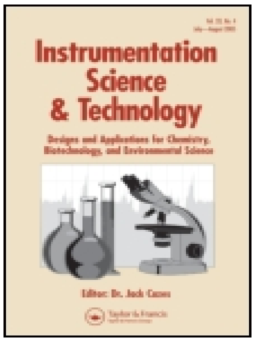

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□ *Developments in distributed sensing, web camera image databases, and automated data visualization and analysis, among other emerging opportunities, have resulted in a suite of new techniques for monitoring habitat at many different scales. Data from these networks can provide important information on the timing of plant phenology with implications for habitat status and condition. In this article, we describe the design and deployment of a small network of cameras established along an elevation gradient in western Alberta, Canada, with the purpose of developing a more comprehensive understanding of seasonal phenophases and the reproductive timing of understory forest vegetation. During an eight-month period in 2009, over 6,700 images were acquired across seven sites throughout the growing season, providing a rich dataset documenting phenological activity of both the under- and overstory forest components. Strong elevation and climate responses were observed. A mathematical function was fitted to the data to demonstrate the capacity to capture phenological trends. This article demonstrates the utility of these types of relatively inexpensive, portable systems for monitoring seasonal vegetation development and change at high temporal resolutions across landscapes.*

Keywords image processing, near remote sensing, plant phenology, time lapse processing

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INTRODUCTION

Phenology is the study of the timing of recurring biological events, such as leaf emergence or animal migrations.[1] The vegetation phenological cycle defines the onset (start of season) and duration of a photosynthetically active canopy, which, for example, influences the magnitude of carbon and water fluxes between the atmosphere and biosphere.[2–4] As a result, vegetation phenology plays a crucial role in the carbon balance of terrestrial ecosystems,[4–8] and changes in the timing of plant developmental phases may signal important interannual climatic variations.[7,9,10]

In addition to influencing carbon uptake in forested ecosystems, the phenological cycle is also a critical driver of resource availability and quality for a wide range of wildlife. For instance, many ungulate species follow temporally and spatially the seasonal "green wave" in plant productivity.[11,12] In some cases, this may even lead to long-distance seasonal movements or migrations of populations along altitudinal or seasonal rainfall gradients to maximize resource availability and quality.[11,13,14] In many ecosystems, particularly grasslands and alpine, the relationship between the seasonal green wave phenomenon and wildlife habitat can be measured using a normalized difference vegetation index (NDVI) or other remote sensing indices.[11,15,16] However, for nonherbivore wildlife species and in habitats where vegetation is structurally more complex (e.g., forests), phenological indices from satellites such as NDVI are unlikely to directly relate to seasonal wildlife habitat quality, since resources being sought are not necessarily herbaceous. For instance, the omnivorous grizzly bear (*Ursus arctos* L.) relies on a diverse array of food resources that often includes herbaceous vegetation, but also roots, hard and soft mast, small mammals, ungulates (often neonates), spawning salmon, or insects, all of which follow a highly predictable seasonal progression (phenology) of use based on availability and nutritional quality.[17–19] Seasonal phenology is therefore a driving force in defining critical habitat for this focal conservation species.[20,21] Thus, for many species, additional methods are needed to relate on-the-ground phenological events to ecological processes and wildlife habitat, as well as to determine whether these relationships can be predicted directly or indirectly by remote sensing technologies.

Traditionally, assessment of plant phenology has relied on a network of observers, often volunteers and amateur naturalists, who record discrete events such as flowering, leaf emergence, and other characteristics depending on location and specific observation goals.[22] These networks, however, are typically made at a very limited number of sites using a range of methodologies by a large number of personnel with variable levels of skill. In contrast, satellite remote sensing technologies can provide detailed information on vegetation phenology; however, it is acquired at large spatial scales (often 500 m spatial resolution or greater),[2,4,7] making species-specific phenological events difficult to ascertain and predict. As a result, linking scales of observation from the individual leaf to the landscape is an ongoing challenge.[1]

The increasing popularity and widespread use of inexpensive visible spectrum digital cameras in recent years offer notable potential in the monitoring and measurement of phenological events.[23–25] Repeat photography allows a very fine temporal sampling, often at daily or hourly intervals, for monitoring vegetation phenology. By mounting these systems on towers, other vertical objects, or surface platforms, data can be acquired at an intermediate scale of observation, providing a link between field-based observation methods and satellite-derived estimates. This intermediate scale of observation, sometimes referred to as "near" remote sensing, allows high temporal and spatial resolution datasets to be developed.

