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PRACTICAL TOOLS

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Estimating canopy fuel load with hemispherical photographs: A rapid method for opportunistic fuel documentation with smartphones

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Abstract

1. Canopy fuel load (CFL) affects wildfire intensity and is a critical input for fire behaviour models; however, measuring CFL in the field is time-consuming and costly.
2. Until recently, hemispherical photographs have been unable to adequately describe canopy metrics in non-diffuse light conditions. Recent developments allow calculation of canopy openness (CO) and leaf area index (LAI) using hemispherical photographs taken in sunny conditions.
3. We describe an inexpensive and effective method for estimating CFL in the field opportunistically using CO and LAI values derived from hemispherical photographs taken in variable lighting conditions with a smartphone and fisheye lens attachment.
4. Implications of this work include: new data for modelling effects of forest structure on fire behaviour; inexpensive assessment and monitoring of forest structure changes over time and in relation to management actions; and decision support for fuel treatment planning and prescribed burning operations.

KEYWORDS

boreal forest, Canada, canopy fuel load, canopy openness, fire behaviour, hemispherical photography, leaf area index

1 | INTRODUCTION

In forest ecosystems that contain flammable conifer trees, the amount of live needles (i.e. foliage) and small branches present in the canopy will in part determine the behaviour of a fire and how intensely it burns. As such, canopy fuel load (CFL) is a common input for wildfire behaviour models. Canopy fuel load is defined as the weight of canopy biomass per unit area that is available for combustion during the passage of a flame front through the canopy. Unfortunately, estimating CFL for fire behaviour modelling is challenging due to the time and expense associated with field measurements.

Canopy fuel load is typically measured manually in field settings by conducting stem inventories in combination with either destructive samples to directly measure fuel weights, or by applying allometric equations estimated in prior destructive sampling studies to compute fuel weights from tree diameter measurements. The documentation of fuel properties during active wildfire situations is generally considered unsafe and impractical due to the substantive time required to collect fuel measurements. Remote sensing technologies such as airborne lidar and drone imagery have the ability to describe forest attributes in detail (e.g. Cameron, 2020) but require extensive planning and cannot be collected opportunistically. Rapid documentation of fuel properties with ground-level photography offers a potential alternative for pairing operational observations of wildfire behaviour with fuel load measurements computed in a standardized manner.

Hemispherical photography is a long-established method for acquiring indirect measurements of the forest canopy (Chianucci, 2020). Hemispherical photographs (HPs) are taken with a fisheye lens and the camera typically pointed upwards to capture canopy geometry. The fraction of visible sky through the canopy (i.e. gap fraction) can be calculated from HPs and used to document key canopy properties such as canopy openness (CO) and infer effective leaf area index (LAI; Gonsamo et al., 2011). Previous studies have demonstrated significant statistical relationships between canopy metrics derived from HPs and CFL (e.g. Clark & Murphy, 2011; Keane et al., 2005); however, a major limitation of HPs is the sensitivity of results to camera exposure and light conditions (Chianucci, 2020). As a result, time-consuming acquisition protocols and specific environmental conditions are required, limiting the use of HPs in operational field settings, where data collection would occur in opportunistic situations. In recent years, algorithms have been developed to reduce classification errors associated with digital HPs acquired under suboptimal light conditions, and these have shown great promise for estimating CO and LAI in variable lighting conditions (Díaz, 2021). In hemispherical photography, the term plant area index (PAI) instead of LAI is often preferred since no distinction between photosynthetic and non-photosynthetic surface is made in the surface calculations. Here we adopt the terms used by Gonsamo et al. (2011).

In addition to advancements in HP processing technologies, the reduced costs of cameras and lenses have recently renewed interest in using HPs to rapidly document canopy structural properties in the field (e.g. Bianchi et al., 2017; Díaz, 2021; Wang et al., 2018). These studies have demonstrated that HP with inexpensive smartphone and fisheye lens equipment is an acceptable alternative to HP using traditional cameras, with the benefits of low cost and high portability. Origo et al. (2017) further established that capturing HPs with fast hand-levelling techniques versus time-consuming tripod-levelling approaches resulted in minimal impacts to photograph quality. These efficient and inexpensive methods have yet to be explored for rapid CFL measurement from HPs.

