ARCTIC
VOL. 63, NO. 3 (SEPTEMBER 2010) P. 315–326

Digital Photograph Analysis for Measuring Percent Plant Cover in the Arctic

ZHAOHUA CHEN,[1,2] WENJUN CHEN,[1] SYLVAIN G. LEBLANC[1] and GREGORY H.R. HENRY[3]

(*Received 11 August 2009; accepted in revised form 12 January 2010*)

ABSTRACT. Long-term satellite remote sensing data, when properly calibrated and validated against ground monitoring, could provide valuable data sets for assessing climate change impacts on ecosystems, wildlife, and other important aspects of life in the Arctic. Percent plant cover is ideal for seasonal and long-term ground monitoring because it can be observed non-destructively and is closely related to other key ecosystem variables, such as biomass and leaf area index (LAI). Accurately measuring percent plant cover in the Arctic, however, has been a challenge. Advances in digital photography and image-processing techniques have provided the potential to measure vegetation cover accurately. In this paper we report an adapted method for quantifying percent plant cover based on plot digital photograph classification (PDPC). In this digital image analysis, the red, green, and blue image channels and the intensity, hue, and saturation image channels were used together to ensure more accurate cover measurement and labeling of plant species. We evaluated the accuracy of the PDPC method and two other techniques, visual estimate and digital grid overlay, by testing against artificial plots with known percent cover, by comparing with destructively measured LAI, and by comparing results of the three methods. Our evaluation indicates that the PDPC method is the most accurate. In addition, PDPC has the advantages of being objective, quick in the field, and suitable for measuring percent plant cover in the Arctic at the level of functional types or species groups.

Key words: percent plant cover, Arctic, visual estimate, digital photograph, image classification, LAI

RÉSUMÉ. Lorsqu'elles sont bien calibrées et qu'elles sont validées contre le dépistage terrestre, les données résultant de la télédétection satellitaire à long terme pourraient fournir d'importants ensembles de données en vue de l'évaluation des incidences du changement climatique sur les écosystèmes, la faune et d'autres aspects-clés de la vie dans l'Arctique. Le pourcentage de couverture végétale est idéal pour le dépistage saisonnier et le dépistage terrestre à long terme parce qu'il peut être observé sans qu'il n'y ait de destruction et parce qu'il est étroitement lié à d'autres variables-clés se rapportant aux écosystèmes, comme la biomasse et l'indice de surface foliaire (ISF). Toutefois, dans l'Arctique, la mesure exacte du pourcentage de couverture végétale représente un défi. Les progrès réalisés dans les domaines de la photographie numérique et des techniques de traitement d'images fournissent la possibilité de mesurer la couverture végétale avec précision. Dans cette communication, nous faisons état d'une méthode adaptée permettant de quantifier le pourcentage de couverture végétale en fonction de la classification de photographies numériques de parcelles. Dans le cadre de l'analyse d'images numériques, les canaux rouges, verts et bleus des images ainsi que les canaux d'intensité, de tonalité et de saturation des images ont été utilisés pour donner lieu à la mesure plus exacte de la couverture végétale et à l'étiquetage des espèces végétales. Nous avons évalué l'exactitude de la méthode de classification de photographies numériques de parcelles de même que celle de deux autres techniques, soit l'estimation visuelle et la superposition de grilles numériques en faisant des essais à la lumière de parcelles artificielles dont le pourcentage de couverture végétale était connu et en les comparant avec des ISF mesurés de manière destructive, puis en comparant les résultats des trois méthodes. Selon notre évaluation, la méthode consistant en la classification de photographies numériques de parcelles PDPC est la plus précise. La classification de photographies numériques de parcelles a également l'avantage d'être objective, d'être rapide sur le terrain et de se prêter à la mesure du pourcentage de couverture végétale dans l'Arctique en ce qui a trait aux types fonctionnels ou aux groupements d'espèces.

Mots clés : pourcentage de couverture végétale, Arctique, estimation visuelle, photographie numérique, classification d'images, indice de surface foliaire

Traduit pour la revue *Arctic* par Nicole Giguère.

[1] Canada Centre for Remote Sensing, Natural Resources Canada, 588 Booth Street, Ottawa, Ontario K1A 0Y7, Canada
[2] Corresponding author: zhaohua.c@gmail.com
[3] Department of Geography, University of British Columbia, Vancouver, British Columbia V6T 1Z2, Canada

INTRODUCTION

Climate change is occurring in the Arctic at double the average global rate and is predicted to continue at an even faster rate (Kattsov et al., 2005). A changing climate may significantly affect the quality of wildlife habitats in the Arctic, the ecological integrity of northern national parks, freshwater resources, and infrastructures of northern communities, as well as global carbon and water cycles (PCA, 2000; McGuire et al., 2002; Klein et al., 2005; Anisimov et al., 2007; Chen et al., 2009a). Satellite earth observation data (such as Landsat and Advanced Very High Resolution Radiometer, or AVHRR) could provide historical and ongoing data sets essential for assessing these climate-change influences if they are properly calibrated and validated against ground observations, especially seasonal and long-term ground monitoring data (Stow et al., 2004; Bunn and Goetz, 2006; Olthof et al., 2008). Seasonal and long-term monitoring also provides a more precise way to document and assess climate-change effects. For example, Stow et al. (2004) found through such monitoring that shrub distribution and density were responding to climate change at Arctic sites.

One of the most commonly observed and potentially most useful ecosystem variables for seasonal and long-term ground monitoring is percent plant cover (Bliss et al., 1984; Kennedy et al., 2001; Krebs et al., 2003; Bonham and Clark, 2005; Chen et al., 2009b). As shown by Chen et al. (2009b), other key ecosystem variables such as aboveground biomass, foliage biomass, and leaf area index (LAI) can be reliably measured in the Arctic using percent plant cover and mean height, not only at the plot-total level, but also at the levels of plant species or function groups. As a result, seasonal and long-term monitoring of key ecosystem variables can be achieved by repeated non-destructive observations of percent cover and mean height at permanent plots and thus provide essential data sets for calibrating and validating remote sensing products. While measurement of mean plant height is straightforward, accurate measurement of percent plant cover has been a challenge.

Traditional techniques to measure the percent cover are ground-based. Two methods are commonly used: visual estimate (VE) and point frame (PF) (Bliss et al., 1984; Kennedy et al., 2001; Krebs et al., 2003; Bean and Henry 2003; Bonham and Clark, 2005; Chen et al., 2009b). The VE method is quick and widely used. However, its reliability is questionable because it is subjective in nature, the overvaluation error increases with the view angle, and it is prone to inter-observer bias (Meese and Tomich, 1992; Dethier et al., 1993; Vanha-Majamaa et al., 2000). The point-frame method is considered to be objective and is the recommended standard protocol for measuring the plant cover in the International Tundra Experiment (ITEX) (Walker, 1996; Bean and Henry, 2003). However, it is time consuming, usually needing 2–3 hours to complete measurements for one plot. This can be a significant constraint because doing fieldwork in the Arctic is very expensive (high helicopter transportation cost) and the growing season is very short. More problematically, this method is suspected to overvalue the percent cover and miss rare species (Bråkenhielm and Liu, 1995; Vanha-Majamaa et al., 2000). The recommended 10 × 10 grid over a 1 × 1 m plot for the PF method means that if a point hits a plant, full plant cover over that 10 × 10 cm cell of the grid is then assumed. In the field, if a 1 × 1 m grid divided into 10 × 10 cm cells is not appropriate for the scale, then point density should be increased.

