Vegetation phenology can be captured with digital repeat photography and linked to variability of root nutrition in *Hedysarum alpinum*


**Abstract**

**Question:** Can repeat (time-lapse) photography be used to detect the phenological development of a forest stand, and linked to temporal patterns in root nutrition for *Hedysarum alpinum* (alpine sweetvetch) an important grizzly bear food species?

**Location:** Eastern foothills and front ranges of the Rocky Mountains in Alberta, Canada. The area contains a diverse mix of mature and young forest, wetlands and alpine habitats.

**Methods:** We deployed six automated cameras at three locations to acquire daily photographs at the plant and forest stand scales. Plot locations were also visited on a bi-weekly basis to record the phenological stage of *H. alpinum* and other target plant species, as well as to collect a root sample for determination of crude protein content.

**Results:** Repeat photography and image analysis successfully detected all key phenological events (i.e. green-up, flowering, senescence). Given the relation between phenology and root nutrition, we illustrate how camera data can be used to predict the spatial and temporal distribution and quality of a key wildlife resource.

**Conclusions:** Repeat photography provides a cost-effective method for monitoring vegetation development, food availability, and nutritional quality at a forest stand scale. Since wildlife responds to the availability and quality of their food resources, detailed information on changes in resource availability helps with land-use management decisions and furthers our understanding of grizzly bear feeding ecology and habitat selection.

**Introduction**

Seasonal changes in vegetation phenology are critical drivers of food availability and quality for a wide variety of animal species. Food availability affects large-scale movements in migratory species such as caribou (Sharma et al. 2009; Festa-Bianchet et al. 2011), as well as the seasonal foraging habitats of species within their home ranges (Nielsen et al. 2003, 2010). This is the case for grizzly bears (*Ursus arctos*), which are considered generalists with diverse diets that change during the course of the year. Individual bears may travel large distances to locate high-quality food sources (Rogers 1987), with a diet comprised of seasonally abundant and nutrient-rich food (Hamer & Herrero 1987; Hamer et al. 1991; Craighead & Summer 1995; McCellan & Hovey 1995; Munro et al. 2006). Within their remaining range in western Canada, grizzly bears have three distinct foraging seasons: hypophagia, early
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hyperphagia, and late hyperphagia (Nielsen et al. 2006). During hypophagia, grizzly bears feed on the roots of Hedysarum spp. (sweetvetch) and other early herbaceous material. During early hyperphagia their diet extends to green herbaceous material such as Heracleum lanatum (cow-parsnip) and Equisetum spp. (horsetail), while in the later season berries such as Shepherdia canadensis (buffalo berry) and Vaccinium spp. (huckleberry, blueberry and lingonberry) make up the majority of their diet. As fruit consumption declines in the autumn, grizzly bears once again dig for sweetvetch roots (Nielsen 2005; Munro et al. 2006; Nielsen et al. 2006, 2010). While animal matter and insects are an important food resource for grizzly bears during spring and early summer, a wide variety of vegetable matter, including roots, forbs and fruit, makes up the majority of their diet from late June through to early October. The amount of animal matter consumed by grizzly bears can also vary by season (moose and other ungulate calves), distribution and abundance (Munro et al. 2006).

In previous work (Bater et al. 2011a,b; Coops et al. 2012) the role of digital cameras in monitoring vegetation phenology across a range in grievably bear habitats of Alberta has been demonstrated. Camera images provide an alternative to traditional assessment of phenology that rely on field observations, often by seasonal workers, volunteers and amateur naturalists, who record discrete events such as flowering, leaf emergence and other characteristics depending on observation goals and site location (Studer et al. 2007; Crimmins et al. 2009). While these observations are a valuable source of information, they are limited in spatial coverage, are often based on varying methodologies and conducted by many observers with different training and skill levels, resulting in data inconsistencies. Repeat photography using ground-based cameras (i.e. near sensing; Jongshaap & Booij 2004) to monitor vegetation phenology allows for very fine temporal sampling (e.g. at daily or hourly intervals) in a consistent and cost-effective manner. In fact, near sensing of vegetation phenology is dramatically increasing in popularity across a diverse range of disciplines, including agriculture (Purcell 2000; Karcher & Richardson 2003; Zerger et al. 2010), plant ecology (Graham et al. 2010; Ide & Oguma 2010; Kurc & Benton 2010) and forestry (Ahr-ends et al. 2008; Polgar & Primack 2011; Sonnentag et al. 2012). However, many of these studies focus on either linking distributed cameras into networks to follow phenological development at national or continental scales (Jacobs et al. 2009; Graham et al. 2010; Ide & Oguma 2010) or observations of a single plant or plot (Karcher & Richardson 2003; Sonnentag et al. 2012).