In this study, we demonstrate a *proof of concept* for rapid fuel documentation with smartphones. Specifically, we test the effectiveness of using smartphone HPs to rapidly estimate CFL in North American boreal conifer forests, a high-hazard fuel complex found in abundance across Canada and Alaska. We use novel processing techniques from the R 'CAIMAN' package (Díaz, 2021) to account for variable lighting conditions. Our approach has been designed for opportunistic use by field staff or non-specialists such as wildland firefighters, to facilitate rapid documentation of fuel structure at wildland fire and fuel management sites.

2 | MATERIALS AND METHODS

2.1 | Plot establishment

Fifteen field plots were established in black spruce *Picea mariana*- and larch *Larix laricina*-dominated stands at two study sites within the boreal forest of Alberta, Canada (Figure 1). Twelve plots were located at the Pelican Mountain Research Site and three plots were established in the vicinity of Calling Lake, a small northern community (Figure 1). Plot locations were selected to represent a range of natural stand structures (Table 1). All plot locations had characteristically flat slopes; however, within each plot, hummocks of moss produced undulating terrain. These nutrient poor sites are associated with low ecosystem productivity and stunted tree growth typical of boreal forests (Willoughby et al., 2019).

2.2 | Fuel sampling

The boreal conifer forest types assessed in this study are prone to high-intensity crown fires that consume canopy foliage and fine branch wood. The assessments of potential fire behaviour in these stands involve partitioning fuel loads into discrete strata relevant to the progression of a surface fire vertically into tree crowns. These strata consist of surface, ladder (i.e. subcanopy shrubs and small trees) and canopy fuels (Van Wagner, 1977). Surface and ladder fuels determine the ease with which a wildfire spreading on the surface can transition into the canopy, whereas canopy bulk density, which is calculated from measurements of CFL, will determine the potential for sustained crown fire spread (Van Wagner, 1977). Canopy fuel load also determines the intensity of the fire, which in turn dictates operational suppression tactics (Hirsch & Martell, 1996).

We hypothesized that rapid estimates of CFL could be acquired opportunistically with smartphones, to generate much needed data for fire behaviour assessment and modelling studies. To model the relationship between hemispherical photography variables and CFL, standard fuel inventory measurements (i.e. Alberta Agriculture & Forestry, 2015) were used to compute CFL at each plot, where HPs were also acquired. We defined CFL as canopy foliage and branch wood, a predominantly fine fuel consumed by fire in these stand types (e.g. Stocks et al., 2004). All trees greater than 1.3 m in height were inventoried and tree height, DBH (1.3 m) and tree species were recorded. Biomass in surface and ladder fuel strata below the 1.3 m height threshold were omitted. To ensure a sufficient number of trees were measured, a nested plot layout was used (Figure 2). For trees with DBH < 9.0 cm, an initial plot radius of 3.57 m was used and increased to 5.64 m if fewer than 20 trees were present. For trees with a DBH ≥ 9.0 cm, plot radius