Many of the early applications of camera technology to studies of phenology started in agriculture.[26] For instance, Purcell[27] utilized digital cameras to detect changes in wheat and soybean canopies at a one-meter spatial resolution over a growing season. Graham et al.[23] acquired daily images of mosses during drying and moistening cycles to develop a comprehensive understanding of their changing status under different climatic conditions. Richardson et al.[22] mounted a commercially available digital camera and web system on a CO_2 flux tower to observe deciduous vegetation green-up and compare it to changes in the fraction of the photosynthetically active radiation absorbed by the canopy. A network of similar instruments is being proposed for a larger number of flux tower sites across North America, with potential integration with the National Ecological Observation Network (NEON; for a description see Ref.[28]). Graham et al.[25] recently assembled a dataset consisting of freely available images from across North America collected using public Internet-connected digital cameras. The ground-based image data were used to model spring green-up and were then compared to co-located satellite-derived estimates. Graham et al.[25] demonstrated that the ground-based cameras were able to detect green-up with equal or better accuracy than the satellite data, and that the cameras were superior in terms of data gaps and consistent image quality. With increasing interest in the available technologies, as well as global growth in citizen sensing and distributed science management, the role of these types of instruments is likely to increase, with broadening use beyond the conventional applications in phenology and climate, including application to biodiversity and conservation management.

In this article, we describe the development and installation of a small network of phenological cameras across an elevation gradient in an isolated area of western Alberta, Canada. The objective of the overall study is twofold: first, to assess the capacity of the network to detect changes in key over- and understory elements of the forest canopy, particularly for plant species important to grizzly bears as a food source; and second, to develop a near-surface based dataset with which to compare and validate simultaneously acquired satellite-derived reflectance and phenology estimates. The first objective has been addressed by Bater et al.,[29] who explain the targeting of specific understory and overstory species for phenological monitoring in a forested environment. Coops et al.[30] outline the application of the camera network towards the second objective, where key indicators of phenological activity from the ground-based network are compared with those derived from a time series of 30 m spatial resolution synthetic Landsat scenes generated at 14-day intervals. Presently, in this foundational article, we describe the camera network, including the design characteristics of the system, the installation across the elevation gradient, examples of the initial datasets, and the nature of trends obtained from the system over the first eight-month acquisition period.

MATERIALS AND METHODS

Study Area

The foothills flanking the Alberta Rocky Mountains in Canada are a diverse region containing a mix of mature and young forest, open meadow alpine areas, provincial and national parks, and resource extraction activities, including forestry, oil and gas exploration and development, and open pit mining. A 90-km-long transect centered over the town of Robb, Alberta (53.22°N, 116.98°W), was designed to capture a range of phenological changes and growing season attributes across known grizzly bear habitat. Cameras were installed at seven sites. Six were selected in pairs at three low to moderate elevation zones to reflect the two main biomes present along the transect. At each elevation, one paired site was placed within a coniferous-dominated stand, while the second was located in a mixed overstory species site consisting of between 20–40% deciduous canopy. A single site was established in a high elevation coniferous stand. However, at this elevation no paired deciduous stand could be found. Details on the sites, including vegetation composition and location characteristics, are summarized in Table 1.

Digital Camera Network Setup

To promote accessibility and portability of the system design, we used standard commercially available digital camera systems designed for extended outdoor use. The seven time-lapse packages were manufactured by Harbortronics (Fort Collins, CO, USA), and each consisted of a Pentax

TABLE 1 Summary of the Camera Sites, Including Forest Cover Type and Coordinates

Site Name	Longitude (Decimal Degrees)[1]	Latitude (Decimal Degrees)[1]	Forest Type	Overstory Species	Elevation (m)*
Fickle Lake	−116.721	53.393	Coniferous	Mature white spruce	951
Fickle Lake	−116.712	53.398	Mixed	White spruce, trembling aspen	970
Bryan spur	−116.970	53.239	Coniferous	Black spruce, lodgepole pine	1,092
Bryan spur	−116.965	53.246	Mixed	Trembling aspen, lodgepole pine, white spruce	1,093
Cadomin	−117.288	53.066	Coniferous	Black spruce, lodgepole pine	1,458
Cadomin	−117.321	53.044	Mixed	White spruce, balsam poplar, willow	1,484
Prospect Creek	−117.327	52.968	Coniferous	Lodgepole pine	1,714

*Ellipsoid: World Geodetic System, 1984.

