve as a common basis of comparison between multiple native species events and satellite-derived metrics (Schwartz, 1994). Thus, an integrated approach that synergistically combines satellite SOS, native species phenology, and indicator clone models offers considerable promise to maximize the overall potential of these valuable data (Schwartz, 1997; Schwartz and Reiter, 2000).

This study is part of a continuing effort to craft an integrated approach to continental-scale monitoring of the onset of mid-latitude spring. The goal is to assess the current potential and limits of satellite-derived SOS measures, and gain insights into possible avenues for improvement of these techniques. Specifically, SOS dates produced by the Reed *et al*. (1994) delayed moving average (DMA) and White *et al*. (2002) seasonal midpoint NDVI (SMN) methods, and Schwartz's (1997) spring indices (SI) modelled surface phenology and were compared at widespread deciduous forest sites during 1990–93 and 1995–99, and these three measures were also matched to native species bud-break data collected at the Harvard Forest (Massachusetts) over the same time period.

2. DATA AND PRELIMINARY PROCESSING

Extensive observations are available in eastern North America on two varieties of cloned honeysuckle (*Lonicera tatarica* 'Arnold Red' and *L. korolkowii* 'Zabeli') and one type of cloned lilac (*Syringa chinensis* 'Red Rothomagensis'). Few individual station records are longer than 10 years, but over 2000 observations for the period 1961–94, extending from approximately 35 to 49 °N latitude and 52 to 104 °W longitude, made for an ideal data set to construct the continental-scale multiple regression-based SI phenological models (Schwartz, 1997; Schwartz and Reiter, 2000).

Daily maximum–minimum temperatures and latitude (for day length determination) are the only input variables required to compute SI for a selected location. The SI consists of three individual indices (model outputs): (1) *composite chill date* — the date when winter cold requirement for the plant has been satisfied, meaning that it is ready to respond to spring warmth; (2) *first leaf date* — an 'early spring' date that lilac/honeysuckle leaves grow beyond their winter bud tips, related to a general onset of vegetative growth in grasses and shrubs; and (3) *first bloom date* — a 'late spring' date that lilac/honeysuckle flowers start to open, related to a general onset of vegetative growth in dominant forest vegetation. Each of these indices is computed by averaging the dates produced by sub-models developed for the three plant varietals (one lilac and two honeysuckles) listed above.

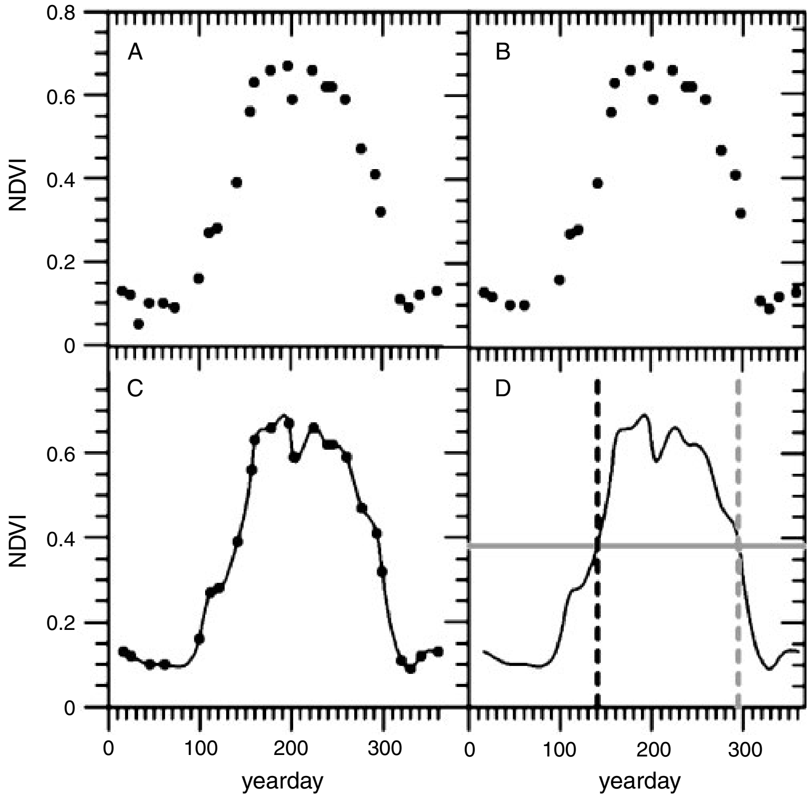

Figure 1. The SMN method of predicting the SOS and end of season. First, for every pixel, the annual cloud-screened minimum and maximum NDVI are selected and the midpoint between them is calculated. This is repeated for every year from 1990 to 1999. The average of these values is the half-maximum NDVI. The following steps illustrated in (a)–(d) are then completed for every pixel: (1) the complete annual time series is obtained (a) and screened to remove cloud-contaminated pixels (b, two points dropped); (2) a spline curve is fit to the data to interpolate NDVI to daily values (c); (3) in (d), the half-maximum NDVI (solid grey horizontal line) is used as a threshold to identify SOS (dashed black vertical line) and end of season (dashed grey vertical line) (White *et al*., 2002)

