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Environmental Modelling
(ENGO 583/ENEN 635)

Lecture Note
on:
Modelling of Vegetation Phenological Stages

Dept. of Geomatics Engineering; and Centre for Environmental Engineering Research and Education
Schulich School of Engineering
University of Calgary

Review of Last Topics

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Topics of Discussion:
Vegetation Phenological Modelling

- **What is vegetation phenology and its importance.**
- **Forest in Canada.**
- **Phenology associated with boreal forest.**
- **Methods of determining phenological stage:**
  - **Ground-based observations**
  - **Modelling of the phenological stages**
  - **Remote sensing-based methods**
- **Case studies**
  - **"Evaluating potential of MODIS-based indices in determining "snow gone" stage over forest-dominant regions."**
  - **"Applicability of remote sensing-based surface temperature regimes in determining deciduous phenology over boreal forest."**

(Sekhon et al., 2010; Hassan and Rahman, 2013)

What is Vegetation Phenology and Its Importance?

- **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).**
- **The phenology for the same species may be differ at different locations within the same geographical region (i.e., spatially dynamic).**
- **In case of forested ecosystem, the understanding of the vegetation phenology is important in relation to several issues, such as:**
  - **vegetation growth,**
  - **rate of carbon sequestration,**
  - **hydrological cycle,**
  - **insect outbreak, and**
  - **forest fire vulnerability, etc.**

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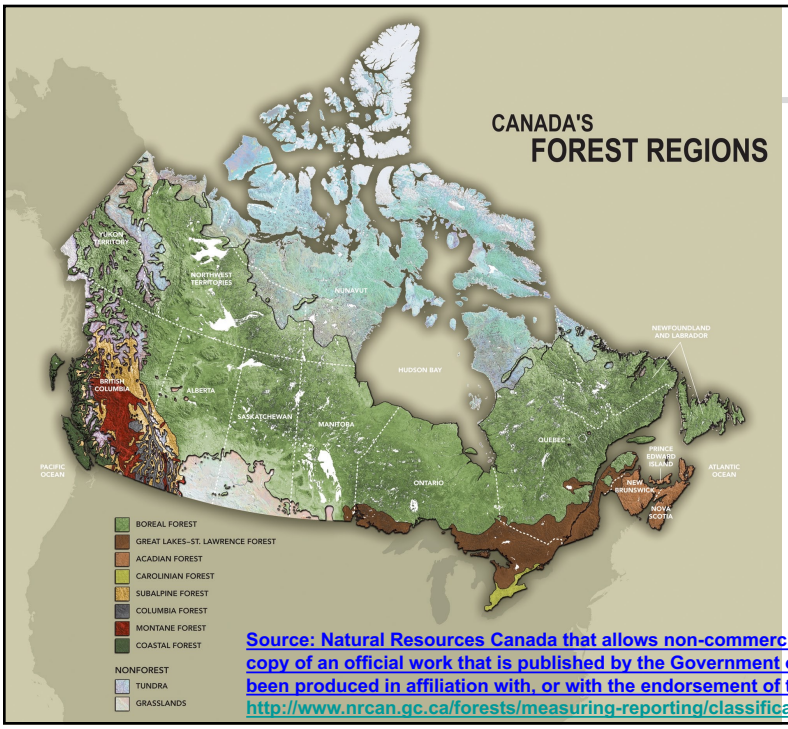
Forest in Canada



- Canada posses ~10% of the global forest
- Forest occupies ~45% of Canada's landmass
- ~77% of the forested area is known as boreal forest

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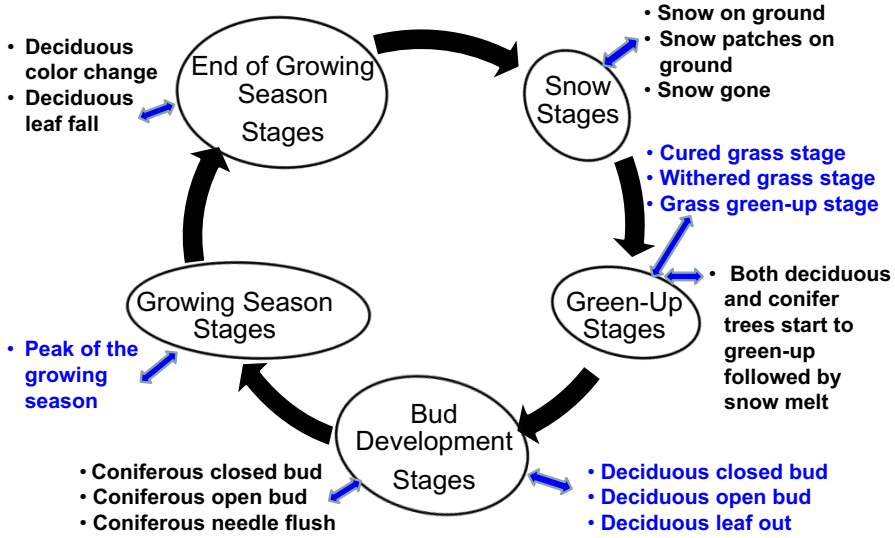
Phenology Associated with Boreal Forest