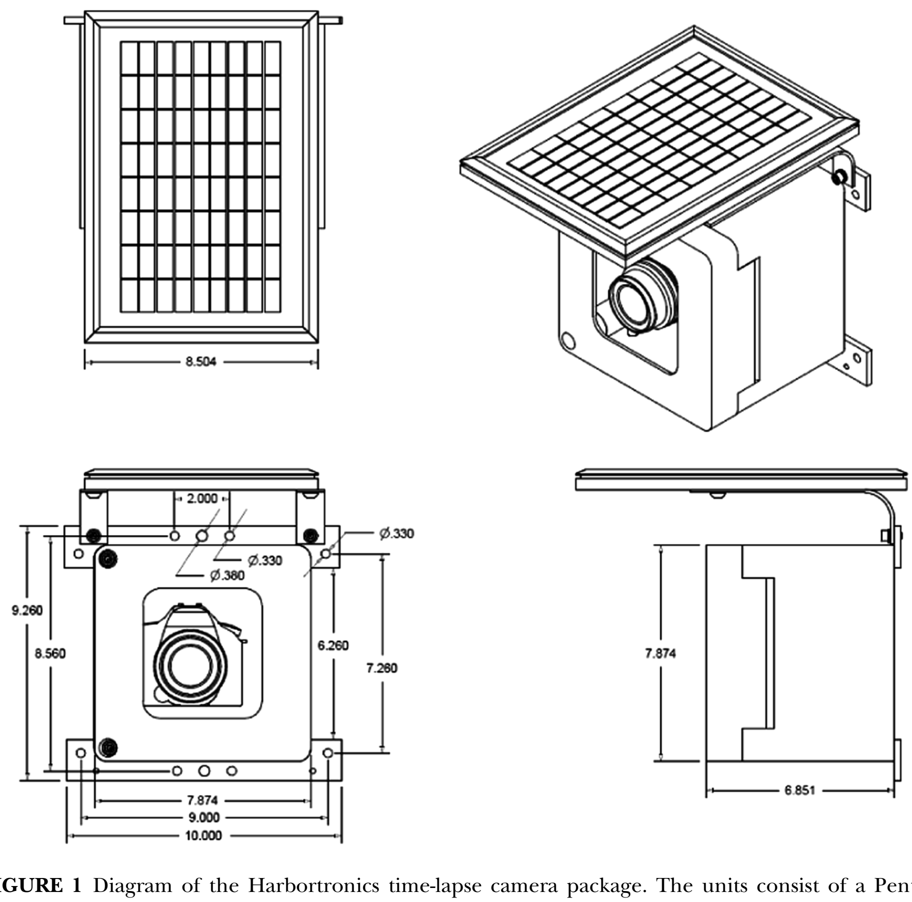

FIGURE 1 Diagram of the Harbortronics time-lapse camera package. The units consist of a Pentax DSLR slaved to an intervelometer, both of which are powered by a lithium ion battery and solar panel.

digital single lens reflex (DSLR) camera slaved to an intervalometer, both of which were sealed in a fiberglass case (Figure 1, Table 2). The cameras had 23.5×15.7 mm CCD sensors with either 6.1 or 10.2 million effective pixels. The camera lenses had a variable focal length of 18–55 mm, and each camera was installed with a 4 GB SD memory card. Many of the advanced camera settings were disabled, including automatic focus, shake reduction, and flash. In addition to the camera, an iButton data logger (model DS1921 G, Dallas Semiconductor Corp., Dallas, TX, USA) was installed to record temperature at each site four times daily.

Cameras were mounted on trees within each of the plots. Candidate trees were tall and dominant in the canopy with no low branches to obstruct the view of the plot. Cameras were mounted approximately three meters above the ground pointing north, while the temperature loggers were installed on the north side of a tree 0.6 m above the ground.

Each camera was set to record five high quality JPEG images per day between 12:00 noon and 1:00 pm local time. Digital images were archived as high quality JPEG images (2000×3008 pixel or 2592×3872 pixel resolution with 3 channels of 8-bit RGB data). Although "non-lossy" TIF or RAW formats may have been preferable, the extended period of time the cameras were deployed without field visits necessitated the use of compressed files. Exchangeable image file (exif) data were recorded with each image and included a date and time stamp for easy reference.

Image Analysis

Our analysis approach adapted the methods described by Richardson et al.[22] Ahrends et al.[31] and Richardson et al.[32] A custom script was written in Python, and images were read sequentially regardless of meteorological conditions or image quality. When required, images were resampled to 2000×3008 pixels using a nearest neighbor approach. Otherwise, no smoothing or filtering was performed to ensure overall objectivity.

Using regions of interest or masks is a commonly accepted method for analyzing specific portions of ground-based images. For example, Ahrends et al.[31] employed regions of interest to isolate portions of individual tree crowns from a mixed canopy beneath a flux tower. Ide and Oguma[33] employed regions of interest to isolate individual species where image resolution and range allowed. Graham et al.[25] segmented images into deciduous, evergreen, and understory regions for analysis. We developed regions of interest by first tessellating images using a 50×50 pixel image-wide grid over the entire frame, which was held constant throughout a given time series. Each cell could be considered a subregion, and by merging these, larger regions of interest were developed for analysis. As the subregions were typically smaller than a given vegetation element at the plant scale, they provided a framework to easily and consistently develop the larger regions, which were subsequently analyzed. For each site, regions of interest were developed at several scales, including single scene-wide regions consisting of all vegetation within view, regions separating understory and overstory, and regions delineating individual plants or species groups. Regions of interest were also placed over elements not expected to exhibit a phenological signal, including large tree stems and open sky.