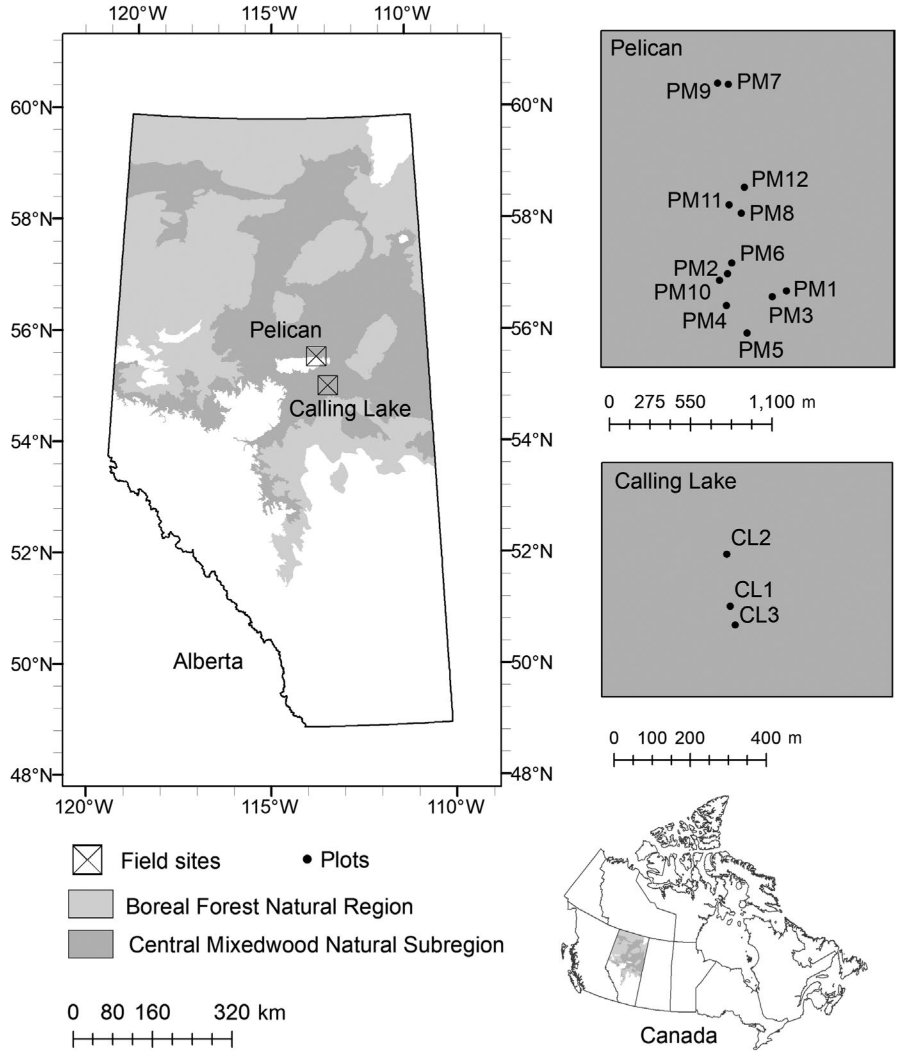

FIGURE 1 Pelican Mountain and Calling Lake field sites and respective plot locations in the Central Mixedwood Natural Subregion, Boreal Forest Natural Region of Alberta, Canada

TABLE 1 Descriptive summary of study plots ($n = 14$). Tree density, species composition, average and range of tree heights, average and range of DBH (1.3 m) and canopy fuel load (CFL) for trees ≥1.3 m. Pelican Mountain and Calling Lake study sites are denoted by PM and CL, respectively, in the plot identification (ID) column. Plot PM12 (data not shown) was determined to be an outlier, and omitted from further analysis

ID	Tree density (stems/ha)	Black spruce (%)	Larch (%)	Other (%)	Avg. height (m)	Height range (m)	Avg. DBH (cm)	DBH range (cm)	CFL (kg/m^2)
PM1	3,848	9.09	90.91	0.00	8.2	1.9–17.5	7.4	1.4–27.1	1.20
PM2	4,698	31.91	68.09	0.00	7.5	2–13.4	7.3	1.5–16.2	1.53
PM3	3,947	65.18	34.82	0.00	4.2	1.9–11.8	4.6	1.6–14.7	0.67
PM4	5,672	78.39	21.17	0.00	7.4	1.5–20.4	6.7	0.5–26.2	2.02
PM5	7,295	73.96	26.61	0.00	4.8	1.5–17.9	3.8	0.6–21.3	1.21
PM6	5,847	5.98	94.02	0.00	7.5	1.6–15.4	6.9	1.6–29.1	1.59
PM7	17,358	99.86	0.00	0.14	3.8	1.4–8	3.4	0.5–10.2	2.33
PM8	6,045	95.87	0.00	4.13	5.9	1.5–12.6	5.7	0.8–12.5	1.80
PM9	20,980	100.00	0.00	0.00	3.8	1.4–11.4	3.2	0.5–12.8	2.65
PM10	10,365	14.46	82.89	2.65	3.6	1.3–7.9	2.5	0.1–19.7	0.74
PM11	7,044	100.00	0.00	0.00	6.6	1.7–12.8	5.7	0.9–14.3	2.23
CL1	17,883	100.00	0.00	0.00	4.9	1.4–11.8	4.2	0.4–16	3.61
CL2	5,595	95.54	4.46	0.00	4.1	1.4–10.4	4.2	0.6–15.4	1.11
CL3	3,102	100.00	0.00	0.00	6.6	1.4–14.7	6.5	0.3–14.6	1.23