The phenological events of boreal forest are broadly classified into the four categories (Sekhon and Hassan, 2010):

- snow stages,
- understory stages,
- deciduous stages, and
- conifer stages.



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Methods of Determining Phenological Stages

The most commonly used methods of determining the phenological stages include (Sekhon and Hassan, 2010):

- **Ground-based observations**
- **Modelling of the phenological stages**
- **Remote sensing-based methods**

Methods of Determining Phenological Stages: Ground-based Observations (1)

- **Historically people have been observing phenological stages due to their cultural or agricultural importance, and for scientific reasons at the recent time.**
- **These observations of phenology are most accurate.**
- **Historic data for some species are available in eastern and European continents.**
- **Alberta Department of Sustainable Resource Development has been recording phenological stages since 1970's.**
- **USA National Phenological Network was established recently to record such data.**
- **Similar other networks also have been operating, e.g.,**
  - **Project Bud Burst,**
  - **Plant Watch,**
  - **Nature's Calendar, and**
  - **European phenology network, etc.**

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Methods of Determining Phenological Stages:
Ground-based Observations (2)

Limitations:

- **Observations are made by individuals subjectively, thus potentially may vary from person to person**
- **Observations are point specific, thus fail to address the spatial dynamics over a large area**
- **Observations are impossible in remote areas**
- **Observations are very scarce to understand dynamics on landscape levels**

Methods of Determining Phenological Stages:
Modelling of the Phenological Stages

- **The important climatic variables in boreal forested ecosystem is favourable temperature (e.g., growing degree days) and soil water content.**
- **Some other controlling variables are soil nutrients, chilling requirements, inter and intra species competition, site adaptability etc.**
- **By gathering information about the regimes of the climatic variable(s) and its coincidence with the phenological stage of interest should be analysed. In such cases, a threshold value of the climatic variable(s) of interest should be determined.**
- **The determined threshold is to be used to model phenological stage on either temporal scale (for other years), spatial scale(throughout the landscape), or both.**

Limitations

- **These are, in general, site or region-specific as the climatic variable(s) are often measurement at point locations. Also, it is difficult to obtain their estimates at remote locations. Thus, generating reasonable maps of climatic variable(s) are quite challenging.**

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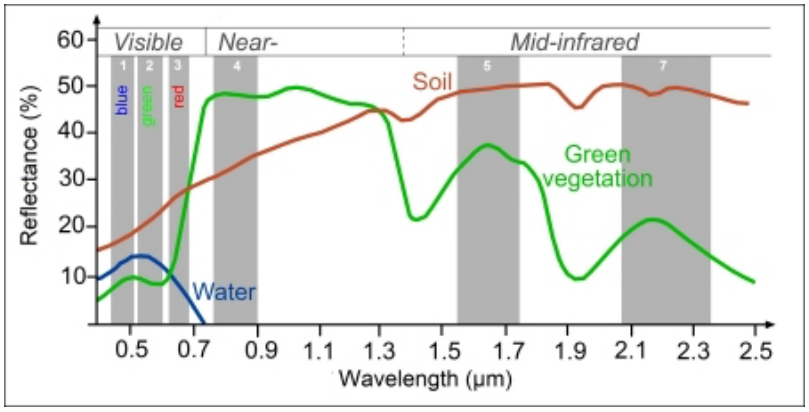
Methods of Determining Phenological Stages: Remote Sensing-based Methods (1)

- **Remote sensors acquire images of the earth surface at different resolutions/scales (spatial, temporal, and spectral), which are useful to comprehend vegetative conditions and their phenological stages.**
- **In such cases, some of the most commonly used remote sensing-based indices in phenological studies include:**
  - **Normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI); both are a measure of greenness**
  - **Normalized difference water index (NDWI: a measure of water content in the vegetation)**
  - **Normalized difference snow index (NDSI: a measure of snow on the ground)**
- **The temporal dynamics of the above-mentioned indices may provide informational about various phenological stages.**

