Land surface phenology dynamics and climate variations in the North East China Transect (NECT), 1982–2000

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Land surface phenology dynamics reflect the response of the Earth’s biosphere to inter- and intra-annual dynamics of the Earth’s climate and hydrologic regimes. Investigations of land surface phenology dynamics and its relation to long-term climate variation could help us to detect the response of regional vegetation to climate variation. The present study developed a new algorithm for detecting regional land surface phenology dynamics (ARLSPD) and demonstrated it in detecting the vegetation response to inter-annual climate variability in the North East China Transect (NECT), a mid-latitude semi-arid terrestrial transect with strong gradients in environmental conditions and vegetation formations. The spatial-temporal patterns of greenup-onset date, maturity date, and senescence date during the period of 1982–2000 are presented. The resultant spatial-temporal patterns of land surface phenology were quite consistent with the land-cover characteristics, moisture, and temperature gradients. The relations between inter-annual variations in phenology and seasonal climate were investigated. It was found that besides human disturbance, land surface phenology depended primarily on the combined effects of preseason temperature and precipitation. The relative influence of preseason temperature and precipitation on land surface phenology was changing, which led to the different responses of land surface dynamics to climate variation along the moisture gradient in the NECT. In the arid and semi-arid region of NECT, the dates of onset for phonological events in temperate typical grassland were most significantly related to the precipitation during the preceding 2–4 months. Temperature-induced drought stress during the preceding months could delay greenup onset in cropland/grassland mosaic, and advance senescence in temporal typical grassland, and in cropland/grassland mosaic. The regional phenology algorithm, theoretically also applicable for complex ecosystems characterized by annual multiple growth cycles, is expected to couple with large-scale biogeochemical models to regulate dynamically land surface phenology.

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1. Introduction

Land surface phenology dynamics reflect the response of the Earth’s biosphere to inter- and intra-annual dynamics of the Earth’s climate and hydrologic regimes (Myneni et al. 1997, White et al. 1997, Schwartz 1999). Few other terrestrial biophysical processes present such an intimate, immediate, and detectable connection to climate variability. Therefore, it is a key bio-indicator for monitoring vegetation development and production, as well detecting the response of terrestrial ecosystem to climate variation. Furthermore, land surface phenology dynamics affect substantially the exchange of heat, moisture and momentum between the land surface and the atmosphere, and therefore are important in land surface and global biogeochemical modelling. The characterization of vegetation phenologies at regional, continental and global scales is required to improve models and the understanding of inter-annual variability in terrestrial ecosystem carbon exchange and climate–biosphere interactions (Tucker et al. 1985, Sellers et al. 1994).

Remote sensing data possess significant potential for monitoring vegetation dynamics at regional and global scales. A number of different methods have been developed to determine the timing of vegetation phenology including greenup (i.e. the date of onset of photosynthetic activity), peak, and senescence using a time series of Normalized Difference Vegetation Index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR). These methods include the use of specific NDVI thresholds (Lloyd 1990, White et al. 1997), the largest NDVI increase (Kaduk and Heimann 1996), backward-looking moving averages (Reed et al. 1994), empirical equations (Moulin et al. 1997), and discrete Fourier transforms (Moody and Johnson 2001). However, such methods have some limitations (Yu et al. 2003), are difficult to apply at regional or global scales, and generally do not account for ecosystems characterized by multiple growth cycles (e.g. double- or triple-crop agriculture). Recently, scientific interest in identifying plant phenology based on remote sensing images has been increasing. Several methods with different focuses have been proposed (e.g. Zhang et al. 2003, Sakamoto et al. 2005, Beck et al. 2006, Delbart et al. 2006, Piao et al. 2006). The phenology algorithms can be generally classified into two methods. One uses a NDVI threshold to identify the beginning of photosynthetic activity in the spring (Lloyd 1990, Fischer 1994, Markon et al. 1995, White et al. 1997, Duchemin et al. 1999, Zhou et al. 2001, Suzuki et al. 2003). The other identifies the period of greatest increase in NDVI as the beginning of growing season (Reed et al. 1994, Kaduk and Heimann 1996, Moulin et al. 1997, Lee et al. 2002, Yu et al. 2003, Zhang et al. 2003). By combining the two methods, Piao et al. (2006) developed an algorithm to derive the onset dates of vegetation greenup and dormancy in the temporal zone of China. The algorithm is effective in capturing the general features of regional vegetation phenology and its response to climate variation. Nevertheless, robust algorithms to capture more detailed characteristics of regional land surface dynamics should be developed.

