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RESEARCH ARTICLE

Applying remote sensing for large-landscape problems: Inventorying and tracking habitat recovery for a broadly distributed Species At Risk

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Abstract

1. Anthropogenic habitat alteration is leading to the reduction of global biodiversity. Consequently, there is an imminent need to understand the state and trend of habitat alteration across broad areas. In North America, habitat alteration has been linked to the decline of threatened woodland caribou. As such, habitat protection and restoration are critical measures to support recovery of self-sustaining caribou populations. Broad estimates of habitat change through time have set the stage for understanding the status of caribou habitat. However, the lack of updated and detailed data on post-disturbance vegetation recovery is an impediment to recovery planning and monitoring restoration effectiveness. Advances in remote sensing tools to collect high-resolution data at large spatial scales are beginning to enable ecological studies in new ways to support ecosystem-based and species-based management.
2. We used semi-automated and manual methodologies to fuse photogrammetry point clouds (PPC) from high-resolution aerial imagery with wide-area light detection and ranging (LiDAR) data to quantify vegetation structure (height, density, class) on disturbances associated with caribou declines. We also compared vegetation heights estimated from the semi-automated PPC-LiDAR fusion to heights estimated in the field, using stereoscopic interpretation, and using multi-channel TiTAN LiDAR.
3. Vegetation regrowth was occurring on many of the disturbance types, though there was local variability in the type, height and density of vegetation. Heights estimated using PPC-LiDAR fusion were highly correlated ($r \geq 0.87$ in all cases) with heights estimated using stereomodels, TiTAN multi-channel LiDAR and field measurements.
4. We demonstrated that PPC-LiDAR fusion can be operationalized over large areas to collect comprehensive and consistent vegetation data across landscape levels, providing opportunities to link fine-resolution remote sensing to landscape-scale

ecological studies. Crucially, these data can be used to estimate rates of habitat recovery at resolutions that are not feasible using more commonly used satellite-based sensors, bridging the gap between resolution and extent. Such data are needed to achieve effective and efficient habitat monitoring to support caribou recovery efforts, as well as a myriad of additional forest management needs.

KEYWORDS
habitat assessment, light detection and ranging, photogrammetry, *Rangifer tarandus*, vegetation recovery

1 | INTRODUCTION

Habitat alteration, as a result of both human land-use and climate change, is disrupting ecosystem processes and leading to the decline of many species across the globe (Betts et al., 2022; Foley et al., 2005; Newbold et al., 2015). The link between habitat alteration and biodiversity declines necessitates assessments of the impacts of habitat change on ecological systems (Díaz et al., 2020; Hansen et al., 2013; Tscharntke et al., 2012). Given the need for habitat assessment is largely global, monitoring and managing problems at regional landscapes is critical (Tscharntke et al., 2012). Measuring and tracking habitat often comes with a trade-off between extent and resolution, and too often a disconnect exists between the information available and the information needed to appropriately understand the status and trend of habitat. The combination of remote sensing tools and ecological research is coming together in promising ways to support species- and ecosystem-based management over broad areas (Cavender-Bares et al., 2022; Queinnec et al., 2021). Large-scale habitat inventories will be necessary for future wildlife, habitat, and land-use management, understanding how global change influences ecological processes and how restoration ecology can address these changes.

Traditionally, habitat assessments have been conducted using field-based sampling to assess metrics of vegetation structure. While these fine-scale assessments are important for activities such as habitat restoration treatment monitoring (Filicetti et al., 2019; Fromm et al., 2019), they lead to inconsistent data collection across landscapes (Fromm et al., 2019; Luoma et al., 2017). At larger scales, forest inventories have traditionally been conducted using remote sensing tools such as aerial imagery and stereoscopic visualization, with recent advances such as the use of photogrammetry point clouds (PPC) supporting more detailed mapping of forest structure (Dietmaier et al., 2019; Jurado et al., 2022). Airborne and terrestrial laser scanning data, such as light detection and ranging (LiDAR), and imagery-based photogrammetry with horizontal and vertical accuracies of centimetres to meters across wide-areas provide the spatial continuity and resolution required for many applications (Hopkinson et al., 2016; Queinnec et al., 2021; Wulder et al., 2012). At larger scales still, satellite-based imagery or laser scanning data are becoming increasingly available at sufficient resolutions for some tasks (Jurado et al., 2022; Nasiri et al., 2022). With the increasing availability of high-resolution data across landscapes, and ability to combine multiple data types (Jurado et al., 2022; Nasiri et al., 2022; Zhang & Lin, 2017), comes improved integration of remote sensing with ecological studies.