For this study, we selected climate stations from the 1221 sites incorporated into the Historical Climatology Network (HCN) daily data set, with updates from cooperative (COOP) network records through 1999. Daily maximum and minimum temperatures at these sites served as input to generate SI first leaf and first bloom dates, as proxy values for spring phenology. Actual phenological data (bud-burst dates for 33 species over the 1990–99 period) recorded at the Harvard Forest, MA (42.53°N, 72.17°W, 340 m above sea level) were also employed for comparative purposes (O'Keefe and Johnson, 2000).

The basic satellite data consisted of 1 km spatial resolution biweekly composite NDVI values for the conterminous USA from AVHRR sensors carried on NOAA-series satellites during the 1990–99 period. These values were subsequently processed into SOS dates at every 1 km pixel, using both the DMA SOS and SMN SOS techniques for the years 1990–93 and 1995–99 (1994 was excluded because of NOAA-13 satellite failure).

The approach taken in the DMA SOS method identifies when the NDVI exhibits a rapid, sustained increase that signals the onset of significant photosynthetic activity by employing a backward-looking or DMA. NDVI data values are compared with the average of the previous (user-defined) n NDVI observations to identify departures from an established trend. The DMA value serves as a predicted value with which the real NDVI values are compared. A trend change is detected where the NDVI value departs from (becomes greater than) the value of the moving average, such as when low NDVI values are predicted by the moving average, but actual NDVI values are higher. This departure is labelled as the start of the growing season (SOS).

The SMN methodology employs techniques originally developed by White *et al*. (1997) and subsequently modified (White *et al*., 1999b, 2002). Figure 1 shows the process by which SOS and end of the growing

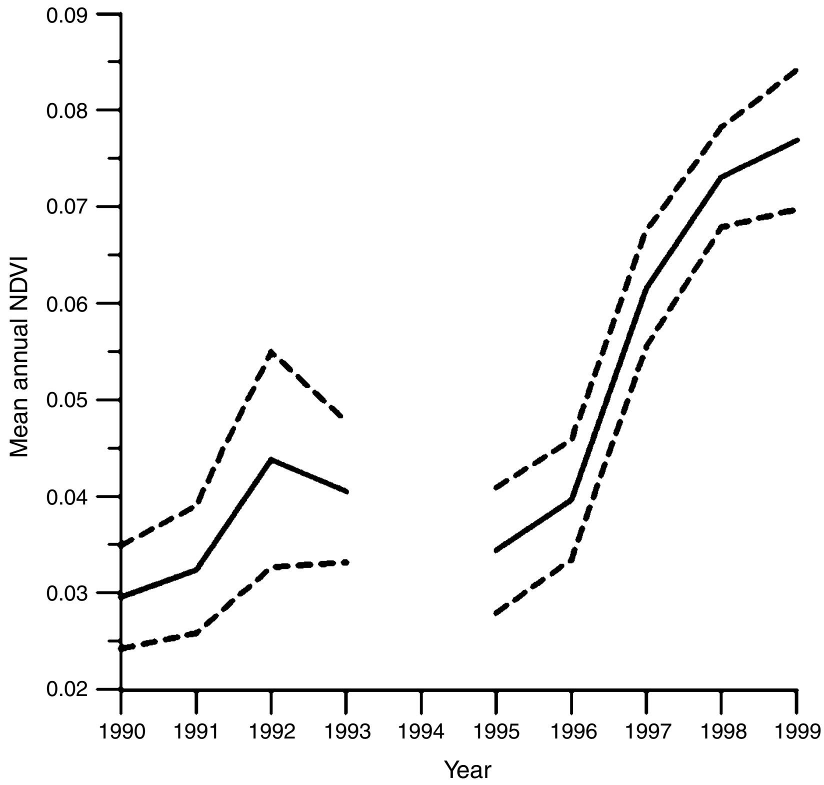

Figure 2. Trend in NDVI values for the White Sands Missile Range in southern New Mexico. Curve is the mean of standardized anomalies for NDVI values in each month. Upper and lower dashed lines are 95% confidence intervals