An increase in the grid resolution could retain the objectivity of the point-frame method and significantly increase the accuracy of percent plant cover estimation. However, the increase in time required to complete one measurement for a plot would make this method impractical if it had to be implemented in the field. This impracticality can be circumvented by an image-based method, taking a nadir-view photograph of the plot in the field and analyzing the photograph later in the laboratory. Using digital grid overlay (DGO), Booth et al. (2006b) measured percent cover over a photograph. However, the contact area of each point (intersection) in the grid was larger than an image pixel in their study. As a result, the large contact area was a factor influencing measurement accuracy when using DGO.

Recent advances in digital photography and image analysis software have provided the potential to measure percent vegetation cover quickly and objectively and to repeat comparable measurements over time (Booth et al., 2006b; Luscier et al., 2006; Laliberte et al., 2007). Several researchers have investigated the feasibility of measuring percent plant cover from a photograph taken by a digital camera over a plot (Richardson et al., 2001; Booth et al., 2004, 2005, 2006b; Luscier et al., 2006; Laliberte et al., 2007). However, most such studies produced only general categories, such as vegetation and non-vegetation (Laliberte et al., 2007). Since wildlife species usually differentiate between vegetation types in their diets (Krebs et al., 2003), categorizing percent plant cover at a more detailed level (e.g., by functional types or species groups, Chen et al., 2009b) is required. With improved image analysis products and methods, such as VegMeasure, a software product developed by Johnson et al. (2003); SamplePoint, developed by Booth et al. (2006a); and eCognition (Definiens, 2003), several studies have measured percent cover for vegetation categories on digital photographs, with promising results (Booth et al., 2005, 2006a, b; Luscier et al., 2006; Laliberte et al., 2007; Booth and Cox, 2008). However, classification error resulting from spectral separation methods (VegMeasure, ERDAS Imagine [ERDAS, 2010], eCognition) can cause confusion among like-colored species.

Our goals were to develop a new, accurate method of measuring cover of key species in the Arctic and to compare its results over a small contact area to those of two other methods: visual estimate and digital grid overlay. Here we report on 1) how we modified standard image-based methods to allow accurate measurement of cover by species, and 2) how we tested the results obtained using our plot digital photograph classification (PDPC) method, which incorporates the modification, and compared them to the VE and DGO results. So far, no investigation of changes in Arctic vegetation over time has been conducted using plot photography.

METHODS AND MATERIALS

Study Area and Field Measurements

Our study on vegetation cover of Arctic tundra ecosystems was conducted around Iqaluit (63˚46′ N, 68˚32′ W) and Clyde River (70˚29′ N, 68˚30′ W) Nunavut, Canada. The field measurements were acquired during 16–27 July 2007. To cover the whole spectrum of vegetation conditions for the purpose of evaluating the three methods, we deliberately selected three different types of sites (with relatively low vegetation cover, medium growth conditions, and high vegetation cover) around each of the two communities. A site was at least 3 × 3 Landsat TM pixels (i.e., 90 × 90 m), to meet the needs for calibrating and validating remote sensing products. Five 0.5 × 0.5 m plots were used for each site, with a central plot located randomly and the other four plots located at 30 m east, south, north, and west of the central plot. The plot was representative of local vegetation conditions and relatively homogenous.

A nadir digital photograph (taken from directly above) at the plot level was taken with a 10-megapixel Nikon D80 digital camera at a height of about 1.5 m above the frame, using a tripod support. The resulting images had a size of 3872 × 2592 pixels (the sensor array of the digital camera), covering the frame and four sides. We selected plots for analysis on the basis of digital photograph quality. The plots were not included in this study if their digital photographs were poorly focused or severely skewed. The 26 plots selected for percent plant cover analysis thus included 11 plots from the three Iqaluit sites and 15 plots from the three Clyde River sites.

In total, 13 vascular plant species were identified in these plots: *Salix arctica*, *Cassiope tetragona*, *Oxytropis arctica*, *Vaccinium uliginosum*, *Poa* sp., *Empetrum nigrum*, *Diapensia lapponica*, *Pedicularis hirsuta* L., *Dryas integrifolia*, *Oxyria digyna*, *Salix reticulata*, *Saxifraga* L., and *Carex membranacea*. Not all the species were observed in each of the 26 plots, and some species were more abundant than others. For example, *Salix arctica* was found in 17 plots, but *Diapensia lapponica*, *Oxyria digyna*, and *Empetrum nigrum* each occurred in only one plot. The total leaf area index (LAI) of a vascular plant species within a plot was determined destructively (Chen et al., 2009b).

The Digital Grid Overlay Method

Since the point-frame method was not applied in the field, in this study we conducted measurements using an improved DGO on the digital ground photos. Thus, we could easily adjust the number of points used within a digital frame with a GIS. The grid intersection was formed over the original digital photograph (3872 × 2592 pixels over 0.25 m^2) on the computer screen, so the contact area of the intersection was the area of a single pixel (0.025 mm^2). No matter how many intersections (10 × 10 grids or 1000 × 1000 grids) we used, the contact area did not change because it was determined only by the resolution of the original image, and the on-screen display allowed us to zoom in to one pixel. By overlaying the frame with a plot digital photograph, the analyst can identify the species of vegetation at each intersection. From the counts of the vegetation intercepted, the percent cover of each species in the plot can be calculated. For the present analysis, we counted only leaf interception to make our results easy to compare with those from other two methods.

The Visual Estimate Method

The VE method as used in this study was an estimate of the percent plant cover of each vascular plant species by nadir-view projection to the ground level within a fixed plot area of 0.5 × 0.5 m. The original estimates of percent plant cover included all aboveground plant components (i.e., leaves, stems, and occasionally flowers) and were made layer by layer from the top to the bottom by averaging estimates from the two to three observers on the field team. To make the results comparable with the LAI, as well as with the measurements from the PDPC method and DGO method that include only percent cover of leaves, we subtracted the percent cover of stems to obtain the percent cover of leaves. The percent cover of stems, visually estimated from the digital photos, was typically much smaller than that of leaves, and occurred only for some woody shrub species (e.g., *Salix arctica*, *Vaccinium uliginosum*). In the following analyses, cover refers only to the percent cover of leaves.

The Plot Digital Photograph Classification Method

The PDPC method includes band transformation, image segmentation, object classification, and species labeling.

1) Band Transformation: Most digital photos are taken in the visible light wavelength region (red, green, and blue or RGB). Different green vegetation may have similar spectral reflectance in the visible light region, thus species are difficult to differentiate in an automatic image analysis using imagery with only RGB bands. RGB images were transformed to intensity-hue-saturation (IHS) images using ERDAS software to reduce the high intercorrelation of RGB bands and to improve the image analysis and vegetation recognition from photos in this study. Vegetation analysis using digital images with IHS transformations increased accuracy over the original RGB bands in several studies (Tang et al., 2000; Hemming and Rath 2001; Karcher and Richardson, 2003; Laliberte et al., 2007). We used both RGB and IHS in our image analyses. IHS images were used for image segmentation and preliminary classification. RGB images were used for visual interpretation in the labeling step.