The overall brightness (red DN + green DN + blue DN) was calculated and used to normalize the brightness of each channel such that the red, green, and blue fractions were calculated as channel percent (%) = channel DN/total RGB DN. Three additional band ratios were also computed. The first ratio, referred to as the vegetation green excess index or 2G-RBi, was originally developed by Woebbecke et al.[34] and has been repeatedly demonstrated to be a robust indicator of changing vegetation phenology.[e.g., 22,32,33] The 2G-RBi index was calculated as (2 * green DN) − (red DN + blue DN). Simple ratios of the raw red to green channels and blue to green channels were also calculated. Finally, the mean of the five images captured each day was calculated for each ratio or index.

Once the various band ratio and index values were calculated for each region of interest within the images, curves were fit to the data to estimate green-up. A variety of equations have been employed to model vegetation phenology. For example, Zhang et al.[3] used logistic functions to estimate phenologically important dates from Moderate Resolution Imaging Spectroradiometer (MODIS) data. Fisher et al.[35] employed pairs of logistic growth sigmoid functions to estimate leaf onset and offset from Landsat data, noting that their curve-fitting methodology was extendable across a range of spatial scales. Richardson et al.[32] employed two sigmoid curves multiplied together to estimate spring green-up and autumn senescence from web camera imagery. In order to quantitatively assess the differences in the change in green-up over the elevation transect, we fitted a sigmoid-shaped function [Equation (1)], which has been shown previously to capture changes in vegetation:[22]

$$f(x) = a + \frac{b}{1 + e^{(c-dx)}}, \tag{1}$$

where the a and b are parameters controlling the scaling of the function between the minimum and maximum observed values, and c and d result in shifts in the response variable x, time or day of year. An important characteristic of the sigmoid function is that the ratio of the *c* and *d* parameters provides an estimate of the day of year where the function achieves its half maximum (known as the seasonal-midpoint technique), which has been shown to predict the initial leaf expansion of broadleaf forests,[36,37] and which has the advantage over other techniques in that it is sensitive to site-specific variations and, as a result, may be more sensitive to local changes in leaf area.[38] The function was applied to the normalized three band spectral data and ratios individually. The *c* and *d* parameters were used to estimate half maximums.

Validation of Green-Up Dates

As a validation exercise, understory green-up dates determined using the sigmoid function parameters were compared to visual estimates.[31,33,35] For each site, the time series was visually inspected. The green-up date was subjectively estimated as the first day when the majority of the understory region of interest was light green.[33]

RESULTS

Following installation, a total of 6,732 images were collected from the seven sites over a single growing season in 2009, ranging from day of year 103 to day of year 300 (or spring snow melt and subsequent green-up, through to the first autumn snow fall). Camera failure rates due to battery power, camera resetting, and miscues totaled less than 10% of the total yield of photos. As would be expected, image quality varied over the eight month installation period due to variable lighting conditions caused by rain, fog, snow, and cloud cover. Example images from a pair of the mid-elevation sites are shown in Figures 2 and 3. These images demonstrate the variability of the scenes across the elevation gradient with respect to the overstory and understory composition, as well as snow cover at the commencement and end of the growing season.

To demonstrate that the camera-derived vegetation indices are sensitive to phenology, seasonal changes in the green fraction are shown for four regions of interest at two sites (Figure 4). At the Fickle Lake Conifer site, one region of interest is placed over a spruce stem, while the second covers the majority of the observable vegetation through the stand (both over- and understory). Similarly, at the Cadomin Conifer site, one region of interest is placed over open sky, while the second is again placed over all vegetation within the scene. Periods of snow cover are also highlighted (Figure 4). These examples show the strong phenological signal produced by changing vegetation throughout the season. In comparison, the regions of interest

