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Climate change mitigation through woodland caribou (*Rangifer tarandus)* habitat restoration in British Columbia

James C Maltman[1,*], **Nicholas C Coops**[1], **Gregory J M Rickbeil**[2], **Txomin Hermosilla**[3] **and A Cole Burton**[1]

[1] Department of Forest Resources Management. Faculty of Forestry, University of British Columbia, Vancouver, BC, Canada
[2] Ecofish Research, Suite 303–2012 Washington Street, Rossland, BC V0G 1Y0, Canada
[3] Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada
[*] Author to whom any correspondence should be addressed.

E-mail: jmaltman@student.ubc.ca

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Abstract

Climate change poses a significant global threat, requiring rapid and effective mitigation strategies to limit future warming. Tree planting is a commonly proposed and readily implementable natural climate solution. It is also a vital component of habitat restoration for the threatened woodland caribou (*Rangifer tarandus)*. There is potential for the goals of caribou conservation and carbon sequestration to be combined for co-benefits. We examine this opportunity by estimating the carbon sequestration impacts of tree planting in woodland caribou range in British Columbia (BC), Canada. To do so, we couple Landsat-derived datasets with Physiological Processes Predicting Growth, a process-based model of forest growth. We compare the sequestration impacts of planting informed by woodland caribou habitat needs to planting for maximum carbon sequestration under multiple future climate scenarios including shared socio-economic pathways (SSP) 2, representing ∼2.7 °C warming, and SSP5, representing ∼4.4 °C warming. Trees were modelled as planted in 2025. Province-wide by 2100, planting for maximum-carbon sequestration averaged 1062 Mg $CO_2 \cdot ha^{-1}$ planted, while planting for caribou habitat resulted in an average of 930 Mg $CO_2 \cdot ha^{-1}$ planted, a reduction of 12%. We found that relative sequestration between herds remained similar across warming scenarios and that, for most ecotypes, sequestration increased from 5% to 7% between the coldest (∼2.7 °C warming) and warmest (∼4.4 °C warming) scenario. Variability in the relative sequestration impacts of planting strategies was observed between herds, highlighting the importance of spatially-explicit, herd-level analysis of future forest growth when planning restoration activities. Our findings indicate a large potential for co-benefits between carbon sequestration and woodland caribou habitat restoration across BC in all warming scenarios modelled. They also underscore the value of process-based forest growth models in evaluating the carbon implications of tree planting and habitat restoration across large areas under a changing climate.

1. Introduction

Climate change is an issue of global concern, particularly in northern countries like Canada, which is experiencing warming at twice the global average (Bush and Lemmen 2019). To keep future warming below 2 °C, mitigation efforts must rapidly accelerate (IPCC 2023). As part of global efforts towards mitigation, natural climate solutions which are based upon natural ecosystems (Osaka *et al* 2021), are frequently discussed (Drever *et al* 2021, Seddon 2022). As they are based on natural processes, natural climate solutions are readily implementable, and can offer a number of co-benefits (Griscom *et al* 2017, Ellis *et al* 2024). Due to their potential for immediate execution they are a core pillar of Canada's climate strategy, with the government committing over $5 billion by 2031 towards implementing them (Environment and Climate Change Canada 2024)

One commonly discussed form of natural climate solution is tree planting, either through afforestation (the planting of trees in areas not formerly forested), or reforestation (restoring formerly forested ecosystems back to a forested state) (Brancalion and Holl 2020). In addition to having large carbon sequestration potential, tree planting programs can create other co-benefits, such as restoring habitat for species at risk (Fargione *et al* 2018), or providing ecosystem services, including recreation and food supply (Mazziotta *et al* 2022). While planting programs undertaken in ecologically unsuitable areas (Kristensen *et al* 2024), or with ecologically unsuitable species (Rana and Varshney 2023) are often ineffective, if local trees are planted in appropriate locations, significant sequestration benefits can occur.

One opportunity for such co-benefits is habitat restoration for the threatened woodland caribou (*Rangifer tarandus)* (Mansuy *et al* 2020, Palm *et al* 2020). Woodland caribou are an ecologically and culturally important species (Festa-Bianchet *et al* 2011), with populations declining across British Columbia (BC), and Canada (Environment Canada 2014, Environment and Climate Change Canada 2020, BC Caribou Recovery Program 2021). While there are many causal factors related to this decline, habitat loss and habitat disturbance are widely accepted as major drivers (Wittmer *et al* 2007, Apps *et al* 2013, Johnson *et al* 2020, Palm *et al* 2020, Dickie *et al* 2021, Serrouya *et al* 2021). Woodland caribou require large, undisturbed areas of old forest to thrive, and the conversion of old conifer forests to early seral, and deciduous dominated stands can have notable negative effects on this species (Environment Canada 2014, Environment and Climate Change Canada 2020, Serrouya *et al* 2021). Other than the direct impact of habitat loss (e.g. loss of forage and thermal cover), disturbance negatively affects woodland caribou through two indirect mechanisms influencing predation: a numerical response increasing predator numbers through disturbance-mediated apparent competition, and a functional response increasing predator efficiency through movement along linear disturbance such as roads and seismic lines (Wittmer *et al* 2007, Festa-Bianchet *et al* 2011, Dickie *et al* 2017, DeMars and Boutin 2018). Disturbance-mediated apparent competition occurs when old forests are converted to early-seral ecosystems, increasing moose and deer populations, which in turn raise wolf populations and predation on caribou (Environment and Climate Change Canada 2020).

Habitat restoration of polygonal (e.g. fire, forest harvesting), and linear (e.g. roads, seismic lines) disturbances, is a key pillar of proposed woodland caribou recovery strategies (Bentham and Coupal 2015, Dickie *et al* 2021, 2023c), which to date has seen limited implementation or efficacy (Tattersall *et al* 2020, Beirne *et al* 2021). Since woodland caribou require large areas of undisturbed old forest to thrive, tree planting efforts can contribute to effective habitat restoration over time by blocking predator movement and accelerating the recovery of disturbed areas from an early-seral state, ultimately increasing overall forested area (Environment Canada 2014, Bentham and Coupal 2015, Dickie *et al* 2023c).

Previous research has evaluated the carbon sequestration potential of tree-planting efforts in Canada, as well as globally, indicating generally positive benefits especially over longer time-horizons (Griscom *et al* 2017, Drever *et al* 2021, du Toit *et al* 2024). There has however been limited research assessing the potential carbon sequestration impacts of highly targeted tree planting in potential habitat restoration sites for threatened species, such as within woodland caribou range. Given the urgency of addressing both challenges and the finite availability of funding and resources, there is a strong need to locate and evaluate synergies between conservation objectives wherever possible (Molina *et al* 2024). With the advent of free and open-access to the Landsat satellite data archive, advances have been made in satellite-based characterization of forested ecosystems, including wall-to-wall mapping of land cover and tree species identification across Canada. These developments can be coupled with process-based models of forest growth to aid in the characterization and identification of opportunities for co-benefits between carbon sequestration and habitat restoration (Hermosilla *et al* 2018, 2022a, Wulder *et al* 2024).

We combine a well-established and parameterized process-based forest growth model with Landsat-derived datasets to evaluate the potential for co-benefits between carbon sequestration and habitat restoration. This approach generates spatially explicit estimates of the potential future carbon sequestration impacts of tree planting efforts in woodland caribou range in BC at 90 m spatial resolution, assuming no subsequent forest harvest. We compare three differing planting strategies: (A) planting which increases high-quality caribou habitat area, (B) planting which maximizes carbon sequestration within each herd range, and (C) planting which restores linear disturbances. Differences in the sequestration impacts of each strategy, in terms of tree biomass, are evaluated by caribou ecotype to determine locations with the highest potential for co-benefits from tree planting, and to identify which caribou ecotype ranges show the greatest potential for sequestration. While in practice, land managers would likely implement a combination of all three of these scenarios, they are highlighted separately in this work in order to individually evaluate the differing impacts on carbon sequestration they may have. Growth is modelled across three future warming scenarios to assess the potential impacts of uncertainty in future levels of climate change. Trees are assumed to be planted in 2025, and growth modelled at two key dates, 2050 and 2100, to evaluate the impacts of both shorter- and longer-term goals (Canada 2020, Johnson and Rea 2024). Results are then compared at a herd as well as ecotype level to identify co-benefit opportunities.

2. Study area

Bounded by the Pacific Ocean on the west, and the Rocky Mountains on the east, BC's environment and ecology are highly varied. From the wet, productive forests of the mountainous coast, to the relatively dry environments in the central interior plateau, BC encompasses a wide range of climatic and environmental conditions (Demarchi 2011).

Woodland caribou habitat spans multiple environments, including mature low-elevation forests, peatlands, subalpine forests, muskegs, and alpine ridges (Environment Canada 2014, Environment and Climate Change Canada 2020). Woodland caribou in BC are classified into 55 separate herds (figure 1), and three ecotypes: Boreal, Northern Mountain, and Southern Mountain, with the Southern Mountain ecotype further divided into the Northern, Central, and Southern groups (BC Caribou Recovery Program 2022).

Woodland caribou habitat in BC is affected by large amounts of forest disturbance (events which alter the structure and composition of an ecosystem, such as fire or forest harvesting), with 16% of forested area in woodland caribou range in BC disturbed between 1985 and 2019 (Environment Canada 2014, Nagy-Reis *et al* 2021, Maltman *et al* 2024). Linear disturbances such as roads and seismic lines affect herds province-wide, with seismic lines from oil and gas exploration typically concentrated in the oil-bearing north and east of the province. Further south, linear disturbances are mainly caused by other activities such as road construction for forestry (Nagy-Reis *et al* 2021). Polygonal disturbances affect all herds, with fire being the dominant stand-replacing disturbance affecting Boreal, Northern Mountain, and Southern Mountain Northern group caribou, and harvesting being the primary disturbance driver for Southern Mountain Central, and Southern Mountain Southern group caribou (Maltman *et al* 2024).

