Applicability of remote sensing-based surface temperature regimes in determining deciduous phenology over boreal forest

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INTRODUCTION

Vegetation phenology is the science of understanding the periodic/cyclic events associated with the plant developmental stages and mainly associated with climatic regimes (Delpierre et al. 2009; Morisette et al. 2009). Over boreal ecosystems, the phenological stages of deciduous tree/plant(s) can broadly be grouped into the categories of (i) bud burst (ii) deciduous leaf out (DLO), (iii) maximum green-up, (iv) leaf senescence timing, (v) deciduous leaf fall and (vi) commence of snowfall (Delbart et al. 2006; Delpierre et al. 2009; Duchemin et al. 1999; Hanes and Schwartz 2010; McClay 2010; Reed et al. 2009). In general, these stages provide valuable information regarding: (i) plant growth (Hari and Nojd 2009), (ii) plants’ ability of exchanging atmospheric carbon dioxide (Cleland et al. 2007), (iii) forest ecohydrology, e.g. evapotranspiration, precipitation, soil moisture, canopy moisture, etc. (Wilson and Baldocchi 2000) and (iv) risk of insect infestation (Hogg 1999), among others.

The most accurate and widely used method of determining the deciduous phenological stages is the employment of in situ observations (Beaubien and Hamann 2011; White et al. 2009). Despite its accuracy, it only provides site-specific information over relatively smaller geographical extent (several hundreds of square metres). Thus, in order to address the spatial dynamics over a large area, it requires alternate approaches. In this context, remote sensing-based methods can be such an alternate, which have already been proven as an effective technological advancement in determining various phenological stages over various biomes across the world (Cleland et al. 2007).
In most of the instances, remote sensing-based vegetation and water content indices are commonly used ones in determining various vegetation developmental stages, e.g. green-up, maturity, etc. Those include the application of (i) normalized difference vegetation index (NDVI: a measure of vegetation greenness) in determining the onset of green-up over temperate deciduous broadleaf forests in France (Duchemin et al. 1999; Soudani et al. 2008) and boreal forest in northern Eurasia (Delbart et al. 2006), (ii) enhanced vegetation index (EV1: a measure of vegetation greenness and canopy structure; Huete et al. 2002) in determining the onset of green-up over deciduous broadleaf forest in USA (Ahl et al. 2006; Liang et al. 2011) and boreal-forested regions in Canada (Sekhon et al. 2010), (iii) leaf area index (LAI: a measure of one-sided green leaf area per unit ground area; Chen and Black 1992) in defining the vegetation maturity over mixed temperate deciduous forest in USA (Hanes and Schwartz 2010) and (iv) normalized difference water index (NDWI: a measure of water/ice/moisture in the canopy) in defining the DLO over boreal forest in central Siberia (Delbart et al. 2005); among others. The temporal trends of these indices are used for detecting the changes in biophysical and/or biochemical characteristics of the vegetation associated with the phenological stage (McCloy 2010; Xiao et al. 2009). Recent studies suggest that the application of both NDVI and EVI in predicting the spring onset induces uncertainty due to the presence of snow on the ground over the boreal-dominant regions in particular (Delbart et al. 2006; Sekhon et al. 2010). Thus, we may assume that the application of LAI also may be affected in a similar fashion. On the other hand, the implementation of NDWI reveals that it is capable of determining the vegetation developmental phases independent of the snow conditions (Delbart et al. 2006; Reed et al. 2009; Sekhon et al. 2010). In general, the temporal trends of these indices are able to determine several phenological stages, such as onset, maturity and end of the growing season depending on the type of the forested ecosystems (Delbart et al. 2005; Zhang et al. 2003). However, some of the intermediate phenological stages (e.g. DLO) during the growing season may require further investigation.

