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Relating Biomass and Leaf Area Index to Non-destructive Measurements in Order to Monitor Changes in Arctic Vegetation

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ABSTRACT. This paper reports an alternative method for seasonal and long-term monitoring of biomass and the leaf area index (LAI) at Arctic tundra sites. Information related to the historical and projected change in abundance and distribution of biomass and LAI is required to address numerous environmental and resource management issues. Observations of earth from satellites could potentially be used to derive seasonal and long-term changes in biomass and the LAI. To realize this potential, seasonal and long-term ground monitoring data for validation are essential; however, the conventional destructive sampling method for measuring biomass and the LAI does not allow repetitive measurements at the same plots and thus is not suitable for monitoring change over time. Alternative methods, such as sampling nearby similar plots, can be laborious and easily subject to large sampling errors, especially in Arctic tundra sites with low vegetation cover. In this study, we developed a practical method for relating non-destructive measurements (percent cover and mean height) to biomass and the LAI for 13 major Arctic plant groups, or seven plant functional types, on the basis of measurements at 196 plots across Canada's Arctic tundra ecosystems. Using the method at the plant group level to estimate plot total vascular aboveground biomass, foliage biomass, and LAI, we had $r^2 = 0.91-0.95$ and relative mean absolute error of 25–29%. By this method, one could monitor seasonal and long-term changes in biomass and the LAI through repeated, non-destructive observations of percent cover and mean height at the same permanent plots.

Key words: monitoring, aboveground biomass, foliage biomass, LAI, percent cover, mean height, vegetation, seasonal change, long-term change, Arctic

RÉSUMÉ. Cette communication présente une méthode de rechange en vue de la surveillance saisonnière et à long terme de la biomasse et de l'indice de surface foliaire (LAI) de sites de toundra de l'Arctique. Afin de relever divers enjeux relatifs à la gestion de l'environnement et des ressources, il faut recueillir des données se rapportant au changement historique et projeté en matière d'abondance et de répartition de la biomasse et du LAI. On pourrait éventuellement recourir aux observations de la Terre à partir de satellites afin de déceler les changements saisonniers et à long terme caractérisant la biomasse et le LAI. Pour en arriver là, il est essentiel de disposer de données saisonnières et à long terme au sol à des fins de validation. Cependant, la méthode d'échantillonnage destructeur classique permettant de mesurer la biomasse et le LAI ne permettent pas la prise de mesures répétitives aux mêmes sites et par conséquent, elle ne convient pas à la surveillance du changement qui s'exerce au fil du temps. D'autres méthodes, telles que l'échantillonnage de sites semblables dans les environs, peuvent s'avérer laborieuses et facilement faire l'objet d'importantes erreurs d'échantillonnage, surtout aux sites de toundra de l'Arctique dont la couverture végétale est basse. Dans le cadre de cette étude, nous avons mis au point une méthode pratique pour établir un rapport entre les mesures non destructives (pourcentage de couverture et hauteur moyenne) et la biomasse et le LAI de 13 groupes végétaux importants de l'Arctique, ou sept types végétaux fonctionnels en fonction de la mesure de 196 sites à la grandeur des écosystèmes de toundra de l'Arctique canadien. En nous appuyant sur la méthode des groupes végétaux pour estimer la biomasse vasculaire totale à ciel ouvert des sites, la biomasse foliaire et le LAI, nous avions $r^2 = 0,91-0,95$ et une erreur absolue relative moyenne de 25 à 29%. Au moyen de cette méthode, il serait possible de surveiller les changements saisonniers et à long terme en matière de biomasse et de LAI grâce à des observations répétées et non destructives du pourcentage de la couverture et de la hauteur moyenne aux mêmes sites permanents.

Mots clés : surveillance, biomasse à ciel ouvert, biomasse foliaire, LAI, pourcentage de couverture, hauteur moyenne, végétation, changement saisonnier, changement à long terme, Arctique

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INTRODUCTION

Information on seasonal and long-term changes in the biomass and leaf area index (LAI) of tundra ecosystems over the Arctic region are important for numerous environmental and resource management issues, such as understanding, monitoring, and managing wildlife habitat, the carbon cycle, the ecological integrity of national parks, permafrost dynamics, freshwater resources, and terrain trafficability (Russell et al., 1992; Shoop, 1993; Parks Canada Agency, 2000; Chen et al., 2000, 2009; McGuire et al., 2002; Krebs et al., 2003; McFadden et al., 2003; Zhang et al., 2003; Raynolds et al., 2006; Cebrian et al., 2008).

Because the Arctic landmass is vast and remote, logistical difficulties and high costs are inherent in conducting field measurements; satellite remote sensing is arguably the only feasible way to obtain information on the distribution of and temporal changes in biomass and the LAI. Most current remote-sensing studies on biomass and LAI over Arctic areas, however, are focused on mapping their spatial distributions (e.g., Gould et al., 2003; Walker et al., 2003; Raynolds et al., 2006). The historical remote-sensing data series, such as the Landsat Thematic Mapper (TM) and the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration's (NOAA) satellites, could date back for several decades, and thus have the potential to quantify long-term changes (e.g., Hansen, 1991; Myneni et al., 1997; Zhou et al., 2001; Stow et al., 2004; Bunn and Goetz, 2006; Olthof et al., 2008). Similarly, observations of earth from satellites such as the AVHRR and Moderate Resolution Imaging Spectrometer (MODIS) have daily coverage over the Arctic landmass, and could potentially be used to derive seasonal changes in biomass and LAI. Yet, so far researchers (e.g., Myneni et al., 1997; Zhou et al., 2001; Stow et al., 2004; Bunn and Goetz, 2006; Olthof et al., 2008) have generally used the Normalized Difference Vegetation Index (NDVI) as a proxy to monitor vegetation changes, although a few studies did report multiple-year changes in biomass (e.g., Asrar et al., 1985; Goward and Dye, 1987; Hansen, 1991; Hope et al., 1993; Shippert et al., 1995; Walker et al., 2003; Riedel et al., 2005). For example, Hansen (1991) developed a relationship between AVHRR NDVI and biomass production for a sheep-farming area in southern Greenland and then applied that relationship to multiple years of AVHRR NDVI data to estimate the changes in biomass production. However, Hansen's results regarding multiple-year changes in biomass production were not validated using independent field monitoring data. Indeed, the lack of corresponding ground monitoring data, which are essential for calibrating and validating remote sensing change detection products, has been one of the key reasons for the lack of progress in detecting seasonal and long-term changes in biomass and LAI over Arctic tundra ecosystems.

The conventional method of measuring biomass and LAI accurately is destructive sampling at a number of plots in a site (Bliss et al., 1984; Gould et al., 2003; Krebs et al., 2003; Walker et al., 2003; Raynolds et al., 2006; Chen et al., 2007). This method does not allow repeated measurement of biomass and LAI changes at the same plots. If nearby similar plots within the site are sampled, the large spatial heterogeneity in the site often results in a very large sampling error in comparison with the temporal change to be detected, especially when the percent cover is very low, which unfortunately is a common feature of Arctic tundra (Fig. 1). Figure 1 indicates that for a site sampled by five plots with a mean vascular percent cover over 20%, the average sampling error for aboveground biomass and LAI is ~20%, and this error increases sharply as the percent cover decreases. Substantially increasing the number of plots could reduce the sampling error, but would likely significantly alter the site condition and thus defeat the purpose of monitoring, as well as substantially increasing the labor cost. Therefore, sampling a large number of nearby, similar plots within a site is not an ideal method for monitoring seasonal and long-term changes in aboveground biomass and LAI, especially over the sparse Arctic tundra ecosystems.

An alternative approach to the destructive monitoring method is to repeatedly measure a set of variables non-destructively, and then relate these non-destructive measurements to biomass and LAI. Several previous studies have investigated this alternative approach (Parker, 1975; Shaver, 1981, 1989; Rottgermann et al., 2000; Krebs et al., 2003; Muukkonen et al., 2006). For example, Shaver (1981, 1989) found that allometric relationships between biomass and the length and diameter of branches can be established for low and high shrub species. Allometric equations have been used widely for relating diameter and height to stem biomass of trees (e.g., Standish et al., 1985; Chen et al., 2002), although it is generally recognized that such equations are less accurate for estimating foliage biomass and LAI. However, this allometric approach is very labor-intensive and does not apply to mat or dwarf shrubs, herbs, lichen, and moss. Other investigators (e.g., Parker, 1975; Rottgermann et al., 2000; Krebs et al., 2003; Muukkonen et al., 2006) have related percent cover to biomass and LAI. Linear relationships between percent cover and aboveground biomass were found for low open Arctic vegetation (Parker, 1975; Rottgermann et al., 2000; Krebs et al., 2003). However, Muukkonen et al. (2006) found that in understory vegetation of boreal coniferous forests, the relationships between biomass and percent cover are generally non-linear and often poor. The difference between the results for low open Arctic vegetation and those for the higher and denser understory vegetation of boreal coniferous forests suggests that the height of vegetation can significantly affect the relationships between percent cover and biomass.