season (not used here) are predicted. The SMN method, though quite simple, has been shown to be related to initial leaf expansion of the broad leaf forest overstory in New England (White *et al.*, 1997), the Global Observations to Benefit the Environment phenology project (White *et al.*, 1999b), and deciduous forests in France (Bondeau *et al.*, 2000). The SMN threshold, as shown in Figure 1, is defined as the average of the nine annual seasonal midpoint NDVIs. An alternative would be to redefine the SMN threshold annually; we explored this approach and found that extensive interannual variation in the minimum NDVI, mostly due to partial snow and/or cloud cover, caused unacceptably large variation in the SMN threshold. We therefore adopted the constant threshold.

The SMN methodology has the advantage of being sensitive to site-specific NDVI amplitude but, with its dependence on a time-constant NDVI threshold, an additional sensitivity to time-dependent drift in sensor calibration. Figure 2 shows that for the White Sands Missile Range (a non-vegetated bright field), NDVI values systematically increased in the late 1990s. Consequently, as the data here were not time-corrected, the following conditions existed: (1) for the reasons discussed above, the SMN threshold was constant for each pixel for the entire record; (2) NDVI values tended to increase late in the record. Thus, the SMN method is expected to predict anomalously early SOS dates later in the record presented here.

Both kinds of SOS date were extracted for 10 km $\times$ 10 km (100 pixels) windows centred on each of the HCN climate sites. Each pixel was then assigned to a land cover class according to the Biosphere Atmosphere Transfer Scheme (BATS) classification system (Dickenson *et al.*, 1986). Land cover information was taken from the US Geological Survey's Land Cover Characterization database (Loveland *et al.*, 1993). Median statistics of the SOS dates for each location were calculated for all 100 pixels and for those within each BATS land cover type. Sites with either deciduous broadleaf tree (class 5) or mixed woodland (class 18)

Figure 3. HCN stations used in the study with surrounding land cover classed as deciduous broadleaf tree (class 5) and mixed woodland (class 18)

vegetation types present were selected for further analysis, as these types have the closest connection to SI phenology (Figure 3).

3. METHODOLOGY

We generated descriptive statistics (n of cases, minimum, maximum, mean, and standard deviation) from the median SOS dates for pixels classed as deciduous broadleaf tree or mixed woodland, and SI first bloom dates, at sites with one or both of these land cover types present (Figure 3). Nine-year (study period) averages of the SOS and SI dates and SOS – SI differences for the two land cover types were also calculated at each station. Mapping these station-average values using isolines facilitated searching for regional or other systematic patterns.

Next, corresponding station-averages were subtracted from the original data in order to render all individual values as departures-from-normal. This step allowed effective comparison of the annual fluctuation in variables with appreciably different mean values in subsequent analyses. We produced graphs of the annual variation in departures to facilitate the assessment. Using the SI dates as an estimate of 'ground truth' produced error statistics (Pearson's r, mean bias error, and mean, 50th percentile, and 90th percentile absolute error) for each SOS technique across the two land cover types. Lastly, error statistics were also generated for the SI dates