In general, the responses of vegetation are largely controlled by the climatic variables (Hassan and Bourque 2009); while remote sensing-based surface temperature ($T_s$) products have been used to determine deciduous phenology, it has been limited in use. For example: (i) Hanes and Schwartz (2010) determined the dynamics of leaf out in a deciduous-dominant mixed temperate deciduous forest in USA as a function of accumulated growing degree days (AGDD: defined as the favourable temperature regime for plant growth) and (ii) Zhang et al. (2004) determined the green-up onset as a function of accumulated chilling days (i.e. days with temperatures experiencing less than a threshold value) in the northern hemisphere between 35 and 70°N. In both of the above cases, Moderate Resolution Imaging Spectroradiometer (MODIS)-based $T_s$ products were directly used without transforming them into equivalent daily average air temperature. As, for the calculation of growing degree days (GDD) and chilling days, it would be very common to use such average air temperature measured near the surface (Li et al. 2010). In this context, the GDD mapping methods (as described in Akther and Hassan 2011; Hassan et al. 2007a, 2007b) using MODIS-based $T_s$ products in conjunction with ground-based air temperature measurements would be a viable alternate.

In this paper, our overall goal was to determine the deciduous phenological stage of DLO associated with trembling aspen (Populus tremuloides) using MODIS-based $T_s$ images over the boreal-dominant forested regions in the Canadian Province of Alberta. The specific objectives were to (i) determine AGDD threshold for predicting DLO at lookout tower sites (for location information see Fig. 1) during 2006, (ii) implement the observed threshold in objective (a) during the period 2007–2008 and compare the predictions with the observed values at the lookout tower sites and (iii) generate DLO maps and discuss their spatial dynamics.

**MATERIALS AND METHODS**

**General description of the study area**
We considered the Canadian Province of Alberta as our study area, which lies in between 49°–60°N latitude and 110°–120°W longitude (Fig. 1). Topographically, the relief ranges from 150 to 3650 m above mean sea level. Climatically, it experiences relatively humid conditions (i.e. annual precipitation in the range 260–1710 mm) with short summers, long and cold winters (where the average annual temperature in the range −7.1 to 6°C) (Dowing and Pettapiece 2006). The province is divided into six natural regions on the basis of climate, soil and vegetation types; and their brief descriptions are provided in Table 1. Among the forest-dominant regions, the most dominant deciduous species are found to be trembling aspen and balsam poplar (Populus balsamifera) (Li et al. 2010). The spatial distribution of the deciduous-dominant stands in the province at 30 m spatial resolution was obtained from Alberta Sustainable Resource Development (SRD) (see the grey shades in Fig. 1a) and the dynamics of DLO were only determined within the deciduous-dominant stands. However, this map was resampled to 500 m spatial resolution to align with the MODIS data set. In this process, we employed dominant method for the up-scaling, which was based on counting dominant values (in this case deciduous-dominant stands) within 17 × 17 window (i.e. ~500 m × 500 m) of the original map. In the resultant map, we found negligible changes (i.e. <1%) in the total area in comparison to the original map.

**In situ phenological and air temperature data**
We obtained phenological data for DLO at the lookout tower sites (marked with black circles in Fig. 1) available from Alberta
Figure 1: (a) map of Alberta showing the location of (i) Environment Canada weather stations where the daily average air temperature was acquired at a height between 1.2 and 2 m above the ground surface and (ii) lookout tower sites where DLO in situ observations were acquired, along with the boundaries of the natural regions. (b) digital elevation model of Alberta along with the location of lookout tower sites.

Table 1: brief description of the study area after Dowing and Pettapiece (2006)