The objective of this study is to investigate the relationships between biomass (or LAI) and percent cover, as well as vegetation height, on the basis of extensive field measurements across Canada's Arctic ecosystems. Knowledge of these relationships is essential to achieving our ultimate goal: non-destructive monitoring of seasonal and long-term changes in aboveground biomass and LAI in the Arctic.

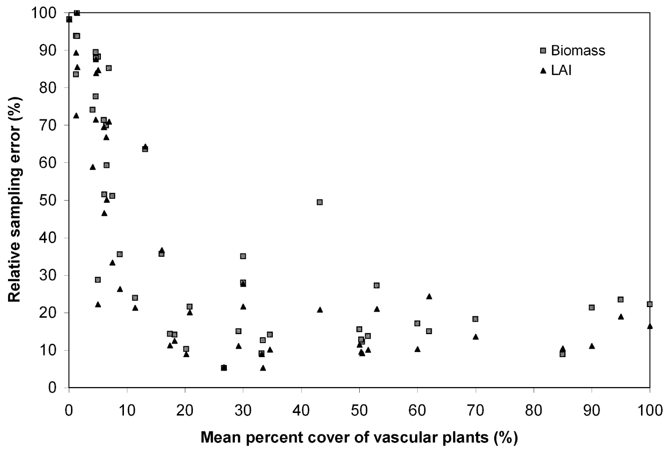

FIG. 1. Relative sampling error plotted against the mean percent cover of vascular plants for sites in Arctic Canada that each had five or more plots with measurements of vascular aboveground biomass, vascular percent cover, and LAI (see locations in Fig. 2). For a site with more than five plots, we randomly selected five plots for calculating the relative sampling error and the mean percent cover of vascular plants. The relative sampling error is calculated as the standard deviation / (mean value × square root of the number of plots).

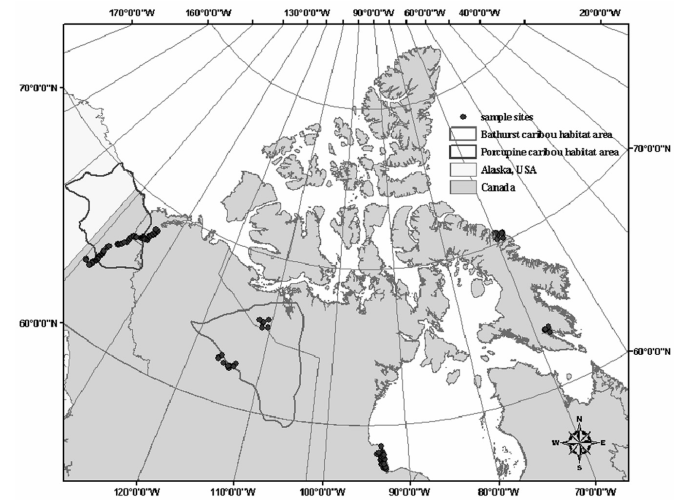

FIG. 2. Locations of sites within Arctic ecosystems across Canada at which we measured percent cover, mean height, aboveground biomass, and LAI of tundra plants in the summers of 2005, 2006, and 2007.

FIELD MEASUREMENTS AND ESTIMATION METHODS

Spatial Domain of Investigation

Percent cover, mean height, aboveground biomass, and LAI of Arctic plants were measured around Yellowknife, Northwest Territories, and the Lupin Gold Mine, Nunavut, in the summer of 2005; along the Dempster Highway transect, Yukon, in the summer of 2006; and over the Wapusk National Park near Churchill, Manitoba, and around Iqaluit and Clyde River, Nunavut, in the summer of 2007 (Fig. 2). All sites were non-treed. However, some of these sites were technically alpine tundra or in the transitional zone from forest to tundra. These sites were included in the analyses for two reasons: to cover as wide a range of vegetation conditions as possible so that the relationships developed from the data sets are widely applicable, and to increase the number of plots so that each group has enough data points to be statistically meaningful.

Measurement Method

The field measurement was conducted during the middle of the growing season, when biophysical parameters (e.g., foliage biomass, LAI) are usually relatively stable.

Satellite remote sensing imagery (Landsat TM or ETM+ at 30 m or Quickbird at 60 cm spatial resolution) was used to select the measurement sites. First, we made an initial spectral cluster image from Landsat. Second, we selected a number of candidate sites that had large homogenous patches (at least 3 × 3 TM pixels, i.e., 90 m × 90 m) on the initial Landsat cluster image. Finally, if the patch shown on the map was indeed relatively homogeneous and large enough when visited on the ground, we selected a field measurement site on the spot.

The plot scheme was different for different vegetation cover types. For an Arctic polar desert or semidesert site, the percentage of vegetation cover is usually low. To adequately represent a site with very low vegetation cover, we used a plot scheme of 20 plots (each 0.25 m^2) at 5 m intervals along a 100 m transect, which reflects most of the variation in vegetation conditions at the site. The number of plots was adjusted according to spatial heterogeneity, i.e., a less heterogeneous site was sampled with fewer plots than a more heterogeneous site.

Cover percentage was estimated visually, layer by layer from top to the bottom, for each plant group within a plot. The mean height of each plant group was the average of the top leaf heights of five randomly sampled plants for each plant group. If five plants for a plant group could not be found within a plot, fewer plants were sampled. For moss, we measured the thickness of its live green part.

Aboveground biomass of each plot was then harvested, sorted according to plant group, and stratified into live and dead. Leaves or needles were separated from stems, and the fresh biomass of each class was weighed and recorded for each shrub, herb or grass, and lichen. For moss, we cut and weighed a representative 0.01 m^2 square of live layer of moss. After the fresh moss biomass was weighed, a fraction of each sample was brought back to the laboratory to obtain the ratio of fresh to oven-dry biomass. The exception was live layer moss, for which the entire sample was dried.

We determined the total maximum projected leaf area index (LAI) of a vascular plant group within a plot by different methods, according to the leaf type. (1) If a plant group had relatively large and flat leaves, we measured its total projected LAI within a plot by scanning every leaf through an LAI meter (LASER area meter CI-203), indoors on the same day of harvest. Because this approach was very time consuming, we also used the specific leaf area (SLA) as an alternative. SLA is the ratio of projected leaf area to weighed oven-dry biomass, expressed as cm^2 per gram. To obtain the SLA of a plant group harvested, we randomly selected a fraction its leaves and measured their projected leaf area using the LAI meter. The leaf sample was then taken back to the laboratory to obtain its oven-dry biomass. With a known SLA, we can estimate the total projected LAI of the plant group within a plot from its total weighed oven-dry foliage biomass. (2) If a plant group had very small leaves or needles, we measured its total projected LAI within a plot using a digital photo method. Like the scanning method described above, this digital photo method can be used either directly (measuring all leaves or needles when the number of leaves or needles is small) or applying the SLA approach. To directly measure the projected LAI for all leaves or needles, we placed all the leaves on a plot on a piece of 8.5 × 11 inch white paper so that no leaves overlapped and took a digital photo looking directly down from a height of about 1 m. The PCI Geomatica software was used to classify the photo and determine the projected leaf area. For the alternative SLA approach, a randomly selected fraction of leaves was placed, photographed, and classified to determine its projected leaf area, and its oven-dry biomass was then determined in the laboratory.

RELATIONSHIPS AND ESTIMATION ERRORS

There are many ways to stratify the data and the relationships between biomass (or LAI) and non-destructive measurements. One way is by plant functional types (PFTs), such as deciduous shrubs, evergreen shrubs, graminoids, forbs, horsetail, lichens, and mosses. Table 1 lists the species included in each plant functional type. Horsetail is an odd species that does not belong to either graminoids or forbs, so it was treated as a separate functional type in this study. However, as some users may prefer more detailed subdivision of these functional types, we have divided the deciduous shrub and evergreen shrub functional types into constituent plant groups, while treating each of the other functional types as a single plant group. For the deciduous shrub functional type, the groups include willow (*Salix* sp.), birch (*Betula* sp.), blueberry–bearberry–soapberry (*Vaccinium uliginosum*, *Arctostaphylos* sp., *Shepherdia Canadensis*), and sweet gale (*Myrica gale*). The evergreen shrub functional type was divided into dwarf Labrador tea (*Ledum decumbens*) and bog rosemary (*Andromeda planifolia*), crowberry (*Empetrum nigrum*) and lingonberry (*Vaccinium vitis-idaea*), white mountain avens (*Dryas integrifolia*) and moss campion (*Silene acaulis*), and Arctic heather (*Cassiope tetragona*).