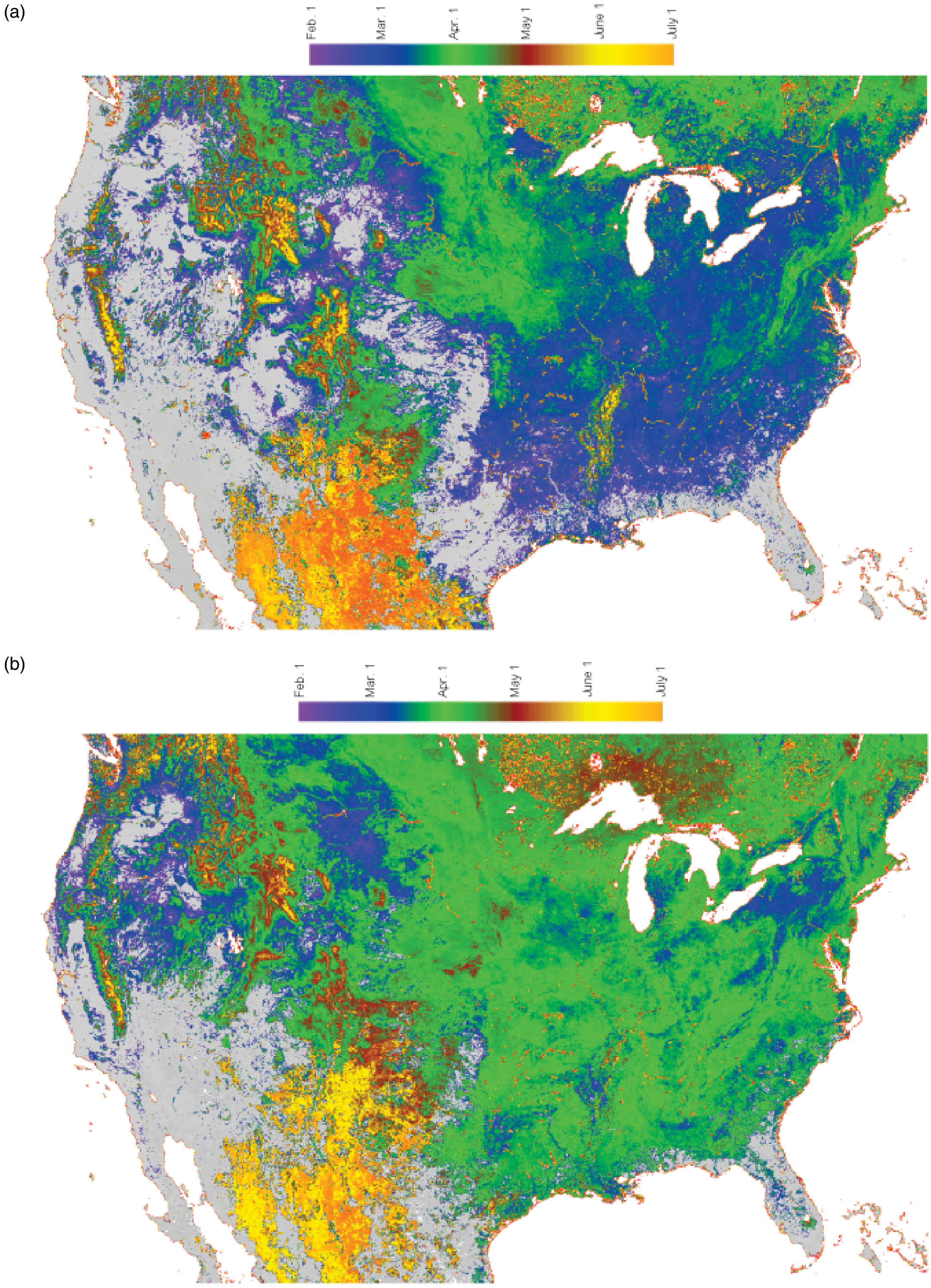

Figure 4. (a) DMA SOS 1995. Dates prior to 1 February are in grey. February dates start purple at the beginning of the month and shift to blue at the end of the month, March dates from blue to green, April dates from green to brown, May dates from brown to yellow, and June dates from yellow to orange. Dates later than June shift from orange to red. (b) DMA SOS 1996, legend as in (a)