2) Image Segmentation: Digital processing of a plot photograph can be performed using pixel-based or object-based image analysis. Pixel-based analysis is a traditional method that assesses each pixel's digital number individually. However, because of spectral similarity between species and high color variation within pixels from the same plant species, pixel-based classification results obtained from spectral information are usually not satisfactory (Vanha-Majamaa et al., 2000). Object-based image analysis, a relatively new method that treats homogenous pixels as objects with regard to spatial or spectral characteristics (Ryherd and Woodcock, 1996), is an effective tool for classification of high-resolution satellite imagery (Herold et al., 2003; Thomas et al., 2003; Laliberte et al., 2004). The extraction of green-vegetation cover by species requires clear boundaries between leaves of each species group. To improve the capability of identifying various species groups and reduce the spectral confusion between species groups, both spectral information and geometric information should be considered. Therefore, we applied a segmentation technique—similar to that used by Luscier et al. (2006) and Laliberte et al. (2007), with special emphasis on the consideration of shape information in image analysis with eCognition—to treat homogeneous areas as objects in plot photographs of this study.

An image of IHS bands was segmented into polygons on the basis of three parameters: scale, color (spectral information), and shape. Considering most species in this study had relatively small leaf sizes, we used the following parameter values for all the images: 20 for the scale parameter, 0.6/0.4 for the color/shape parameter, and 0.9/0.1 for the smoothness/compactness parameter. Setting a larger value for scale parameter will result in larger image objects (Laliberte et al., 2007). Using these parameters, an individual leaf can mostly be treated as a polygon, although some small leaves may be grouped into one polygon, and occasionally, a big leaf may be split into several polygons.

3) Object Classification: In automated classification, different green vegetation species with similar shape, color, or both are very difficult to separate using the limited spectral information contained in RGB bands. Frequently, the result is classification confusion between vegetation species. Therefore, automated classification for various species was not adopted in this study. After segmentation, all objects in the image can be classified into general categories by determining the threshold values in the IHS bands. In this study, we first separated two general categories, green vegetation and non-green vegetation. Although some non-green vegetation areas may be included in the category of green vegetation because of the spectral confusion or geometric intermixing, these areas can be eliminated later on. From this point forward, only green vegetation was of concern and was further classified. Using a scale parameter of 20, a large number of polygons were created. Since classification and editing of such a large number of polygons can be time-consuming even with only green vegetation species, further grouping on the basis of unique vegetation characteristics was necessary. Size and geometric characteristics (e.g., the length/width ratio) can be useful to distinguish various green vegetation species. Ratio of length/width was calculated for each polygon. Since plant species with long leaves had large length/width ratios and those with round leaves had low values, each green vegetation object was then classified on the basis of a threshold value of length/width ratio.

4) Species Labeling: In addition to the spectral information, RGB images may also contain other information about the objects, such as shape, size, texture, pattern, association, and shadow. The human mind is good at recognizing and associating these complex elements in an image. Information about color, texture, shape, and context and expert knowledge of vegetation can be useful to identify each polygon in an image. Overlaying the polygon layer of green vegetation with the RGB composite images aided with visual interpretation, we labeled each polygon by plant species in a GIS environment. At this stage, we eliminated the non-green vegetation polygons that had been misclassified as green ones. Although the visual identification of each polygon was time-consuming, the results were very accurate, as the segmentation was conducted at a scale that almost equaled individual leaf size. The labeling procedures can be faster and easier in the plots that contain fewer species or are more homogeneous, or after the analyst has gained experience. Once all species were correctly labeled and separated, layers containing different species were combined to form a vegetation map of the plot. Finally, the percent cover of each species and plot total percent cover were calculated.

Estimation Error Analysis

Given that there is no proven method with which we can obtain the true values of percent plant cover over a plot in the field with certainty, it is difficult to assess which one of these three methods (VE, DGO, or PDPC) is the most accurate. In this study, we evaluated the estimation errors of these methods in the following ways.

Testing Against Artificial Plots with Known Percent Plant Cover

To mimic typical Arctic tundra ecosystems, which rarely have more than 30% vegetation cover, we assumed eight categories: 890, 1780, 2670, 5340, 7120, 8910, 10690, and 13360 oval shape leaves of 2 mm wide and 3 mm long, randomly distributed over a 0.5 × 0.5 m monochromatic test plot without overlap. These figures gave a percent plant cover of about 1.68%, 3.36%, 5.03%, 10.06%, 13.43%, 16.78%, 20.14%, and 25.18%, respectively. Each given percent plant cover was tested with five random distributions. For the DGO method, we investigated grids with different resolutions: the ITEX-recommended 10 × 10 grids, as well as 5 × 5 grids, 15 × 15 grids, 20 × 20 grids, 50 × 50 grids, 100 × 100 grids, 200 × 200 grids, 500 × 500 grids, and 1000 × 1000 grids. The PDPC method was also tested against the artificial plots. The estimation error, E, was calculated as follows:

$$E = \frac{\text{estimated percent cover - true percent cover}}{\text{true percent cover}} \times 100\% \quad (1)$$

Comparison with LAI Measured Destructively

According to its definition, the percent cover, C, is given by

$$C = 1 - P(\theta) \quad (2)$$

where $P(\theta)$ is the gap fraction at the view zenith angle θ = 0 and is related to the total projected LAI, L_t (Nilson, 1971; Chen et al., 1997), as follows:

$$P(0) = \exp(-G(0)\Omega L_t) \quad (3)$$

where $G(0)$ is the projection coefficient characterizing the foliage angle distribution, and Ω is a parameter determined by the spatial distribution pattern of leaves. When the foliage spatial distribution is random, $\Omega = 1$. When leaves are clumped, Ω is less than 1. Foliage in plant canopies is generally clumped, and hence Ω is often referred to as the clumping index. Combining equation (2) and (3), we have

$$-\ln(1 - C) = G(0)\Omega L_t \quad (4)$$

Since the value of $G(0)\Omega$ is generally below 1, so the value of $-\ln(1 - C)$ should be less than L_t. In other words, L_t represents the maximum possible value of $-\ln(1 - C)$, in which all leaves are positioned randomly, without clumping, and parallel to the ground surface. In reality, most leaves are clumped and are positioned at a certain angle relative to the ground surface. Overlap of leaves exists in most plots. Consequently, it can be concluded with certainty that if the percent cover measured or estimated by a method is found to be larger than the corresponding L_t, this method overvalues cover. Conversely, if an estimate of percent cover by a method is found to equal zero, while the corresponding L_t is larger than zero, it can be concluded with certainty that this method makes a mistake of 100% undervaluation.

Besides making these magnitude comparisons, we can also assess the LAI–percent cover relationship. For a given species of vascular plant, the leaf distribution and overlap should be similar between different plots, especially when low, sparsely distributed tundra plots in the Arctic are concerned. If the percent cover is measured or estimated accurately, a strong linear relationship between L_t and $-\ln(1 - C)$ is expected. As a result, if the relationship between L_t and $-\ln(1 - C)$ estimated by a method has a low R_2 value, the method is likely to be less accurate.

Inter-comparison between Methods

Inter-comparison of different methods is a common practice, although it could be inconclusive if none of the methods compared is accurate (Floyd and Anderson, 1987). Fortunately, the two approaches noted above (artificial plot evaluation and comparison with total LAI) can determine which one of the three methods is most accurate. If we consider the estimates made using the most accurate method as the "true" values, we can evaluate the estimates derived from digital photographs of Arctic tundra plots using other methods.