The boreal forests of Canada are relatively intact compared to other nations (Coristine et al., 2019; Watson et al., 2016); yet, the cascading influence of anthropogenic habitat alteration has been linked to the decline of threatened woodland caribou (*Rangifer tarandus caribou*, hereafter termed 'caribou'). Caribou habitat overlaps areas with high value for forestry and energy resources (Hebblewhite, 2017). As such, caribou ranges across western Canada are facing accelerating habitat loss (Nagy-Reis et al., 2021). Anthropogenic habitat alteration in particular has changed the predator–prey dynamics and ecological processes in which caribou evolved. Vegetation regrowth in polygonal disturbances (e.g. forest harvest areas) provides competing ungulates with increased forage availability (Serrouya et al., 2011). The resulting increase in the density of competing ungulates, such as white-tailed deer *Odocoileus virginianus* and moose *Alces alces*, which have higher fecundity than caribou, augments predator numbers and leads to unsustainable predation on caribou (Serrouya et al., 2021; Wittmer et al., 2005). Furthermore, energy developments in the boreal forests create linear forest clearings such as pipelines, roads and seismic lines used to delineate and access oil and gas reserves underground (termed 'linear features'). These narrow linear features are associated with increased hunting efficiency of predators such as wolves *Canis lupus* (Dickie, Serrouya, McNay, et al., 2017; McKenzie et al., 2012), increased predator use of caribou habitat (DeMars & Boutin, 2017) and increased caribou predation (McKay et al., 2021).

Effective habitat management, including protection and restoration, requires up-to-date and accurate information about habitat status and post-disturbance vegetation recovery. Within the context of recovering threatened caribou populations, recent work has set the stage by estimating the net rate of change in forest cover by quantifying habitat loss and gain across western Canada's caribou ranges (Nagy-Reis et al., 2021). While these satellite-based metrics provide consistent and replicable tracking across large areas, the lack of updated and detailed vegetation data across the vast areas of the boreal forest has been highlighted as an impediment to recovery planning, especially because many disturbance types are poorly tracked using traditional remote sensing methods (Nagy-Reis et al., 2021). Localized studies have revealed thresholds between vegetation structure and reduced travel speed by both wolves and humans on linear features (Dickie, Serrouya, DeMars, et al., 2017; Finnegan, Pigeon, et al., 2018; Pigeon et al., 2016). Likewise, the replacement of mature trees with early-seral forage, particularly within polygonal features such as forest harvest areas, is linked to increased use and abundance of ungulates such as moose (Mumma et al., 2020), with an expected increase in wolf abundance and therefore decreased caribou persistence (Wittmer et al., 2007). Therefore, vegetation height and density by class (i.e. shrub versus coniferous or deciduous trees) are considered key metrics to track the functional recovery of caribou habitat. However, given the magnitude of anthropogenic habitat alteration within boreal caribou ranges (Nagy-Reis et al., 2021), tracking post-disturbance recovery at scale remains a daunting challenge.

Despite the growing evidence that optical and laser-scanning data can provide accurate estimations of vegetation structure (St-Onge et al., 2015; Wang et al., 2019), the use of high-resolution forest structure information has yet to be widely adopted in ecological studies. We demonstrate the use of high-resolution remote sensing across broad areas to collect up-to-date and accurate information on post-disturbance vegetation structure to support tracking habitat change for a threatened ungulate. We first fuse PPC from high-resolution aerial imagery with LiDAR data to quantify vegetation structure on polygonal and linear features associated with caribou declines. We interpret these vegetation metrics within the context of caribou habitat recovery. We then validated vegetation structure metrics derived from PPC-LiDAR fusion by comparing them to field-based measurements (i.e. the 'gold standard' for validation), manual stereoscopic visualization (i.e. a traditional technique for remotely sensed vegetation inventorying), and multi-channel TiTAN LiDAR measurements (Hopkinson et al., 2016; i.e. a state-of-the-art technique for high-resolution remotely sensed vegetation inventorying). Finally, we discuss data limitations and the next steps for the application of these methods to support local and regional vegetation assessments and habitat management.