Methods of Determining Phenological Stages: Remote Sensing-based Methods (2)

Use the following spectral response curve of vegetation to calculate NDVI, EVI, NDWI, and NDSI



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$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$$

$$EVI = 2.5 \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + 6\rho_{Red} - 7.5\rho_{Blue} + 1}$$

$$NDWI_{2.13\mu m} = \frac{\rho_{NIR} - \rho_{SWIR\ at\ 2.13\mu m}}{\rho_{NIR} + \rho_{SWIR\ at\ 2.13\mu m}}$$

$$NDSI = \frac{\rho_{Green} - \rho_{SWIR\ at\ 1.64\mu m}}{\rho_{Green} + \rho_{SWIR\ at\ 1.64\mu m}}$$

ρ is the reflectance from the respective spectral band

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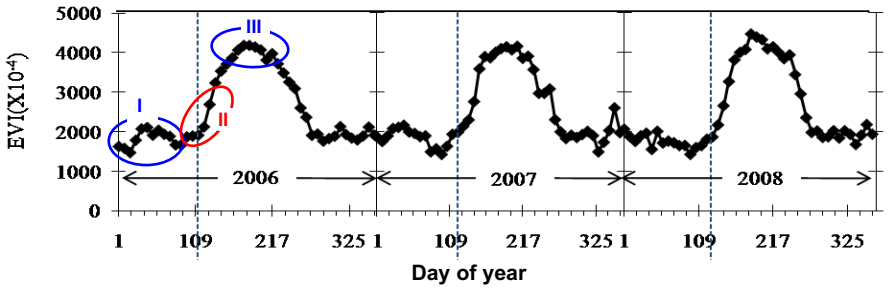
Methods of Determining Phenological Stages: Remote Sensing-based Methods (3)



- EVI-values exhibit low magnitudes during the winter season.
- EVI-values start to increase following the snowmelt (see dotted vertical line indicates snow disappearance).
- However, EVI values doesn't saturate during the peak of growing season over dense vegetation.

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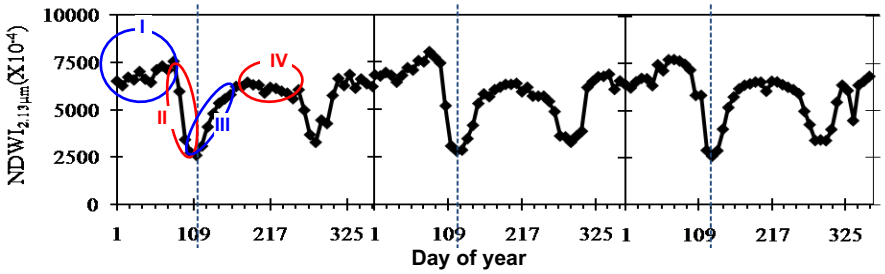
Methods of Determining Phenological Stages: Remote Sensing-based Methods (4)



- Initially the values of NDWI are high during the snow covers.
- NDWI-values decrease with snow melting.
- NDWI-values then increase with growing season. So, NDWI potentially captures greening-up free of snow effect and better than previously discussed indices.
- NDWI-values reach to high values during the peak of growing season and than start to drop at the end of the growing season.

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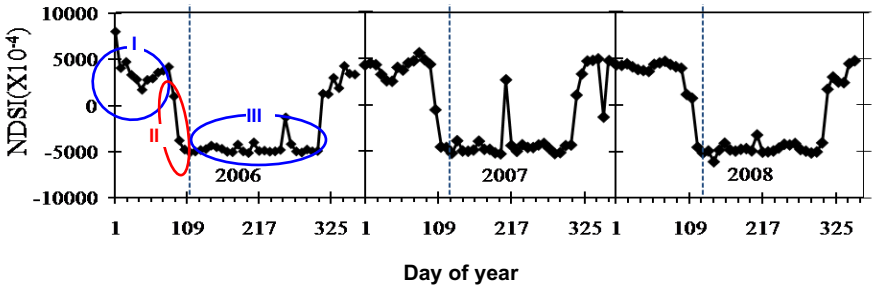
Methods of Determining Phenological Stages: Remote Sensing-based Methods (5)



- During the winter NDSI-values are high (≥ 0.40).
- NDSI-Values decrease with snow- melt.
- These values are negative until the begin of snow accumulation.