By mounting camera systems on towers, trees or platforms, data can be acquired at an intermediate scale of observation, providing a link between field-based observation methods and satellite-derived estimates (Hufoekens et al. 2012). Bater et al. (2011b) confirmed that spectral indices derived from these camera systems relate significantly to field observations of both the green-up and senescence of vegetation, with mean absolute differences in residuals between the predicted and observed dates of green-up and length of growing season reported as 4 and 6 d, respectively. These measures of vegetation phenology from ground-based cameras also significantly relate to satellite-derived measures of greenness (Coops et al. 2012).

Despite the demonstrated capacity to monitor vegetation phenology remotely, changes in vegetation greenness detected by cameras do not necessarily directly correspond to other factors affecting use of those resources, such as nutrient quality. For example, in the case of grizzly bears, the nutritional content of Hedysarum alpinum (alpine sweetvetch) roots varies significantly throughout the growing season, with highest nutritional concentration occurring prior to and during the initial green-up phase (Hamer et al. 1991; Coogan et al. 2012). Once the above-ground biomass component of H. alpinum has reached its peak, corresponding to the mid-point of the growing season, the nutritional value of the roots substantially decreases when compared to the initial green-up earlier in the season or senescence in the autumn (Coogan et al. 2012). As a result, there is a need to link remote sensing-derived observations of greenness to not only vegetation activity, but also to the nutritional value of the above- and below-ground components of the vegetation.

The main objectives of this study are two-fold. First, examine changes in vegetation phenology of key individual plant species critical to grizzly bear diet using very high spatial resolution digital camera data. Changes in vegetation phenology (spectral greenness) for individual plants were examined over a full growing season and compared to phenophase observations of the above-ground vegetation component, as well as to the nutritional content of the below-ground roots. The second objective of the study is to demonstrate if individual species-based models, such as H. alpinum, can be scaled up using stand-scale digital camera observations. If these relationships exist, then the distribution and timing of forage availability can be predicted at broader scales.

Methods

Study area

The focus of this study was the foothills in western Alberta, Canada. The area contains a diverse mix of mature and young forest, wetlands and alpine habitats. Three sample sites were located near the towns of Robb and Cadomin, Alberta (53.2°N, 117.0°W) in order to observe the range of
phenological changes and growing season conditions across known grizzly bear habitat. At each site, a pair of cameras was installed with different fields of view (see camera setup section below); one camera focused on individual plants (plant scale), while the second camera focused on the forest stand (stand scale). Details on the sites, their vegetation composition and location are summarized in Table 1.

Digital camera setup

Six standard commercially available digital camera systems manufactured by Harbortronics (Gig Harbor, Washington, WA, USA) were installed at the three sites. The camera systems include a Pentax K100D digital SLR camera (Pentax Corporation, Tokyo, Japan) mated to an intervalometer. The camera was sealed in a fiberglass case with a solar panel and lithium ion battery to provide power. At each of the three plots, one camera was mounted 3 m above the ground on a tall and dominant tree and pointed north (as described in Bater et al. 2011a) with images capturing conditions of the forest stand (Fig. 1, right). A second camera was mounted close to the first camera, but with a reduced field of view (ca. 5 × 5 m) in order to monitor a small number of individual plants (Fig. 1, left), hereafter referred to as the plant scale. To minimize directional effects caused by solar movements, all cameras acquired five images per day between noon and 13:00 hr, local time, at regular intervals. Digital images were archived as full resolution JPEG files (3008 × 2008 pixels) and ancillary data included a time stamp for easy reference of the date of acquisition.