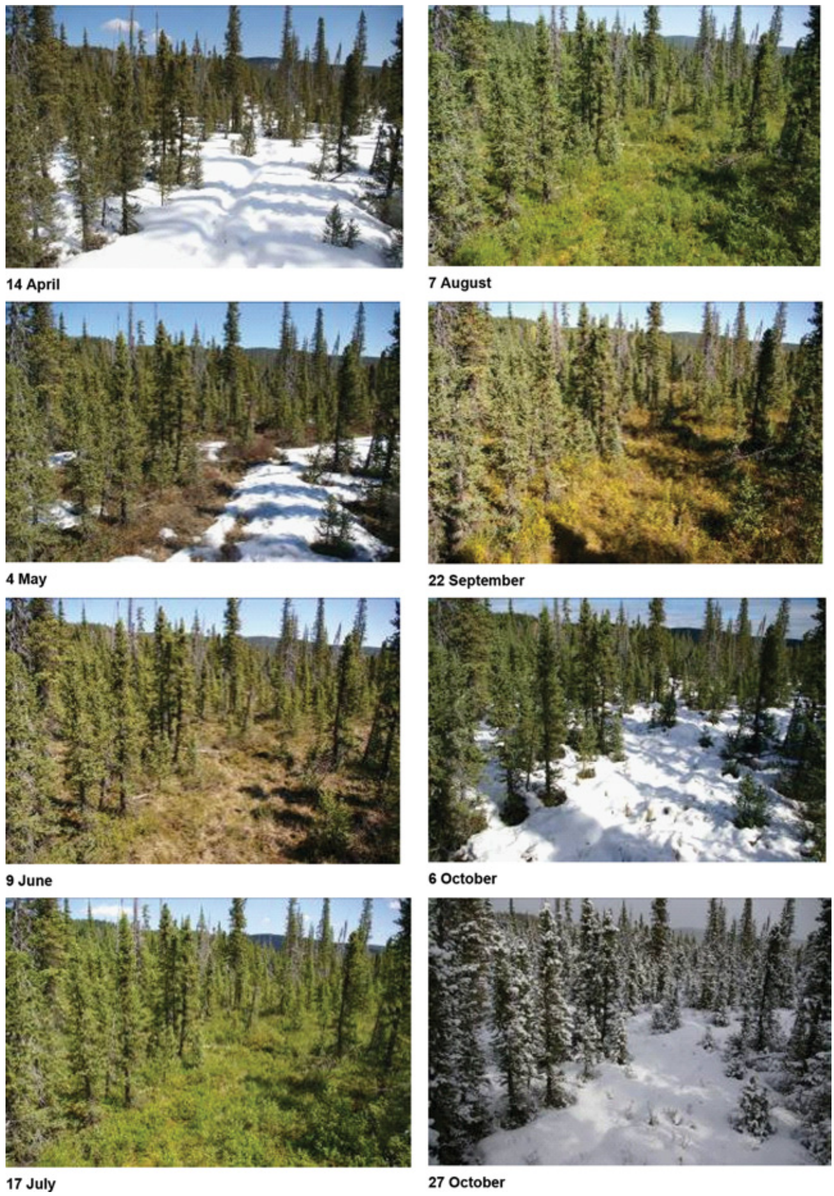

FIGURE 2 Example images from the Cadomin conifer site (see Table 1 for site description). (Figure is provided in color online.)

covering the spruce stem and sky, which should exhibit little or no change, are relatively stable. For all regions of interest, snow cover in particular has a noticeable effect on the values of the green fraction. This is the result of image-wide shifts in color temperature towards blue hues when snow is