was increased progressively from 5.64 to 7.98 m to a maximum of 11.28 m in an effort to obtain measurements for a minimum of 20 trees. Allometric equations (Lambert et al., 2005) were used to compute CFL for each inventoried tree from DBH measurements and divided over the sampling area. Canopy fuel load (kg/m^2) for the plot was computed as the sum of individual crown fuel loads (Cruz et al., 2003).

2.3 | Photograph acquisition

Digital HPs were taken 5 and 10 m from plot centre on transects extending in each of the four cardinal directions for a total of eight HPs per plot (Figure 2). Hemispherical photographs were taken with an Olloclip fisheye lens mounted on an iPhone 7 equipped with a 12 MP camera (Figure 3) that the photographer oriented perpendicular to the transect line. Images were captured during peak daylight hours between 9:00 and 16:30. The HPs of 3,024 × 4,032 pixel size represent a 165° maximum field of view (Díaz, 2021) but due to the fitting of the Olloclip on the iPhone 7, part of the circular image is not represented (Figure 4).

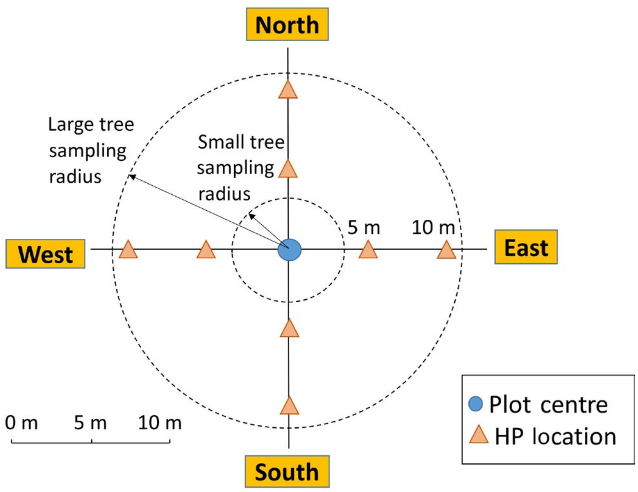

FIGURE 2 Plot layout. Locations where hemispherical photographs (HPs) were acquired are denoted by triangle symbols. Large and small tree sampling radii used for stem inventories were determined by tree density

FIGURE 3 Hemispherical photographs were captured with an Olloclip fisheye lens attachment mounted on an iPhone 7 smartphone

Photographs were taken at eye level and levelled by hand. Multiple photographers captured the photographs for this study and due to undulating, hummocky terrain within a given plot and varied photographer heights, a consistent reference plane could not be used without time-consuming efforts that were not compatible with our goal. Photographs were typically captured 1.5 to 2.0 m above an imaginary levelled plane that passed through the plot centre. By taking the HPs at eye level, the photographer could quickly hand-level the camera's thin, linear profile. This enabled a lean, flexible sampling protocol unencumbered by tripods or levelling devices that would have been incompatible with the characteristically uneven terrain; however, it also introduced a source of potential error when relating HP metrics to ground measurements. The area covered by a given HP will depend on lens height, tree height and tree distance to the lens (Leblanc et al., 2005). It is possible for HPs to oversample the canopy inside the plot or include canopy regions outside the plot (Leblanc et al., 2005; Zou et al., 2020). Due to the homogeneity of the forest canopy in our study area, we expect these factors to have a negligible impact on our results; however, in more heterogeneous forest ecosystems, the plot layout and procedures used in this study may not be suitable.