Field validation, phenophase codes and root nutrition data

Two sets of imagery acquired at the three sites provided a range of homogenous understorey and overstorey species-specific regions of interest, observable on the digital camera imagery. All sites were visited weekly between April and October 2010 to record the phenophase codes (Table 2) of the vegetation, following the practices of Dierschke (1972). In the further analyses, we use summarized phenological scale with pre-leaf: Vegetative ≤ 4, leaf: Vegetative ≥ 5, flower: Reproductive ≥ 6, seed: Reproductive ≥ 10 and dormant: Vegetative ≥ 9 (Table 2). The green-up, flower and senescence dates are defined as the first occurrence of leaf, flower and dormant, respectively. Observable species included H. alpinum (alpine sweet-vetch), Sheperdia canadensis (buffalo berry), Lathyrus ochroleucus (cream pea), Vaccinium vitis-idaea (lingonberry), Arctostaphylos uva-ursi (bearberry) and Dryas octopetala (mountain avens). In addition to the phenophase observations, H. alpinum plants just outside of the observable images were also sampled for nutritional content. In total, 66 samples were collected and analysed for crude protein content following the procedures described in Coogan et al. (2012). All protein measurements were normalized as a fraction of the total dry matter. To allow comparisons between the camera information, phenology data and root protein data, root samples were grouped into five phenological stages (pre-leaf, leaf, flower, seed and dormant).

Image analysis

As discussed in Bater et al. (2011a), a number of approaches exist to extract phenological information from a time series of remotely sensed spectral data. Information on key dates, such as green-up and senescence, has precedence in the literature (e.g. Waring et al. 2006). In our

<table>
<thead>
<tr>
<th>Plot</th>
<th>Coordinates (UTM 11N)</th>
<th>Elevation (m)</th>
<th>Vegetation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinnan creek</td>
<td>N5894401; E465076</td>
<td>1356</td>
<td>Spruce and pine forest</td>
</tr>
<tr>
<td>Folding mountain</td>
<td>N5900374; E447823</td>
<td>1139</td>
<td>Spruce forest</td>
</tr>
<tr>
<td>Cardinal divide</td>
<td>N5860769; E483439</td>
<td>2025</td>
<td>Alpine meadow</td>
</tr>
</tbody>
</table>

Fig. 1. Example images at the plant scale (left) and forest stand scale (right) taken at the Cardinal Divide site near Cadomin, Alberta. Both images taken on 15 July 2010.
case, to extract the phenological response from the image sequences, the five images collected each day were averaged into a single daily scene to reduce the effects of differential exposure and shading in the images. These daily averages were then filtered using a $4 \times 4$ mean kernel to reduce data volumes and the effects of plant parts moving in the time between images caused by plant growth or, more notably, wind.

In order to extract a single spectral index indicative for vegetation activity from the blue, green and red spectral channels we calculated the $2G-RBi$ index (Richardson et al. 2007), hereafter noted as $2G-RBi$. The $2G-RBi$ compares the green channel of the RGB image to the red and blue channels to derive excess greenness corrected for illumination differences:

$$2G_{RBi} = 2\mu_G(\mu_R + \mu_B)$$

where $\mu_G$, $\mu_R$ and $\mu_B$ are the camera observed brightness values (image DN) in the green, red and blue channels, respectively. All images where snow was present in the scene were removed from further analysis, and a smoothing spline with rigidity of $2/3$ was fitted to the $2G-RBi$ data for each pixel, similar to that of Richardson et al. (2009). Key dates from the fitted spline were then extracted, including date of green-up, end of season and flowering of the $H. alpinum$ (Fig. 2). To do so, green-up was defined as the first date that greenness was higher than that of pixels robust half-max (90th percentile–10th percentile/2); senescence was defined as the last date that greenness was higher than that of pixels robust half-max. The robust half-max was chosen above a standard half-max or inflexion point to account for the increased amount of scattering present in the by-pixel data, as opposed to analysis of averages over larger predefined areas. The half-max is commonly used to detect the dates of start of season in