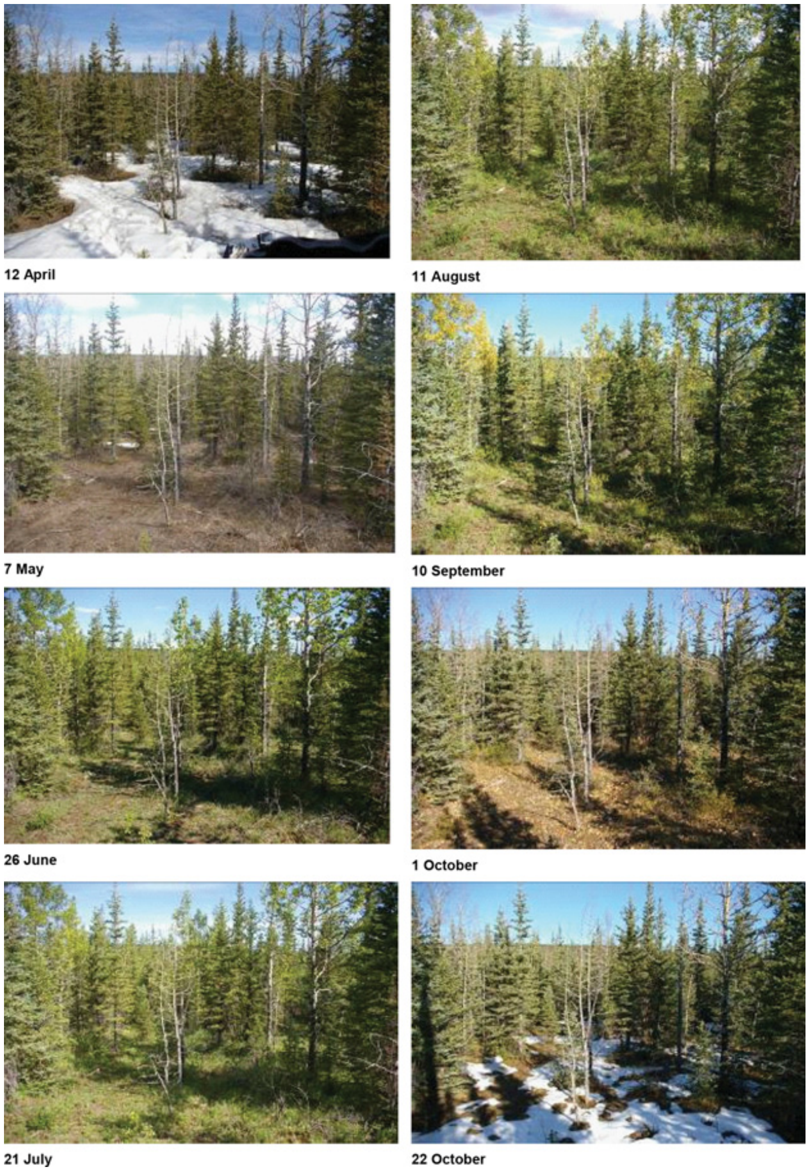

FIGURE 3 Example images from the Cadomin mixed site (see Table 1 for site description). (Figure is provided in color online.)

present, which in turn causes a reduction in the values of the green fraction.

Results of the validation exercise are shown in Table 3, as are the parameters derived from fitting sigmoid functions to understory 2G-RBi data. Figure 5 shows the locations of the regions of interest employed in the

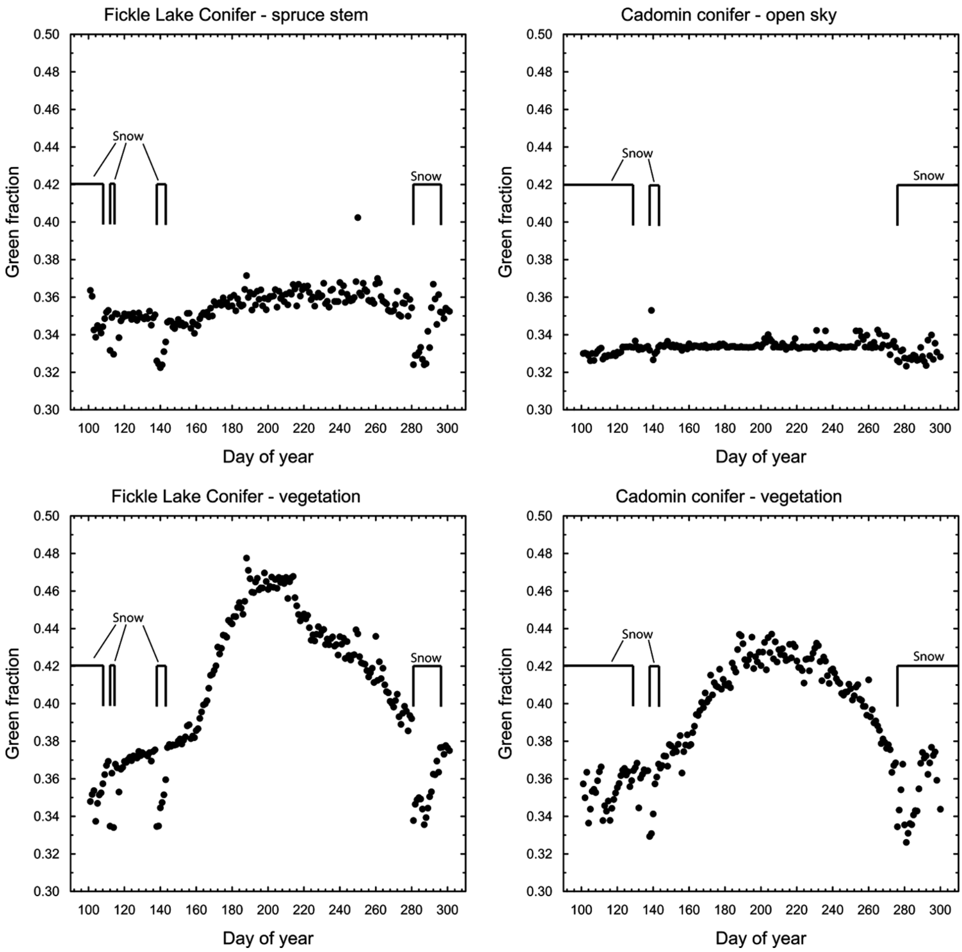

FIGURE 4 Seasonal changes in green fraction for four regions of interest at two sites. At the Fickle Lake Conifer site, one region covers a spruce stem, while another is established over under- and overstory vegetation. At the Cadomin conifer site, one region is located over open sky, while the second is again positioned over under- and overstory vegetation. Periods with snow cover are also highlighted.