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Methods of Determining Phenological Stages: Remote Sensing-based Methods (6)

Limitations

- Atmospheric conditions often cause noise in the data.
- Some of the phenological stages don't have a clear indication, e.g., conifer needle flush, deciduous leaf out, deciduous leaf fall, etc.
- A threshold may be not be applicable over a large area or different biome.
- Both NDVI and EVI are unable to depict the onset of green-up over boreal forested regions due to snow melt effect.
- Ground observations are often required for validation.

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"Evaluating potential of MODIS-based indices in determining "snow gone" stage over forest-dominant regions"

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Determining Snow Gone Stage (SGN): Assumptions

- **Snow gone stage is defined as the date when 25% or less of the area surrounding a tower is covered by snow (FFMT, 1999).**
- **EVI may exhibit a fuzzy indication about the snow gone stage.**
- **NDSI may not be effective over forest-dominant regions.**
- **NDWI may be effective as demonstrated elsewhere. However, it may be calculated using various wavelengths within the SWIR spectral ranges, e.g., centered at 1.24 µm, 1.64 µm, and 2.13 µm.**
- **Here, we intend to use two SWIR bands from MODIS, *i.e.,* centered at 1.64 µm, and 2.13 µm.**

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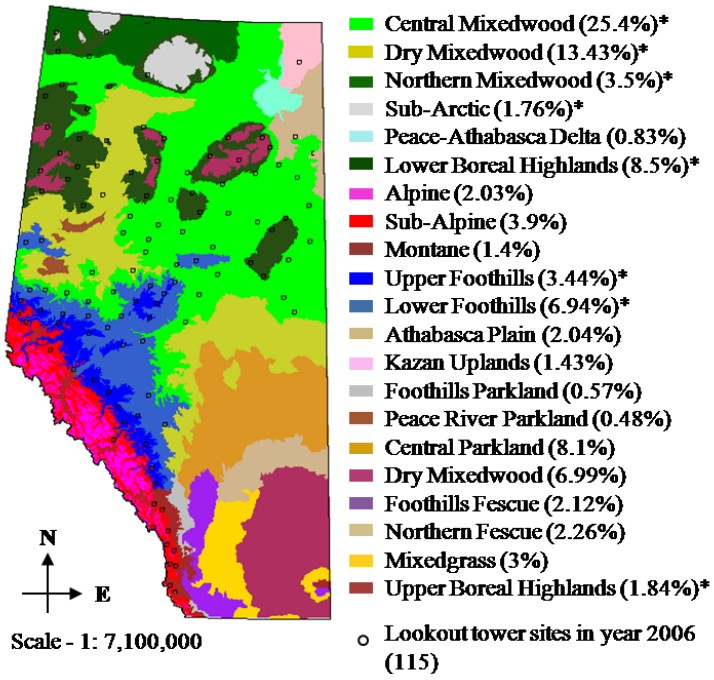
Determining Snow Gone Stage (SGN): Model Developments (1)

- Alberta consists of 21 natural subregions, where the 'Central Mixwood' covers ~25% of the total area.
- In this subregion, there were 24 lookout tower sites, where we measured the 'snow gone day'.
- Upon averaging these 'snow gone day' regimes, we then compared it against some spatial index at 500m resolution averaged over the entire subregion. Those include:
  - Enhanced vegetation index (EVI)
  - Normalized difference water index (NDWI)
  - Normalized difference snow index (NDSI)