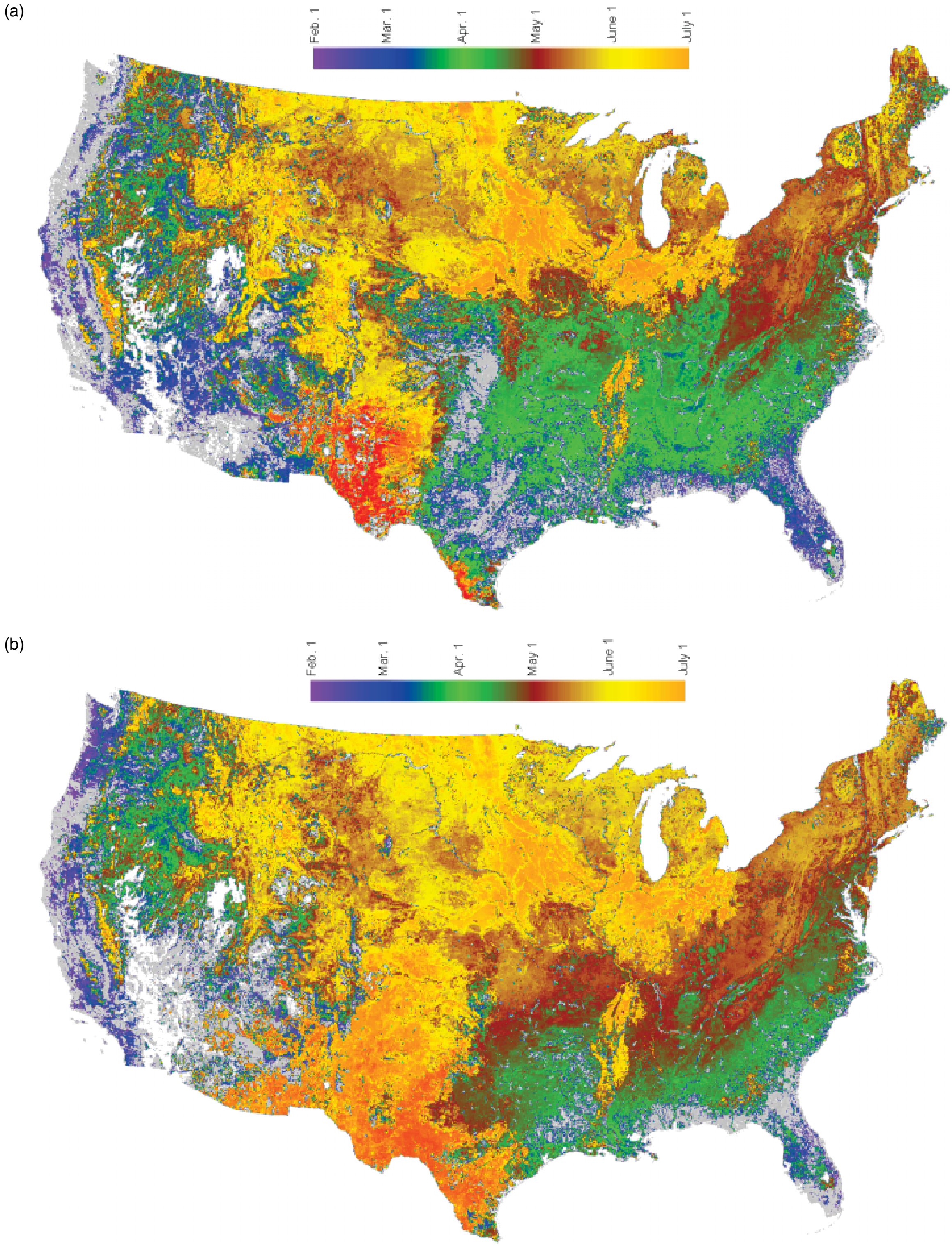

Figure 5. (a) SMN SOS 1995, legend as in Figure 4(a); (b) SMN SOS 1996, legend as in Figure 4(a)