3. Data and methods

3.1. Overview

We utilized a well-established and parametrised forest growth model (Physiological Processes Predicting Growth (3PG)) (Landsberg and Waring 1997, Nole *et al* 2009, Headlee *et al* 2013, Amichev *et al* 2016, Gupta and Sharma 2019, Trotsiuk *et al* 2020, Forrester *et al* 2021) to model carbon accumulation across all area defined as plantable within caribou range in BC. Growth is modelled based on a combination of tree-species and site-specific parameters including fertility, available soil water (ASW), and climate data. Multiple climate scenarios are considered to account for uncertainty in future warming, incorporating a climate model which takes into account the fine scale impacts of elevation on climate. Potential carbon sequestration is then compared across three separate areas of opportunity for planting (AO) to evaluate the impacts of differing priorities when planting, assuming no logging is undertaken in planted areas.

Forest carbon accumulation was modelled at 90 m spatial resolution for all AOs for all woodland caribou herd ranges in BC. To ensure ecological suitability the most common tree species found within each herd range was selected as the tree planted, and held constant across all three AOs (Brancalion and Holl 2020, Rana and Varshney 2023). 2025 was chosen as the planting year, and for comparability, all trees were assumed to be planted on the same date. Initial planting density was set at 2000 stems/ha. Total biomass accumulation per hectare for each pixel was modelled at two time-steps: 2050, and 2100; 2050 was chosen for comparison with Canada's commitment to net-zero emissions by 2050 (Environment and Climate Change Canada 2021), and 2100 was used to evaluate the longer term impacts of planting. The carbon content of tree biomass was converted to CO_2 accumulation by dividing tree biomass by two to acquire carbon content, and then multiplied by 3.67 (stoichiometric ratio of C in CO_2) to acquire CO_2 accumulation (Kurz 1992, Kauppi *et al* 1995, Kurz *et al* 2009).

3PG, developed by Landsberg and Waring (1997) is a physiologically-based process model, which has been widely used to characterize forest growth (Gupta and Sharma 2019) over large areas to generate spatial predictions of forest growth (Coops *et al* 1998, Coops and Waring 2011, Trotsiuk *et al* 2020). The model deterministically calculates rates of photosynthesis, growth allocation, litter production, self-thinning and transpiration on a monthly time step and on a per-hectare basis (Coops and Hember 2009) and it is applicable across a wide range of tree species (Landsberg *et al* 2003). Self-thinning is modelled using the $-3/2$ self-thinning rule to determine the maximum potential mass of a single stem given total stem population (Sands and Landsberg 2002). Model inputs include climatic data for the site, soil characteristics for the site,

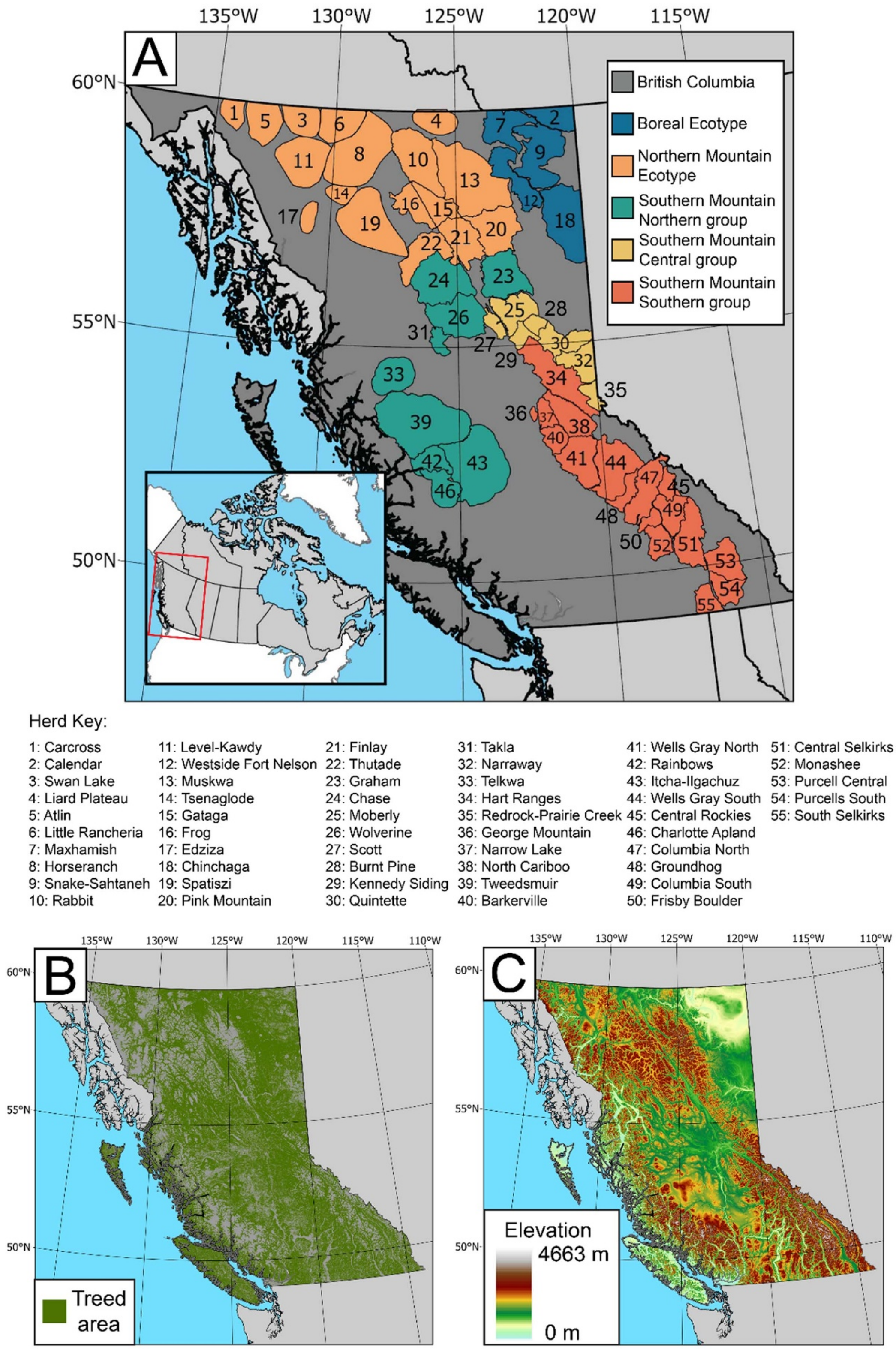

Figure 1. Map of British Columbia displaying (A): Woodland caribou herds by ecotype, (B): Treed area in 2019, (C): Elevation.

including fertility, and maximum-ASW, and a species-specific set of parameters (Coops *et al* 1998). Carbon accumulation is partitioned between three pools in the model: foliage, stem, and root biomass. As the model is a physiological model of tree growth, only biomass accumulated by modelled trees is considered.

By incorporating a climate model which takes into account the fine scale impacts of elevation on climatic variables such as temperature, precipitation, and growing season, with multiple future warming scenarios, and a physiological rather than empirical model of tree growth, this modelling approach allows for the consideration of potential increases in productivity in northern areas and upward shifts in treeline due to climate change (Davis *et al* 2020).

3.2. Data

3.2.1. Herd boundaries

Herd locations in BC were delineated using herd boundaries from the BC Caribou Recovery Program (2022). The product designates boundaries based on the area required for a herd to be self-sustaining, using best-available science and expert knowledge. The layer defines 55 herds in BC, including five currently extirpated herds. While some herd ranges extend outside of BC, they are truncated at the border to fit within BC's geographic constraints.

3.2.2. Climate data

To account for the variability of future climate, three future warming scenarios were evaluated in this study; shared socio-economic pathways (SSP) 2,3, and 5 (Riahi *et al* 2017). Each SSP represents a distinct scenario of which future socioeconomic developments might take, and their subsequent impacts on climate change. SSP2 represents a 'middle of the road' scenario, and a likely increase of global temperatures of 2.7 °C, SSP3 represents a scenario of 'regional rivalry', and consequent likely warming of 3.6 °C, while SSP5 represents a scenario of 'fossil-fuelled development' and likely warming of 4.4 °C (Riahi *et al* 2017, IPCC 2023).

Historical climate data for the three future warming scenarios were derived from the ClimateBC application (Wang *et al* 2016). The application downscales 800 m scale PRISM data for historical climate values, and 1° Global Circulation Model data for future climate scenarios to scale-free point estimates, using elevation data to adjust relevant climate values due to altitude (Wang *et al* 2016). This methodology allows for the incorporation of the impacts of complex topography on climate variables at a relatively fine spatial resolution. Elevation values were derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer global digital elevation model (NASA *et al* 2019). Climate variables utilized included monthly minimum and maximum temperature, precipitation, and number of frost-free days. Monthly estimates of mean daily total downward incoming short-wave radiation ($MJ \cdot m^{-2} \cdot d^{-1}$) were used, averaged from 1971–2000 from Hember *et al* (2017), available at 1 km spatial resolution.

3.2.3. Other model inputs

Soil fertility data were derived from a 1 km spatial resolution fertility layer for forested areas in the Pacific Northwest generated by Coops *et al* (2012). The fertility parameter in 3PG is a unitless variable between 0 and 1, indicating relative soil fertility. The layer was derived by comparing observed leaf area index with 3PG modelled forest growth to infer soil characteristics. Data gaps in the layer, including all non-forested areas were infilled first by applying a single pass of a 5 × 5-pixel focal mean filter. Remaining no-data pixels were assigned the mean fertility value for the corresponding herd range. Infilling accounted for 41% of all pixels.