2 | MATERIALS AND METHODS

We leveraged two data sets to measure post-disturbance vegetation recovery on polygonal and linear features linked to caribou declines. On most disturbance types, we fused a digital surface model (DSM) derived from high-resolution optical imagery PPC with a bare earth digital terrain model (DTM) derived from wide-area LiDAR in a semi-automatic process to quantify structure (height and density) of shrubs and trees. PPC provides estimates of tree-top locations, but visual obstruction of the ground creates difficulties with accurately estimating bare earth (and so, height). We therefore used previously collected wide-area LiDAR data to derive bare earth measurements. Wide-area LiDAR data with older vintages are often not collected at sufficient resolutions for estimating vegetation metrics, but do provide useful information on bare earth. The fusion of these two data sets allowed us to first estimate tree-top locations, and second subtract the difference between the two metrics (DSM-DTM), yielding estimates of vegetation height. Using this semi-automated process, we combined the tree-top locations with estimated heights to estimate the height and density of trees post-disturbance across large areas. We supplemented the semi-automated PPC-LiDAR process using stereoscopic interpretation of vegetation structure and class on narrower features, such as seismic lines, where adjacent canopy prohibited the automated PPC-LiDAR process. We first describe the methodological details developed to estimate vegetation structure using PPC-LiDAR fusion (Developing and applying PPC-LiDAR fusion), then describe the methodology used to validate our PPC-LiDAR height measurements (Testing accuracy of vegetation height estimates).

2.1 | Developing and applying PPC-LiDAR fusion

2.1.1 | Study area

We assessed post-disturbance vegetation recovery at approximately 20 townships (~94 km^2 per township; total of 1883 km^2) distributed across four areas in northwestern Alberta, Canada (Figure 1) in two caribou ranges. The Chinchaga (17,643.64 km^2) and Caribou Mountains (20,658.73 km^2) caribou ranges are located in the boreal forest of northwestern Alberta. The area is characterized by a mosaic of upland forests dominated by white spruce *Picea glauca*, trembling aspen *Populus tremuloides*, and balsam poplar *Populus balsamifera*, mixed with poorly drained lowlands. The Caribou Mountains caribou range overlaps a low plateau left unglaciated during the last ice age, leaving behind unique remnant communities of lichens, vascular plants and mosses not found in the surrounding areas.

Approximately 19% of the boreal forests of Alberta are directly impacted by human footprint (Alberta Biodiversity Monitoring Institute, 2018a). The majority of this human footprint is from the agriculture (11.5%), forestry (3.8%) and energy (1.8%) sectors. Approximately 74% of the Chinchaga range and 23% of the Caribou Mountains range is influenced by anthropogenic habitat alteration (defined as habitat alteration buffered by 500 m; Environment Canada, 2012; Environment and Climate Change Canada, 2017). Additionally, fire impacts approximate 8% of the Chinchaga range and 44% of the Caribou Mountains range.

2.1.2 | Data collection

We produced a DSM using PPC data derived from optical imagery. Imagery was acquired using a Piper PA31 Navajo aircraft during the leaf-on season of 2020 (September 8, 10 and 22) across three areas in Chinchaga (C1: 380.03 km^2, C2: 379.93 km^2, C3: 383.79 km^2) and two areas in Caribou Mountains that were then combined (CM: 739.43 km^2). Imagery was flown at an average altitude of 3550 m above terrain. The areas were selected based on overlap with caribou range, presence of energy footprint and accessibility for field measurements. We used a high-end, large-frame Leica Digital