A number of studies have also documented the shift of vegetation phenological phases in the last few decades in Europe, and the cool and temperate zones of the Northern Hemisphere (Menzel and Fabian 2000, Beaubien and Freeland 2000, Jaagus and Ahas 2000, Menzel et al. 2001, Zhou et al. 2001) and its relation to climate variation (Sparks and Carey 1995, Yu et al. 2003, Chmielewski et al. 2004, Zhang et al. 2004, Piao et al. 2006, Tao et al. 2006). The studies suggested that it was necessary to develop phenological models to estimate the effects of climate variation on various biomes in different regions of the world (Chmielewski et al. 2004).
In this study, we aim to (1) develop a new automated, objective and flexible algorithm for detecting regional land surface phenology dynamics (ARLSPD); (2) demonstrate the algorithm by using it to investigate the spatial–temporal patterns of land surface phenology in the North East China Transect (NECT) during the period of 1982–2000; and finally (3) analyse the land surface phenology dynamics and their relations with climate variation.

2. Study area

The study area ranges from 43° to 46° N latitude and from 112° to 130.5° E longitude (figure 1), which is within the NECT (42° to 46° N, 106° to 134° E). It extends from the Inner Mongolia Plateau, Daxingan Mountain, the Northeast China Plain, and Changbai Mountain from west to east. The NECT was identified as a mid-latitude semi-arid terrestrial transect by Global Change and Terrestrial Ecosystems, a core project of the International Geosphere–Biosphere Programme (IGBP). The transect is characterized by a large moisture gradient, ranging from 709 mm of annual precipitation at the eastern end to only 177 mm in the west, with
substantial inter-annual fluctuations and inner-annual changes. A north–south difference in mean annual temperature ranges from less than 3°C in the north-west and north-east to 3–7°C in the middle (Ni and Zhang 2000). The NECT reflects the comprehensive effects of monsoon climate, drought climate and the Tibetan Plateau (Zhou et al. 2002). Vegetation along the transect varies gradually from temperate conifer–broadleaf mixed forests, deciduous broadleaf forests, and woods and shrubs in the east, through meadow steppes and agricultural lands in the middle, to typical steppes and desert grasslands in the west (Zhang et al. 1997). The NECT has become a favourite experimental region for many global change studies in the last decade (e.g. Gao and Yu 1998, Zhou et al. 2002).

3. Data and methods

3.1 Climatic data and AVHRR NDVI

Monthly temperature and precipitation data from 1981 to 2000 at 14 meteorological stations (figure 1) in the study area were collected from the Chinese Meteorological Bureau. The meteorological stations are distributed almost evenly in the study area. Among them, four stations (stations 1, 2, 3 and 4 in figure 1) are located in grassland, three stations (stations 5, 6 and 7 in figure 1) are in cropland/grassland mosaic, and seven stations (stations 8–14 in figure 1) are in dryland cropland and pasture. The AVHRR NDVI data used in this study are from the ‘Twenty-year (1981–2000) Global 4-minute AVHRR NDVI Dataset of Chiba University’ (Tateishi et al. 1997). The dataset was processed from Pathfinder global 10-day composite 8-km AVHRR NDVI data (http://asiaserv.cr.chiba-u.ac.jp/frame.htm) by the Temporal Window Operation (TWO) method (Park et al. 1999).

Old version pathfinder data have some major problems in terms of cloud and aerosol effects, satellite drift, sensor signal degradation from NOAA-7 to NOAA-14, etc. To reduce such effects, some composite techniques have been developed. Most often used for the data from the AVHRR onboard the NOAA satellites are Maximum Value Composition (MVC), cloud-screening procedures, and Maximum Value Interpolation (MVI), etc. However such composites almost always contain some cloudy or partly cloudy pixels, representing areas that are cloudy on the available image (Park et al. 1999). A simple solution for removing residual cloud is to extend the composite period. But this method will lose the information of seasonal change of vegetation. Another possibility is the use of cloud-screening procedures on single image to identify and mask out the contaminated pixel. But cloud-screening techniques are more difficult to apply to land area because of high spatial heterogeneity and their sensitivity to seasonal and regional influences. They are also limited for detecting cloud, subpixel cloud and cloud shadows. Park et al. (1999) developed TWO, an algorithm to detect and remove cloud contamination and atmospheric effect using NDVI time series profile without ancillary dataset for global land cover monitoring. TWO assumes that NDVI value can only decrease as a result of atmospheric attenuation, solar zenith angle (SZA) and cloud. Therefore, the ‘true’ NDVI value for a vegetated surface during composite period can be assumed to be as high as, or higher than, the maximum NDVI value recorded for that pixel. The TWO algorithm procedures the NDVI trajectory of each pixel by finding the ‘low’ NDVI values and replacing them by the linearly interpolated values of the NDVI profile. The TWO algorithm starts at the beginning of the NDVI (start point) curve and checks whether the NDVI for the current period is equal to or
greater than the previous NDVI value within the window. If it is higher, the current value is assigned as the start point of the next window. If there is no higher value within the window, select the largest value as the start point of the next window and replace the NDVI values within the current window by the linearly interpolated value from the current start point to the next start point. The resultant NDVI correction was improved in comparison with the MVC, MVI and cloud-screening procedures (Park et al. 1999).