RESULTS AND DISCUSSION

Errors Evaluated Using Artificial Plots with Known Percent Cover

We evaluated the errors in estimates of percent cover against artificial plots with known percent plant cover ranging from 1.68% to 25.18%. Figure 1 shows that for the digital grid overlay method, the errors in percent cover range from -100% to 257% using 5 × 5 grids (DGO5×5) and from -100% to 78% using the ITEX-recommended 10 × 10 grids (DGO10×10). The errors decrease to nearly zero for grids reaching 1000 × 1000. The PDPC method, at the highest resolution, with 3872 × 2592 grids, was found to be 100% accurate in estimating percent cover for the artificial plots with known percent plant cover.

Comparison Results with LAI

For *Salix arctica*, 6 out of 17 samples investigated at the species level for tundra plots around Iqaluit and Clyde River by the VE method had an estimated $-\ln(1 - C)$ greater than the total projected LAI (Fig. 2 and Table 1). Therefore, we can conclude with certainty that in 6/17 or 35% of cases, the VE method overvalues. The DGO method (DGO5×5 and DGO10×10) also overvalued to a similar degree as the VE. Using the PDPC method, we found no cases in which the estimated $-\ln(1 - C)$ was greater than the total projected LAI for *Salix arctica*.

Similar results were found for other vascular plant species (Table 1), although the rates of overvaluation varied somewhat from species to species. The PDPC method continued to be the most accurate method. However, in the cases of *Carex membranacea*, *Vaccinium uliginosum*, and *Poa* sp., we did find 1/15, 1/7, and 2/9 cases, respectively, in which the PDPC estimate for $-\ln(1 - C)$ was greater than the total projected LAI. Several explanations are possible. First, some leaves might be mistakenly merged and mislabeled in applying the PDPC method, so that leaves that belonged to other species were misclassified as those of *Carex membranacea*, *Vaccinium uliginosum*, and *Poa* sp. In addition, during the destructive harvest of plants in the field, it was inevitable that some of the plant components were omitted. As a result, the destructively measured LAI was less than the actual LAI, which in turn could result in the estimated percent cover of leaves surpassing the total projected LAI measured destructively.

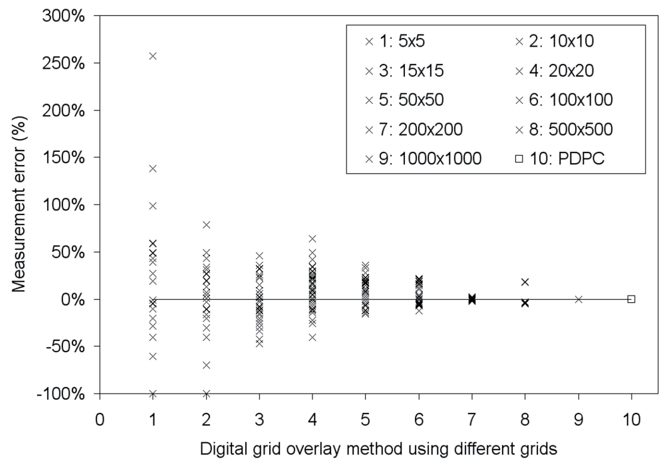

FIG. 1. Errors in percent cover estimates made by the digital grid overlay (DGO) method using different grid resolutions and by the plot digital photograph-based classification method (PDPC) for artificial plots with known percent cover values.

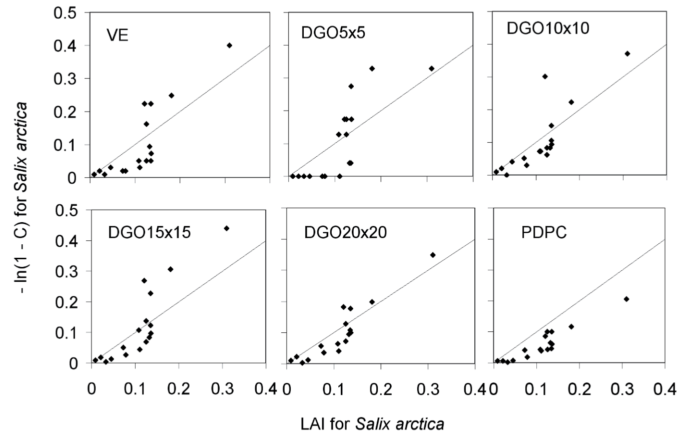

FIG. 2. Comparison between leaf area index (LAI) and –ln (1 - *C*), where *C* is percent cover of *Salix arctica*, measured or estimated using the visual estimate method (VE), the DGO method with different grid resolutions, and the PDPC method. Slopes are 1:1 lines.

TABLE 1. Fraction of samples for which –ln (1 - percent cover) was greater than the total LAI. The percent cover was estimated using the visual estimate (VE) method, the digital grid overlay (DGO) using different grids, and the plot digital photograph classification method (PDPC).

	VE	DGO5×5	DGO10×10	DGO15×15	DGO20×20	PDPC
Salix arctica	6/17	8/17	5/17	6/17	7/17	0/17
Dryas integrifolia	4/7	1/7	1/7	2/7	1/7	0/7
Vaccinium uliginosum	3/7	4/7	4/7	5/7	3/7	1/7
Carex membranacea	6/15	2/15	5/15	2/15	2/15	1/15
Poa sp.	4/9	3/9	3/9	2/9	2/9	2/9
All samples at the species level	29/75	25/75	25/75	23/75	20/75	7/75
At the plot total level	15/26	13/26	11/26	9/26	7/26	0/26

Nevertheless, when all 75 samples at the species level were included, the PDPC method was found to have the lowest overvaluation rate at 9%, in comparison to 38% for the VE method, 33% for the DGO5×5 and DGO10×10, 31% for the DGO15×15, and 27% for the DGO20×20 methods (Fig. 3 and Table 1). When results were aggregated to the plot total level, the errors caused by misclassification disappeared, resulting in 0% overvaluation for the PDPC method (Fig. 4 and Table 1). However, the VE method and the DGO using different grids still had overvaluation rates of 27% to 58%. The overvaluation of vegetation cover by the VE method and the DGO was also reported by Dethier et al. (1993) and Vanha-Majamaa et al. (2000).

In contrast to the situation of overvaluation, the DGO method could entirely miss a species. As shown in Table 2, the DGO5×5 entirely missed a species in 43% cases when all plant species were summarized. The rate of missing species is only 15% for the DGO10×10 and 7% for the DGO15×15 and the DGO20×20. For the VE and PDPC methods, no cases of missing a species occurred.

Significant correlations at the 95% confidence level between LAI and –ln (1 - *C*) were found for the five species listed in Table 3, except for *Vaccinium uliginosum* using the DGO10×10 and for *Poa* sp. using the DGO5×5 and DGO10×10. Overall, values from the PDPC method show the best correlation between LAI and –ln (1 - *C*), both at the species level and at the plot total level (Figs. 3 and 4). At the plot total level, the value of R^2 was 0.88 for the PDPC method, compared to 0.56 for the VE method and 0.58 to 0.79 for the DGO method using different grids.

On the basis of the testing results using artificial plots and comparison results with LAI, we concluded that the PDPC method was the most accurate of the three methods investigated here. Therefore, we used the PDPC values of percent cover for tundra plots in Nunavut as the “true” values against which to evaluate the methods of VE and DGO (using different grid resolutions).