validation. The day of year of the beginning of the green-up period as estimated using the camera data was based on the c/d parameters, while the visual estimates were based on when the majority of the understory appeared to be light green. The camera at the Cadomin Mixed site failed during the green-up period, so the green-up date could not be included in the validation. When the two methods were compared, the mean absolute differences between the two were 4.7 days ($n = 6$ sites, standard error of the mean $= \pm 0.95$ days). The sigmoid function fitted the start of green-up closely. The ratio of the c/d parameters provides an indication of the half

TABLE 2 Descriptions of the Intervalometers and Cameras Employed for the Phenology Monitoring Program

Intervalometer	Model	Harbortronics Digisnap 2000
	Time of first daily capture	12:00 noon
	Number of captures	5
	Interval between captures	12 minutes
	Model	Pentax KX00D digital single lens reflex
	Sensor	23.5×15.7 mm CCD; 6.1–10.2 million effective pixels
	Lens	18–55 mm, f 3.5–5.6
	Memory card	4 gigabyte SD
	File type	High quality JPEG
	White balance	Sunlight
Camera	Mode	Program auto exposure (P)
	ISO	200
	Focus	Manual, set to infinity
	Focal length	18 mm
	Shake reduction	Disabled
	Flash	Disabled

maximum green-up time, and demonstrates that, as expected, the lower elevation sites had earlier green-up dates than the higher elevation sites. Coniferous sites across the transect were more similar than the mixed sites, which contained a significant proportion of deciduous vegetation. A comparison of the sigmoid functions fitted to the 2G-RBi data from the seven sites is shown in Figure 6.

TABLE 3 Camera-Based and Visual Estimated Dates of Green-Up

Site Name	Forest Type	Elevation (m)*	Sigmoid function Parameters *a*	*b*	*c*	*d*	Camera-based Estimate of Beginning of Green-up (Day of Year)	Visual Estimate of Beginning of Green-up (Day of Year)	Difference (Days)
Fickle Lake	Coniferous	951	17.04	52.88	7.51	0.11	169	165	4
Fickle Lake	Mixed	970	7.24	17.97	4.72	0.08	158	162	−4
Bryan spur	Coniferous	1,092	4.91	61.81	3.44	0.06	163	171	−8
Bryan spur	Mixed	1,093	5.33	61.5	5.18	0.09	157	154	3
Cadomin	Coniferous	1,458	4.77	57.74	4.22	0.07	161	168	−7
Cadomin	Mixed	1,484	5.25	36.74	22.81	0.32	174	NA	NA
Prospect Creek	Coniferous	1,714	4.88	80.13	6.43	0.09	174	172	2

*Ellipsoid: World Geodetic System, 1984.

Sigmoid fitting functions for Eq. (1) for the 2G-RBi index are shown. *a* and *b* are parameters controlling the scaling of the function between the minimum and maximum observed values, and *c* and *d* result in shifts in time (day of year). The ratio of the *c* and *d* parameters provides an estimate of the day of year when green-up begins. Note that the parameters have been rounded to two decimal places.