<table>
<thead>
<tr>
<th>Natural region no.</th>
<th>Natural region name</th>
<th>% of Alberta</th>
<th>Mean annual temperature (°C)</th>
<th>Mean annual precipitation (mm)</th>
<th>Main vegetation coverage</th>
<th>Number of lookout towers (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Boreal</td>
<td>55.3</td>
<td>−0.2</td>
<td>469</td>
<td>Mixedwood: dominant aspen, white spruce and black sprue, shrubby understories, jack pine</td>
<td>68</td>
</tr>
<tr>
<td>II</td>
<td>Canadian Shield</td>
<td>3.5</td>
<td>−2.6</td>
<td>380</td>
<td>Rock barrens (mixed with aspen, open jack pine, birch), dry jack pine forests, dunes largely unvegetated</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>Foothills</td>
<td>10.3</td>
<td>1.7</td>
<td>603</td>
<td>Mainly closed coniferous forests (aspen-lodgepole pine, lodgepole pine-black spruce, white spruce)</td>
<td>33</td>
</tr>
<tr>
<td>IV</td>
<td>Parkland</td>
<td>9.2</td>
<td>2.3</td>
<td>447</td>
<td>Aspen forests with grass lands</td>
<td>0</td>
</tr>
<tr>
<td>V</td>
<td>Rocky Mountain</td>
<td>7.4</td>
<td>−0.4</td>
<td>798</td>
<td>Mixed aspen and conifer forests (lodgepole pine, white spruce, douglas fir)</td>
<td>11</td>
</tr>
<tr>
<td>VI</td>
<td>Grassland</td>
<td>14.3</td>
<td>4</td>
<td>374</td>
<td>Grasslands (blue grama, needle and thread), shrublands</td>
<td>0</td>
</tr>
</tbody>
</table>
SRD during the period 2006–2008. The DLO stage was defined as the time when 75% or more of the leaves would open with a length of at least 1.25 cm in diameter for the trembling aspen trees in the surrounding area of a lookout tower sites (FFMT 1999). The number of lookout tower sites was ~110 per year and these were spanning approximately in the (i) elevation range 350–2500 m and (ii) latitude range 49–60°N. In general, we observed that the timing of DLO increased from low to high latitudes and/or elevations. These data were recorded in the form of day of year (DOY: 1–365 or 366 depending on the leap year), thus we transformed them into equivalent 8-day period coinciding with that of MODIS 8-day composites using the following expression (Sekhon et al. 2010):

\[ P = \left( \frac{\text{DOY} - 1}{8} \right) + 1, \]  

where \( P (=1–46) \) is the equivalent number of periods that falls during the MODIS 8-day composites, and always, it will be an integer (e.g. \( P = 24 \) if the Eq. 1 produces values in the range 24.125–24.875). Upon implementation, we observed the average period of DLO was the 18th period for the years 2006–2008.

We also obtained daily average air temperature acquired at 1.2–2 m above the surface at 182 weather stations (for location information see Fig. 1) during the years 2006–2008, available from Environment Canada. These data were averaged at 8-day intervals, which also had to coincide with the MODIS 8-day composites. Both of the phenological and air temperature data sets were employed in calibrating and validating MODIS-based estimations of DLO stage.

**Satellite data and their processing**

We used MODIS-based data available from NASA during the growing seasons (i.e. April–October) for the years 2006–2008. These included (i) 8-day composites of \( T_s \) (i.e. MOD11A2 V.005) at 1 km spatial resolution and (ii) 8-day composites of surface reflectance (MOD09A1 V.005), which were then used to calculate EVI at 500 m spatial resolution using the following expression (Huete et al. 2002):

\[ \text{EVI} = \frac{2.5 (\rho_{\text{NIR}} - \rho_{\text{Red}})}{\rho_{\text{NIR}} + 6\rho_{\text{Red}} - 7.5\rho_{\text{Blue}} + 1}, \]  

where \( \rho \) is the surface reflectance for the near infrared (NIR), red and blue spectral bands. We preferred to calculate the EVI images at 8-day intervals to match the temporal resolution of the \( T_s \) images instead of MODIS EVI products (i.e. MOD13Q1 V.005, only available in the form of 16-day composites). Both of the data sets (i.e. \( T_s \) and EVI) were used to calculate GDD by adopting the empirical methods described in Akther and Hassan (2011). It consisted of several steps:

(i) We extracted the MODIS-based instantaneous 8-day composites of \( T_s \) at each of the single pixels (i.e. acquired between 10:30 and 12:00 local time) at the 182 weather stations and compared them with the 8-day average air temperature (\( T_s \)) during 2006 (Fig. 2a).

(ii) In order to validate the observed relation in Step (i), we used it at the sites of the same 182 weather stations during the years 2007–2008 and compared with the \( T_s \) (Fig. 2b).