These plant groups were stratified according to vegetation classification (Viereck et al., 1992). In cases where groups had very few data points, we further merged groups with similar plant size and foliage form, so that each group had enough data points to be statistically meaningful. We now had a total of 13 plant groups: graminoids, forbs, horsetail, lichens, mosses, willow, birch, sweet gale, blueberry–bearberry–soapberry, Labrador tea and *Andromeda*, crowberry and lingonberry, *Dryas* and *Silene*, and *Cassiope*.

Krebs et al. (2003) found good relationships between biomass and percent cover of five plant groups over areas with low open vegetation, with r^2 values ranging from 0.73 to 0.96. The linear relationships imply negligible effects of changes in plant height and aboveground biomass bulk density on aboveground biomass. This implicit assumption could be true in some specific cases, but is generally invalid (see Krebs et al., 2003; Muukkonen et al., 2006; Fig. 3). Figure 3 shows relationships between aboveground biomass and percent cover for four representative Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens. The willows have a spatial distribution that extends from sub-Arctic sites in the Yellowknife area and along the Dempster Highway transect to High Arctic sites around Clyde River. Their mean height ranges from 0.005 m to 5 m. The graminoid, *Dryas* and *Silene*, and lichen groups also have large variations in mean height and geographical locations. The data points in Figure 3 can be better described by a power function, which assumes that the variations in mean height and aboveground bulk density can be accounted for by percent cover. Yet, the fact that the data points scatter substantially from either the linear relationship or the power function suggests that the effects of mean height and bulk density on biomass cannot be neglected. Therefore, explicit consideration of mean height and bulk density is needed in order to obtain strong relationships between aboveground biomass and non-destructive variables. In addition to considering the commonly used linear relationships and power function with percent cover, we will examine the effects of mean height and bulk density on relationships between aboveground biomass and non-destructive variables as follows:

1. Linear relationships between aboveground biomass and percent cover (C-L method): $b = a_1 \times c$, where b is aboveground biomass (g/m^2), a_1 is the slope of the linear relationship with 0 intercept, and c is percent cover within a plot (in percentage units, with 10% = 10).
2. Power relationships between aboveground biomass and percent cover (C-P method): $b = a_2 c^p$, where a_2 and p are coefficients.
3. Linear relationships between aboveground biomass and percent cover × mean height (CH method): $b = a_3 c \times h$, where c is percent cover (in unit of m^2, with 10% of a 1 m^2 plot = 0.1 m^2), h is mean height (m), and a_3 is the slope of the linear relationship with 0 intercept.
4. Linear relationships between aboveground biomass and percent cover × mean height × estimated aboveground biomass bulk density (CHD method): $b = a_4 c \times h \times d(h)$, where c and h are the same as CH method, a_4 is the slope of the linear relationship with 0 intercept, and $d(h)$ is the estimated aboveground biomass bulk density (in units of g/m^3). The measured aboveground biomass bulk density was calculated as $b/(c \times h)$, and the estimated aboveground biomass bulk density $d(h)$ was then computed as

TABLE 1. Major plant species included in a plant group or a plant functional type (PFT). Also included are values of specific leaf area (SLA); i.e., the ratio of leaf area per unit dry foliage biomass.

Plant Functional Types	Species	SLA (cm^2/g)
Sub-groups		
Graminoids	*Carex siccata*, *C. limosa*, *C. chordorrhiza*, *C. aquatilis*, *C. tenuiflora*, *Poa* sp., *Eriophorum* sp., *Alopecurus alpinus*	131
Forbs	*Pedicularis arctica*, *P. capitata*, *Epilobium angustifolium*, *E. latifolium*, *Oxyria digyna*, *Oxytropis arctica*, *Saxifraga tricuspidata*, *S. cernua*	163
Horsetail	*Equisetum fluviatile*	171
Lichens	*Flavocetraria nivalis*, *Cladina mitis*, *C. rangiferina*, *Rhizocarpon geographicum*, *Cladonia sulphurina*, *Cladina stellaris*, *Cetraria nivalis*, *Alectoria ochroleuca*	
Mosses	*Sphagnum riparium*, *S. girgensohnii*, *S. angustifolium*, *Helodium blandowii*, *Brachythecium turgidum*, *B. rivulare*	
Deciduous shrubs:		
Willow	*Salix reticulata*, *S. alaxensis*, *S. herbacea*, *S. pedicellaris*, *S. planifolia*, *S. candida*, *S. arctica*, *S. lanata*	145
Birch	*Betula pumila*, *B. glandulosa*	186
Sweet gale	*Myrica gale*	145
Blueberry, bearberry and soapberry	*Vaccinium uliginosum*, *Arctostaphylos alpina*, *A. rubra*, *Shepherdia canadensis*	205
Evergreen shrubs:		
Labrador tea and *Andromeda*	*Ledum decumbens*, *Andromeda polifolia*	66
Crowberry and lingonberry	*Empetrum nigrum*, *Vaccinium vitis-idaea*	53
Dryas and *Silene*	*Dryas integrifolia*, *Silene acaulis*	140
Cassiope	*Cassiope tetragona*	50

a function of h, using relationships between measured aboveground biomass bulk density and h.

The relationship between LAI and percent cover was similar to that between biomass and percent cover (Table 2). Consequently, we will also investigate the effects of mean height and bulk density on relationships between LAI (as well as foliage biomass) and non-destructive variables.

To compare the reliability of estimates of the four types of relationships, statistical criteria are needed. Many statistics exist to express the error in estimations, such as the value of r^2, which is the fraction of variation in data explained by an equation; the standard error of estimate (SEE); the root mean squared error (RMSE); the mean absolute error (MAE); the relative mean absolute error (RMAE); the mean absolute percentage error (MAPE); the median absolute percentage error (MedAPE); and the mean error (ME). A good summary measure of error should meet the following basic criteria: ease of interpretation, clarity of presentation, reliability, and robustness (Tayman et al., 1999). A measure is reliable and robust if a small subset of the sample does not have a disproportionate effect on its value.

The r^2 and SEE are the statistics that normally take precedence over the others in regression analysis. However, compared to other measures, the values of r^2 and SEE are more sensitive to the occasional large error: the squaring process gives disproportionate weight to very large errors when the aboveground biomass or LAI has a very large value. If the true cost of an error is roughly proportional to the size of the error, not the square of the error, as is certainly the case for biomass and LAI, then the MAE may be a more relevant criterion. There is no absolute criterion for a "good" value of SEE or MAE: it depends on the units in which the variable is measured and on the degree of forecasting accuracy (as measured in those units) that is sought in a particular application. Therefore, for purposes of measuring the "goodness" of estimation in terms of percentage error, we selected two relative statistics: RMAE and MedAPE. RMAE is computed as MAE divided by the corresponding average value of measured aboveground biomass ($\bar{b}$) or LAI ($\overline{LAI}$). Thus, the value of RMAE is more sensitive to errors if biomass or LAI has a large value, and a few very large absolute errors could substantially skew the RMAE. In contrast, the value of MedAPE generally gives more weight to percentage errors corresponding to low aboveground biomass or LAI, because plots with low biomass or

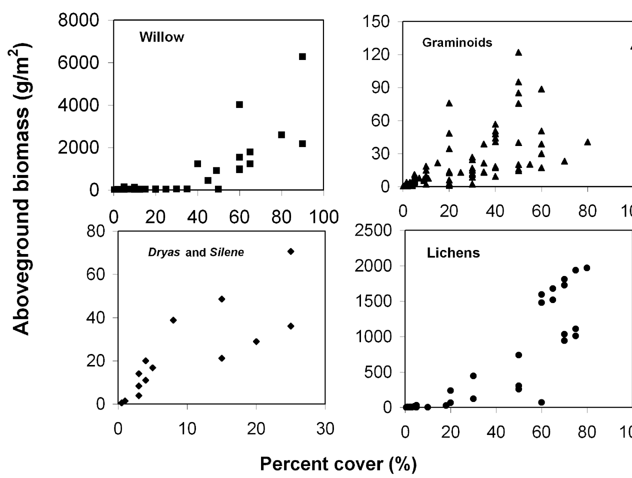

FIG. 3. Relationships between aboveground biomass and percent cover for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens.

TABLE 2. Statistics for the relationships between aboveground biomass b and non-destructive variables[1] for the 13 plant groups, two functional types (deciduous and evergreen shrubs), and all vascular plants at the plot level. For each plant group, n = number of sample plots, and $\bar{b}$ = mean aboveground biomass (g/m^2) averaged over all plots containing species of the group. To ensure comparability, the value of r^2 in the table is the square of the linear correlation coefficient between measured and estimated biomass, instead of that of the fitting equations.