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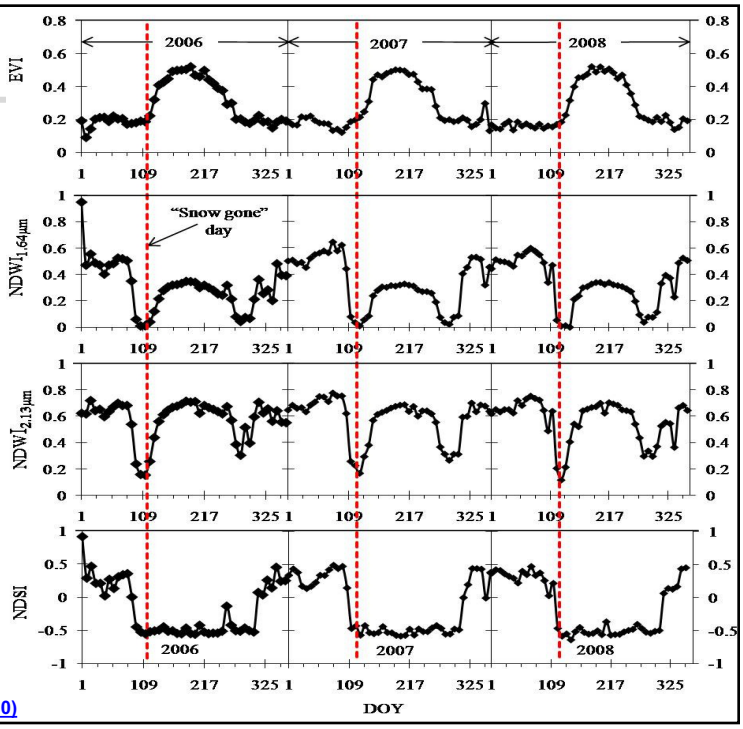
Determining Snow Gone Stage (SGN): Model Developments (2)

- The temporal trends of EVI did not clearly indicate the snow gone day.
- In terms of NDSI, we observed that the deviation between the ground-based observations of 'snow gone day' and NDSI-based estimates were found in the range of −3 to −5 periods (i.e., −24 days to −40 days).
- The NDWI's showed a distinct temporal pattern (*i.e.*, the lowest values were found in the early spring) with the ground-based 'snow gone day' stages, we considered these two as the efficient indices.



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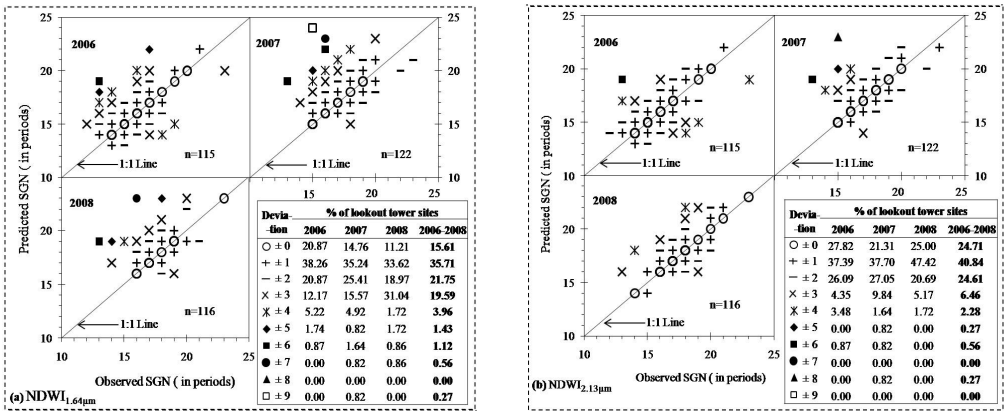
Determining Snow Gone Stage (SGN): Model Developments (3)



Deviation	% of lookout tower sites 2006	2007	2008	2006-2008
○ ±0	20.87	14.76	11.21	**15.61**
+ ±1	38.26	35.24	33.62	**35.71**
− ±2	20.87	25.41	18.97	**21.75**
× ±3	12.17	15.57	31.04	**19.59**
✳ ±4	5.22	4.92	1.72	**3.96**
◆ ±5	1.74	0.82	1.72	**1.43**
■ ±6	0.87	1.64	0.86	**1.12**
● ±7	0.00	0.82	0.86	**0.56**
▲ ±8	0.00	0.00	0.00	**0.00**
□ ±9	0.00	0.82	0.00	**0.27**

Deviation	% of lookout tower sites 2006	2007	2008	2006-2008
○ ±0	27.82	21.31	25.00	**24.71**
+ ±1	37.39	37.70	47.42	**40.84**
− ±2	26.09	27.05	20.69	**24.61**
× ±3	4.35	9.84	5.17	**6.46**
✳ ±4	3.48	1.64	1.72	**2.28**
◆ ±5	0.00	0.82	0.00	**0.27**
■ ±6	0.87	0.82	0.00	**0.56**
● ±7	0.00	0.00	0.00	**0.00**
▲ ±8	0.00	0.82	0.00	**0.27**
□ ±9	0.00	0.00	0.00	**0.00**

- **Right and left sides of the 1:1 line represent early and delayed prediction respectively.**
- **$NDWI_{2.13\mu m}$ demonstrated better prediction capabilities (i.e., on an average ~90% of the observations fell within ±16 days of deviation) in comparison to $NDWI_{1.64\mu m}$ (i.e., on an average ~73% of the observations fell within ±16 days of deviation).**