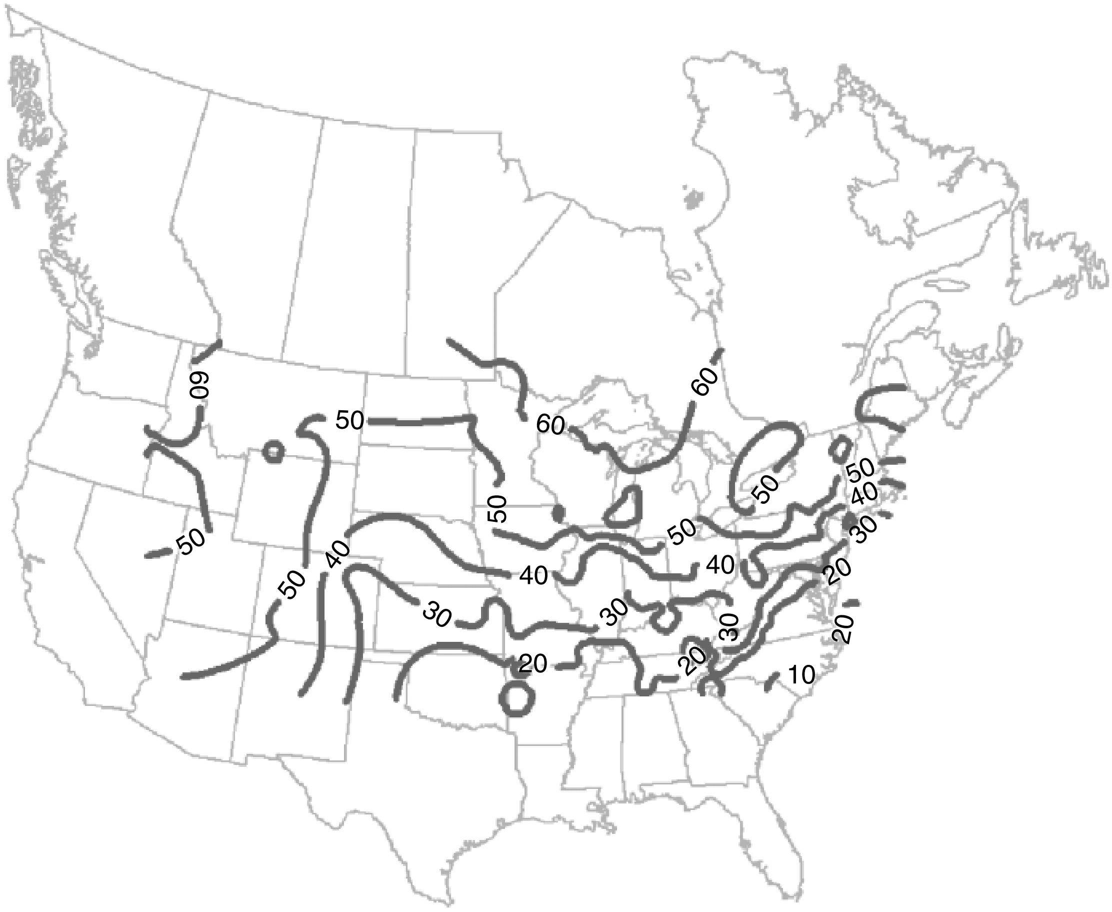

Figure 6. Average difference in days between SI first bloom date and DMA SOS date

Table I. USA summary statistics at BATS deciduous broadleaf tree sites (class 5) $n = 2193$

Variable	Minimum	Mean	Maximum	Standard deviation
SI first bloom date (SIFB) (day-of-year)	69	121.08	174	19.30
Departure of SIFB (days)	−23	0.00	17	6.83
DMA SOS date (day-of-year)	27	79.84	127	9.67
Departure of DMA SOS (days)	−33	−0.10	32	7.00
Bias error of DMA SOS departure (days)	−42	−0.10	33	8.75
Absolute error of DMA SOS departure (days)	0	6.87	42	5.43
SMN SOS date (day-of-year)	−4	121.82	190	20.83
Departure of SMN SOS (days)	−71	0.37	51	11.77
Bias error of SMN SOS departure (days)	−75	0.37	48	10.96
Absolute error of SMN SOS departure (days)	0	8.23	75	7.25

Table II. USA summary statistics at BATS mixed woodland sites (class 18) $n = 1322$

Variable	Minimum	Mean	Maximum	Standard deviation
SIFB (day-of-year)	71	126.13	186	22.16
Departure of SIFB (days)	−26	−0.01	17	7.00
DMA SOS date (day-of-year)	37	81.30	132	12.25
Departure of DMA SOS (days)	−30	−0.09	28	7.90
Bias error of DMA SOS departure (days)	−43	−0.09	27	9.47
Absolute error of DMA SOS departure (days)	0	7.44	43	5.86
SMN SOS date (day-of-year)	19	123.01	227	23.03
Departure of SMN SOS (days)	−99	0.33	80	13.41
Bias error of SMN SOS departure (days)	−103	0.33	74	12.84
Absolute error of SMN SOS departure (days)	0	8.70	103	9.45

Table III. USA absolute error statistics (values in days)

Variable	50th percentile of absolute error	90th percentile of absolute error
DMA SOS class 5 departure	5.3	13.9
SMN SOS class 5 departure	5.8	17.0
DMA SOS class 18 departure	5.6	15.0
SMN SOS class 18 departure	5.5	19.1

and SOS techniques at the Harvard Forest site, but using average bud-burst date for the 33 native species collected on-site as the standard of actual phenology.

4. RESULTS

Examination of the SOS values across the continental USA for all land cover types and in contrasting years revealed fundamental differences between the DMA and SMN SOS techniques. The years 1995 and 1996 were chosen as examples of 'early' and 'late' years for visual comparison, based on their average SI first bloom dates (day-of-year 123 and 128 respectively). DMA SOS dates are earlier and display smaller land cover/geographical variations (Figure 4(a) and (b)). SMN SOS dates are later and display considerably larger land cover/geographical variations (Figure 5(a) and (b)). Both techniques capture the relative 'earliness' of 1995 (Figures 4(a) and 5(a)) and relative 'lateness' of 1996 (Figures 4(b) and 5(b)). Further inspection also showed that DMA SOS dates are systematically biased relative to SI first bloom dates, with differences between the two dates increasing for events occurring later in the spring season (Figure 6). SMN SOS dates were not biased relative to SI first bloom dates in this fashion.