Plant Group	Relationship (b =)	r^2	RMAE[2] (%)	MedAPE[3] (%)
Willow	27.65 c	0.60	94	720
n = 64	1.7328 $c^{1.3331}$	0.66	81	64
$\bar{b}$ = 396.6	1225.1 $c \times h$	0.93	30	84
	$c \times h \times d(h)$	**0.93**	**30**	**49**
Birch	9.2801 c	0.46	85	167
n = 47	1.5205 $c^{1.3144}$	0.50	57	37
$\bar{b}$ = 210.8	973.68 $c \times h$	0.90	28	30
	$c \times h \times d(h)$	**0.90**	**25**	**26**
Sweet gale	3.9038 c	0.09	80	109
n = 11	1.6803 $c^{1.1264}$	0.09	73	78
$\bar{b}$ = 99.7	884.26 $c \times h$	0.84	29	26
	$c \times h \times d(h)$	**0.84**	**29**	**26**
Blueberry, bearberry, and soapberry	1.4783 c	0.27	44	15
n = 17	5.3671 $c^{0.6168}$	0.31	42	33
$\bar{b}$ = 34.2	10543 $c \times h$	0.81	35	47
	$c \times h \times d(h)$	**0.81**	**35**	**47**
Labrador tea and *Andromeda*	2.5462 c	0.45	49	45
n = 42	1.0983 $c^{1.2064}$	0.45	48	45
$\bar{b}$ = 50.8	1093 $c \times h$	0.63	43	47
	$c \times h \times d(h)$	**0.66**	**36**	**32**
Crowberry and lingonberry	1.7419 c	0.44	48	47
n = 22	5.1425 $c^{0.6176}$	0.41	46	44
$\bar{b}$ = 33.8	2699.5 $c \times h$	0.75	37	37
	$c \times h \times d(h)$	**0.75**	**37**	**37**
Dryas and *Silene*	2.017 c	0.67	41	40
n = 16	1.9624 $c^{1.0697}$	0.66	45	54
$\bar{b}$ = 22.3	29388.6 $c \times h$	0.87	24	26
	$c \times h \times d(h)$	**0.87**	**24**	**26**
Cassiope	2.6217 c	0.90	25	33
n = 11	2.9827 $c^{1.0005}$	0.90	29	31
$\bar{b}$ = 21.4	5060.3 $c \times h$	0.86	26	39
	$c \times h \times d(h)$	**0.86**	**26**	**39**

Plant Group	Relationship (b =)	r^2	RMAE[2] (%)	MedAPE[3] (%)
Graminoids	0.8166 c	0.51	59	48
n = 105	0.726 $c^{0.9547}$	0.50	56	50
$\bar{b}$ = 17.7	261.24 $c \times h$	0.77	41	75
	$c \times h \times d(h)$	**0.74**	**43**	**47**
Forbs	1.1919 c	0.72	37	40
n = 20	1.2831 $c^{0.9648}$	0.72	39	38
$\bar{b}$ = 2.7	1188.2 $c \times h$	0.24	75	76
	$c \times h \times d(h)$	**0.82**	**31**	**36**
Horsetail	0.8439 c	0.98	15	44
n = 7	1.5541 $c^{0.8073}$	0.97	25	35
$\bar{b}$ = 15.2	143.81 $c \times h$	0.98	20	58
	$c \times h \times d(h)$	**0.98**	**20**	**58**
Lichens	19.17 c	0.80	44	362
n = 53	1.1762 $c^{1.554}$	0.83	47	54
$\bar{b}$ = 519.7	31456 $c \times h$	0.92	20	36
	$c \times h \times d(h)$	**0.92**	**20**	**36**
Mosses	0.7158 c	0.50	288	70
n = 13	.0068 $c^{0.5972}$	0.20	256	78
$\bar{b}$ = 26.7	2535.6 $c \times h$	0.70	50	50
	$c \times h \times d(h)$	**0.70**	**50**	**50**
Deciduous shrubs	16.38 c	0.42	100	42
n = 107	1.2167 $c^{1.3612}$	0.47	70	60
$\bar{b}$ = 378.6	1197.1 $c \times h$	0.93	27	53
	$c \times h \times d(h)$	**0.93**	**26**	**35**
Evergreen shrubs	2.25 c	0.45	44	42
n = 75	2.6881 $c^{0.9277}$	0.45	44	44
$\bar{b}$ = 46.7	1216.4 $c \times h$	0.60	52	64
	$c \times h \times d(h)$	**0.61**	**38**	**34**
Vascular plants	9.39 c	0.29	130	363
n = 175	1.252 $c^{0.9277}$	0.31	82	52
$\bar{b}$ = 242.8	1176.5 $c \times h$	0.93	37	66
	$c \times h \times d(h)$	**0.93**	**36**	**46**

[1] Variables are percent cover, c; mean height in metres, h; and estimated aboveground biomass bulk density in grams per cubic metre, $d(h)$. Percent cover (c) is expressed in percentage units, e.g., 10% = 10 when used alone and = 0.1 m^2 when used in $c \times h$ and $c \times h \times d(h)$.

[2] RMAE = relative mean absolute error.

[3] MedAPE = median absolute percentage error.

LAI values can easily result in large absolute percentage error. MedAPE is not sensitive to a few very large absolute or percentage errors. In fact, if an equation estimates accurately for slightly more than half of the data points but gives large errors for the remaining data points, the MedAPE can be quite small. Clearly, we cannot argue that such an equation gives an accurate estimation overall. Therefore, a good estimation should have both a low RMAE value and a low MedAPE value.

RESULTS

Relationships between Aboveground Biomass and Non-destructive Variables

With an improvement in r^2 values and reduction in error statistics, the percent cover $c \times$ mean height h, also known as the bulk volume (Fig. 4), is a much better predictor of aboveground biomass b than the percent cover alone (Fig. 3) for the four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens. Table 2 lists the statistics of the relationships shown in Figure 3 and Figure 4. Overall, we

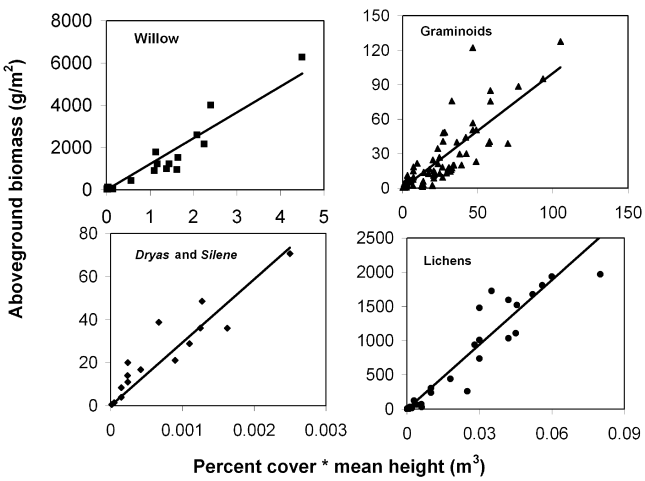

FIG. 4. Relationships between aboveground biomass and percent cover × mean height for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens.

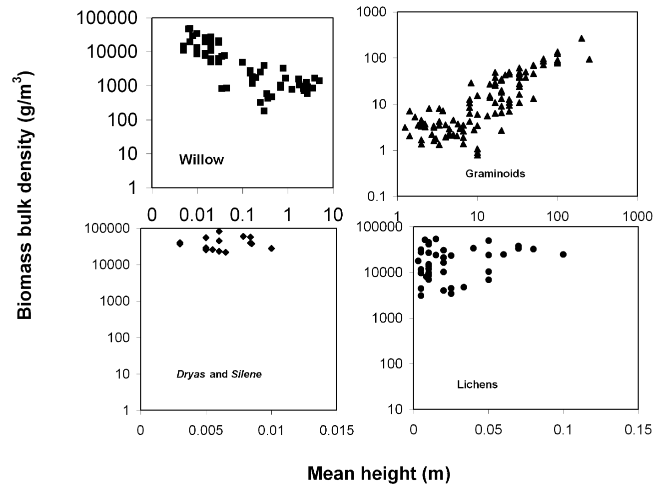

FIG. 5. Variation of aboveground biomass bulk density with mean height for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens.

found that using the CH method (as compared to the C-L method) resulted in a significant increase in r^2 values and a reduction in error statistics for all plant groups. Taking the willow group as an example, we found that the CH method increases the r^2 from 0.6 to 0.93, and reduces RMAE from 94% to 30% and MedAPE from 720% to 84%. However, the value of MedAPE is still quite high at 84%. Using the C-P method instead of the CH method resulted in a still lower MedAPE value of 64%.