(iii) We then applied the observed relation in Fig. 2a in converting the MODIS-based \( T_s \) images into equivalent \( T_s \). These were then used to calculate GDD maps at 1 km spatial resolution using the following expression (Heidi and Ari 2008):

\[ \text{GDD} = T_s - T_{\text{base}}, \]  

where \( T_{\text{base}} \) is the base temperature (=278.15 K), which is considered to be the minimum requirement for plant growth in our study area (Dowing and Pettapiece 2006; Hassan et al. 2007b). (iv) We implemented a data fusion technique initially described in Hassan et al. (2007a) in enhancing the spatial resolution of GDD maps from 1 km to 500 m using EVI images as a basis of fusion. It was possible as GDD and EVI were found to be linearly correlated (i.e. \( r^2 = 0.87 \); Hassan et al. 2007b). Mathematically, the data fusion process could be expressed as follows (Hassan et al. 2007a):

\[ \text{GDD}_{500m} = \frac{\text{EVI}_{\text{ins}}}{\text{EVI}_{\text{avg}}} \times \text{GDD}_{1km}, \]  

where \( \text{EVI}_{\text{ins}} \) is the instantaneous value of EVI at the centre of a 3 × 3 moving window, \( \text{EVI}_{\text{avg}} \) is the average value of all of the EVI values within the moving window. The ratio between \( \text{EVI}_{\text{ins}} \) and \( \text{EVI}_{\text{avg}} \) acts as a weighted function in the calculation of GDD at 500 m resolution. (v) At each of the period, we calculated AGDD using the following expression:

\[ \text{AGDD} = \sum_{i=1}^{n} (8 \times \text{GDD}_{500m}), \]  

where \( i \) is the first 8-day period of the growing season and \( n (=1–27) \) is the 8-day period of interest during the growing season.
Determining DLO threshold and its implementation

During the years of 2006–2008, we extracted the temporal trends of both GDD and AGDD at the lookout tower sites with available in situ DLO records. For the determination of DLO threshold, we divided the data set into calibration and validation ones. We used ~34% data points (i.e. during 2006) in calibration and the remaining ~66% data points (i.e. during 2007–2008) in validation purposes. We performed the calibration for DLO in two distinct steps:

(i) Calculated the average and standard deviation (SD) of AGDD during the average in situ DLO observation period. The observed average AGDD value was then considered as an initial ‘threshold’ for DLO determination (i.e. either equal or greater amount of AGDD would be the minimum requirement for DLO occurrence).

(ii) Performed sensitivity analysis for the initial threshold in determining the DLO stage in the range ‘initial threshold ± 1 SD’. The optimal threshold was then determined when deviations between the predicted and observed DLO period would be reasonable for the most of the cases (for more details, see ‘Results’ section and Table 2). In terms of illustrating early and delayed predictions with compare to the in situ DLO observation periods, we used the signs of ‘−’ and ‘+’ deviations, respectively, throughout the manuscript.

In the scope of validation, we predicted the periods for DLO during the years 2007–2008 using the optimal threshold observed in the calibration phase as discussed above. We then calculated the deviations between the predicted and observed DLO periods in determining the agreements between the data sets (for more details, see ‘Results’ section and Table 3). Finally, we generated the spatial dynamics of DLO using the optimal threshold over the deciduous-dominant stands shown in Fig. 1.

Table 2: implementation of different AGDD thresholds in determining the optimal threshold by evaluating the deviations between observed and predicted DLO periods at each of the lookout tower sites using the data from 2006

<table>
<thead>
<tr>
<th>AGDD threshold</th>
<th>0</th>
<th>±1</th>
<th>±2</th>
<th>±3</th>
<th>±4</th>
<th>±5</th>
<th>±6</th>
<th>±7</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>30.4</td>
<td>87.8</td>
<td>98.3</td>
<td>99.1</td>
<td>99.1</td>
<td>99.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>31.3</td>
<td>87.8</td>
<td>98.3</td>
<td>99.1</td>
<td>99.1</td>
<td>99.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td><strong>80</strong></td>
<td><strong>35.7</strong></td>
<td><strong>86.1</strong></td>
<td><strong>98.3</strong></td>
<td><strong>99.1</strong></td>
<td><strong>99.1</strong></td>
<td><strong>99.1</strong></td>
<td><strong>100</strong></td>
<td>100</td>
</tr>
<tr>
<td>90</td>
<td>39.1</td>
<td>80.9</td>
<td>94.8</td>
<td>99.1</td>
<td>99.1</td>
<td>99.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>34.8</td>
<td>73.9</td>
<td>92.2</td>
<td>98.3</td>
<td>99.1</td>
<td>99.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>33.0</td>
<td>67.8</td>
<td>87.0</td>
<td>96.5</td>
<td>99.1</td>
<td>99.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>27.8</td>
<td>60.9</td>
<td>81.7</td>
<td>93.0</td>
<td>98.3</td>
<td>98</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>20.9</td>
<td>53.9</td>
<td>77.4</td>
<td>91.3</td>
<td>97.4</td>
<td>97</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>13.9</td>
<td>47.0</td>
<td>68.7</td>
<td>89.6</td>
<td>97.4</td>
<td>97</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

The bold row indicates the optimal threshold and its performance.