Maximum ASW (ASW_{Max}) was estimated for every pixel using the ASW-TOP algorithm, based on topographic wetness index (TWI) and case-specific coefficients determined by previously-obtained local reference values (Zheng *et al* 1996). Reference values for use in the algorithm were derived from a 1 km spatial resolution ASW_{Max} layer for forested areas across BC from Coops *et al* (2012), TWI was calculated based on the DEM utilized for elevation data (NASA *et al* 2019).

For model parameterization and accuracy assessment, estimated tree height derived from the 3PG model was compared to pre-existing measures of tree productivity derived from the BC site productivity layer (BC Government 2021a). The site productivity layer is a 100 m spatial resolution data product which indicates the expected height of a given tree species at 50 years of age across its range in BC. It is based on existing provincial predictive ecosystem mapping and terrestrial ecosystem mapping data where available, and estimates site index based on biophysical data and species ranges in areas of data gaps (BC Government 2021a).

3.2.4. Landsat-derived data

Landsat-derived data products were utilized for delineation of areas of opportunity for planting (AO), as well as for selection of planted species, and included land cover and disturbance history covering a period from 1985–2019, and dominant species for the year 2019. Forest disturbance was identified from disturbance layers generated via the Composite2Change (C2C) approach from (Hermosilla *et al* 2016). C2C generates 30 m spatial resolution, annual, best-available-pixel (BAP) image composites (White *et al* 2014). Image composites are further refined through the temporal analysis of the Normalized Burn Ratio values (Hermosilla *et al* 2015a). Disturbances are identified using a breakpoint detection algorithm and disturbance agent is then attributed to the change event using a random forests classification model (Hermosilla *et al* 2015b). Disturbance agents identified in the dataset are fire, forest harvesting, and non-stand replacing disturbance, with fire and forest harvesting being considered in this paper. Reported accuracy of the data product is 90% for spatial identification of disturbance, 89% of detected changes were assigned the correct occurrence year and 98% were identified within ±1 year (Hermosilla *et al* 2016).

Land cover was determined using the annual Canada-wide land cover layers from Hermosilla *et al* (2022b), derived using the virtual land cover engine (VLCE) methodological framework. VLCE takes advantage of the long time series of data available in the Landsat record, and annual BAP surface reflectance image composites, to derive annual, change-informed maps of land cover across Canada's forested ecosystems from 1984–2019 (2018, Hermosilla *et al* 2022b). These 30 m spatial resolution data products are comprised of 12 land cover classes including coniferous, broadleaf, exposed/barren land, shrubs, herbs, and bryoids. The overall accuracy of the land cover product was found to be 77.9% ± 1.4% (95%-confidence interval) (Hermosilla *et al* 2022b).

Forested area was identified using the forest mask for the year 2019 from Wulder *et al* (2020). While treed area refers to areas currently covered by trees (land cover class of deciduous, coniferous, mixedwood, or wetland-treed), forested area refers to an area that has a land use of forest, including areas both currently covered by trees, as well as formerly treed areas expected to recover to a treed land cover class after a disturbance. To determine forested area, spatial and temporal rules were applied to annual disturbance and land-cover layers to meet the UN Food and Agriculture Organization (FAO) definition of forest (FAO 2020). Following this definition, all areas which had a treed land cover class (deciduous, coniferous, mixedwood, or wetland-treed) were considered forest. Additionally, all areas that were not currently treed, but were treed for a number of years before a stand-replacing disturbance were considered forest, as they were expected to recover to a treed condition. This distinction recognizes the difference between land use (long-term status of an area), and land cover (characterization of what is currently on the landscape). Agricultural areas as indicated by the Agriculture and Agri Food Canada masks were excluded from the analysis.

Dominant tree species within each herd range were derived from the leading tree species map for the year 2019 from Hermosilla *et al* (2022a). This layer identifies 37 tree species at 30 m spatial resolution over the forested ecosystems of Canada. It was generated using the Landsat BAP image composite for the year 2019, along with other supplementary climatic, phenologic, topographic and geographic data. Regional random forests models were then applied to predict the dominant tree species within each pixel (Hermosilla *et al* 2022a). Accuracy assessment conducted using independent validation data indicated an overall accuracy of 93.1% ± 0.1% (95%-confidence interval).

3.2.5. Biogeoclimatic ecosystem classification (BEC) zones

BC BEC zones were used as part of the delineation of AOs. BEC zones classify BC's ecosystems into zones and subzones based on a number of variables including topography, vegetation, and soils, with these zones mapped across BC (BC Government 2021a).

3.2.6. Linear disturbance datasets

We identified the location of linear disturbances from the BC cumulative effects human disturbance and integrated roads datasets (BC Government 2021b, 2021c). The datasets are consolidations of publicly accessible roads and human disturbance data, and while not exhaustive or complete, give a general indication on levels of disturbance within large areas. Data from the human disturbance dataset is represented by polygons denoting disturbed area, while data from the roads dataset is represented by lines denoting road course.

3.3. Methods

3.3.1. Area of opportunity delineation

Three planting AOs were considered to compare the potential impacts of differing planting priorities. The first, linear AO, is comprised of linear forest disturbances within each herd range, and represents the potential carbon impacts of restoration and tree planting on these disturbances. The second, caribou-focused AO, constrains non-linear plantable areas by a set of requirements based on woodland caribou habitat needs, and represents the potential sequestration impacts of planting to increase the area of high-quality woodland caribou habitat. The third, maximum-carbon AO, covers the same total area as the woodland caribou AO, consists of the most productive non-linear plantable areas within each herd range, and represents an upper bound of the maximum sequestration possible from tree planting within each herd range. AOs do not represent recommendations that the entire area should be planted, rather they highlight areas which could be planted under specific requirements. Carbon sequestration is therefore reported in megagrams of CO_2 sequestered per hectare planted within each herd range, rather than total CO_2 sequestration.

Similarly, AOs do not represent the assumption that the area will be a productive forest. They are necessarily broad, to account for potential future shifts in productive area due to climate change, or areas which may support productive tree growth but are not currently forested for a variety of reasons (Coops and Waring 2011, Fradette *et al* 2021). As 3PG is a process-based model which bases its growth estimates on fine scale climatic and soil variables, if climatic conditions such as a short growing season or low precipitation do not allow for productive tree growth, the model would indicate low to no growth, and thus that the area is not a good choice to plant.

The linear-feature focused AO was determined from maps of roads and oil and gas exploration. All linear disturbances labelled as 'Oil and Gas Geophysical' in the human disturbance dataset, representing seismic lines, and all unpaved roads classified as resource roads, skid tracks, or unclassified were considered for planting. Due to the poor reliability of information regarding resource road use status in BC, all roads meeting this definition were considered to be plantable (BC Government 2021b). As seismic lines from oil and gas exploration are often abandoned after the initial survey, all oil and gas exploration disturbances were also considered plantable (Bayatvarkeshi *et al* 2024). Seismic line area represents the area of cleared vegetation for seismic surveys. In order to obtain an approximate area of roads, lines representing road courses were buffered by 8 m, representing a wide singletrack forest road, to derive plantable area (BC Ministry of Forests 2002). Road beds were assumed to have received necessary mechanical treatments for planting to address soil compaction issues as a part of the tree planting activities (Lacerte *et al* 2021, St-Pierre *et al* 2021). While road beds can be much less productive than surrounding areas if untreated, with appropriate restoration and soil decompaction, productive tree growth can occur (Lacerte *et al* 2021). To ensure tree planting was appropriate restoration for the identified disturbances, linear disturbances had to be adjacent to or located on a pixel classified as treed in the land cover dataset for the year 2019.

Non-linear plantable areas were areas that met one of two conditions based on either land cover and land use, or disturbance history. Areas considered plantable based on land cover/land use were areas classified as exposed/barren land or shrubs in the land cover product for the year 2019 (Hermosilla *et al* 2018). No other land cover types were considered plantable based on this rule. Areas classed as herbs (including grasslands) bryoids, and all wetlands (including shrubby wetlands) were notably not considered as plantable areas under this rule as these areas hold significant carbon stores, and that in many cases, afforestation of these areas may result in a net carbon source rather than sink (Wulder *et al* 2008, Veldman *et al* 2015, Friggens *et al* 2020). To recognize the distinction between land cover and land use, areas which met the land cover requirement, but were considered forested in the forest mask- indicating they were forested areas which had recently been disturbed- were not considered plantable, as they are expected to regrow naturally to a treed state.

In addition to areas considered plantable based on land cover/land use, to account for disturbed forests where recovery could benefit from planting, areas were also considered plantable based on disturbance history. All areas classified as forested in the forest mask but affected by natural disturbances (e.g. fire) that had not recovered to a treed land cover class (conifer, deciduous, mixedwood, wetland-treed) within twenty years were also considered plantable, regardless of land cover in the year 2019 (Bartels *et al* 2016, White *et al* 2017). Twenty years was chosen as a conservative threshold for areas where planting may be beneficial to aid recovery, being roughly double the amount of time it takes on average for forests in this region to recover to a forested state both structurally (Bartels *et al* 2016), as well as spectrally (White *et al* 2017). From this plantable area, the caribou-focused and maximum-carbon AOs were derived. Additional information on these rules is available in supplementary material figure 1.

The caribou-focused AO selects areas that have the potential to expand existing treed areas, rather than creating isolated patches of new forests from the overall plantable area, as a proxy for high quality caribou habitat. To this end, the woodland caribou AO was defined using the following criteria. Plantable area was subset to pixels which were (i) within 5 km of a contiguous treed area over 5,000 ha, to ensure compactness of planting areas, and (ii) not located in a BEC zone classified as alpine, recognizing that non-forested alpine areas are important seasonal habitats for many woodland caribou populations in BC (Environment Canada 2014, Environment and Climate Change Canada 2020). To minimize edge effects, which increase predation risk, (iii): only pixels which were arranged in a spatially contiguous patch of plantable pixels which were greater than 5 ha were included in the AO (Dabros *et al* 2022). Additionally, to ensure that planting made a contribution towards increasing the size of forested patches to one large enough to be beneficial to woodland caribou (iv) these patches had to be adjacent to treed areas greater than 5,000 ha (Lesmerises *et al* 2013).