The large MedAPE of 84% and relative low RMAE of 30% suggest significant errors for data points with low willow aboveground biomass, indicating that the assumption of little change in bulk density of aboveground biomass with changing plant height is invalid in this case. We plotted the measured aboveground biomass bulk density, $b/(c \times h)$, against h for the four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens in Figure 5. The plots show that for willow and graminoid groups, measured aboveground biomass bulk density decreases by orders of magnitude with the height of the vegetation. One explanation for this result is that in the High Arctic, the strong winter wind, combined with ice particles, kills all components of a plant exposed above snow cover (Billings, 1974). Consequently, Arctic vegetation generally crowds together, with a prostrate or cushion growth form, resulting in the phenomenal increase in the aboveground biomass bulk density for very low-growing Arctic vegetation. For willow and graminoid plants taller than about 0.1 m, the effect is not as significant, so there is little change in aboveground biomass bulk density (Fig. 5). To better reflect the little to no change in biomass bulk density, the maximum option was introduced for the bulk density function $d(h)$, which means the bulk density will not further decrease as mean plant height increases to a certain level. These taller plants grow in the warmer parts of the Arctic, where snow depths tend to be deeper (Raynolds et al., 2008). No systematic change in measured aboveground biomass bulk density was observed for the *Dryas* and *Silene* group, which has a mat growth form. This group was found only around Clyde River and Iqaluit in our data sets. Although lichens are widely distributed and found at all areas in our data sets, they do not show any systematic change in measured aboveground biomass bulk density either, as their growth form does not change dramatically with height.

Statistics for the relationships between aboveground biomass bulk density and mean height are shown in Table 3. Our data sets suggest significant changes in the aboveground biomass bulk density with mean height change for five Arctic plant groups—willow, birch, Labrador tea and *Andromeda*, graminoids, and forbs—while other Arctic plant groups show no systematic change. The negative power relationships between aboveground biomass bulk density and mean height suggest a lesser impact of height change on aboveground biomass for low-growing vegetation. This explains why Parker (1975), Rottgermann et al. (2000), and Krebs et al. (2003) found linear relationships between percent cover and aboveground biomass for low open Arctic vegetation. The impact of height change on aboveground biomass is as important as that of percent cover change for Arctic plant groups that show no systematic change in aboveground biomass bulk density with mean height. For some of those Arctic plant groups, the number of plots was quite small, and data were collected in only one or two study areas. Consequently, the result might change as more data become available over more diverse sampling areas. For other plant groups, such as lichens, the number of plots was quite large, and data were collected over a wide range of study areas, and the result remains no systematic change in aboveground biomass bulk density with mean height.

Using the relationships between the measured aboveground biomass bulk density and h (Table 3), we can estimate the bulk density as a function of h, $d(h)$. While there appears to be some circularity in using measured aboveground biomass to derive $d(h)$, it is not the case at all if

TABLE 3. Statistics for the relationship of mean height h to the bulk density of aboveground biomass, foliage biomass, and leaf area index (LAI) for 13 Arctic plant groups, deciduous shrub and evergreen shrub functional types, and all vascular plants at plot level (n = number of sample plots).

	Aboveground Biomass	r^2	Foliage Biomass	r^2	LAI	r^2	N
Willow	Max(1224.8, 512.93$h^{-0.7603}$)	0.49	Max(129.2, 264.28$h^{-0.8862}$)	0.45	Max(0.891, 1.8226$h^{-0.8862}$)	0.45	64
Birch	Max(971.9, 629.07$h^{-0.4965}$)	0.29	Max(279, 186.74$h^{-0.9549}$)	0.52	Max(1.5, 1.004$h^{-0.9549}$)	0.52	47
Sweet gale	884.26		Max(145, 210.24$h^{-0.5357}$)	0.61	Max(1, 1.4499$h^{-0.5357}$)	0.61	11
Blueberry, bearberry, and soapberry	10543		11221.5		54.739		17
Labrador tea and *Andromeda*	Max(872, 655.67$h^{-0.4122}$)	0.26	Max(139.26, 100.35$h^{-0.4754}$)	0.34	Max(2.11, 1.5204$h^{-0.4754}$)	0.34	42
Crowberry and lingonberry	2698.9		426.25	8.0425			22
Dryas and *Silene*	29388.6		21201.6		151.44		16
Cassiope	5063		808.2		16.164		11
Graminoids	Max(233.48, 79.85$h^{-0.9172}$)	0.73	Max(400.73, 119.14$h^{-0.9796}$)	0.72	Max(3.059, 0.9095$h^{-0.9796}$)	0.72	105
Forbs	Max(675, 503.93$h^{-0.5958}$)	0.35	Max(994.3, 745.73$h^{-0.6013}$)	0.36	Max(6.1, 4.575$h^{-0.6013}$)	0.36	20
Horsetail	143.8		228.2		1.3345		7
Lichens	31456						53
Mosses	2535.6						13
Deciduous shrubs	Max(1196.502, 363.82$h^{-0.8818}$)	0.59	Max(68.415, 57.558$h^{-0.961}$)	0.59	Max(1.041, 1.0173$h^{-0.977}$)	0.61	107
Evergreen shrubs	Max(1052.1, 245.89$h^{-0.9001}$)	0.72	Max(398.04, 151.88$h^{-0.8189}$)	0.64	Max(2.60, 0.4302$h^{-1.0972}$)	0.67	75
Vascular plants	Max(1175.009, 233.32$h^{-0.9318}$)	0.62	Max(83.35, 92.59$h^{-0.9018}$)	0.66	Max(1.246, 1.1273$h^{-0.8944}$)	0.75	175

we look at the actual form of $d(h)$ in Table 3. As shown in Table 3, $d(h)$ is a combination of a constant and a power function of mean height h. Consequently, $c \times h \times d(h)$ can be viewed as $c\times$ power function of h. In other words, because of the decrease in bulk density with height, biomass increases with height at a slower-than-linear rate for some plant species. We could directly use the form of c× power function of h to account for the impacts of changes in percent cover, height, and bulk density on biomass and LAI, although in this case the physical meaning is less clear. As a result, we keep the form of $c \times h \times d(h)$, and emphasize that the only information needed here is c and h.

For many of the groups, the best method is thus to include $d(h)$ in the equation. The results in Figure 6 show good linear relationships between b and $c \times h \times d(h)$ for the four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens. For the five Arctic plant groups in which we observed significant changes in the aboveground biomass bulk density (i.e., willow, birch, Labrador tea and *Andromeda*, graminoids, and forbs), the use of $c \times h \times d(h)$, or the CHD method, significantly improves the estimation of aboveground biomass (Table 2). The reduction in MedAPE using the CHD instead of the CH method is especially significant, from 84% to 49% for willow, 30% to 26% for birch, 47% to 32% for Labrador tea and *Andromeda*, 75% to 47% for graminoids, and 76% to 36% for forbs. For the other seven Arctic plant groups studied in this paper, the results from the CHD method are the same as those from the CH method, because no systematic change in the aboveground biomass bulk densities was found.

The results for the plant functional types are similar to those for the plant groups (Tables 2 and 3). For deciduous shrubs, the CHD method increases the value of r^2 to 0.93 (from 0.42 by the C-L method and 0.47 by the C-P method). While the CHD method gave r^2 and RMAE values similar to those from the CH method, it reduced the MedAPE from 53% to 35% for deciduous shrubs. The CHD-method values of r^2, RMAE, MedAPE for the deciduous shrubs compared well with those for the willow, birch, sweet gale, and blueberry–bearberry–soapberry plant groups, indicating that the aggregation of these plant groups into the deciduous shrub functional type did not result in a decrease in estimation accuracy for aboveground biomass. For the evergreen shrub plant functional group, although the CHD method continued to outperform the C-L, C-P, and CH methods, it gave a relatively low r^2 of 0.61, and a relatively high RMAE of 38%. Thus the aggregation of Labrador tea and *Andromeda*, crowberry and lingonberry, *Dryas* and *Silene*, and *Cassiope* plant groups into the evergreen shrub PFT resulted in poorer estimates of biomass by the CHD method, with lower r^2 and higher RMAE values compared to those for the individual plant groups.