3.2 An algorithm for detecting regional land surface phenology dynamics (ARLSPD)

In ARLSPD, the annual cycle of vegetation phenology inferred from remote sensing is characterized by three key transition dates, which define the key phenological phases of vegetation dynamics at annual timescales: (1) greenup; (2) maturity, the date at which plant green leaf area is maximum; and (3) senescence, the date at which photosynthetic activity and green leaf area begin to decrease rapidly. The algorithm to identify the transition dates of the vegetation key phenological phases is shown in figures 2 and 3. Generally the algorithm has two parts. The first identifies the number of growing cycles in a year, and the second identifies the transition dates of the vegetation key phenological phases for each growth cycle. Since one annual growth cycle is dominant in the NECT, we applied the algorithm for one growth cycle in the study. First, the 10-day composite AVHRR NDVI data (NDVI(t)) were smoothed (SNDVI(t)) by the five-point ranging mean method, by which a growth peak (corresponding to a growth cycle) can be identified as follows: two continuous periods with increasing NDVI and three continuous periods with equal or decreasing NDVI. A typical growth cycle includes at least the six stages: greenup, pre-maturity, maturity, post-maturity, senescence, and post-senescence. From greenup to pre-maturity, and from pre-maturity to maturity period, NDVI should increase. Thereafter from maturity to post-maturity, from post-maturity to senescence, and from senescence to post-senescence, NDVI should remain unchanged or decrease. A growth cycle could be neglected if too many or too few periods were included. Moreover, it is enough to prevent the disturbance of noise in NDVI series by using the five-point ranging mean NDVI (NDVI_mean in figure 3) and the NDVI changes in the five periods.

The number of growth cycles in 1 year can be determined by the total occurrence frequency of the event. Once the number of growth cycles is determined, the transition dates can be identified one by one for each growth cycle according to the procedures as follows: firstly we applied the spline-smoothing technique (Woltring 1986) to the NDVI time series to get a smoothed NDVI curve \( s_0(t) \) in figures 2 and 3. Transition dates correspond to the times at which the rate of change in curvature of the smoothed NDVI curve exhibits local minima or maxima. Then we calculated the first derivative \( d_1(t) \) in figures 2 and 3 and the second derivative \( d_2(t) \) in figures 2 and 3 of the smoothed NDVI curve, which represent the change and the rate of change in curvature of the smoothed NDVI curve, respectively. To avoid the effects of non-vegetation NDVI change, the NDVI threshold should be set to greater than 0.05. Vegetation greenup onset in the NECT should occur sometime between the middle of March and the middle of July, with a maximum change rate \( d_2 \) maximum) and a positive change \( d_1>0 \); figure 3). Vegetation maturity in the NECT should occur sometime between early June and the end of September, with a negative change rate \( d_2<0 \) and at the turning point from a positive change to a
negative change \((d_1(t) \times d_1(t+1)<0; \text{ figure 3})\). Vegetation senescence in NECT should occur sometime between early August and the end of October, with a maximum change rate \((d_2 \text{ maximum})\) and a negative change \((d_1<0; \text{ figure 3})\). The exact Julian calendar day of the transition date of the vegetation key phenological phases was taken to be the day midway through the 10-day period in which the event occurred. The time range for each transition date was set to be wide enough to cover the phenology of the region. Nevertheless, the resulting Julian calendar day for each
pixel can be exact. The algorithm is flexible enough to apply to a complex ecosystem characterized by multiple annual growth cycles. For example, in figure 3(b), we illustrate the scheme using the NDVI time series at a grid with multiple growth cycles in southern China. The only requirement is to set the general range for each transition date of each growth cycle in the study region.