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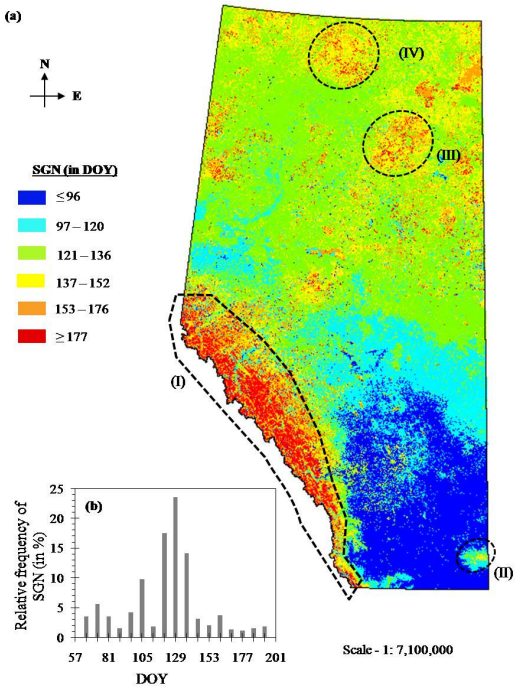
Determining Snow Gone Stage (SGN): Model Output

- **In general, temperature decreases northwards in the northern hemisphere (Hassan et al., 2007), so that the northward increment of SGN stages in our study would be expected.**
- **The natural subregions in the high elevation areas (i.e., alpine and sub-alpine as shown in polygon I; montane in the middle of polygon II; upper boreal highlands in the middle of polygon III; and sub-alpine in polygon IV experienced relatively high SGN stages (i.e., in the range of 137–200 DOY). This is reasonable as the high elevation areas experience relatively cooler temperature regime, which influences the snow to stay relatively longer period of time.**



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

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Determining Deciduous Leaf Out (DLO) Stage: Assumptions

Credits: Photo by Robin Lilly, USDA Forest Service.

- **DLO stage is 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 (*Populus tremuloides*) trees in the surrounding area of a lookout tower sites (FFMT, 1999).**
- **Climatic variables, e.g., temperature and water control the DLO if nutrient and other biological factors are not limiting ones.**
- **Snow-melting during spring is often fulfilling the water requirements; and chilling requirements are often fulfilled due to cold temperatures during winter.**
- **Here, we investigate favourable temperature [i.e., growing degree days (GDD)/accumulated GDD (AGDD)] in modelling DLO.**

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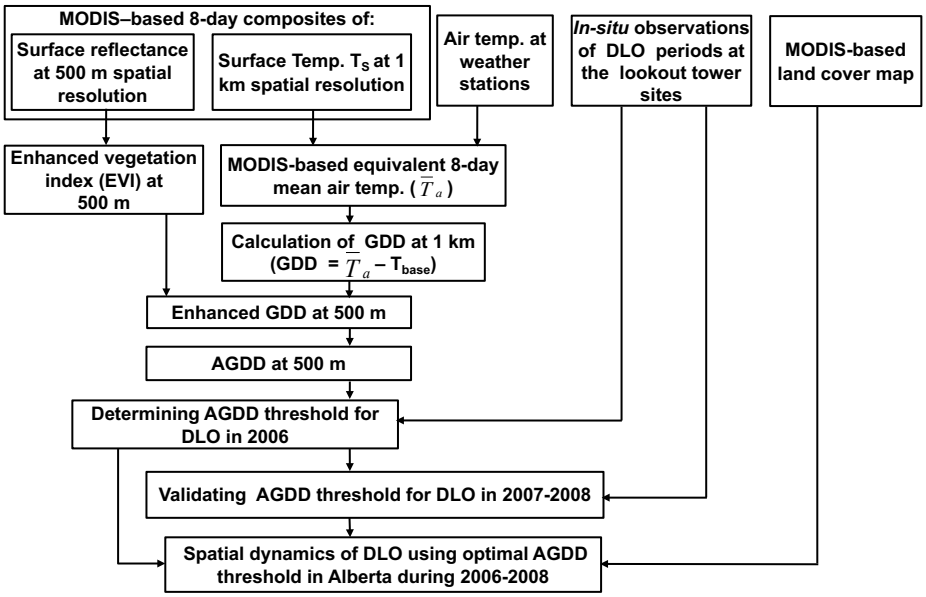
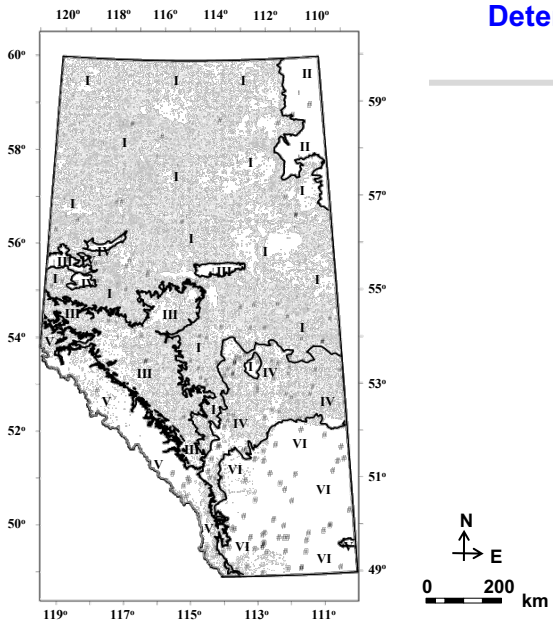
Determining Deciduous Leaf Out (DLO) Stage: Conceptual Model