The maximum-carbon AO for each herd selected areas of maximum productivity within each herd range, to represent a planting strategy targeted towards locally maximal carbon sequestration. The purpose of this AO is to inform on the maximum productivity within each herd range, to compare productivity between herds, and to compare the potential productivity of caribou-focused planting strategies to local maxima. To derive this AO, the most productive pixels in each herd range were selected, until an area equal to the size of the caribou AO was obtained.

3.3.2. Tree species parameterization and agreement assessment

The dominant tree species in each herd range was selected, resulting in a total of five species: Subalpine fir (*Abies lasiocarpa*), Lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), Black spruce (*Picea mariana*), and Western hemlock (*Tsuga heterophylla*). Where available, 3PG parameters for each species were selected from existing literature. When no 3PG parameter was found for a given species, we utilized parameters for the most similar species of the same genus, modified to be more representative of the species. Parameter files, sources, and modifications made are available in supplementary materials table 1. Tree species chosen per herd are available in supplementary materials table 2. To ensure effective model parameterization, modelled growth rates were compared with provincial site productivity information for each species. To do so we used historical climate data from ClimateBC, and each species was modelled in 3PG to an age of 50 years, from 1970–2019 across the range indicated by the site productivity layer in BC. Predicted diameter at breast height (DBH) was converted to height using existing DBH-height allometric equations from the literature. Equations for Subalpine fir, Lodgepole pine, Engelmann spruce, and Western hemlock were sourced from Zhang *et al* (1997), while the DBH-height equation for black spruce was sourced from Peng *et al* (2004). Mean height across the species range was evaluated, as well as pixel-level root-mean squared deviation (RMSD).

4. Results

4.1. Agreement assessment and validation

We found high agreement between 3PG estimated height growth at 50 years and the provincial site productivity layer used for validation for all five tree species. The largest differences were found for subalpine fir, with a root mean square deviation (RMSD) of 3.7 m (table 1). Mean estimated site index height for this species was 14.7 m, while reported site index height was 16.4 m. The smallest disagreement was found for black spruce, with a RMSD of 2.5 m. For Subalpine fir, Lodgepole pine, Engelmann spruce, and Western hemlock mean 3PG-estimated site index height was lower than the reported site index height.

4.2. Modelling results

4.2.1. Province-wide results

Province wide, under the moderate SSP2 scenario and long time-horizon of 2100, planting in the maximum-carbon AO sequestered an average of 1062 Mg $CO_2 \cdot ha^{-1}$ planted, planting in the caribou-focused AO sequestered an average of 930 Mg $CO_2 \cdot ha^{-1}$, and planting in the linear AO disturbances sequestered an average of 734 Mg $CO_2 \cdot ha^{-1}$. This sequestration increased to 1138 Mg $CO_2 \cdot ha^{-1}$, 991 Mg $CO_2 \cdot ha^{-1}$ and 753 Mg $CO_2 \cdot ha^{-1}$ respectively in SSP5. Across all timeframes and SSPs, planting in the maximum-carbon AO sequestered the most carbon per hectare planted, followed by the caribou-focused AO (12%–14% less carbon than the carbon-focused AO), with the linear disturbance AO having the lowest sequestration potential per hectare planted (30%–33% less carbon than the carbon-focused AO).

4.2.2. Warming impacts

Median sequestration per hectare planted increased slightly from SSP2 to SSP5 for all ecotypes of caribou other than Boreal (figure 2). Mean sequestration in 2100 for the maximum-carbon AO increased by between 5% and 7% for all ecotypes except for the Boreal, where it decreased by 0.5% between SSP2 and SSP5. Similarly, sequestration increased between SSP2 and SSP5 in 51 out of 55 herds, with the only herds showing a decrease being those where black spruce was the planted species. Variation between ecotypes and herds remained similar in each warming scenario. For the remainder of the results section, sequestration values will be only reported for SSP2, with herd-level values for all three SSPs, as well as plantable area per herd available in supplementary materials tables 3,4,5,6.

4.2.3. Sequestration by ecotype

Sequestration potential was highest within Southern Mountain caribou range across all AOs and timeframes. All three groups of Southern Mountain caribou had similar levels of potential sequestration in 2050, ranging from 419.6 Mg $CO_2 \cdot ha^{-1}$ for the Northern group, to 456.8 Mg $CO_2 \cdot ha^{-1}$ for the Central group in the maximum-carbon AO. By 2100, differences between the groups increased, with the Northern group sequestering 1002.6 Mg $CO_2 \cdot ha^{-1}$, and the Central and Southern groups respectively sequestering 1261.0, and 1266.4 Mg $CO_2 \cdot ha^{-1}$ in the maximum-carbon AO (table 2, figure 3).

Northern ecotype caribou showed slightly lower sequestration potential relative to Southern Mountain ecotype caribou. In 2100, in the maximum-carbon AO, Northern ecotype caribou had a sequestration

Table 1. Mean 3PG estimated site index height compared to mean reported site index height in meters for all 5 modelled tree species, as well as associated differences.

Species	Number of herds	Mean height 3PG (m)	Mean height site index (m)	RMSD (m)
Subalpine fir	27	14.7	16.4	3.7
Lodgepole pine	13	16.7	18.4	3.5
Engelmann spruce	7	13.1	14.8	2.7
Black spruce	7	12.9	10.5	2.5
Western hemlock	1	21.4	22.2	2.8

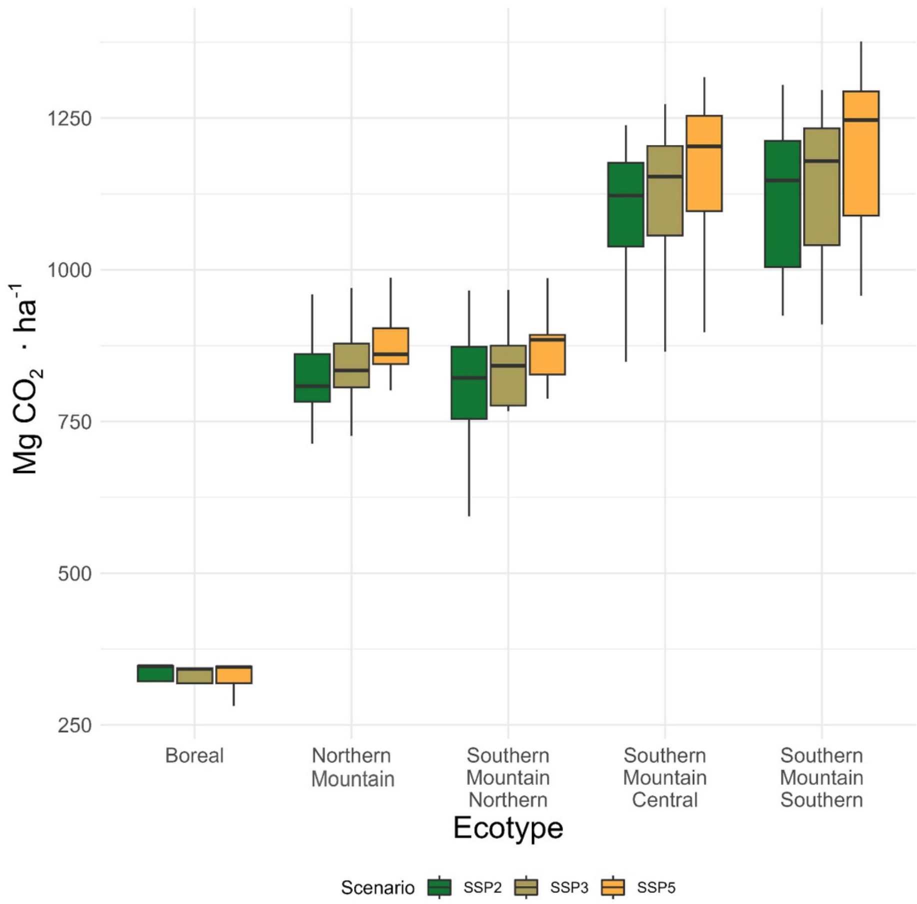

Figure 2. Carbon sequestration impacts of planting in the caribou-focused area of opportunity in 2100 for all herds, across ecotypes and warming scenarios.

potential of 932.0 Mg $CO_2 \cdot ha^{-1}$ planted, compared to the 1002.6 Mg $CO_2 \cdot ha^{-1}$ planted for Southern Mountain Northern group caribou.

Boreal ecotype caribou showed the lowest sequestration potential of all ecotypes across all planting strategies and eras. In 2100, for the maximum-carbon AO, they had a sequestration potential of 368.1 Mg $CO_2 \cdot ha^{-1}$ planted, over 3 times lower than the same values for the Southern Mountain Central and Southern Mountain Southern groups.

Potential sequestration between all caribou ecotypes other than Boreal was similar in 2050, and differentiated more by 2100 (figure 4). In 2050, for the maximum-carbon AO, the difference in potential sequestration between Northern ecotype caribou (lowest potential sequestration other than Boreal) and the Southern Mountain Central group (highest potential sequestration) was only 69.7 Mg $CO_2 \cdot ha^{-1}$. However, by 2100, the difference between the ecotype with the lowest potential sequestration, and the highest potential sequestration (Northern ecotype and Southern Mountain Southern group, respectively), rose to 334.3 Mg $CO_2 \cdot ha^{-1}$ planted. This pattern is also apparent on a herd level, with many herds across the province showing similar levels of potential sequestration in 2050, but a much wider gap in sequestration levels by 2100 (figure 4).

Table 2. Total carbon sequestration in Mg $CO_2 \cdot ha^{-1}$ planted for Linear, Caribou, and Carbon focused planting strategies in 2050, and 2100, in SSP2.