RESULTS

Relation between MODIS-based $T_s$ and 8-day average air temperature

The relation between MODIS-based instantaneous 8-day composites of $T_s$ and 8-day average air temperature ($\bar{T_a}$) during 2006 revealed reasonably strong relations (i.e. $r_s^2 \approx 0.69$ with a slope of 0.61 ± 0.01 and intercept of 103.66 ± 3.55 at 95% confidence level for the regression line with $P$ value < 0.0001; Fig. 2a). We observed a similar relationship (i.e. $r_s^2 \approx 0.70$ with a slope of 0.78 ± 0.01 and intercept 63.17 ± 3.05 at 95% confidence level for the regression line with $P$ value < 0.0001; Fig. 2b) for ~97% of the cases during 2007–2008 period. The remaining 2.87% of the data points (i.e. 254 of 8848) were found to be in southern Alberta, where the land cover is primarily agriculture area and therefore excluded from the above-mentioned analysis. Note that similar agreements (i.e. $r_s^2 \approx 0.70$) were also observed in other studies (Akther and Hassan 2011).

Determination of DLO threshold and its validation

Fig. 3a illustrates the averaged temporal trends of GDD and AGDD during 2006 upon considering all of the 115 lookout tower sites. We found that the initial AGDD threshold was 101 degree days with a SD of ±40 degree days during the period of in situ DLO as shown with the vertical dotted line in Fig. 3a. We then analysed the distribution of the individual AGDD thresholds (Fig. 3b); ~82% of the cases were found to be in the range 60–140 degree days (i.e. ~initial threshold ± 1 SD). Due to the observed variability’s in the individual AGDD thresholds, we performed a sensitivity analysis for the range 60–140 degree days (Table 2). We decided that the threshold of 80 would be the optimal selection; which yielded 35.7, 86.1, and 98.3% agreements under various climatic conditions (e.g. dry, normal and wet, e.g. some areas in northeast, northwest and southern Alberta, while the land cover is primarily agriculture area and therefore excluded from the above-mentioned analysis. Note that similar agreements (i.e. $r_s^2 \approx 0.70$) were also observed in other studies (Akther and Hassan 2011).

Spatial dynamics of DLO

Fig. 4 shows the spatial dynamics of DLO over the deciduous-dominant stands across Alberta during 2008 upon applying the observed optimal threshold of AGDD. It revealed that the DLO occurred during the periods 17–19 (i.e. 8–31 May 2008) for ~85% of the cases (Fig. 4).
Table 3: relation between observed and predicted DLO periods at each of the lookout tower sites during 2007–2008 using the optimal AGDD threshold of 80 degree days

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of lookout tower sites (n)</th>
<th>Deviations (in periods)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2007</td>
<td>110</td>
<td>30.9</td>
</tr>
<tr>
<td>2008</td>
<td>113</td>
<td>37.2</td>
</tr>
<tr>
<td>2007–2008</td>
<td>223</td>
<td>34.1</td>
</tr>
</tbody>
</table>

The ‘+ve’ and ‘−ve’ signs represent positive (i.e. delayed) and negative (i.e. early) predictions, respectively.

**DISCUSSION**

**AGDD threshold for determining DLO**

The variability in AGDD (i.e. ~82% of the cases in between 60 and 140 degree days) thresholds during the calibration phase (Fig. 3b) might be related with one or more of the following causes:

(i) Apart from the temperature regimes, the phenological stages would also be influenced by other climatic variables, e.g. photosynthetically active radiation and water regimes, which were not considered in the scope of this study.