Determining Deciduous Leaf Out (DLO) Stage: Study Area



- I Boreal (55.3 %)
- II Canadian Shield (3.5 %)
- III Foothills (10.3 %)
- IV Parkland (9.2 %)
- V Rocky Mountain (7.4 %)
- VI Grassland (14.3 %)

- Deciduous stands
- ▲ Environment Canada weather stations in 2006 (182)
- • Lookout tower sites

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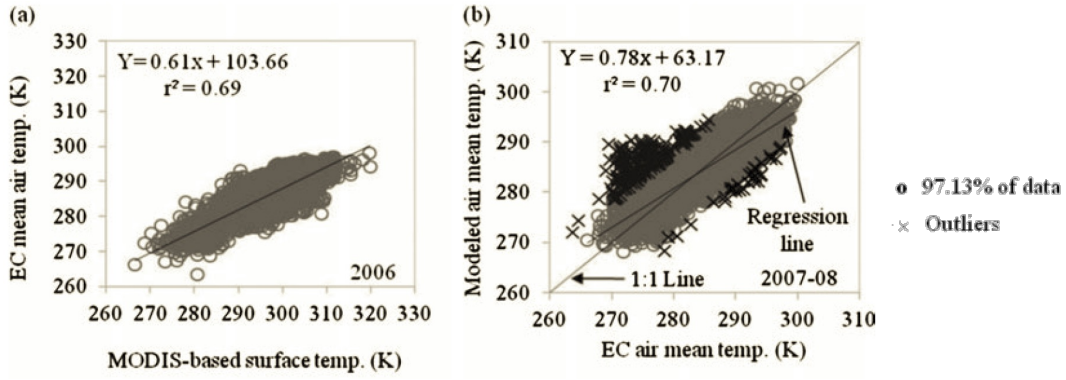
Determining Deciduous Leaf Out (DLO) Stage:
Temperature Conversion



Temperature conversion: calibration & validation

(a) Reasonably strong relation between the MODIS-based 8-day surface temperature and 8-day average air temperature during 2006.

(b) Validation of the relation observed during 2006 and its comparison with the 8-day average air temperature during 2007-2008 also reasonably strong.

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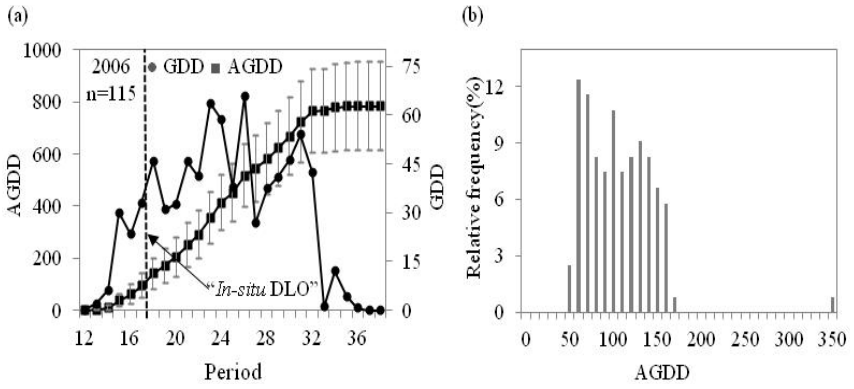
Determining Deciduous Leaf Out (DLO) Stage:
Threshold Determination (1)



GDD threshold determination (calibration)

(a) averaged temporal trends of GDD and accumulated GDD (AGDD) at all of the lookout tower sites during 2006; and the dotted vertical line is the averaged ground-based DLO observation period.