	Size (ha)			Total capture 2050 Mg $CO_2 \cdot ha^{-1}$			Total capture 2100 Mg $CO_2 \cdot ha^{-1}$		
Ecotype	All Plantable Area	Linear AO	Caribou/Carbon AO	Linear AO	Caribou AO	Carbon AO	Linear AO	Caribou AO	Carbon AO
Boreal	138 657	99 452	7121	120.1	113.8	127.4	347.5	329.2	368.1
Northern	3585 982	27 252	1187 899	316.7	340.7	387.1	724.6	801.0	932.0
Southern Mountain Northern	1321 416	54 823	78 792	339.5	348.6	419.6	783.6	813.6	1002.6
Southern Mountain Central	260 585	29 517	418 561	386.2	400.5	456.8	998.1	1091.2	1261.0
Southern Mountain Southern	1491 630	95 816	888 756	381.1	388.7	434.1	1040.8	1126.4	1266.4

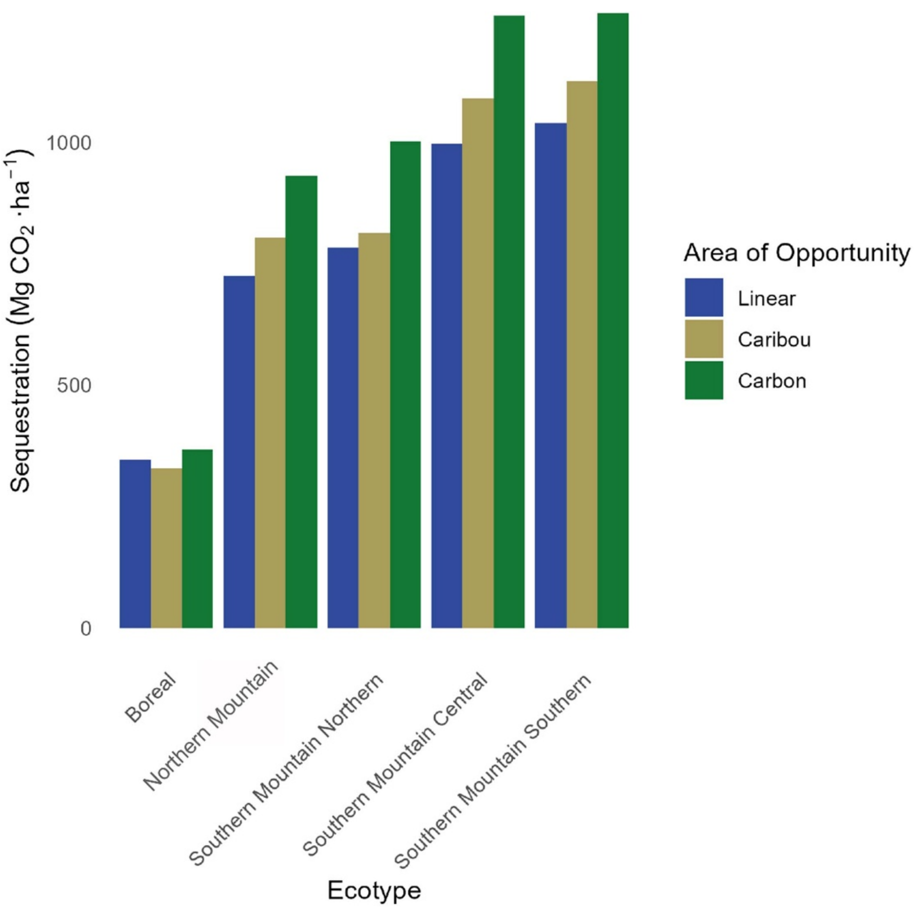

Figure 3. CO_2 Sequestration per woodland caribou ecotype by 2100 for SSP2, comparing Linear, Caribou, and Carbon AO.

4.2.4. Sequestration by area of opportunity

Boreal caribou and Southern Mountain southern group caribou had the smallest difference between the caribou-focused and maximum-carbon AO, with the caribou AO sequestering 11% less carbon than the maximum-carbon AO by 2100. For other ecotypes, the caribou-focused AO sequestered between 13% (Southern Mountain Central group) and 19% (Northern ecotype) less carbon per hectare planted by 2100 (figure 3). Percentage difference in sequestration between the AOs remained consistent between 2050 and 2100.

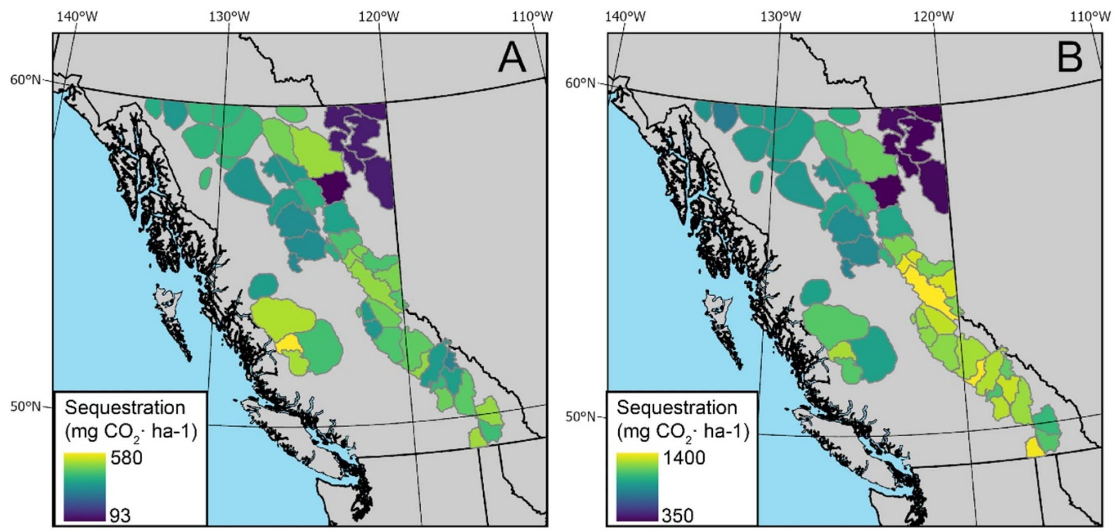

Figure 4. CO_2 Sequestration in Mg $CO_2 \cdot ha^{-1}$ planted by herd, for caribou area of opportunity in (A): 2050, and (B): 2100 in SSP2.

Boreal woodland caribou showed the smallest difference in potential sequestration between the maximum-carbon and linear AO, with the linear AO sequestering only 6% less CO_2 per ha planted by 2100 compared to the maximum-carbon AO. This was the only ecotype for which the linear AO was more productive than the caribou AO, with the linear AO sequestering 6% more carbon than the caribou AO. For other ecotypes, planting linear disturbance was found to have between 18% and 22% lower sequestration potential when compared to the maximum carbon AO and between 4% and 10% when compared to the caribou AO (figure 3)

4.2.5. Herd-level variability in relative sequestration

A large amount of variation was observed between herds within the same ecotype when comparing the relative sequestration impacts of different AOs (figure 5). While at an ecotype level, for all ecotypes other than the Boreal, the linear AO sequestered less carbon than the caribou AO, in fifteen herds, the linear AO was more productive than the caribou AO, sequestering between 0.1% and 21% more carbon. For one herd (Frisby Boulder) the linear AO was more productive than the maximum-carbon AO by 5%.

For all but one Boreal herd, percentage difference in sequestration between AOs was relatively similar with the Caribou AO sequestering between 7% and 8% less carbon than the maximum-carbon AO, and the linear AO sequestering 7% less carbon than the maximum-carbon AO. However, the Westside-Fort Nelson herd had much lower sequestration in the caribou AO and much higher sequestration in the linear AO, with the caribou AO sequestering 22% less carbon than the maximum-carbon AO, and the linear AO sequestering only 1% less carbon.

The Northern ecotype displayed a similar pattern to the Boreal, with all but one herd sequestering between 7% and 16% less carbon in the caribou AO than the maximum-carbon AO. In the Finlay herd, however, the caribou AO sequestered 26% less carbon than the maximum-carbon AO. The linear AO had a large amount of variability in relative productivity between herds, ranging from 7% lower than the maximum-carbon AO for the Liard Plateau and Pink Mountain herds, to 45% lower for the Finlay herd.

For Southern Mountain southern group caribou, the percent decrease in sequestration between the caribou AO and the maximum-carbon AO in 2100 was relatively consistent, and for all but three herds ranged from 6% to 12%. The difference in sequestration between the linear AO and the maximum-carbon AO however was more variable, with the linear AO ranging from being 5% more productive than the maximum-carbon AO in the Frisby Boulder herd (the only with an observed increase) to 30% less productive for the Columbia South herd. Southern Mountain central and northern group herds showed similar patterns, with the percent difference between the maximum-carbon AO and the caribou AO being less variable than percent difference with the linear AO.