Summary statistics for the deciduous broadleaf tree (Table I) and mixed woodland (Table II) land cover types revealed similar patterns. SMN SOS dates and SI first bloom dates occur at roughly the same times, whereas DMA SOS dates are about 40 days earlier. After transformation of all three variables into departures-from-normal, both SOS techniques showed minimal bias error (less than 0.5 day) relative to SI first leaf. Average absolute errors are greater for SMN SOS dates than DMA SOS dates by about 1.3 days for both land cover types (Tables I and II). However, examination of 50th and 90th percentiles of the absolute errors indicate that this difference is more related to a small number of dates with large errors, rather than substantially larger overall error (Table III). Correlation analysis suggests that SMN SOS dates are capturing more of the annual variability in SI first bloom than DMA SOS dates, but, even so, both are still only modestly correlated (Table IV).

Consistent with other results, SMN SOS dates mimic the SI first bloom year-to-year departure pattern more closely, but show considerably greater differences in value (Figure 7). DMA SOS dates are the most conservative of the three measures, with the smallest annual departures from zero. Clearly, however, the standard errors show that, even when rendered as departures, all three measures are still statistically distinct across the USA sites.

At the Harvard Forest, native species bud-burst data were available to use as a firmer control of phenological response. The error patterns of the two SOS techniques at this site were somewhat different from those shown over the entire USA. SMN SOS average absolute errors were considerably greater than DMA SOS absolute errors (by almost 8 days), compared with average native species phenology, and the 50th percentile error

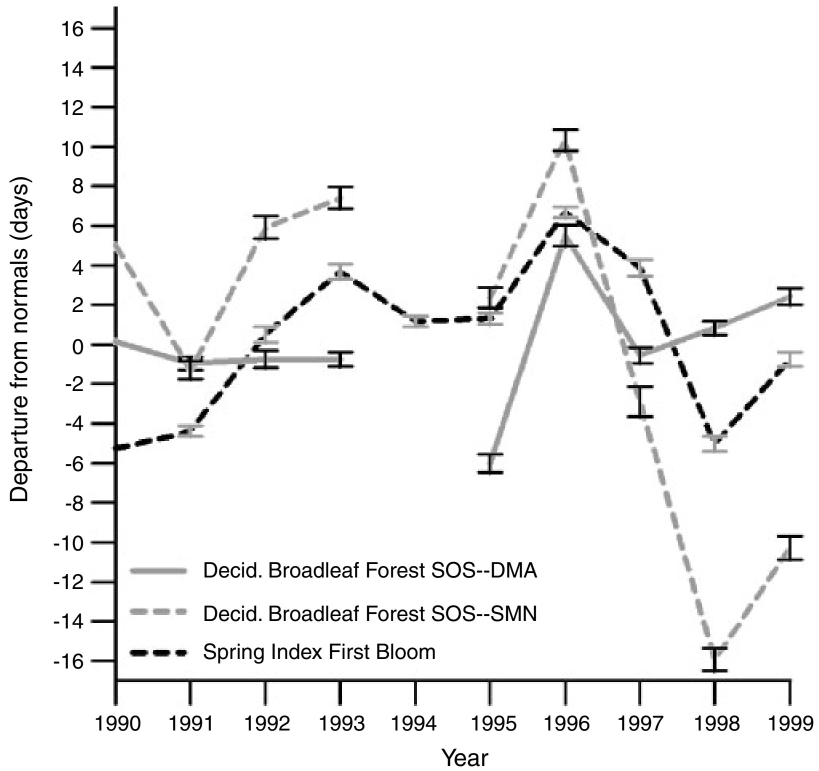

Figure 7. Annual comparison averaged for HCN stations across the USA, with plus/minus one standard error bars

Table IV. USA Pearson's r correlation matrix (two-tailed, all significant at 0.01 level)

	SIFB departure class 5	SIFB departure class 18
DMA SOS class 5 departure	0.199	
SMN SOS class 5 departure	0.404	
DMA SOS class 18 departure		0.196
SMN SOS class 18 departure		0.342

indicated that the error was more prevalent over all years, and not just the extremes (Table V). DMA SOS dates were also slightly better correlated than SMN SOS dates with the native species bud burst. However, SI first bloom date was the only one of the three measures significantly correlated with the native species bud burst, also being within one standard error in most years (Figure 8). The year 1996 at Harvard Forest is quite interesting, as it is the worst year for the SI first bloom relative to the native species bud burst. DMA SOS appears to be more correctly measuring the relative earliness of 1996, whereas SMN SOS tags it as even later than the SI first bloom date.