Landscape forage quality

Based on the derived relationship between phenological development and root protein content of $H. alpinum$, we inferred the nutritional value available in the stand as derived from a time series of the stand-scale photographs. The clearly outstanding colour of the pink $H. alpinum$ flowers allows for detection of this species throughout the stand, as the flowers have a negative greenness value. The detected flowers are buffered in a 25-pixel radius, excluding any bare areas, to create a mask of $H. alpinum$ plants. The area within this mask was used to derive the phenological development of $H. alpinum$ throughout the growing season, as well as the dates of green-up, flowering and senescence for this species. The phenological events for $H. alpinum$ as detected by the camera system is linked to underground root nutrition by the temporal relation between root crude protein content and above-ground phenology (Coogan et al. 2012). Repeat photography provides information on both the location of the species of interest ($H. alpinum$) and the timing of phenological events. The combination of the development and location provides insights into the availability of high-quality forage on a landscape scale.

Results

Approximately 850 images were obtained from each camera, covering the period from mid-April to mid-October.

<table>
<thead>
<tr>
<th>Vegetative</th>
<th>Reproductive</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Closed bud</td>
<td>0. Without blossom buds</td>
</tr>
<tr>
<td>1. Green leaf-out but not unfolded</td>
<td>1. Blossom buds recognizable</td>
</tr>
<tr>
<td>2. Green leaf-out, start of unfolding</td>
<td>2. Blossom buds strongly swollen</td>
</tr>
<tr>
<td>3. Leaf unfolding up to 25%</td>
<td>3. Shortly before flowering</td>
</tr>
<tr>
<td>4. Leaf unfolding up to 50%</td>
<td>4. Beginning bloom</td>
</tr>
<tr>
<td>5. Leaf unfolding up to 75%</td>
<td>5. Up to 25% in blossom</td>
</tr>
<tr>
<td>6. Full leaf unfolding</td>
<td>6. Up to 50% in blossom</td>
</tr>
<tr>
<td>7. Stem/first leaves fading</td>
<td>7. Full bloom</td>
</tr>
<tr>
<td>8. Yellowing up to 50%</td>
<td>8. Fading</td>
</tr>
<tr>
<td>9. Yellowing over 50%</td>
<td>9. Completely faded</td>
</tr>
<tr>
<td>10. Dead</td>
<td>10. Bearing green fruit</td>
</tr>
<tr>
<td></td>
<td>11. Bearing ripe fruit</td>
</tr>
<tr>
<td></td>
<td>12. Bearing overripe fruit</td>
</tr>
<tr>
<td></td>
<td>13. Fruit or seed dispersal</td>
</tr>
</tbody>
</table>

Table 2. Phenological phases as observed in the field plots, based on Dierschke (1972).
Figure 3(a) provides an example of a typical field of view at the plant scale during flowering of *H. alpinum*. The image clearly shows the leaf structure and flowers of the plant. The 2G-RBi image is shown in Fig. 3(b), with white areas indicative of very green vegetation and darker areas showing non-vegetated scene components. The derived start and end of growing season images are shown in Fig. 3(c,d), respectively.

Camera-derived dates of phenological events and the field-observed dates are strongly correlated ($r^2 = 0.89$, $P < 0.01$, $N = 16$), except for evergreen Ericaceae shrubs (e.g. *V. vitis-idaea*, *A. uva-ursi*), which did not exhibit easily detectable changes in phenology or greenness and show up as clear outliers below the 1:1 line (Fig. 4). The relationship between the field-measured phenophase and the protein content of *H. alpinum* is shown in Fig. 5, and demonstrates a reduction in protein content while plants are actively growing. The pre-leaf phenological stage had the highest nutritional value, while the flower and seed phenophases had the lowest nutritional values. Also apparent is the high nutritional load of the below-ground component when the species are dormant, and the variability of root protein across the three sites.

**Landscape forage quality**

Based on a time series of images at the forest stand scale, we detected both the spatial distribution and phenological development of *H. alpinum*. Figure 6 shows a forest stand-scale photograph at the Cardinal Divide site, with areas marked in pink representing the area of *H. alpinum* plants.