4.2.6. Herd exemplar

Figure 6 provides a spatial example of potential sequestration by 2100 at the herd level for the Takla herd. The herd has the lowest productivity of any Southern Mountain Central group herd with a potential sequestration of 822.3 Mg $CO_2 \cdot ha^{-1}$ planted by 2100 in the maximum-carbon AO. For this herd, the linear

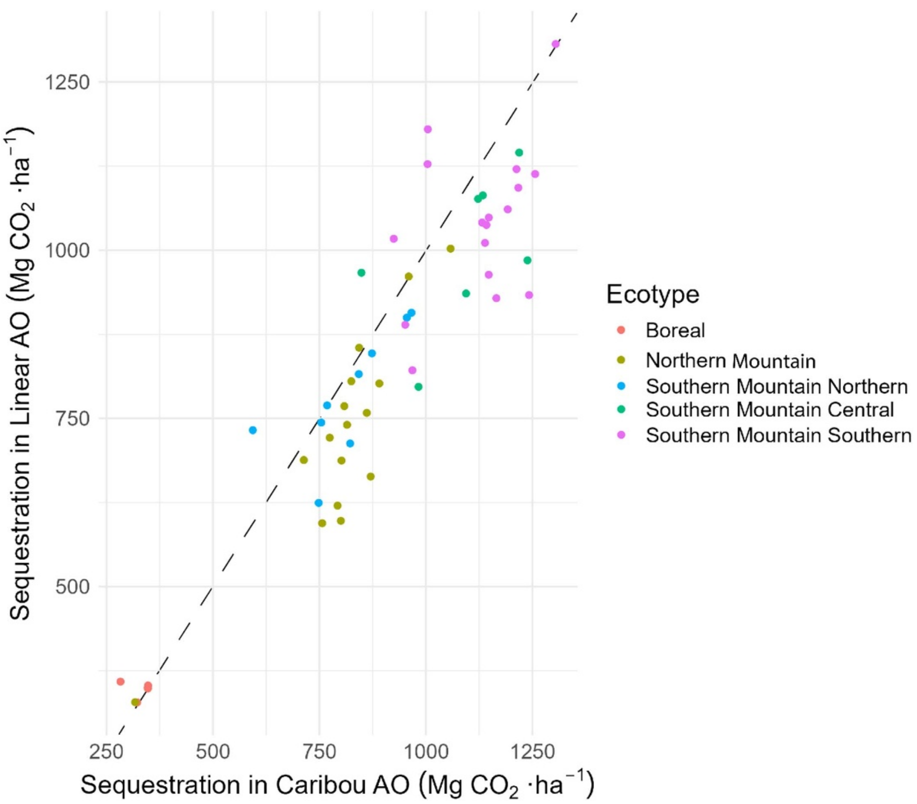

Figure 5. Sequestration in caribou and linear AOs by herd in 2100, for SSP2, colour indicates herd ecotype, dashed line indicates 1:1 line.

AO was more productive than the Caribou AO, sequestering 732.5 Mg $CO_2 \cdot ha^{-1}$ planted by 2100, compared to 593.6 Mg $CO_2 \cdot ha^{-1}$ planted. The caribou AO for this herd is much less productive than the maximum-carbon AO, sequestering 28% less carbon by 2100, compared to the 13% decrease from the maximum-carbon AO to the caribou AO seen in the ecotype as a whole. The linear AO by contrast, had a much smaller than average decrease, being only 11% less productive than the maximum-carbon AO, compared to the 21% average decrease for the ecotype.

5. Discussion

5.1. Impacts of planting priorities on sequestration potential

The results of our analysis indicate that there is high potential for co-benefits between caribou habitat restoration and carbon sequestration. By 2100, for all ecotypes of caribou, the caribou-focused AO sequestered only between 11% and 19% less carbon than the maximum-carbon AO. This relatively small decrease in carbon sequestration observed between the maximum carbon sequestration possible in a herd range, and the carbon sequestration from caribou-focused planting indicates that for most herds there is likely little loss in carbon sequestration from incorporating caribou habitat requirements into planting strategies, especially in the ranges of Southern Mountain Southern group, and Boreal ecotype caribou, where the decrease was only 11%.

While linear disturbance restoration is a fundamental component of woodland caribou habitat restoration, our findings indicate that there is a much greater difference in sequestration levels between planting initiatives focused solely on linear disturbance and those focused on carbon for all ecotypes of caribou other than Boreal (Serrouya *et al* 2020, Dickie *et al* 2023b). Planting in linear disturbances typically resulted in a much larger reduction in sequestration compared to planting in the caribou-focused AO.

In more forestry-dominated ecotypes of woodland caribou, such as the Southern Mountain groups, this lower observed productivity is possibly because the main linear disturbances are resource roads, which are often located towards the bottoms of valleys, which receive less solar radiation, decreasing productivity for the dominant species on the landscape (Dodson 2021, Nagy-Reis *et al* 2021). For many herds, especially those where subalpine fir was the selected species, it may also be due to the fact that the selected tree species for the herd is more suited for growth at higher elevations, and thus was not as suitable for these lower-valley locations. In contrast, for herds in the Boreal ecotype, where the main linear disturbance is from seismic

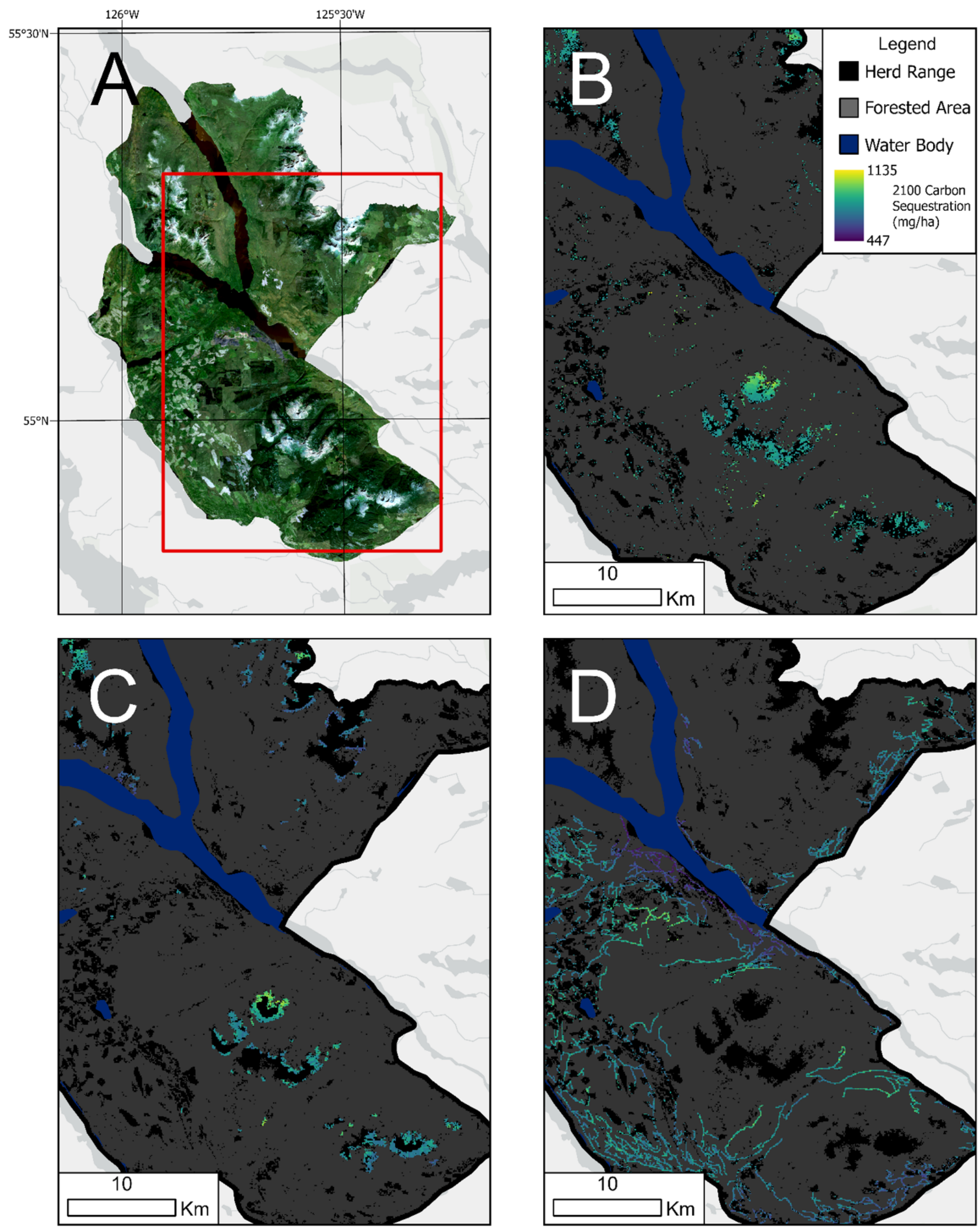

Figure 6. Exemplar map of carbon accumulation in Mg $CO_2 \cdot ha^{-1}$ planted by 2100 for the Takla caribou herd in (B): maximum-carbon area of opportunity, (C): caribou-focused area of opportunity, and (D): linear area of opportunity. (A): shows a Landsat composite of the herd range.

lines, which are less affected by this topographic variation, the linear AO was in fact more productive than the caribou AO.

Productivity on linear disturbances may be lower than modelled if costly site preparations are not undertaken, as the creation of these features leads to issues such as soil compaction, which have been shown to reduce plant growth on linear disturbances by a large degree (van Rensen *et al* 2015, St-Pierre *et al* 2021). This has also been shown to result in a corresponding decrease in efficacy as habitat restoration for caribou (Tattersall *et al* 2020). When mechanical site preparation has been accomplished however, growth rates can be similar to non-compacted areas (Lacerte *et al* 2021, St-Pierre *et al* 2021)

Unlike other ecotypes, we found very similar levels of potential carbon sequestration for Boreal caribou between the three differing areas of opportunity. This indicates that while overall productivity is much lower for this ecotype, if tree planting initiatives are undertaken in these areas, there is large opportunity for co-benefits by incorporating caribou habitat restoration goals into planting strategies. The similar productivity observed between AOs is possibly due to more uniform limitations on growth resulting in less variation. The boreal region of BC has much less topographic variability than in other regions, leading to reduced variability in limiting factors to growth such as precipitation and temperature, in turn likely limiting variation between AOs (Demarchi 2011).