(b) Relative frequency distribution of AGDD at all of the lookout tower sites.

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Determining Deciduous Leaf Out (DLO) Stage: Threshold Determination (2)

% out of 115 lookout towers (2006)

AGDD Threshold	Deviations (in periods)							
	0	± 1	± 2	± 3	± 4	± 5	± 6	± 7
60	30.4	87.8	98.3	99.1	99.1	99.1	99.1	100
70	31.3	87.8	98.3	99.1	99.1	99.1	100	100
80	35.7	86.1	98.3	99.1	99.1	99.1	100	100
90	39.1	80.9	94.8	99.1	99.1	99.1	100	100
100	34.8	73.9	92.2	98.3	99.1	99.1	100	100
110	33.0	67.8	87.0	96.5	99.1	99	100	100
120	27.8	60.9	81.7	93.0	98.3	98	100	100
130	20.9	53.9	77.4	91.3	97.4	97	100	100
140	13.9	47.0	68.7	89.6	97.4	97	100	100

GDD threshold determination (calibration)

The AGDD threshold of 80 was considered as the optimal one.

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Determining Deciduous Leaf Out (DLO) Stage: Threshold Determination (3)

Year	No. of lookout tower sites (n)	Deviations (in periods)						
		0	± 1	± 2	± 3	± 4	± 5	± 6
2007	110	30.9	78.2	94.5	98.2	99.1	100	100
2008	113	37.2	81.4	89.4	93.8	97.3	98.2	100
2007-2008	223	34.1	79.8	91.9	96.0	98.2	99.1	100

Validation for AGDD threshold during 2007-2008

On an average the predictions were very much reasonable.

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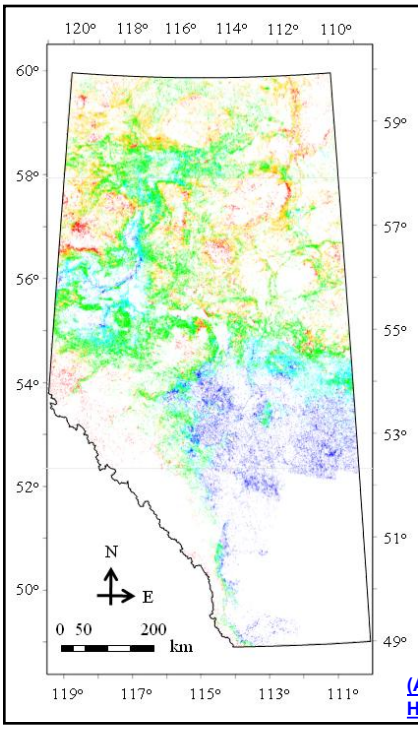
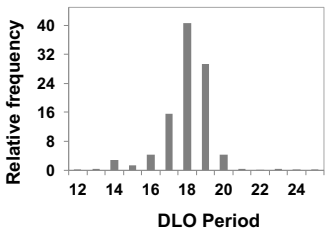
Determining Deciduous Leaf Out (DLO) Stage: Model Output





DLO Period

- ≤16
- 17
- 18
- 19
- ≥ 20

- **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).**
- **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., 2007; Sekhon et al., 2010).**

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Sample Review Questions

- **Define vegetation phenology and its significance.**
- **What are the different phenological stages associated with boreal forest?**
- **What are the commonly used methods in determining phenological stages? Describe their advantages and limitations.**
- **Consider that the values of surface reflectance-values in the range 0.3-3μm are provided. Calculate the values of the following indices:**
  - **Normalized difference vegetation index (NDVI),**
  - **Enhanced vegetation index (EVI),**
  - **Normalized difference water index (NDWI),**
  - **Normalized difference snow index (NDSI).**
- **What is the advantage of using NDWI over NDVI/EVI/NDSI in determining the snow gone stage over the boreal forest?**
- **What are the assumptions of modelling the stages of: (i) snow gone, and (ii) deciduous leaf out.**
- **Describe steps associated with the modelling of: (i) snow gone, and (ii) deciduous leaf out.**

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