Relationships Relating Non-Destructive Measurements to LAI and Foliage Biomass

The results for LAI are similar to those for aboveground biomass. The use of both percent cover and mean height substantially improves the linearity and error statistics between LAI and non-destructive measurements (Figs. 7 and 8, Table 4). For the five Arctic plant groups in which no systematic change in the LAI bulk densities was found (*Dryas* and *Silene*, blueberry–bearberry–soapberry, crowberry and lingonberry, *Cassiope*, and horsetail; Table 3), the effect of changes in mean height on LAI is as important as that of percent cover changes. As a result, the CH method significantly improves the linearity between LAI and non-destructive measurements and significantly reduces estimation errors. Taking the *Dryas* and *Silene* group as an example, the CH method increased the r^2 from 0.68 (with the C-L method) to 0.89, with corresponding reduction in RMAE (from 40% to 24%) and MedAPE (from 51% to 24%;

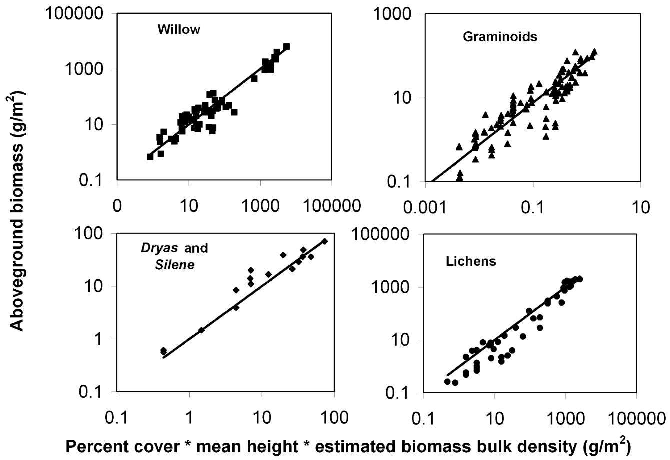

FIG. 6. Log-log scatter plots of aboveground biomass and percent cover × mean height × estimated aboveground biomass bulk density for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and lichens.

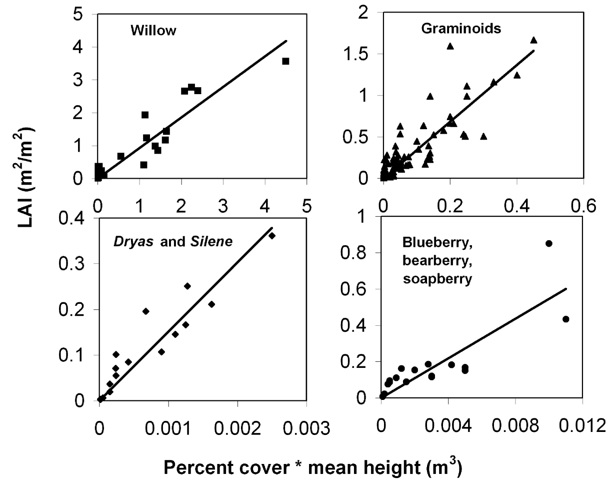

FIG. 7. Relationships between LAI and percent cover × mean height for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and blueberry–bearberry–soapberry.

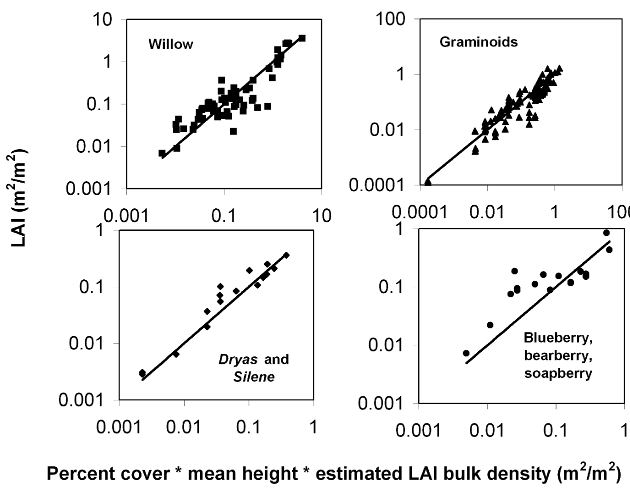

FIG. 8. Log-log scatter plots of LAI and percent cover × mean height × estimated LAI bulk density for four Arctic plant groups: willow, graminoids, *Dryas* and *Silene*, and blueberry–bearberry–soapberry.

Table 4). The CHD method for these Arctic plant groups gives the same results as the CH method. Again, because of the small samples for some Arctic plant groups whose LAI bulk density does not vary with height, the result might change as more data become available. Collecting more data for these Arctic plant groups over more diverse sampling areas should be a priority in our future fieldwork.

For the other six Arctic plant groups (willow, graminoids, birch, sweet gale, Labrador tea and *Andromeda*, and forbs), our data sets show systematic change in the LAI bulk density with mean height (Table 3). The negative power function between the LAI bulk density and mean height indicates a smaller effect of changes in mean height on LAI. As a result, the CH method increased r^2 and reduced RMAE, but often resulted in a rather large MedAPE. The reason for this result is that the relationship between LAI and $c \times h$ was largely determined by data points with large values of LAI or $c \times h$, and could not properly account for the order-of-magnitude increase in LAI bulk density for low-growing plants. Consequently, the effect of LAI bulk density must be incorporated, and the CHD method gave the best results for these six Arctic plant groups. For the willow group, the CHD method reduced RMAE from 41% to 35% and MedAPE from 97% to 34%, in comparison with the CH method (Table 4).

Because the values of foliage biomass and LAI are convertible using the specific leaf areas listed in Table 1 for the 13 Arctic plant groups, the values of r^2, RMAE, and MedAPE for estimating foliage biomass were the same as those for estimating LAI, but with different coefficients of the equations for calculating foliage biomass (Table 5).

Tables 4 and 5 show that at the plant functional type level, results for estimating foliage biomass and LAI were similar to those for estimating aboveground biomass. The CHD method continued to outperform other methods. For the aggregation of Labrador tea and *Andromeda*, crowberry and lingonberry, *Dryas* and *Silene*, and *Cassiope* plant groups into the evergreen shrub PFT, the CHD method gives a lower r^2 and higher RMAE compared to individual values for these plant groups. We would also like to draw readers' attention to the fact that LAI and foliage biomass for the deciduous shrub and evergreen shrub PFTs are not directly convertible because values of SLA are different for plant groups in each PFT. Consequently, the results for estimating foliage biomass were not exactly the same as those for estimating LAI.

Estimation Errors for Plot Total Vascular Aboveground Biomass, LAI, and Foliage Biomass

In many cases, estimations of plot level aboveground biomass, LAI, and foliage can be of great importance. Figure 9 shows the 1:1 comparison between measured and estimated values of (a) vascular plant aboveground biomass for a plot,

TABLE 4. Relationship between leaf area index (LAI) and non-destructive variables (details as in Table 2), where $\overline{\text{LAI}}$ is the mean measured LAI for all plots containing species of the group.

Plant Group	Relationship (b =)	r^2	RMAE (%)	MedAPE (%)
Willow	$0.024\ c$	0.76	59	55
$n = 64$	$0.0186\ c^{0.8714}$	0.73	62	43
$\overline{\text{LAI}} = 0.40$	$1.0193\ c \times h$	0.91	41	97
	$c \times h \times d(h)$	**0.89**	**35**	**34**
Birch	$0.0157\ c$	0.55	51	57
n = 47	$0.0093\ c^{1.0515}$	0.56	44	36
$\overline{\text{LAI}} = 0.4$	$1.4477\ c \times h$	0.91	39	63
	$c \times h \times d(h)$	**0.92**	**26**	**35**
Sweet gale	$0.0093\ c$	0.12	43	37
$n = 11$	$0.0377\ c^{0.5606}$	0.14	40	43
$\overline{\text{LAI}} = 0.25$	$1.5741\ c \times h$	0.71	45	50
	$c \times h \times d(h)$	**0.65**	**22**	**14**
Blueberry, bearberry,	$0.0071\ c$	0.15	50	36
and soapberry	$0.0253\ c^{0.6502}$	0.18	48	27
$n = 17$	$54.739\ c \times h$	0.71	42	41
$\overline{\text{LAI}} = 0.18$	$c \times h \times d(h)$	**0.71**	**42**	**41**
Labrador tea	$0.0085\ c$	0.32	63	65
and *Andromeda*	$0.0031\ c^{1.1788}$	0.31	52	47
n = 42	$2.7341\ c \times h$	0.44	51	54
$\overline{\text{LAI}} = 0.14$	$c \times h \times d(h)$	**0.47**	**44**	**39**
Crowberry and	$0.0053\ c$	0.43	46	45
lingonberry	$0.0216\ c^{0.5306}$	0.40	44	45
$n = 22$	$8.0425\ c \times h$	0.74	39	38
$\overline{\text{LAI}} = 0.107$	$c \times h \times d(h)$	**0.74**	**39**	**38**
Dryas and *Silene*	$0.0104\ c$	0.68	40	51
$n = 16$	$0.0095\ c^{1.0868}$	0.67	44	51
$\overline{\text{LAI}} = 0.11$	$151.44\ c \times h$	0.89	24	24
	$c \times h \times d(h)$	**0.89**	**24**	**24**
Cassiope	$0.0083\ c$	0.92	17	20
$n = 11$	$0.0064\ c^{1.1339}$	0.92	25	28
$\overline{\text{LAI}} = 0.06$	$16.201\ c \times h$	0.89	20	21
	$c \times h \times d(h)$	**0.89**	**20**	**21**
Graminoids	$0.0107\ c$	0.51	60	48
$n = 105$	$0.0095\ c^{0.9547}$	0.50	56	50
$\overline{\text{LAI}} = 0.23$	$3.4171\ c \times h$	0.77	41	75
	$c \times h \times d(h)$	**0.74**	**43**	**44**
Forbs	$0.0096\ c$	0.71	38	38
$n = 20$	$0.01\ c^{1.0223}$	0.71	39	36
$\overline{\text{LAI}} = 0.02$	$10.26\ c \times h$	0.31	71	74
	$c \times h \times d(h)$	**0.87**	**26**	**29**
Horsetail	$0.0078\ c$	0.98	15	44
$n = 7$	$0.0144\ c^{0.8073}$	0.97	25	35
$\overline{\text{LAI}} = 0.14$	$1.3345\ c \times h$	0.98	20	58
	$c \times h \times d(h)$	**0.98**	**20**	**58**
Deciduous shrubs	$0.01916\ c$	0.63	56	74
$n = 107$	$0.0128\ c^{0.967}$	0.62	49	41
$\overline{\text{LAI}} = 0.50$	$1.0606\ c \times h$	0.84	45	83
	$c \times h \times d(h)$	**0.85**	**32**	**38**
Evergreen shrubs	$0.006467\ c$	0.35	45	33
$n = 75$	$0.01133\ c^{0.8228}$	0.36	44	36
$\overline{\text{LAI}} = 0.14$	$3.1463\ c \times h$	0.34	62	71
	$c \times h \times d(h)$	**0.38**	**44**	**38**
Vascular plants	$0.016096\ c$	0.55	61	61
$n = 175$	$0.01024\ c^{0.9858}$	0.55	54	43
$\overline{\text{LAI}} = 0.58$	$1.2847\ c \times h$	0.84	51	79
	$c \times h \times d(h)$	**0.85**	**33**	**41**