5.2. Impacts of climate scenarios on sequestration potential

As warming scenarios increased in warming intensity from SSP2 (∼2.7 °C warming) to SSP5 (∼4.4 °C warming), for most herds, we found that the potential productivity of planted trees is likely to increase by a small amount. This observed increase in productivity across warming scenarios indicates that for most woodland caribou herds in BC, the currently dominant tree species will likely still remain a productive choice no matter the warming scenario. These findings are consistent with previous research which has indicated that at a broad scale, BC is expected to become warmer and wetter with more severe climate change (Gayton 2008), which may prove advantageous for some tree species (Latta *et al* 2010, Coops and Waring 2011).

The only tree species considered which saw a decrease in productivity in warmer climate scenarios was black spruce, For four out of seven herds where black spruce was planted, productivity slightly decreased across warming scenarios. This indicates that in more severe climate scenarios, black spruce will become a less-appropriate species to plant for these herds in BC. This is consistent with other studies which have indicated that more severe climate change is likely to negatively affect black spruce productivity at the south-western edge of its range (Lesven *et al* 2024). It is likely that given climate change, other species may need to be chosen to plant in many areas of this region, based on site-specific considerations, and that these other species may be more productive on a given site.

To account for potential upwards shifts in productivity and treeline due to climate change, alpine areas were considered to be plantable area in the maximum-carbon AO (Davis *et al* 2020). As the maximum-carbon AO only selected the most productive areas from the total plantable area, these alpine areas were only included in the AO if they were projected to be highly productive in future climate scenarios, given that major constraints on treeline in BC are often driven by climatic variables (Griesbauer and Bevington 2024). While potentially undesirable from an ecological perspective, including for caribou conservation (Duncan 2015), the goal of the maximum-carbon AO was to represent the maximum possible carbon sequestration in an area, to represent an upper bound against which the caribou and linear AO could be compared, not to act as a recommendation that all areas considered in this AO be planted.

5.3. Impacts of ecotype on sequestration potential

Following an expected productivity gradient, herds located in the southern regions of the province tended to have higher sequestration potential than those located in the north, with the Southern Mountain southern and central groups showing the highest sequestration potential of any ecotype for all planting strategies. Additionally, Southern Mountain southern group caribou had the lowest decrease in productivity between planting for maximum-carbon and planting for caribou habitat.

Boreal ecotype caribou showed the lowest sequestration potential of any ecotype, with over 3 times lower sequestration potential than the next lowest ecotype. It is important to note that this does not indicate that this ecotype of woodland caribou should be the lowest priority area for planting efforts, given their threatened status, and the large amounts of disturbance affecting them (Hebblewhite 2017, BC Caribou Recovery Program 2021) rather this simply indicates that the magnitude of potential carbon sequestration when planting in this ecotype is lower than other regions.

The timeframe considered had a large impact on the differences in sequestration levels between ecotypes. In 2050, there was only a difference of 329 Mg $CO_2 \cdot ha^{-1}$ planted between the most productive, Southern Mountain central group, and the least productive Boreal ecotype. For many policymakers, 2050 may be the most salient target year, in alignment with Canada's commitment to net-zero emissions by 2050 (Canada 2020), and the relatively similar sequestration levels between herds would likely indicate that even if sequestration was the main objective of a planting program, other factors such as a herd's population and disturbance status may have a larger influence on decision-making, as sequestration is likely to be relatively similar. However, by 2100, the gap in potential sequestration rose to 892 Mg $CO_2 \cdot ha^{-1}$ planted, and would indicate that if sequestration was a main goal of a planting project, herd and ecotype choice would be a more important variable.

Our findings indicate that tree planting in caribou range in BC could make an important contribution to Canada's commitment to net-zero emissions by 2050. For example, if one tenth of the Caribou AO (258,113 ha) was planted in each ecotype range across BC, our results indicate that 94.6 Mt of CO_2 would be sequestered by 2050, for context, equivalent to roughly one seventh of Canada's 2023 emissions of 694 Mt of CO_2e (Canada 2024). While only a fraction of one year's emissions, this would still be a large contribution to

Canada's net-zero progress. Cost is likely the main limiting factor to these tree planting initiatives, given the large area of opportunity considered.

5.4. Herd level variability in sequestration impacts

The observed herd-level variability in the sequestration impacts of differing planting strategies highlights the importance of spatially-explicit, herd-level information on potential sequestration when designing planting strategies to optimize co-benefits (Di Sacco *et al* 2021) as uniform approaches may overlook opportunities for optimizing both habitat restoration and carbon sequestration at the herd level.

For example, while for 54 out of 55 herds, planting in the linear AO sequestered less carbon than the maximum-carbon AO, for the Frisby-Boulder herd, the linear AO was in fact slightly more productive and for fifteen herds, the linear AO was more productive than the caribou-focused AO. This indicates that while, in general, planting in linear disturbances is a less productive location than other options, for some herds the opposite is true, and if a blanket decision to avoid planting linear disturbances for carbon was made, opportunities for co-benefits could be lost.

The Takla herd highlights the importance of a local understanding of productivity when designing planting strategies which can achieve co-benefits (Brancalion and Holl 2020). While planting for high-quality caribou habitat in this herd range had very low sequestration potential, planting over linear disturbances had relatively high sequestration potential, opposite of what is typical for herds of this ecotype. This is likely due to the fact that most of the linear disturbances for this herd are found at lower elevations in the southwest of the herd range, while most of the plantable area for high-quality caribou habitat was found in higher elevation, less-productive areas in the north and southeast. This indicates that under climate change, these higher elevation areas in the herd range are unlikely to increase in productivity, and that a planting strategy for this herd aiming for co-benefits would therefore likely prioritize planting in linear disturbances instead of the caribou AO.

5.5. Challenges and opportunities

While future climate scenarios were incorporated into the growth model utilized, uncertainty in future climate may impact the conclusions of this work. Climate data was input as 30 year normal in the modelling process, and thus the mortality-related impacts of extreme weather events such as flooding or extreme heat were not evaluated (Gayton 2008). Similarly, mortality due to stand-replacing disturbances, such as fire or harvesting, is not a component of the model utilized, and was thus not evaluated. With increasing climate change, disturbance levels are expected to increase significantly, and thus it is possible that many planted areas will experience mortality due to fire (Parisien *et al* 2023). Long term estimates of sequestration potential outlined in this work could therefore be higher than actuality due to mortality. Incorporating stand-replacing disturbances could improve future works, but would require intensive modelling of burn probability such as that undertaken in Mulverhill *et al* (2024) to accomplish in a spatially-explicit manner compatible with the methods utilized in this study.

The focus of this study was on evaluating the impacts of planting a single, locally common, tree species per herd range. It is possible, and for some herds likely, that land managers may choose to plant other tree species, which may have differing carbon-sequestration implications (DellaSala *et al* 2022). Differing warming scenarios may also change growth rates of species at differing rates (Coops and Waring 2011). Additionally, it is likely that a singular tree species would produce suboptimal sequestration results when planted across an entire herd range, especially across elevation gradients. Future work could assess the impacts of planting different species, and determine the best species to plant per location and climate scenario. Similarly, future works could investigate the effects of planting a mix of species per location. Planting a mix of species is an important consideration for habitat restoration and ecological needs, and has also been shown to reduce fire risk depending on species composition (Hély *et al* 2000, Brancalion and Holl 2020, Peris-Llopis *et al* 2024). As such, determining what mix of tree species is likely to grow best in differing climate scenarios would be informative for land managers trying to design planting strategies. However, it would require extensive parameterization and validation of each species for the 3PG model outside the scope of this work.

The AOs used to identify planting areas in this study were broad, in order to capture the full variability in potential productivity in each area. Due to the unreliability of information on road use status in BC, all linear disturbances in the linear AO were considered to be plantable, regardless of use status. The total plantable area in the linear AO is likely lower than considered in this work due to this assumption, as sequestration potentials are reported on a per-hectare planted basis however, this larger area is unlikely to have a large effect on results.

The lack of comprehensive soil fertility values across BC required that fertility information for a large percentage of pixels be inferred from average fertility in the local area. However, as a large portion of these areas requiring infilling are areas with very low natural fertility, such as exposed or barren land, it is likely that this approach may over-estimate soil fertility in these regions, resulting in an overprediction of forest productivity.

While considered separately in this work in order to elucidate the impacts of differing potential priorities, in practice, a combination of these AOs would likely be planted. When designing planting programs, managers will likely need to make restoration decisions based on factors not considered in this work, including land ownership, and more detailed assessments of caribou ecological needs (Ray 2014). Managers, for instance, may utilize stand age, critical habitat maps, or radio-collar data to identify key areas for planting which would have the highest positive impact on caribou habitat (Dickie *et al* 2023a). Additionally, with limited resources, land managers will need to determine priorities for restoration, deciding between targeting restoration to the most threatened herds versus those more likely to persist. Climate change is also likely have an impact on woodland caribou habitat utilization and location, which managers will need to take into account when designing these strategies (Dawe and Boutin 2016, Neilson *et al* 2022).

6. Conclusion

We evaluated the carbon sequestration impacts of tree planting in woodland caribou habitat in BC, and compared the impacts of planting purely for carbon, planting informed by woodland caribou habitat needs, and planting to restore linear disturbances. We found that tree planting in the range of Southern Mountain southern and central group caribou was likely to sequester the most carbon, and that planting in Boreal ecotype caribou range was likely to sequester the least carbon. For most woodland caribou ecotypes, we found relatively low tradeoffs of 11%–19% between planting informed by woodland caribou habitat needs and planting purely for carbon, and larger tradeoffs of 18%–22% between planting as linear disturbance restoration and planting for carbon. Large variation between herds of the same ecotype in sequestration levels in the differing AOs was found, highlighting the importance of spatially-explicit, herd level information for designing planting strategies that maximize co-benefits. Restoring habitat for caribou is not only critical for recovery of this threatened species, but can also provide significant benefits for climate mitigation. Similarly, planting trees for carbon sequestration can be tailored toward threatened species recovery with minimal loss of benefit, if native species are planted and logging ceases. These two management goals are typically considered separately but our work highlights how they can be brought together to maximize multiple benefits simultaneously for managed landscapes.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Authorship contribution statement

J.C.M.: Conceptualization, Methodology, Investigation, Visualization, Software, Writing—review & editing.