Given the stunted nature of the forest stands in the sample plots and the height of the camera above-ground, shrubs and ladder fuels beneath the canopy were omitted from the images and the characteristically narrow tree crown morphology did not fully obscure the sky. These conditions permitted image acquisition with the phone's automatic exposure, following Díaz (2021). At each plot, photographs were taken in a systematic sequence, and plot ID, transect number and transect position were documented in the image filename for archiving. In operational settings, where HPs and any associated observations would be acquired opportunistically, reference locations could be documented with a screenshot of a smartphone location (e.g. Theodolite App), a photograph of a GPS unit display, or with an electronic data collection log. Auto-tagged location coordinates embedded in the HP image file by the iPhone's geolocation services may also be helpful for reference purposes, depending on study objectives and factors such as canopy structure (e.g. Tomaštík et al., 2017).

2.4 | Model building

The 'CAIMAN' R package (Díaz, 2021) and CIMES software package (Gonsamo et al., 2011) were used to calculate CO and LAI for each photograph and averaged by plot. Canopy openness is a geometric descriptor where LAI was calculated following the Miller theorem (Miller, 1967) with the clumping index based on Chen and Cihlar (1995). The HPs were binarized using the R script provided in Díaz (2021), previously adapting it for the iPhone 7 resolution. For practicality, the same script was applied without taking into account illumination conditions. Processing time would be diminished by removing steps from the script that are unnecessary for photographs acquired in overcast conditions. We compared CO and LAI to field-measured CFL in black spruce- and larch-dominated stands. Following Clark and Murphy

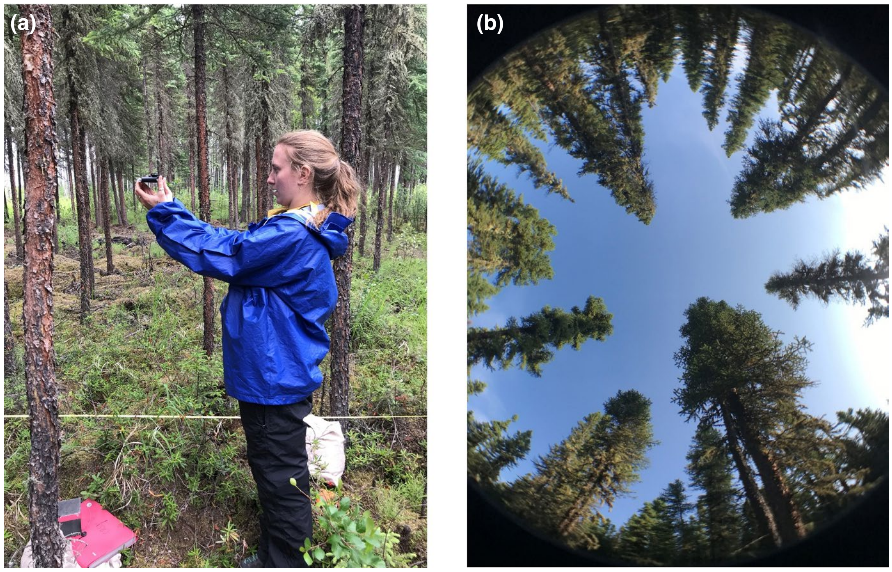

FIGURE 4 Hemispherical photograph (HP) image acquisition method and output: (a) study photographer demonstrates eye-level smartphone hand-levelling perpendicular to transect line; and (b) example HP acquired with the Olloclip fisheye lens attachment mounted on an iPhone 7 smartphone

(2011) and Steele-Feldman et al. (2006), the relationship between CO and LAI and field-measured CFL was modelled with linear regression.