Inter-comparison Results

Figure 5 shows the visual representation of plant cover distribution for an example plot. It shows the original digital photograph and images of cover measured using the PDPC method and the DGO method at different grid resolutions. A close resemblance in plant cover distribution can be found between the original digital photograph and the measurement using the PDPC method. Much of the spatial distribution detail is lost in the measurement using the DGO method, especially with DGO5×5, resulting in overvaluation of percent cover for some species and undervaluation

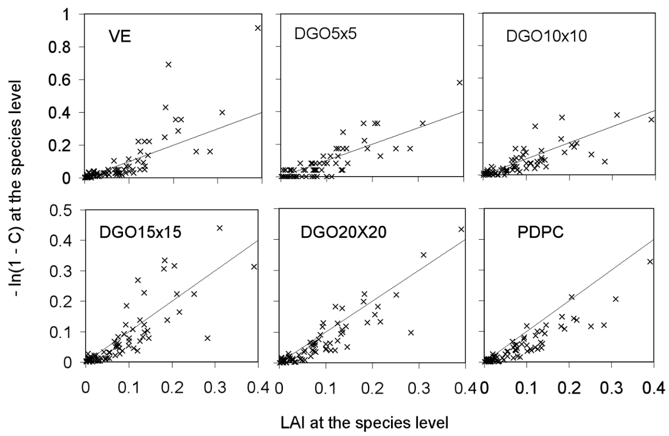

FIG. 3. Comparison between LAI and –ln (1 - *C*) for all species, where *C* is percent cover of a species measured or estimated using the VE method, the DGO method with different grid resolutions, and the PDPC method. Slopes are 1:1 lines.

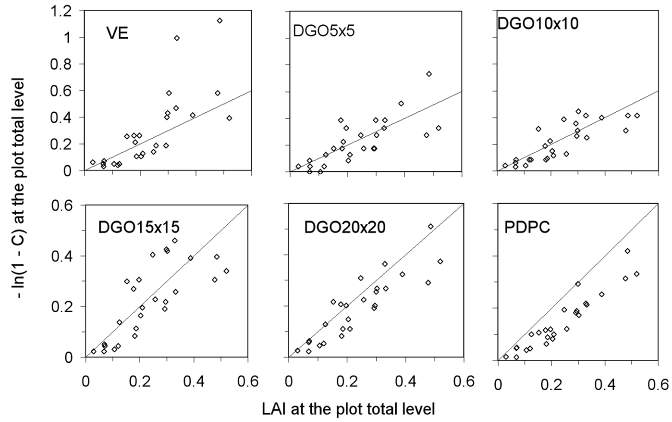

FIG. 4. Relationships between plot-total LAI and –ln (1 - *C*), where *C* is the percent cover at the plot total level measured or estimated using the VE method, the DGO method with different grid resolutions, and the PDPC method. Slopes are 1:1 lines.

TABLE 2. Fraction of samples for which the total LAI is greater than 0 while the estimate of percent cover = 0, for estimates of percent cover made with the VE, DGO using different grids, and PDPC methods.

	VE	DGO5×5	DGO10×10	DGO15×15	DGO20×20	PDPC
Salix arctica	0/17	7/17	1/17	0/17	0/17	0/17
Dryas integrifolia	0/7	2/7	0/7	0/7	0/7	0/7
Vaccinium uliginosum	0/7	0/7	1/7	0/7	0/7	0/7
Carex membranacea	0/15	7/15	1/15	1/15	0/15	0/15
Poa sp.	0/9	5/9	2/9	1/9	0/9	0/9
All samples at the species level	0/75	32/75	11/75	5/75	5/75	0/75
At the plot total level	0/26	2/26	0/26	0/26	0/26	0/26

for other species. For example, in relation to the “true” value measured by the PDPC method, the DGO5×5 method undervalued the percent cover of *Carex membranacea* in the plot by 116% and that of *Oxytropis arctica* by 100% (Table 4).

Even larger errors were found when all 75 samples were analyzed at the species level (Fig. 6). The errors range from -87% to 1941% for the VE method, -100% to 950% for the DGO5×5, -100% to 2075% for the DGO10×10, -100% to 770% for the DGO15×15, and -100% to 646% for the DGO20×20. For percent cover measurement at plot total level, the error range was smaller: -48% to 332% for the VE method, -100% to 191% for the DGO5×5, -16% to 188% for the DGO10×10, -22% to 155% for the DGO15×15, and -11% to 93% for the DGO20×20. The main reason for the decrease in error from the species level to the plot total level is compensating errors in the aggregation process.

Such mutual cancellation of errors may also explain why the error range decreases when percent cover value increases for *Salix arctica* and all species in Arctic tundra plots around Iqaluit and Clyde River. From Figure 7, we can clearly see that the largest percentage errors occur when the percent cover is less than 1%. This relationship also partially explains why the error ranges for the actual tundra plots in Figure 6 are much larger than that for the artificial plots in Figure 1. For the artificial plots in Figure 1, the smallest percent cover used was 1.68%, while many plots in Figure 6 had percent cover of less than 1%. When comparison was made at the plot level, we found similar magnitudes of error for both the actual plots in Nunavut and the artificial plots. In both cases, we found a decreasing trend in measurement error as percent cover increased.

Technical Considerations for Using the Plot Digital Photograph Classification Methods

We found that the combination of IHS and RGB images was effective in identifying vegetation cover by species. IHS transformation and object-based segmentation techniques were effective for processing plot photographs and segmenting the green leaves of vegetation species into relatively homogeneous polygons. The adjustable IHS threshold values performed well at mapping out green vegetation polygons in this study. At a proper scale, a polygon may be composed of an individual leaf (for big leaves) or a cluster of leaves (for small leaves) from the same species. Along with visual interpretation of RGB images, we used GIS editing to correct boundary outlining and increase the accuracy of species labeling for each polygon. This approach was useful in calculating the percent cover from plot photographs in this study. Since individual blades were identified for most leaves of different species, we consider that the percent cover measured using this method was close to the true value.

TABLE 3. R^2 values for the linear, intercept = 0 correlation between LAI and –ln (1 - C), estimated using the VE, DGO using different grids, and PDPC methods. For other species that had a sample size less than 5, values of R^2 were not calculated. Asterisks represent statistical significance at the 90% (*) and 95% (**) confidence levels.