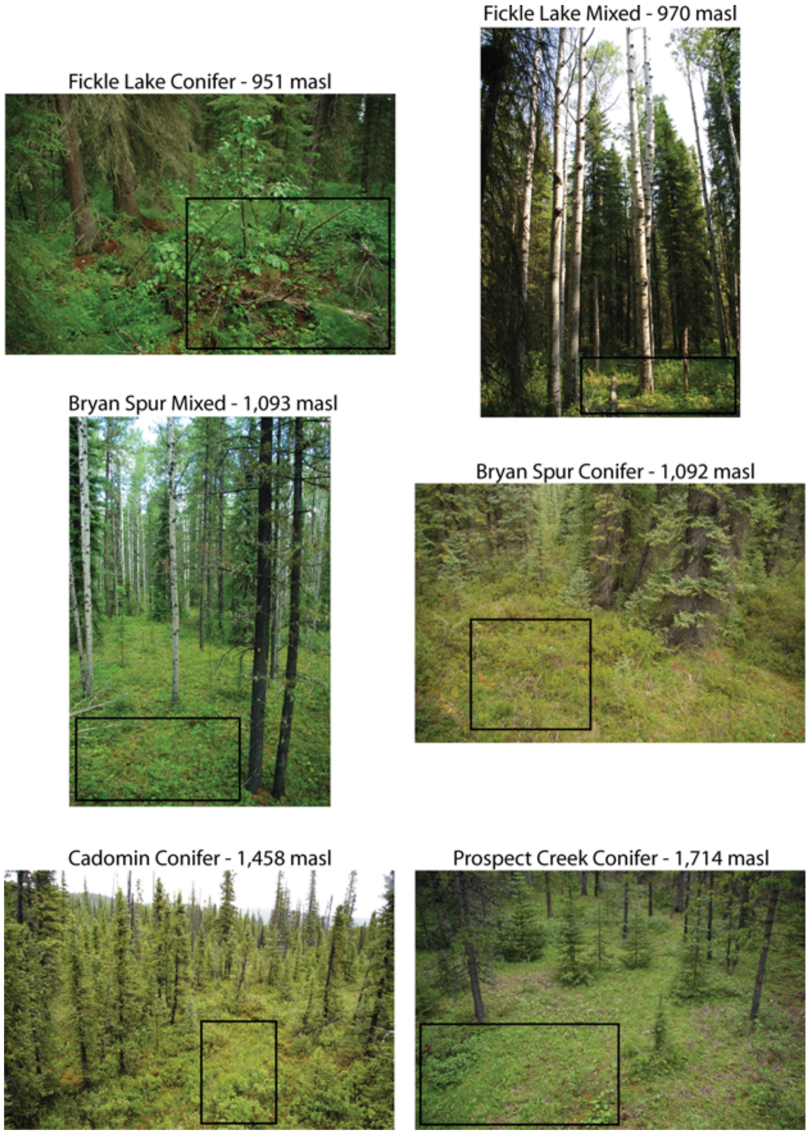

FIGURE 5 Locations of understory regions of interest employed in the validation exercise. (Figure is provided in color online.)

DISCUSSION AND CONCLUSION

Initial analysis of data from the transect of phenological cameras indicates that standard, commercially available digital camera systems designed for extended outdoor time-lapse deployment can be used to extract information on canopy and understory phenology. Given that these cameras are

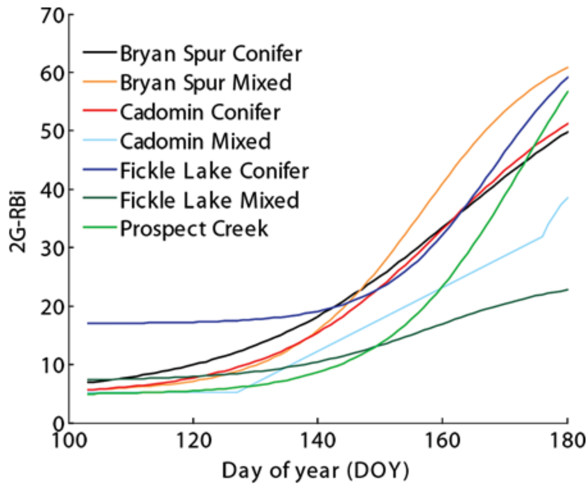

FIGURE 6 Examples of the 2G-RBi trajectories for all sites during spring green-up. (Figure is provided in color online.)

relatively inexpensive, require little in the way of maintenance, and are commercially available, their placement over a range of sites and conditions is more readily achievable than with systems that rely on external power sources and Internet connectivity.

The 2G-RBi index appears to be sensitive to vegetation change, producing high model correlations that were superior to those achieved using the individual normalized bands or other indices. The fact that these ratios performed more consistently than individual brightness changes is logical given the day-to-day variations in illumination that occur within the frame. Other image derivatives being explored include those described by Proulx and Parrott,[39,40] including mean information gain, which is related to structural complexity. Additional information related to different canopies' responses may be extracted from these data, and may in fact lead to a better understanding of the phenology of smaller regions within the scene, such as discrete areas of understory that contain species critical for habitat and food resources for many animals.[29]

In this application, we have focused our initial analysis on green-up, which is essentially the development of green vegetation within the field of view. As digital camera technology becomes more common for monitoring vegetation, other researchers are correlating responses with fluxes related to carbon and water, such as CO_2 exchange, leaf area index, and the fraction of absorbed photosynthetically active radiation.[32] Additional instrumentation co-located with the camera network would be required to investigate these additional aspects of forest function. However, information on of the timing and location of vegetation phenological phases is critical to understanding the behavior and habitat usage of animals such as grizzly bears, and we believe the application of these systems to biodiversity-related issues is a logical and important extension of ongoing work.

We readily acknowledge that these inexpensive systems have some disadvantages when compared to other technologies. The observed brightness changes are essentially uncalibrated. We have no reference panel in the field of view to allow correction of atmospheric effects, and detailed information on in-camera image processing and the spectral sensitivity of the CCD sensor itself is often difficult to obtain from the manufacturers. As a result, computation of reflectance from the camera data is not possible. However, the development of inexpensive, commercially available systems, such as the one described in this article, will be critical to improving our understanding of seasonal variations in vegetation phenology, the detection of changing vegetation dynamics for biodiversity and wildlife management, and for the calibration of datasets obtained from other remote sensing technologies.

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