Figure 3. Procedure for calculating transition dates using NDVI, five-point ranging mean NDVI (NDVI_mean), smoothed NDVI curve (s0), and its first derivative (d1) and second derivative (d2): (a) for a single growth cycle, (b) for a multiple growth cycle.
3.3 Analysis

We analysed the spatial–temporal patterns of the three temporal NDVI metrics including greenup-onset date, maturity date, and senescence date, as well their relations to climate variation by a statistical method. For each NDVI metric, we plotted the spatial pattern of its mean, standard deviation, and the significance level of its trend (slope from the regression equation between the NDVI metric and time) during the period of 1982–2000. The F-test was used to test the significance of the trend. In comparing two independent samples of size \( n_1 \) and \( n_2 \), the F-test provides a measure for the probability that they have the same variance. We used the time-series of derived NDVI metrics in the pixels that contained meteorological stations to evaluate the correlation between the NDVI metrics and seasonal climate. The Pearson correlation coefficient (\( r \)) between them was calculated, and its significance was tested by the two-tailed t-test. The two-tailed test is a statistical test used in inference, in which a given statistical hypothesis will be rejected when the value of the statistic is either sufficiently small or sufficiently large. Through the whole paper, the trend or correlation is taken to be significant when \( p < 0.05 \), and most significant when \( p < 0.01 \).

4. Results

4.1 Spatial and temporal patterns of land surface phenology

4.1.1 Greenup. The spatial pattern of greenup onset among biomes in the NECT was generally linked to land cover characteristics, moisture and temperature gradients (figure 4(a), (b)). Forests had the earliest greenup onset, followed by grassland, croplands had the latest (figure 4(a)). During the period of 1982–2000, the greenup onset of grassland in the Inner Mongolia Plateau had the largest inter-annual variation (figure 4(b)). The greenup-onset dates of biomes in the region along Daxingan Mountain had a uniform change during the period (figure 4(c)). The greenup onset of typical grassland and vegetation mosaic along Daxingan Mountain had a negative trend, suggesting the greenup-onset dates of these biomes advanced during the period of 1982–2000. In contrast, the greenup onset of cropland and pasture in the Northeast China Plain had a significantly positive trend (\( p < 0.05 \)) (figure 4(c)), suggesting the greenup-onset dates of these biomes delayed significantly during the period of 1982–2000. The change pattern could be attributed to the combined effects of climate variation and human disturbance, which will be further analysed later.

4.1.2 Maturity. Forests around Changbai Mountain had the earliest dates of maturity, however grassland in the Inner Mongolia Plateau had the latest (figure 5(a)). The maturity dates of forests around Changbai Mountain had the largest inter-annual variation, with a general positive trend, suggesting the maturity delayed during the period of 1982–2000. In contrast, the maturity dates of cropland and pasture in the Northeast China Plain had the smallest inter-annual variation (figure 5(b)), however with a general negative trend during the period of 1982–2000 (figure 5(c)). In addition, the maturity advanced for the grassland in the Inner Mongolia Plateau, however, it was delayed for the cropland and grassland mosaic during the period.

4.1.3 Senescence. The senescence dates of deciduous broadleaf forests around Changbai Mountain came earliest (figure 6(a)), and also had the largest inter-annual
Figure 4. Mean (a), standard deviation (b) and significance level (c) of time trend in greenup-onset date during the period of 1982–2000. The values in (c) with the sign ‘−’ represent negative trend, otherwise represents positive trend. The greenup-onset date cannot be detected at the black areas of (a) and (b). Trends are not significant at the black areas of (c) at the level of 0.3.
Figure 5. Mean (a), standard deviation (b) and significance level (c) of time trend in maturity date during the period of 1982–2000. The values in (c) with the sign ‘–’ represent negative trend, otherwise represents positive trend. The maturity date cannot be detected at the black areas of (a) and (b). Trends are not significant at the black areas of (c) at the level of 0.3.
Figure 6. Mean \((a)\), standard deviation \((b)\) and significance level \((c)\) of time trend in senescence date during the period of 1982–2000. The values in \((c)\) with the sign ‘-’ represent negative trend, otherwise represents positive trend. The senescence date cannot be detected at the black areas of \((a)\) and \((b)\). Trends are not significant at the black areas of \((c)\) at the level of 0.3.
variability (figure 6(b)). In contrast, cropland and pasture had the latest and least variable senescence dates. During the period of 1982–2000, the senescence dates advanced for cropland and pasture in the Northeast China Plain, and for grassland in the Inner Mongolia Plateau. In contrast, the senescence dates of forests delayed (figure 6(c)).