	VE	DGO5×5	DGO10×10	DGO15×15	DGO20×20	PDPC	*n*
Salix arctica	0.67**	0.60**	0.67**	0.72**	0.81**	0.84**	17
Dryas integrifolia	0.67**	0.70**	0.79**	0.90**	0.87**	0.82**	7
Vaccinium uliginosum	0.70**	0.78**	0.50*	0.72**	0.66**	0.83**	7
Carex membranacea	0.69**	0.73**	0.75**	0.82**	0.78**	0.87**	15
Poa sp.	0.55**	0.01	0.24	0.93**	0.62**	0.80**	9
At the plot total level	0.56**	0.58**	0.66**	0.57**	0.79**	0.88**	26

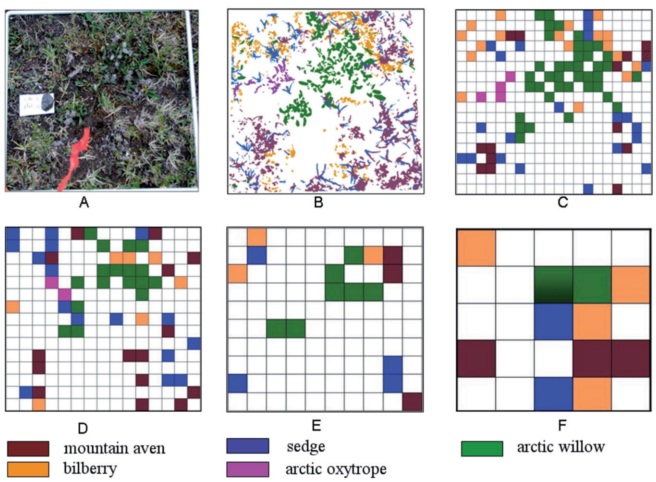

FIG. 5. Visual illustrations of plant cover distribution in an example plot. (A) shows the original digital photograph, and (B) shows distribution measured by the PDPC method. The remaining blocks show distributions from the DGO method with four different grids: (C) 20 × 20, (D) 15 × 15, (E) 10 × 10, and (F) 5 × 5. Percent cover values for each species are listed in Table 4.

In plots containing *Poa* sp. and *Carex membranacea*, the ratio of length to width was useful for separating these two species from the rest of the green vegetation. Vegetation with wider leaves, such as *Salix arctica*, *Salix reticulata*, and *Oxytropis arctica*, can also be separated easily from the surroundings. The boundaries of vegetation with small leaves, such as the *Dryas integrifolia* and *Vaccinium uliginosum*, can be hard to define because the leaves are clustered together.

The time for processing a plot photograph ranged from 30 to 90 minutes depending on the complexity of the vegetation. Compared to the quick VE method in the field, the PDPC method takes more time. However, analysis of plot photographs can be faster once the method is developed, and the results and photographs of different dates can be used to assess vegetation dynamics for monitoring purposes. In addition, photographs can be acquired quickly, archived easily, and used for future change analysis. Indeed, as several researchers have noted, one of the great advantages of measuring cover from digital images is that analysis can be done in the lab after the field investigation. Field research in the Arctic is time-consuming, labour-intensive, and logistically expensive. In contrast to the results from the VE method, which have high observer-to-observer variability (Meese and Tomich, 1992), the results from the PDPC method are relatively consistent between analysts because the accuracy of the percent cover in plot photograph analysis is largely dependent on polygons with clear boundaries produced at the segmentation stage, which is a more standardized step.

However, application of the PDPC method in this paper also raises a few issues for future study:

1) The results from the PDPC method may be more reliable for vegetation of greenish appearance than for vegetation of less greenish appearance. For vegetation species with grey or brown color, such as *Cassiope tetragona* and *Pedicularis hirsuta* L., some polygons representing leaves were masked out as non-green vegetation during the preliminary digital classification using the IHS threshold.
2) Shadow area varies in each image and affects the percent cover measurement. Shadow is always a problem in very high-resolution images because it occurs both on the non-vegetation area and within the vegetation canopy, making it hard to identify whether shadow area belongs to vegetation or non-vegetation. Therefore, most shadow areas were treated as non-vegetation areas using only IHS threshold values during the segmentation. Shadow affects the measurement of percent cover more for small-leaf species than for big-leaf species. Some shadow may be included in a polygon containing a few small leaves during the segmentation stage and cause over-estimation for species with small leaves. High dynamic range nadir images may provide a solution for reducing the shadow problem (Cox and Booth, 2008). In contrast, the green vegetation in the shadow areas can be clearly identified by the VE method or the point-frame method conducted in the field.
3) Limited error may be caused by mixed pixels. Color differences in the boundaries caused mixed pixels to be created in a captured digital image, and these pixels became inherent error sources (Booth et al., 2006a). Fuzzy edges of leaves may cause errors in image segmentation and area calculation, but the size of such errors may be minimal in an image of very high resolution.
4) Acquisition of plot photographs should be standardized in order to achieve better results. At the beginning of this study, some of the plot photographs were not well focused and distorted and therefore were not usable. Also, during the field measurement, the analysts tied ribbons on the

TABLE 4. Percent cover estimates (%) of five species in an example plot, estimated by different methods: VE, DGO using different grids, and PDPC.

	VE	DGO5×5	DGO10×10	DGO15×15	DGO20×20	PDPC
Salix arctica	12	8	7	7.6	10	6.3
Dryas integrifolia	20	12	3	6.2	4.5	11.4
Vaccinium uliginosum	15	16	3	5.8	4.7	4.7
Carex membranacea	5	8	4	4.9	7	3.7
Oxytropis arctica	0.1	0	0	0.8	1	0.8

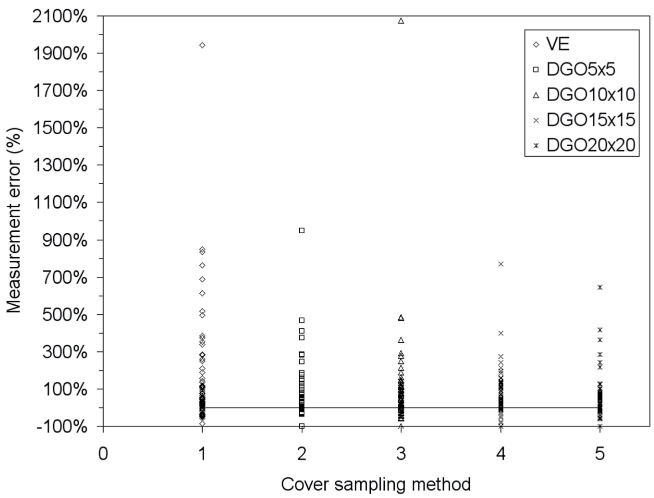

FIG. 6. Errors in percent cover estimates for various species in tundra plots around Iqaluit and Clyde River, Nunavut. Estimates from the VE method and the DGO method using different grids are compared to the "true" values obtained by the PDPC method.

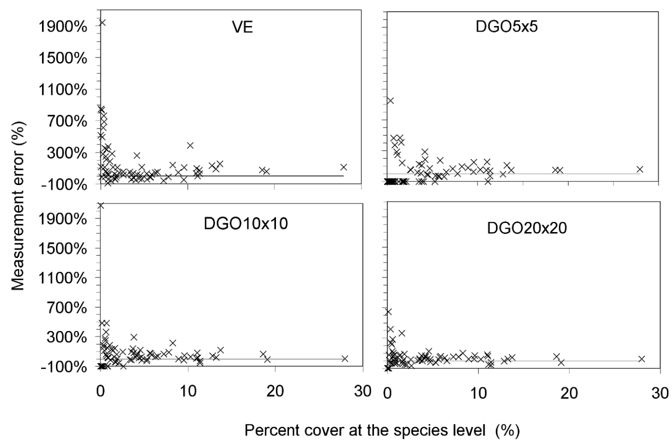

FIG. 7. Measurement errors in relation to percent cover value for all species in the Arctic tundra plots. Estimates from the VE method and the DGO method are compared to the "true" values obtained by the PDPC method. All the graphs show a clear trend: measurement error decreases as percent cover increases.

frames and put labels inside the plot for the convenience of recording. Consequently, these ribbons and labels were also included in the photos used for analysis. These added objects obviously hindered the image interpretation of the objects underneath. Therefore, no information was available from those areas using the DGO method and the PDPC method.