TABLE 5. Relationship between foliage biomass (b_f) and non-destructive variables (details as in Table 2), where $\overline{b_f}$ is the mean measured foliage biomass for all plots containing species of the group.

Plant Group	Relationship (b =)	r^2	RMAE (%)	MedAPE (%)
Willow	$3.48\ c$	0.76	59	55
$n = 64$	$2.697\ c^{0.8714}$	0.73	62	43
$\overline{b_f} = 58.15$	$147.7985\ c \times h$	0.91	41	97
	$c \times h \times d(h)$	**0.89**	**35**	**34**
Birch	$2.9202\ c$	0.55	51	57
$n = 47$	$1.7298\ c^{1.0515}$	0.56	44	36
$\overline{b_f} = 74.03$	$269.2722\ c \times h$	0.91	39	63
	$c \times h \times d(h)$	**0.92**	**26**	**35**
Sweet gale	$1.3485\ c$	0.12	43	37
$n = 11$	$5.4665\ c^{0.5606}$	0.14	40	43
$\overline{b_f} = 36.4$	$228.2445\ c \times h$	0.71	45	50
	$c \times h \times d(h)$	0.65	22	14
Blueberry, bearberry,	$1.4555\ c$	0.15	50	36
and soapberry	$5.1865\ c^{0.6502}$	0.18	48	27
$n = 17$	$11221.495\ c \times h$	0.71	42	41
$\overline{b_f} = 36.29$	$c \times h \times d(h)$	0.71	42	41
Labrador tea	$0.561\ c$	0.32	63	65
and *Andromeda*	$0.2046\ c^{1.1788}$	0.31	52	47
$n = 42$	$180.4506\ c \times h$	0.44	51	54
$\overline{b_f} = 8.91$	$c \times h \times d(h)$	**0.47**	**44**	**39**
Crowberry and	$0.2809\ c$	0.43	46	45
lingonberry	$1.1448\ c^{0.5306}$	0.40	44	45
$n = 22$	$426.2525\ c \times h$	0.74	39	3
$\overline{b_f} = 5.67$	$c \times h \times d(h)$	0.74	39	38
Dryas and *Silene*	$1.456\ c$	0.68	40	51
$n = 16$	$1.33\ c^{1.0868}$	0.67	44	51
$\overline{b_f} = 15.96$	$21201.6\ c \times h$	0.89	24	24
	$c \times h \times d(h)$	**0.89**	**24**	**24**
Cassiope	$0.415\ c$	0.92	17	20
$n = 11$	$0.32\ c^{1.1339}$	0.92	25	28
$\overline{b_f} = 3.2$	$810.05\ c \times h$	0.89	20	21
	$c \times h \times d(h)$	**0.89**	**20**	**21**
Graminoids	$1.4017\ c$	0.51	60	48
$n = 105$	$1.2445\ c^{0.9547}$	0.50	56	50
$\overline{b_f} = 30.26$	$447.6401\ c \times h$	0.77	41	75
	$c \times h \times d(h)$	**0.74**	**43**	**44**
Forbs	$1.5648\ c$	0.71	38	38
$n = 20$	$1.63\ c^{1.0223}$	0.71	39	36
$\overline{b_f} = 3.59$	$1672.38\ c \times h$	0.31	71	74
	$c \times h \times d(h)$	**0.87**	**26**	**29**
Horsetail	$1.3338\ c$	0.98	15	44
$n = 7$	$2.4624\ c^{0.8073}$	0.97	25	35
$\overline{b_f} = 24.11$	$228.1995\ c \times h$	0.98	20	58
	$c \times h \times d(h)$	**0.98**	**20**	**58**
Deciduous shrubs	$1.1923\ c$	0.60	62	89
$n = 107$	$0.7192\ c^{0.979}$	0.59	52	46
$\overline{b_f} = 31.05$	$69.248\ c \times h$	0.89	40	81
	$c \times h \times d(h)$	**0.89**	**29**	**38**
Evergreen shrubs	$1.0025\ c$	0.41	44	40
$n = 75$	$1.1787\ c^{0.9425}$	0.41	43	40
$\overline{b_f} = 21.25$	$469.67\ c \times h$	0.40	61	72
	$c \times h \times d(h)$	**0.50**	**41**	**38**
Vascular plants	$1.1586\ c$	0.53	56	47
$n = 175$	$0.9053\ c^{0.9725}$	0.52	51	41
$\overline{b_f} = 37.9$	$88.12\ c \times h$	0.81	56	86
	$c \times h \times d(h)$	**0.83**	**34**	**39**

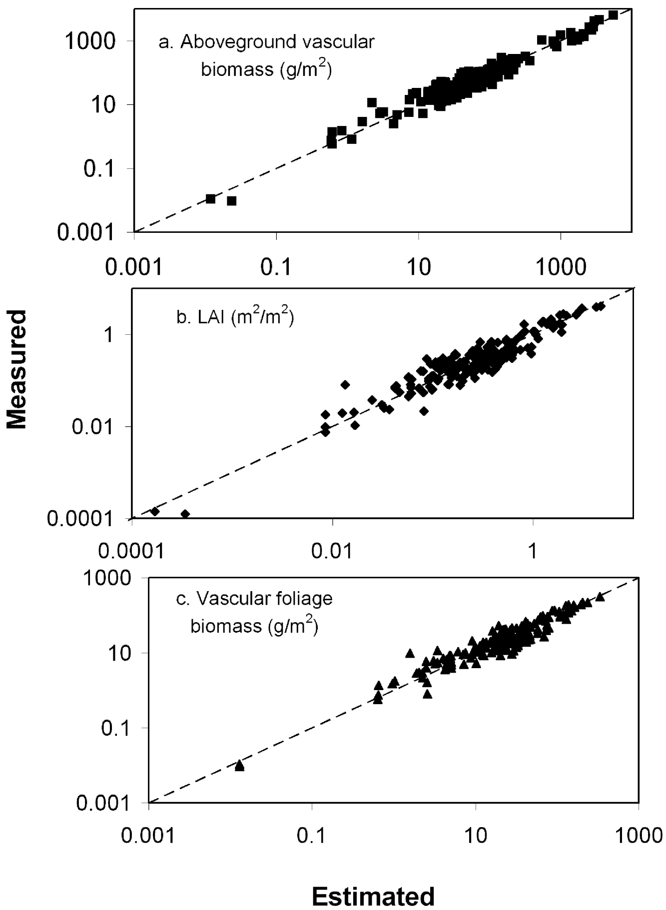

FIG. 9. The 1:1 comparison between measured and estimated values of (a) vascular plant aboveground biomass for an entire plot, (b) LAI, and (c) foliage biomass. The estimated value at the plot level was calculated by summing the values estimated for each plant species from percent cover × mean height × estimated aboveground biomass bulk density at the plot. For clarity in the low biomass range, the values are plotted in log-log scales.