3 | RESULTS

The inspection of descriptive structural characteristics summarized in Table 1 resulted in removal of one plot (PM12) from further analysis, due to its shorter stature which was inconsistent with the typical black spruce- and larch-dominated stand structures represented in the remaining plots. Logarithmic transformations were applied to the CFL values to generate a linear relationship. Despite the relaxed protocols used, a significant linear regression equation (Table 2; Figure 5) was found between log-transformed CFL and both CO ($F(1, 12) = 86.32$, $p < 0.000$) and LAI ($F(1, 12) = 64.74$, $p < 0.000$).

A remarkably high proportion of the variance in log-transformed CFL was predicted from CO ($R^2 = 0.878$) and LAI ($R^2 = 0.8436$) computed from HPs. The strength of these results suggest that cloud cover did not confound the relationships between CFL and HP canopy metrics, given that images were acquired under varied cloud cover.

TABLE 2 Regression model parameter estimates for the linear relationship between log-transformed canopy fuel load (CFL, kg/m^2) measurements and canopy metrics computed from hemispherical photographs (HPs): (a) canopy openness (CO) expressed as a proportion; and (b) leaf area index (LAI)

Term	Coefficient	*SE*	*t*	*p*
(a)				
Intercept	0.7043	0.0591	11.917	<0.000
CO	−2.0579	0.2215	−9.291	<0.000
(b)				
Intercept	−0.66112	0.10794	−6.125	<0.000
LAI	0.47140	0.05859	8.046	<0.000

4 | DISCUSSION

Forest managers and practitioners require detailed forest structure information to plan for, respond to and model wildfire events. Satellite remote sensing tools can provide coarse evaluations of fuel characteristics, but finer resolution data (i.e. <30-m spatial resolution) are required to model and understand local forest structure (Reeves et al., 2009). Photograph guides have been developed to help practitioners visually estimate canopy fuel characteristics at the local scale (e.g. Lavoie et al., 2010; Scott & Reinhardt, 2005), but few studies have estimated quantitative relationships between photograph-derived metrics and field-measured fuel attributes like CFL. Hyperspectral or multispectral remote sensing images collected at lower altitudes have been used successfully to characterize fuels at a fine scale (e.g. Shin et al., 2018), but these technologies require extensive planning for data collection and are not suitable for opportunistic situations. In recent years, HPs have been identified as a potential method for CFL estimation, and studies in select forest types have reported strong statistical relationships between HP-derived forest canopy metrics and CFL (e.g. Clark & Murphy, 2011; Keane et al., 2005; Steele-Feldman et al., 2006). Unfortunately, time-consuming HP protocols and the inability to process HPs acquired in non-diffuse light conditions have limited use of these methods in opportunistic field settings.

By integrating relaxed acquisition protocols suggested by Origo et al. (2017), smartphones equipped with inexpensive fisheye lens equipment and novel processing techniques from the R 'CAIMAN' package (Díaz, 2021), we found strongly significant statistical relationships between field-measured CFL and two common canopy metrics derived from HPs—CO and LAI. Compared with LAI, the model estimated with CO produced slightly better results; and given the

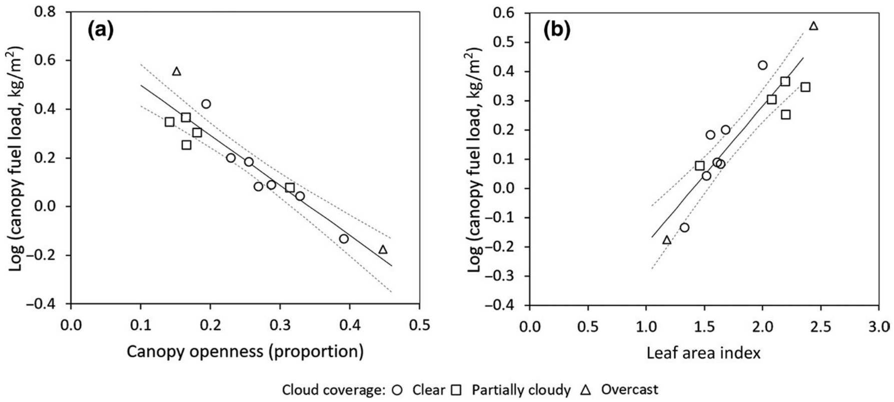

FIGURE 5 Relationship between log-transformed canopy fuel load (kg/m^2) measurements and canopy metrics computed from hemispherical photographs: (a) canopy openness (CO) expressed as a proportion and (b) leaf area index. Dashed lines denote 95% confidence intervals

intuitive meaning of this metric and ease with which it can be communicated, we recommend practitioners use CO for obtaining rapid estimates of CFL.