5) Both the PDPC method and the DGO method used here are two-dimensional measurements, while VE is a three-dimensional estimation that takes multi-layer vegetation into consideration. Because the photographs are taken from above, only the surface part of the vegetation can be viewed in the images, and the underlying vegetation cannot be seen. As a result, image-based analysis cannot identify multilayered species. Thus the PDPC method may underestimate percent cover because leaves overlapped by other leaves cannot be treated individually, while the VE method at the field site can detect underlying vegetation and provide the better estimation. In addition, the plot photograph may be more suitable for identifying vegetation with spreading leaves, and less suitable for species with tightly packed, pointy leaves, such as *Cassiope tetragona*. However, a visual estimate is one person's opinion and cannot be validated, whereas plot photographs are a permanent record that can be reanalyzed if questions arise.

6) The artificial plots with known quantities used in this study are two-dimensional and therefore much simpler than the real world. Such artificial plots have many limitations: constancy of shape and color, restriction of no overlap, and non-random distribution at the edges, as suggested by Schultz et al. (1961) and Booth et al. (2006b). But even though artificial plots do not accurately reflect the real world, they do serve the purpose of demonstrating the influence of changing sampling density on accuracy when using the DGO and the PDPC methods.

7) The PDPC method could be useful in landscape monitoring. However, landscape monitoring requires adequate sample density and distribution. Many images may be used to cover a study area. For this use, cover measurements for an image would have to be completed in a very short time (less than an hour processing time per image). Note that in this study site selection was focused more on the value of the three categories of plant coverage—low, medium, and high plant cover—rather than the randomization. More randomly selected sites may be needed to verify the relationship established here between plant cover measured by PDPC and LAI. Inadequate sampling at the landscape level affects accuracy as much or more than limited sample points at the plot or sample level. Although batch processing of hundreds of images is possible at the stage of image segmentation if large areas are being monitored and hundreds of plots (samples) need

to be analyzed, our suggestion in this study of species labeling in a GIS, aided by visual interpretation of RGB images, can be time-consuming.

SUMMARY

An object-oriented digital image analysis was adapted for measuring plant cover by key species in Arctic ecosystems. The innovation with respect to previous studies of digital image analysis is that RGB and IHS images were used together to ensure more accurate species labeling and cover measurement.

We evaluated the accuracy of three methods (VE, DGO, and PDPC) in three ways: by testing against artificial plots with known percent cover, comparison with destructively measured LAI, and inter-comparison among methods.

The testing against artificial plots with known percent cover indicates, as others have reported, that the measurement errors in percent cover decrease as the sample point density (or DGO method grid resolution) increases. Using the 3872 × 2592 grids, the sensor array of the digital camera used for this study, the PDPC method was found to be the most accurate of the three methods in percent cover measurement.

Theoretically speaking, if percent cover of leaves C is estimated correctly, the value of $-\ln(1 - C)$ should be greater than the total projected LAI. For all 75 cases at the species level, we found that the PDPC method has the lowest overvaluation rate at 9%, compared to 39% for the VE method and 27%–33% for the DGO method using various grids. When estimates were aggregated to the plot total level, compensating errors resulted in a 0% overvaluation for the PDPC method (compared to 58% for the VE method and 27%–50% for the DGO method using various grids). On the other hand, the DGO method could entirely miss a species, and the rate of missed species decreased as the sampling density increased. Using the VE and PDPC methods, no species were missed. At the plot total level, the value of R^2 between LAI and $-\ln(1 - C)$ was 0.88 for the PDPC method, compared to 0.56 for the VE method and 0.58–0.79 for the DGO method using various grids.

Inter-comparison of methods also revealed that errors usually decreased as the percent cover value increased. All these evaluations suggest that the PDPC method was the most accurate of the three methods for vegetation cover measurement in the Arctic ecosystem.

The PDPC method has clear advantages over previously used methods for measuring vegetation cover in the Arctic: it is accurate and objective; it reduces the time needed in the field; and it provides a permanent record that can be re-analyzed. Image analysis can be performed in an office or laboratory; however, it is more time-consuming than a visual estimate in the field. This method depends on the quality of the initial image: correct and consistent methods of taking digital photos must be followed to ensure images will be usable. With further technical improvements that will reduce the distorting effects of shadows and overlap, the PDPC method has a promising future.

ACKNOWLEDGEMENTS

The work was financially supported by the Canada International Polar Year initiative, through the project entitled “Climate Change Impacts on Canadian Arctic Tundra Ecosystems: Interdisciplinary and Multi-scale Assessments (CiCAT),” and by Natural Resources Canada, through the Enhancing Resilience to a Changing Climate program. The Nunavut Research Institute helped us in obtaining a research license. We are grateful to Jackie Bourgeois (Climate Change Coordinator, Government of Nunavut), Michelle Bertol (Director, Land and Planning, City of Iqaluit), James Qillaq and Nick Illauq (Councilors, Clyde River, Nunavut), Lee Ann Pugh and Jayko Ashvak (local residents), and many members of the Clyde River Hunters and Trappers Association for assistance with logistical arrangements and participation in the fieldwork in 2006. Drs. Yu Zhang and Junhua Li internally reviewed the manuscript. We also thank the three anonymous reviewers for their constructive comments and suggestions.

REFERENCES

Anisimov, O.A., Vaughan, D.G., Callaghan, T.V., Furgal, C., Marchant, H., Prowse, T.D., Vilhjálmsson, H., and Walsh, J.E. 2007. Polar regions (Arctic and Antarctic). In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J., and Hanson, C.E., eds. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. 653–685.

Bean, D., and Henry, G.H.R. 2003. CANTTEX Field Manual: Part A – Setting up a basic monitoring site. Burlington, Ontario: Ecological Monitoring and Assessment Network, Environment Canada.

Bliss, L.C., Svoboda, J., and Bliss, D.I. 1984. Polar deserts, their plant cover and plant production in the Canadian High Arctic. Holarctic Ecology 7:305–324.

Bonham, C.D., and Clark, D.L. 2005. Quantification of plant cover estimates. Grassland Science 51:129–137.

Booth, D.T., and Cox, S.E. 2008. Image-based monitoring to measure ecological change. Frontiers in Ecology and the Environment 6:185–190.

Booth, D.T., Cox, S.E., Louhaichi, M., and Johnson, D.E. 2004. Lightweight camera stand for close-to-earth remote sensing. Journal of Range Management 57:675–678.

Booth, D.T., Cox, S.E., Field, C., Phillips, M., and Williamson, N. 2005. Image analysis compared with other methods for measuring ground cover. Arid Land Research and Management 19:91–100.

Booth, D.T., Cox, S.E., and Berryman, R.D. 2006a. Point sampling digital imagery with ‘Samplepoint.’ Environmental Monitoring and Assessment 123:97–108.

Booth, D.T., Cox, S.E., Meikle, T.W., and Fitzgerald, C. 2006b. The accuracy of ground-cover measurements. Rangeland Ecology & Management 59:179–188.

Bråkenhielm, S., and Liu, Q. 1995. Comparison of field methods in vegetation monitoring. Water, Air and Soil Pollution 79: 75–87, doi:10.1007/BF01100431.

Bunn, A., and Goetz, S. 2006. Trends in satellite-observed circumpolar photosynthetic activity from 1982 to 2003: The influence of seasonality, cover type, and vegetation density. Earth Interactions 10:1–19.