(b) LAI, and (c) vascular plant foliage biomass. The estimated values at the plot level were calculated by summing the estimates for each plant group in the plot using the CHD method. This calculation was done for the 196 plots measured along the Dempster Highway in Yukon, around Yellowknife in the Northwest Territories, in Wapusk National Park in northern Manitoba, and around the Lupin Gold Mine, Iqaluit, and Clyde River in Nunavut. For clarity in the low biomass range, the values were plotted in log-log scales. For vascular plant aboveground biomass, the resulting values were r^2 = 0.95, RMAE = 25%, and MedAPE = 29% (Table 6). Similar results were found for LAI (r^2 = 0.91, RMAE = 28%, and MedAPE = 28%) and for vascular plant foliage biomass (r^2 = 0.91, RMAE = 23%, and MedAPE = 27%). The r^2 values and error statistics estimated at plot level were generally better than those of individual plant groups, probably because some of the errors canceled each other out; that is, an underestimation in percent cover for one plant group likely resulted in an overestimation for another plant group. In comparison, Steltzer and Welker (2006) investigated four types of models, and found the best result for estimating LAI was achieved by incorporating the effect of species percent cover into a ground-observed normalized difference vegetation index (NDVI) with an r^2 value of 0.82 for the 29 Arctic tundra plots in Kap Atholl, Greenland. The higher r^2 value that we obtained using the CHD method in this study suggests the importance of incorporating the effects of changes in mean height and bulk density.

Although these plot-level values of RMAE obtained with the CHD method appear to be in the same range as the sampling error shown in Figure 1, the two error measurements are fundamentally different in terms of monitoring accuracy. With the CHD method, one would repeatedly observe percent cover and mean height of the same permanent plot, thus avoiding the additional error caused by heterogeneity of plots. For example, if one observes an average 10% increase in percent cover of willow leaves and little change in mean height at the same five plots of a site between two dates within a growing season, one can quite confidently assume that there is a corresponding increase in LAI and foliage biomass at the site, despite the ~30% RMAE result from the CHD method. The same, however, cannot be confidently assumed if the 10% increase in percent cover of willow leaves is observed between two sets of five plots at a site on different dates, in which case the measurement sampling error caused by heterogeneity would be ~30%.

Table 6 also lists r^2 values and error statistics for estimating plot total vascular aboveground biomass, foliage biomass, and LAI using relationships developed at the PFT level, as well as those directly relating percent cover and mean height to the plot total vascular aboveground biomass, foliage biomass, and LAI (Tables, 2, 3, and 4). Overall, applying the CHD method to plant groups and then aggregating their results to the plot total gives the highest r^2 values and lowest RMAE and MedAPE for estimating plot total vascular aboveground biomass, foliage biomass, and LAI. Using relationships at the plant group level to estimate plot total vascular aboveground biomass, foliage biomass, and LAI, we had r^2 values of 0.91–0.95, RMAE of 25–29%, and MedAPE of 28–30%, compared to 0.81–94, 35–38%, and 38–39% when using PFT relationships, and 0.83–93, 33–36%, and 39–46% when using the plot total level relationships. Nevertheless, we noticed that when using the CHD method to estimate aboveground biomass, foliage biomass, and LAI, the errors were still quite large. Several sources of error exist, especially the potential error in the visual estimation of percent cover. The accuracy of visual estimation of percent cover may vary between observers, and a large percentage error can easily occur when the percent cover is low (e.g., in the single digits).

As observation standards and observers change, the current visual estimation of percent cover can result in large errors in monitoring seasonal and long-term changes, especially for areas where the percent cover is low. To implement the findings of this paper for long-term monitoring of biomass and LAI in the Arctic, we need to develop an

TABLE 6. Statistics for calculating vascular aboveground biomass, foliage biomass, and leaf area index totals with the CHD method, $c \times h \times d(h)$, for a plot, a plant group within a plot, or a functional type within a plot.

		r^2	RMAE (%)	MedAPE (%)
Aboveground biomass	At the plot total level	0.93	36	46
	At the functional type level	0.94	35	39
	At the plant group level	**0.95**	**25**	**29**
Foliage biomass	At the plot total level	0.83	34	39
	At the functional type level	0.81	38	37
	At the plant group level	**0.91**	**23**	**27**
LAI	At the plot total level	0.85	33	41
	At the functional type level	0.86	36	38
	At the plant group level	**0.91**	**28**	**28**

objective method for determining percent cover. The point-frame method for measuring the composition and abundance of low-stature vegetation, such as the forbs, graminoids, and dwarf shrubs that characterize Arctic tundra, is a standard method that has been adopted by the International Tundra Experiment (Bean and Henry, 2003). Another potential method is to take a good-quality digital photograph directly over a permanent sample plot that has been marked and framed and classify the photograph into percent cover of plant groups within the plot, aided by remote sensing techniques (Luscier et al., 2006). The standard point-frame method can usually be completed in about two hours by a field observer familiar with the procedure. The method has a 10 × 10 resolution for a 1 × 1 m plot, so each observation point represents a 10 × 10 cm area. However, since Arctic plant leaves are generally small enough to be measured in millimeters, the chance that they will not be hit by the point is quite large; thus, the method is inaccurate. In contrast, a one-megapixel digital photograph of a 1 × 1 m plot has a resolution of 1000 × 1000, or a pixel size of 1 × 1 mm. Therefore, the digital photo method could easily increase the measurement points from 10 × 10 of the standard point-frame method to 1000 × 1000 (or 10 000 times as many), greatly enhancing the accuracy of percent cover estimation. This digital photo method is also faster and easier to implement in the field, since image analysis can be completed in the laboratory at a later date. We will report details of the image analysis method and results, as well as the limitations of the method, in a separate paper.

CONCLUSIONS

We reached the following conclusions about the relationships between aboveground biomass and LAI and non-destructive measurements of percent cover and mean height:

1. Arctic plant parameters measured in this study can vary by several orders of magnitude. Therefore, we cannot neglect the effect of changes in height and bulk density on biomass and LAI, especially if the study area includes diverse vegetation conditions.
2. The CHD method, which integrates the effects of changes in percent cover, mean height, and aboveground biomass bulk density, produces the smallest errors in estimation of aboveground biomass, LAI, and foliage biomass.
3. The best estimations resulted from applying the CHD method to individual plant groups and aggregating the results to estimate the plot total.
4. The biomass of lichen and moss can outweigh vascular biomass in many Arctic ecosystems. Mean height is especially important in its estimation, since these plants show no systematic change in aboveground biomass density with height change.

Importance of the CHD Method

The CHD method avoids additional error caused by heterogeneous plots because it uses repeated non-destructive observations at the same permanent plots. Long-term monitoring or repeated observations of percent cover at several Arctic sites have been reported previously (Kennedy et al., 2001; Wahren et al., 2005), and many other vegetation measurements have been done in the circumpolar Arctic in the last half-century, especially during the International Biological Programme in 1968–75 (e.g., Bliss et al., 1984). Plant height measurements for each species are included in Wahren's data and in data collected at Toolik Lake, Alaska, to monitor changes in cover after experimental treatments (Shaver and Chapin, 1991). However, LAI was not measured directly before the 1980s, and biomass data are lacking in many cases. The CHD method could be applied to those old data to estimate LAI, and even biomass, using traditional vegetation data such as height and coverage, and then compared with recent LAI and biomass data over the same plots.

The CHD method could also be used to improve the accuracy of LAI measurement with optical instruments such as the LAI-2000, especially for low-stature vegetation. Often, the gap-fraction sensor either cannot get totally underneath the plant canopy, and thus misses part of the leaf area present, or is too close to the individual leaves, and thus distorts the LAI estimate. Van Wijk and Williams (2005) reported that LAI of Arctic vegetation could be estimated accurately and rapidly by combining field measurements of canopy reflectance (NDVI) for low, open vegetation and light penetration through the canopy (gap-fraction analysis using a LI-COR LAI-2000) for high, dense vegetation. The

CHD method and corresponding field observation of percent cover and mean height have the potential to achieve the same goal.

Given the labor-intensive character of this data collection, and the importance of having good value for the equations, all the data were used to develop the relationships. It is important to test these relationships further with other data and in other parts of the Arctic. To this end, we plan to collect more field data in different areas (such as the Ivvavik National Park in northern Yukon and the Torngats National Park in northern Labrador) in coming years, and to develop the technique of digital photo image analysis to improve measurement of percent cover.

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