4.2 Relationship between variations in land surface phenology and seasonal climate

Among other factors, inter-annual climate variation could play a key role in inter-annual variability of phenology (Yu et al. 2003, Chmielewski et al. 2004, Zhang et al. 2004, Piao et al. 2006, Tao et al. 2006). To investigate the factors underlying land surface phenology dynamics along the moisture gradient in the NECT, we analysed the correlation between variations in land surface phenology and seasonal climate in temperate typical grassland at four meteorological stations (i.e. stations 1, 2, 3 and 4 in figure 1), in cropland/grassland mosaic at three meteorological stations (i.e. stations 5, 6 and 7 in figure 1), in dryland cropland and pasture in the semi-arid and semi-humid region at four meteorological stations (i.e. stations 8, 9, 10 and 11 in figure 1), and in dryland cropland and pasture in the semi-humid region of NECT at three stations (i.e. station 12, 13 and 14 in figure 1). At the four meteorological stations in temperate typical grassland, mean greenup-onset dates and maturity dates advanced insignificantly during the period of 1982–2000. In contrast, senescence dates advanced significantly by 0.54 days per year (figure 7(a)). In the arid and semi-arid region, preseason precipitation had direct effects on phenology dynamics. The dates of onset for phonological events were most significantly related to the precipitation during the preceding 2–4 months (figure 7(b)). For example, precipitation during the preceding 2–4 months could advance greenup onset most significantly, while increase in temperature during the preceding 1 month could advance greenup onset insignificantly. Preseason precipitation could advance maturity and delay senescence significantly. However temperature increase during the preceding 4–6 months could induce drought (Barber et al. 2000, Tao et al. 2003) and advance senescence most significantly.

At the three meteorological stations in cropland/grassland mosaic, there were no significant trends in phonological events during the period of 1982–2000 (figure 7(c)). In the semi-arid region, the greenup-onset dates were most significantly and positively related to the temperature during the preceding 2–4 months (figure 7(d)), however insignificantly and negatively related to preseason precipitation, suggesting temperature-induced drought could delay greenup onset here. The maturity dates were most significantly and positively related to the temperature during the preceding 2–5 months, however significantly and negatively related to preseason precipitation. Preseason precipitation could delay onset of senescence, however temperature increase during the preceding 4–6 months could induce drought and advance senescence.

At the four meteorological stations in dryland cropland and pasture in the semi-arid and semi-humid region, there were also no significant trends in phonological events during the period of 1982–2000 (figure 7(e)). The greenup-onset dates were most significantly and negatively related to preseason temperature (figure 7(f)). In addition, they were also significantly and positively related to preseason precipitation. The maturity dates were only significantly related to preseason precipitation. The senescence dates were little affected by climate variation, suggesting the influences of agricultural management.
At the three meteorological stations in the semi-humid region of NECT, mean greenup-onset dates delayed significantly by 0.45 days per year during the period of 1982–2000. Both maturity and senescence dates delayed insignificantly (figure 7(g)). The negative however insignificant correlation between greenup-onset dates and the temperature suggested that preseason temperature increase could advance greenup onset (figure 7(h)). Preseason precipitation could advance maturity and senescence significantly.

5. Discussion
5.1 Drought stress, human disturbance and land surface phenology dynamics

It is commonly believed that the greenup onset of vegetation (including cultivation) has advanced, and the senescence has delayed due to the warming trends in spring and autumn during the last two decades, resulting in lengthened growing season duration (e.g. Zhou et al. 2001, Piao et al. 2006). However our studies in NECT showed that drought stress and human disturbance could complicate the relationship between land surface phenology and seasonal temperature. Besides human disturbance, land surface phenology depended primarily on the combined effects of preseason temperature and precipitation. The relative influence of preseason temperature and precipitation on land surface phenology was changing along the moisture gradient in the NECT. At the arid and semi-arid regions such as the western part of NECT, where vegetation suffers from water stress (Tao et al. 2003), preseason precipitation had direct effects on phenology dynamics. The dates of onset for phonological events in temperate typical grassland were most significantly related to the precipitation during the preceding 2–4 months. Increase in preseason temperature could advance significantly greenup onset only for dryland cropland and pasture in the semi-arid and semi-humid region of NECT (figure 7(f)). Instead, increase in preseason temperature could induce drought stress (Tao et al. 2003). Temperature-induced drought during the preceding 2–4 months could delay greenup onset in cropland/grassland mosaic (figure 7(d)). Except for forests, increase in preseason temperature did not delay senescence either. It also induced drought stress and advanced senescence in temporal typical grassland (figure 7(b)), and in cropland/grassland mosaic (figure 7(d)). In addition, we also found that the mean NDVI during the growing season in temporal typical grassland was significantly and positively related to summer (June–July–August) precipitation, and negatively related to summer temperature. Therefore, temperature-induced drought stress, which was found to reduce growth in high northern latitudes in the twentieth century (Barber et al. 2000), could also occur in the NECT, the middle latitude region. In the humid region of NECT, i.e. the eastern part of NECT, the effects of water stress on phenology dynamics were less (figure 7(h)). Ni (2003) also found that the combined effect of precipitation and temperature is significantly correlated with the distribution of plant functional types (PFTs) in NECT, especially for C3 species (i.e. plants that survive solely on C3 carbon fixation in photosynthesis) and forbs (broad-leaved herbaceous plants).