Table V. Harvard Forest error statistics and Pearson's *r* correlations

Variable	Mean bias error	Mean absolute error	50th percentile absolute error	90th percentile absolute error	Correlation (two-tail significance) with departure of 33-species bud burst
SIFB departure	−0.67	2.89	1.8	6.0	0.818 (0.007)
DMA SOS departure	−1.89	5.44	3.5	11.0	0.473 (0.199)
SMN SOS departure	−0.78	13.22	9.5	19.0	0.350 (0.357)

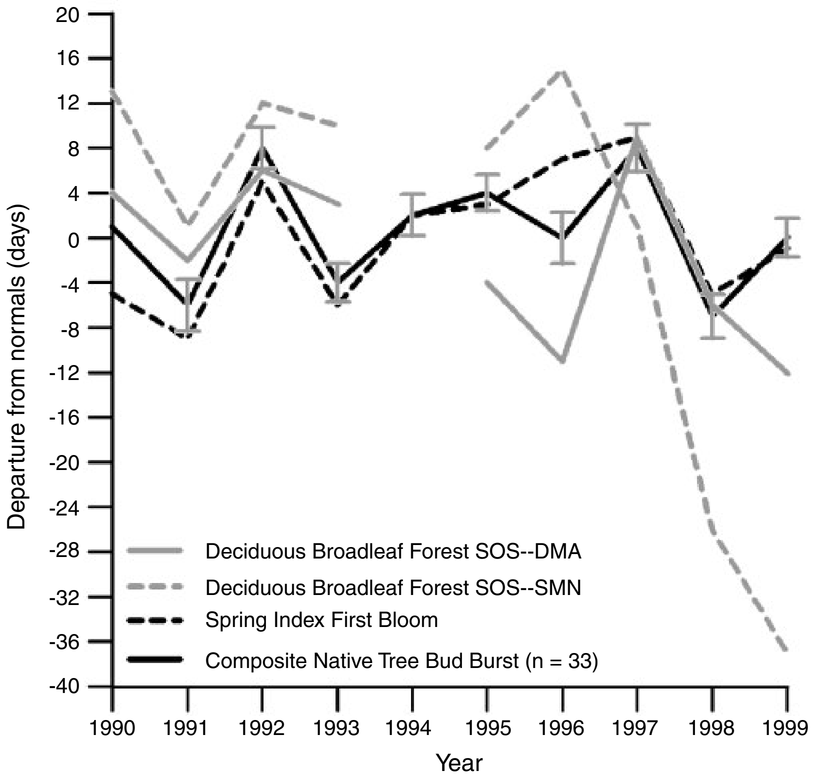

Figure 8. Annual comparison at Harvard Forest, MA, with plus/minus one standard error bars for native tree bud burst

5. DISCUSSION

We feel it is important to emphasize that each of the three techniques considered in this study, though all assessing the start of spring vegetation growth in some fashion, are effectively measuring different processes. DMA SOS is designed to detect the first sustained positive change in the NDVI signal during spring, whereas SMN SOS indicates attainment of a 'half-maximum' NDVI level designed to predict the initial leaf expansion of dominant overstory species. Both SOS measures are based on remote-sensed reflectance variations across a discrete area, a quite different approach than the SI models, which simulate plant development from daily maximum–minimum temperatures at a specific site. Further, the SI models are based on the responses of understory shrubs, which has additional implications for comparability. Thus, some of the differing characteristics of the measures (relative earliness of the DMA SOS, greater land cover dependence of the SMN SOS, and strong connection of the SI models to native species bud burst at a specific site) were fully anticipated.

Beyond these expected results, our findings indicate that the DMA and SMN SOS techniques are both capable of moderately accurate detection of annual variations in the onset of deciduous forest growing seasons. This ability holds at both the individual site and continental scale, and prevails despite the temporal limitations imposed by biweekly NDVI data. DMA SOS appears to be the more conservative measure and to have a systematic bias related to time of year (Figure 6). Some of this bias may be due to real differences in native vegetation response, as northern plant species are able to initiate growth with less energy than southern species in more moderate climates (Schwartz and Crawford, 2001). However, the size of the bias suggests that non-biological factors may also be responsible.

SMN SOS appears to be more successful in tracking the overall pattern of annual variations, but with greater errors in individual years and a probable sensitivity to sensor calibration problems late in the study period. Even the SI models, which have an excellent connection to the onset of deciduous tree growth at specific sites, can be 'out of step' in individual years like 1996 (Figure 8). Therefore, our results affirm that an integrated approach that synergistically combines satellite SOS, native species phenology, and indicator clone models offers considerable promise to maximize the overall potential of these valuable data as part of continuing efforts at continental-scale monitoring of the onset of mid-latitude spring.

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