The temporal patterns of major phenological events in the cells containing *H. alpinum* are shown in Fig. 7. Green-up starts halfway through June, with the peak of growth 2 wk later. Flowering lasts approximately 3 wk, between mid-July and the first part of August. The decline in greenness starts around mid-August, with all above-ground components senesced by mid-September.
Discussion

While broad-scale patterns in phenology can provide an overall assessment of available food resources and inter-annual changes in forest productivity, a key limitation of working at this scale is an inability to detect subtle or species-specific phenological events that occur at the temporal and spatial scale at which animals perceive their environment and that are critical for food modelling (Nielsen et al. 2003, 2010). In this paper, we use two sets of cameras configured to capture imagery at the plant- and forest stand-scale. This paired design allowed the precise timing of initial leaf unfolding and the development of fruits to be observed and subsequently linked to the nutritional value of the below-ground food resource. Placing cameras in close proximity to plants offers the advantage of continuous data and the possibility of a reduced frequency of field visits for collection of phenological data (phenophase monitoring). This study confirms that ground-based cameras can be employed to simultaneously monitor phenology of multiple plant species within the image footprint, and that images capturing different scales can be linked with landscape assessments of vegetation nutritional value. The phenological development of *H. alpinum* indicates that high protein roots were available before the start of July and again after the end of August (Coogan et al. 2012). This pattern corresponds well with root consumption patterns observed in grizzly bear faeces (Munro et al. 2006) and GPS telemetry data on habitat selection (Coogan et al. 2012), which show most root consumption in late April to June, and resuming from August to October.

From a wildlife management and monitoring point of view, we believe it is the linking of Figs 5 and 7 in this work that provides the most important insights. While there is considerable variability around the root nutritional value at the sampled sites (initial high nutritional value, followed by a reduction at flowering and seed production, and an increase again at dormancy), the pattern of nutritional status throughout the season is similar to many understory species. Most of these species allocate more resources above the ground for reproduction at certain times of the year, thereby reducing resources below the ground and at other times. With few above-ground resources to support at pre-leaf and dormant stages, the below-ground component of the vegetation gains comparatively more resources and thus nutrient content. This pattern of below-ground nutrient availability is the inverse of the camera observable greenness, and thus the link is an inverse one for forest managers. The portion of the scene shown in Fig. 7 at each of the key, above-ground phenological phases can essentially be inversely multiplied by the nutritional value in Fig. 5 to provide a landscape estimate of the nutrient carrying load of this specific vegetation type for wildlife. In this example at Cardinal Divide, nutritional availability of food is highest between 1 June and 1 July (before maximum green-up) and after 15
August (during senescence). The capacity to provide explicit dates of when these maximum nutritional load events occur across the landscape is of significant benefit to managers, as it provides key time periods when bear activity in these areas is most likely, or conversely least likely, to occur due to root forage quality and availability. While other food sources, and management activities, will of course also impact bear movements and locations, this information provides one key perspective on the overall bear landscape. Multiple cameras at multiple sites characterize the key bioclimatic zones across the region would, when combined, provide a region-wide bear forage availability map that could be updated in real time and provide an immediate perspective on the nutritional load for the bears within this area.

For the stand-scale detection of forage availability, improvements can be made to the current camera setup. Because the cameras have a highly oblique view, only part of the image frame can be used for reliable detection of phenological development in individual species. In areas far from the camera position, the spatial resolution is reduced. The potential to install the cameras with a field of view closer to nadir would decrease perspective issues, as well as potentially provide better separation between taller and adjacent shorter vegetation. However, such a setup would require a higher mounting point for the cameras and, possibly, installation on a mast or structure other than a tree, which would increase deployment costs and reduce the area observed.

As this study demonstrates, unique challenges remain for detecting phenological events in evergreen species. Evergreen species show a less pronounced response in camera-measured greenness and are therefore not reliably identified with the current system. Improved detection of the phenology of evergreen species may be provided using a modified camera system that detects changes in near-infrared reflection, which is known to be highly sensitive to changes in vegetation activity.

Conclusions

In this paper, we describe a system and approach to detect the phenological development of individual plant species from daily camera images at both a plant and forest stand scale. The phenological development of certain species is closely linked with the nutritional value of above- and below-ground parts of these plants, and therefore the availability of high-quality forage for grizzly bear. The use of repeat photography provides a cost-effective way to assess vegetation development and food availability at a forest stand scale, improving information availability for management of bear habitat and providing a tool for increasing our understanding of grizzly bear feeding ecology.

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References


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