(ii) Some other climatic condition during the prior winter season, i.e. the fulfillment of the chilling requirements would also a critical parameter (Morin et al. 2009).

(iii) It would be possible that the optimal amount of nutrient might not be available for all of the lookout tower sites.

(iv) Biological factors, such as the inter- and intra-species competition, were not take into consideration.

(v) The differences in genetic compositions among the inter- and intra-species might differ in terms of their growth requirements observed in other studies (Li et al. 2010), among others.

Upon analysing the sensitivity of the AGDD threshold (for details see Table 2), we found the optimal threshold (i.e. 80 degree days). This AGDD threshold was found to be similar (i.e. in the range 80–100 degree days) when compared to other studies conducted over western Canadian boreal forests (Barr et al. 2004; Parry et al. 1997).

During the DLO validation phase, the relatively high deviations (i.e. >±2 periods) between the MODIS-predicted and in situ observations were found to be ~10% of the cases. These were attributed due to the following reasons:

(i) The in situ measurements were on the basis of visual observations, thus, the operators’ interpretation skills would be critical (Sekhon et al. 2010).

(ii) At each of the lookout tower sites, ~20 to 100 trees were sampled to define the occurrence of the phenological stage of interest (Dylan Heerema: a veteran lookout tower operator, personal communication). Thus, it would be possible that the spatial resolution of the in situ observations might not have similar dimension as of MODIS data for some cases.

(iii) One global threshold might not be able to delineate the entire spatial dynamics across the study area (Li et al. 2010).

**Robustness of AGDD threshold**

The optimal threshold of AGDD (i.e. 80 degree days) for DLO was determined using the calibration data from the year 2006 and then evaluated using the validation data from the period 2007 to 2008. The observed agreements in calibration (i.e. ~98.3% of the cases) and validation (i.e. ~91.9% of the cases) phases were similar. Despite these reasonable agreements, it would be important to investigate how robust these thresholds under various climatic conditions (e.g. dry, normal and wet years). Such climatic conditions in comparison to long-term average data during the period 1960–2007 were reported by Alberta Department of Agriculture and Rural Development (ACIS 2009) and summarized over the forested regions as follows:

(i) During 2006, the climatic conditions were spanning from dry to wet, e.g. some areas in northeast, northwest and southwest were having dry conditions.

(ii) The year 2007 was mostly near normal to wet except some pockets of dry areas in northeast and southwest

(iii) The year 2008 was mostly dry except some pockets.

**Spatial dynamics of DLO**

In terms of the spatial dynamics of DLO stage, we observed the following generalized patterns:

(i) The occurrence of DLO was found to be relatively earlier (≤16 period, i.e. before 8 May 2008) primarily in the natural
region of parkland and also along the river bodies. These are related to the fact that these regions experience relatively warm temperature regimes (Dowing and Pettapiece 2006). (ii) The timing of DLO occurrence happened to be delayed towards northward directions. This would be related to the fact that temperature regimes decrease in the northward directions in the northern hemisphere (Hassan et al. 2007b; Sekhon et al. 2010).

Contributions

In the scope of this paper, we studied a topical theme, i.e. application of remote sensing in understanding vegetation phenology. However, it would be worthwhile to note that the proposed methodology (i.e. integration of MODIS-based TV and EVI products) is unique in mapping the beginning (i.e. leaf out) of the growing season for the deciduous-dominant stands over boreal-forested regions. Apart from the general applications of phenological stages mentioned in the first paragraph of ‘Introduction’ section, we believe that the DLO stages could also be important in (i) understanding forest fire danger conditions, (ii) modelling of forest fire behaviour in the event of fire occurrences and (iii) quantifying the impact of climate change (Cleland et al. 2007), among others.

CONCLUDING REMARKS

Here, we demonstrated the potential of MODIS-based AGDD in determining the phenological stage of DLO over the boreal-forested regions in Alberta. It revealed that the DLO could be determined with reasonable agreements (i.e. within ±2 periods or ±16 days of deviations) for 91.9% of the cases. The proposed methods would be useful in delineating DLO stage in the remote areas of the landscape, where the in situ observations would be difficult. However, it would be worthwhile to mention that the suitability of the optimal AGDD (i.e. 80 degree days) should be evaluated against longer time period.

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REFERENCES