Human disturbance, such as agricultural management and land use change, could mask the correlation between phenology dynamics and climate variation (Geerken and Iliawi 2004). As we showed above, for the dryland cropland and pasture in the eastern part of NECT, the greenup onset delayed significantly, with little correlation with climate variation (figure 7(g) and (h)); the maturity dates and senescence dates of
(a) 

(b) 

(c) 

(d) 

(e) 

(f) 

(g) 

(h)
dryland cropland and pasture had the smallest inter-annual variation (figures 5(b) and 6(b)). The results suggest that agricultural management practices, such as changing planting dates according to local climate and water conditions, should influence phenology more than climate.

In addition, the inter-annual climate variability is larger in the temperate typical grassland area in comparison to other areas (see also Ni and Zhang 2000). The phenology of temperate typical grassland is more sensitive to seasonal climate variability and consequently has larger inter-annual variability in comparison to other vegetation (figures 4(b), 5(b) and 6(b)).

5.2 Regional land surface phenology algorithms

In comparison with previous algorithms (e.g. Piao et al. 2006), ARLSPD is objective and flexible in detecting more detailed regional land surface phenology dynamics, which have been documented to influence exchange of heat, moisture and momentum between the land surface and the atmosphere substantially (e.g. Sellers et al. 1995). As the first step, we only demonstrate ARLSPD in the NECT in this paper; we are applying it in other regions with annual multiple growth cycles. As we showed above, theoretically it is also applicable in complex ecosystems characterized by annual multiple growth cycles. ARLSPD can be expected to couple with large-scale biogeochemical models to regulate dynamically land surface phenology.

6. Conclusions

In this study, we presented a quantitative, objective and flexible regional phenology algorithm ARLSPD, and demonstrated it in the NECT in detecting the vegetation response to inter-annual climate variability. ARLSPD, theoretically also applicable to complex ecosystems characterized by annual multiple growth cycles, can be expected to couple with large-scale biogeochemical models to regulate dynamically land surface phenology.

In the NECT, the mid-latitude semi-arid terrestrial transect, drought stress and human disturbance could complicate the relationship between land surface phenology and seasonal temperature variation. Besides human disturbance, land surface phenology depended primarily on the combined effects of preseason temperature and precipitation. The relative influence of preseason temperature and precipitation on land surface phenology was changing, which led to the different responses of land surface dynamics to climate variation along the moisture gradient in the NECT. In the arid and semi-arid region of NECT, temperature-induced drought stress during the preceding months could delay greenup onset and advance senescence.

Figure 7. Trends in mean phenological transition dates (in days of year: DOY) and their correlations with seasonal temperature (T) and precipitation (P) variations in temperate typical grassland at meteorological stations 1, 2, 3 and 4 in figure 1 ((a) and ((b)), in cropland/grassland mosaic at stations 5, 6 and 7 ((c) and (d)), in dryland cropland and pasture in the semi-arid and semi-humid region at stations 8, 9, 10 and 11 ((e) and (f)), and in dryland cropland and pasture in the semi-humid region of NECT at stations 12, 13 and 14 ((g) and (h)). For greenup, maturity and senescence, the x-coordinate (i) denotes, respectively, the period from i months before early May through early May, before early August through early August, and before early October through early October. For example, the number 2 denotes the period from early March to early May for greenup, from early June to early August for maturity, and from early August to early October for senescence.
ARLSPD and its successful application in the NECT further demonstrate the potential to investigate the complex interactions between atmosphere and land surface, as well to detect regional ecosystem problems, using multi-year satellite observations.

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