To acquire the HPs, no other equipment was required apart from the smartphone and Olloclip lens attachment; however, a portable power supply and waterproof carrying case is recommended for extended field campaigns. The high correlation between field-measured CFL and our HP-derived metrics indicate that the varying heights at which the HPs were collected had minimal effect on results; however, if the terrain offers a more even surface, the photographs should be taken at a constant height that reflects the targeted canopy layer.

Rapid estimation of CFL using statistical models estimated from HP metrics could have profound impacts on furthering our understanding of wildland fire behaviour. The systematic documentation of canopy fuel conditions at fire locations using smartphones with hemispherical lens attachments could be completed by fire suppression personnel when operational activities permit. These empirical data could eventually enable improved statistical models for predicting fire behaviour.

Although strong relationships were found between HP-derived canopy metrics and CFL, the models reported in this study are primarily intended to demonstrate a *proof of concept* for rapid fuel documentation in conifer forests with smartphones, which we hope will facilitate broader use and acceptance of these methods. The development of models for predicting CFL in other stand types and site conditions will require site-specific acquisition of HPs and CFL field measurements. In forests with broadleaf species present, images could potentially be acquired prior to leaf flush or following leaf-fall to estimate conifer canopy fuel load available for combustion.

The quality of our predictive models depends on the accuracy of the CFL data we computed from our field measurements. We estimated CFL with published biomass equations, which is customary but also a potential source of error. Uncertainty in CFL estimates can result from multiple steps during the measurement process including insufficient sampling, field measurement errors and errors in the allometric relationships applied, which can all propagate through subsequent statistical analysis (Nickless et al., 2011; Qin et al., 2020). The direct measurement of CFL by destructive sampling and development of biomass equations specific to the study area is an alternative approach that could potentially reduce error. While beyond the scope of the present study, more research is needed to thoroughly document and address sources of measurement error and uncertainty in boreal CFL data estimated from field inventory methods and the propagation of that error in statistical models.

The northern conifer stand types included in our analysis were well-suited for HPs acquired with an automatic camera exposure. In closed canopies and diffuse light conditions, camera exposure should be manipulated to ensure well-exposed photographs; in other lighting conditions, the appropriate protocol has yet to be determined, but automatic exposure is generally considered inadequate (Díaz, 2021). A limitation of our study is the small sample size (n = 14); however, the strong correlations we found suggest additional data were not necessary in our case, but could be required in other forest types.

5 | CONCLUSION

In this study, we developed a simple method to predict CFL using metrics computed from HPs. Strong relationships between CFL and HP metrics were confirmed in black spruce and larch forest ecosystems, despite HP acquisition in non-diffuse light conditions and use of protocols designed to help photographers work efficiently. Our *proof of concept* for rapid crown fuel measurement in conifer stands with smartphone devices suggests these methods can be deployed effectively for opportunistic HP acquisition in operational settings such as wildfire and fuel management sites. The development of statistical models for predicting CFL from HP metrics in dominant fuel complexes could eventually be used to supply much needed stand structural information for fire behaviour modelling; assess and monitor forest structure changes over time and in relation to management actions; and inform fuel treatment and prescribed burn planning.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

J.L.B. conceptualized the study and designed the HP acquisition protocol and HP field methods; H.A.C. and G.M.D. processed study data and designed and conducted analysis; H.A.C. led manuscript preparation. All authors contributed to analysis, manuscript writing, review and editing.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data and code have been deposited to the Open Science Framework Repository https://doi.org/10.17605/OSF.IO/XQRBU (Cameron et al., 2021).

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