Chen, J.M., Rich, P.M., Gower, S.T., Norman, J.M., and Plummer, S. 1997. Leaf area index of boreal forests: Theory, techniques, and measurements. Journal of Geophysical Research 102(D24): 29429–29443.

Chen, W., Blain, D., Li, J., Fraser, R., Zhang, Y., Leblanc, S., Koehler, K., Olthof, I., Wang, J., and McGovern, M. 2009a. Estimating carbon release caused by land use changes over Canada's North during 1985–1990 and 1990–2000 using satellite earth observation. Journal of Geophysical Research, 114, G01017, doi:10.1029/2007JG000631.

Chen, W., Li, J., Zhang, Y., Zhou, F., Koehler, K., Leblanc, S., Fraser, R., Olthof, I., Zhang, Y.S., and Wang J. 2009b. Relating biomass and leaf area index to non-destructive measurements in order to monitor changes in Arctic vegetation. Arctic 62(3):281–294.

Cox, S.E., and Booth, D.T. 2008. Shadow attenuation with high dynamic range images. Environmental Monitoring and Assessment 158:231–241, doi:10.1007/s10661-008-0577-y.

Definiens Imaging. 2003. eCognition version 4.0.6 user guide. Munich, Germany: Definiens Imaging GmbH.

Dethier, M.N., Graham, E.S., Cohen, S., and Tear, L.M. 1993. Visual versus random-point percent cover estimations: Objective is not always better. Marine Ecology Progress Series 96:93–100.

ERDAS. 2010. ERDAS Imagine. http://www.erdas.com/84/currentid/1050/default.aspx.

Floyd, D.A., and Anderson, J.E. 1987. A comparison of three methods for estimating plant cover. Journal of Ecology 75:221–228.

Hemming, J., and Rath, T. 2001. Computer vision-based weed identification under field conditions using controlled lighting. Journal of Agricultural Engineering Research 78(3):233–243.

Herold, M., Liu, X., and Clarke, K.C. 2003. Spatial metrics and image texture for mapping urban land use. Photogrammetric Engineering and Remote Sensing 69(9):991–1001.

Johnson, D.E., Vulfson, M., Louhaichi, M., and Harris, N.R. 2003. VegMeasure Version 1.6 user's manual. Corvallis: Department of Rangeland Resources, Oregon State University.

Karcher, D.E., and Richardson, M.D. 2003. Quantifying turfgrass color using digital image analysis. Crop Science 43:943–951.

Kattsov, V.M., Kallen, E., Cattle, H., Christensen, J., Drange, H., Hanssen-Bauer, I., Johannesen, T., et al. 2005. Future climate change: Modeling and scenarios for the Arctic. In: Arctic climate impact assessment. Cambridge: Cambridge University Press. 100–150.

Kennedy, C.E., Smith, C.A., and Cooley, D.A. 2001. Observations of change in the cover of polar grass, *Arctagrostis latifolia*, and arctic lupin, *Lupinus arcticus*, in upland tundra on Herschel Island, Yukon Territory. Canadian Field-Naturalist 115: 323–328.

Klein, D.R., Baskin, L.M., Bogoslovskaya, L.S., Danell, K., Gunn, A., Irons, D.B., Kofinas, G.P., et al. 2005. Management and conservation of wildlife in a changing Arctic environment. In: Symon, C., Arris, L., and Heal, B., eds. Arctic climate impact assessment. Cambridge: Cambridge University Press. 597–648.

Krebs, C.J., Danell, K., Angerbjörn, A., Agrell, J., Berteaux, D., Bråthen, K.A., Danell, Ö., et al. 2003. Terrestrial trophic dynamics in the Canadian Arctic. Canadian Journal of Zoology 81:827–843.

Laliberte, A.S., Rango, A., Havstad, K.M., Paris, J.F., Beck, R.F., McNeely, R., and Gonzalez, A.L. 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. Remote Sensing of Environment 93:198–210, doi:10.1016/j.rse.2004.07.011.

Laliberte, A.S., Rango, A., Herrick, J.E., Fredrickson, E.L., and Burkett, L. 2007. An object-based image analysis approach for determining fractional cover of senescent and green vegetation with digital plot photography. Journal of Arid Environments 69:1–14.

Luscier, J.D., Thompson, W.L., Wilson, J.M., Gorham, B.E., and Dragut, L.D. 2006. Using digital photographs and object-based image analysis to estimate percent ground cover in vegetation plots. Frontiers in Ecology and the Environment 4(8):408–413, doi:10.1890/1540-9295(2006)4[408:UDPAOI]2.0.CO;2.

McGuire, A.D., Wirth, C., Apps, M., Beringer, J., Clein, J., Epstein, H., Kicklighter, D.W., et al. 2002. Environmental variation, vegetation distribution, carbon dynamics, and water/energy exchange in high latitudes. Journal of Vegetation Science 13:301–314.

Meese, R.J., and Tomich, P.A. 1992. Dots on the rocks: A comparison of percent cover estimation methods. Journal of Experimental Marine Biology and Ecology 165:59–73.

Nilson, T. 1971. A theoretical analysis of the frequency of gaps in plant stands. Agricultural Meteorology 8:25–38, doi:10.1016/0002-1571(71)90092-6 .

Olthof, I., Pouliot, D., Latifovic, R., and Chen, W. 2007. Recent (1986–2006) vegetation-specific NDVI trends in northern Canada from satellite data. Arctic 61(4):381–394.

PCA (Parks Canada Agency). 2000. "Unimpaired for future generations"? Protecting ecological integrity with Canada's national parks, Vol. II: Setting a new direction for Canada's national parks. Report of the Panel on the Ecological Integrity of Canada's National Parks. Ottawa: Minister of Public Works and Government Services.

Richardson, M.D., Karcher, D.E., and Purcell, L.C. 2001. Quantifying turfgrass cover using digital image analysis. Crop Science 41:1884–1888.

Ryherd, S., and Woodcock, C. 1996. Combining spectral and texture data in the segmentation of remotely sensed images.

Photogrammetric Engineering and Remote Sensing 62(2): 181–194.

Schultz, A.M., Gibbens, R.P., and Debano, L. 1961. Artificial populations for teaching and testing range techniques. Journal of Range Management 14:236–242.

Stow, D.A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrice, F., Houston, S., et al. 2004. Remote sensing of vegetation and land-cover change in Arctic tundra ecosystems. Remote Sensing of Environment 89:281–308.

Tang, L., Tian, L., and Steward, B.L. 2000. Color image segmentation with genetic algorithm for in-field weed sensing. Transactions of the American Society of Agricultural Engineers 43(4):1019–1027.

Thomas, N., Hendrix, C., and Congalton, R.G. 2003. A comparison of urban mapping methods using high-resolution digital imagery. Photogrammetric Engineering & Remote Sensing 69(9):963–972.

Vanha-Majamaa, I., Salemaa, M., Tuominen, S., and Mikkola, K. 2000. Digitized photographs in vegetation analysis: A comparison of cover estimates. Applied Vegetation Science 3:89–94.

Walker, M. 1996. Community baseline measurements for ITEX studies. In: Molau, U., and Mølgaard, P., eds. International Tundra Experiment (ITEX) manual. Copenhagen: Danish Polar Center. 5–47.