N.C.C: Conceptualization, Methodology, Investigation, Writing—review & editing.

G.J.M.R.: Conceptualization, Methodology, Investigation, Writing—review & editing.

T.H.: Methodology, Investigation, Visualization, Writing—review & editing.

A.C.B: Methodology, Investigation, Writing—review & editing.

ORCID iDs

James C Maltman https://orcid.org/0000-0002-1747-2974
Nicholas C Coops https://orcid.org/0000-0002-0151-9037
Gregory J M Rickbeil https://orcid.org/0000-0003-3195-5128
Txomin Hermosilla https://orcid.org/0000-0002-5445-0360
A Cole Burton https://orcid.org/0000-0002-8799-3847

References

Amichev B Y, Bentham M J, Kurz W A, Laroque C P, Kulshreshtha S, Piwowar J M and Van Rees K C J 2016 Carbon sequestration by white spruce shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 model simulations *Ecol. Modelling* **325** 35–46

Apps C D, McLellan B N, Kinley T A, Serrouya R, Seip D R and Wittmer H U 2013 Spatial factors related to mortality and population decline of endangered mountain caribou *J. Wildl. Manage.* **77** 1409–19

Bartels S F, Chen H Y H, Wulder M A and White J C 2016 Trends in post-disturbance recovery rates of Canada's forests following wildfire and harvest *For. Ecol. Manage.* **361** 194–207

Bayatvarkeshi M, Ketcheson S, Weiland L and Strack M 2024 An initial assessment of winter microclimatic conditions in response to seismic line disturbance in a forested peatland *Hydrol. Process.* **38** e15243

BC Caribou Recovery Program 2021 Population estimates for caribou herds of British Columbia

BC Caribou Recovery Program 2022 Caribou herd locations for BC

BC Government 2021a Provincial site productivity layer (version 8.0)—site index by tree species rasters

BC Government 2021b BC cumulative effects framework integrated roads

BC Government 2021c BC cumulative effects framework human disturbance layer (available at: https://catalogue.data.gov.bc.ca/dataset/ce-disturbance-2021) (Accessed 6 June 2024)

BC Ministry of Forests 2002 Forest road engineering guidebook

Beirne C, Sun C, Tattersall E R, Burgar J M, Fisher J T and Burton A C 2021 Multispecies modelling reveals potential for habitat restoration to re-establish boreal vertebrate community dynamics *J. Appl. Ecol.* **58** 2821–32

Bentham P and Coupal B 2015 Habitat restoration as a key conservation lever for woodland caribou: A review of restoration programs and key learnings from Alberta *Rangifer* **35** 123–47

Brancalion P H S and Holl K D 2020 Guidance for successful tree planting initiatives *J. Appl. Ecol.* **57** 2349–61

Bush E and Lemmen D S 2019 *Canada's Changing Climate Report* (Government of Canada)

Canada, E. and C.C 2024 Canada's preliminary greenhouse gas emissions 1990–2023 (available at: www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory/preliminary-emissions-1990-2023.html) (Accessed 15 January 2025)

Canada, S 2020 Net-zero emissions by 2050 (available at: www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html) (Accessed 15 May 2024)

Coops N C and Hember R A 2009 Physiologically derived predictions of Douglas-fir site index in British Columbia *For. Chron.* **85** 733–44

Coops N C and Waring R H 2011 Estimating the vulnerability of fifteen tree species under changing climate in Northwest North America *Ecol. Modelling* **222** 2119–29

Coops N C, Waring R H and Hilker T 2012 Prediction of soil properties using a process-based forest growth model to match satellite-derived estimates of leaf area index *Remote Sens. Environ.* **126** 160–73

Coops N C, Waring R H and Landsberg J J 1998 Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity *For. Ecol. Manage.* **104** 113–27

Dabros A, Higgins K L and Pinzon J 2022 Seismic line edge effects on plants, lichens and their environmental conditions in boreal peatlands of Northwest Alberta (Canada) *Restor. Ecol.* **30** e13468

Davis E L, Brown R, Daniels L, Kavanagh T and Gedalof Z 2020 Regional variability in the response of alpine treelines to climate change *Clim. Change* **162** 1365–84

Dawe K L and Boutin S 2016 Climate change is the primary driver of white-tailed deer (Odocoileus virginianus) range expansion at the northern extent of its range; land use is secondary *Ecol. Evol.* **6** 6435–51

DellaSala D A, Keith H, Sheehan T, Strittholt J, Mackey B, Connolly M, Werner J R and Fredeen A L 2022 Estimating carbon stocks and stock changes in Interior Wetbelt forests of British Columbia, Canada *Ecosphere* **13** e4020

Demarchi D A 2011 *An Introduction to the Ecoregions of British Columbia* (Ecosystem Information Section, BC Ministry of Environment)

DeMars C A and Boutin S 2018 Nowhere to hide: effects of linear features on predator–prey dynamics in a large mammal system *J. Animal Ecol.* **87** 274–84

Di Sacco A *et al* 2021 Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits *Glob. Change Biol.* **27** 1328–48

Dickie M, Bampfylde C, Habib T J, Cody M, Benesh K, Kellner M, McLellan M, Boutin S and Serrouya R 2023a Where to begin? A flexible framework to prioritize caribou habitat restoration *Restor. Ecol.* **31** e13873

Dickie M, Love N, Steenweg R, Lamb C T, Polfus J and Ford A T 2023b In search of evidence-based management targets: a synthesis of the effects of linear features on woodland caribou *Ecol. Indic.* **154** 110559

Dickie M, McNay R S, Sutherland G D, Sherman G G and Cody M 2021 Multiple lines of evidence for predator and prey responses to caribou habitat restoration *Biol. Conserv.* **256** 109032

Dickie M, Serrouya R, McNay R S and Boutin S 2017 Faster and farther: wolf movement on linear features and implications for hunting behaviour *J. Appl. Ecol.* **54** 253–63

Dickie M, Sherman G G, Sutherland G D, McNay R S and Cody M 2023c Evaluating the impact of caribou habitat restoration on predator and prey movement *Conserv. Biol.* **37** e14004

Dodson E M 2021 Challenges in forest road maintenance in North America *Croat. J. For. Eng.* **42** 107–16

Drever C R *et al* 2021 Natural climate solutions for Canada *Sci. Adv.* **7** eabd6034

du Toit F, Coops N C, Mulverhill C and Toomey A 2024 Assessing the impact of afforestation as a natural climate solution in the Canadian boreal *Environ. Res. Ecol.* **3** 035004

Duncan S J 2015 Woodland caribou alpine range restoration: An application for lichen transplants *Ecol. Restor.* **33** 22–29

Ellis P W *et al* 2024 The principles of natural climate solutions *Nat. Commun.* **15** 547

Environment and Climate Change Canada 2020 Woodland caribou, boreal population (Rangifer tarandus caribou): amended recovery strategy 2020 (available at: www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/recovery-strategies/woodland-caribou-boreal-2020.html) (Accessed 6 June 2023)

Environment and Climate Change Canada 2021 *Environmental Sustainability Indicators: Progress Towards Canada's Greenhouse Gas Emissions Reduction Target*

Environment and Climate Change Canada, 2024. Nature smart climate solutions fund—Canada.ca (available at: www.canada.ca/en/environment-climate-change/services/environmental-funding/programs/nature-smart-climate-solutions-fund.html) (Accessed 10 June 2024)

Environment Canada 2014 *Recovery Strategy for the Woodland Caribou, Southern Mountain Population (Rangifer Tarandus Caribou) in Canada., Recovery Strategy Series* (Environment Canada)
FAO 2020 Global forest resources assesment 2020 terms and definitions (No. Working Paper 188) (UN FAO)
Fargione J E *et al* 2018 Natural climate solutions for the United States *Sci. Adv.* **4** eaat1869
Festa-Bianchet M, Ray J C, Boutin S, Côté S D and Gunn A 2011 Conservation of caribou (Rangifer tarandus) in Canada: an uncertain future1This review is part of the virtual symposium "flagship species – flagship problems" that deals with ecology, biodiversity and management issues, and climate impacts on species at risk and of Canadian importance, including the polar bear (Ursus maritimus), Atlantic cod (Gadus morhua), piping plover (Charadrius melodus), and caribou (Rangifer tarandus) *Can. J. Zool.* **89** 419–34
Forrester D I, Hobi M L, Mathys A S, Stadelmann G and Trotsiuk V 2021 Calibration of the process-based model 3-PG for major central European tree species *Eur. J. For. Res.* **140** 847–68
Fradette O, Marty C, Faubert P, Dessureault P-L, Paré M, Bouchard S and Villeneuve C 2021 Additional carbon sequestration potential of abandoned agricultural land afforestation in the boreal zone: a modelling approach *For. Ecol. Manage.* **499** 119565
Friggens N L, Hester A J, Mitchell R J, Parker T C, Subke J-A and Wookey P A 2020 Tree planting in organic soils does not result in net carbon sequestration on decadal timescales *Glob. Change Biol.* **26** 5178–88
Gayton D V 2008 Impacts of climate change on British Columbia's biodiversity: a literature review *J. Ecosyst. Manage.* **9** 26–31
Griesbauer H and Bevington A 2024 Recent changes in forest structure and growth at the alpine-treeline ecotone in the Rocky and Columbia Mountains of central British Columbia, Canada *J. Biogeogr.* **51** 677–93
Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
Gupta R and Sharma L K 2019 The process-based forest growth model 3-PG for use in forest management: a review *Ecol. Modelling* **397** 55–73
Headlee W L, Zalesny R S, Donner D M and Hall R B 2013 Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA *Bioenergy Res.* **6** 196–210
Hebblewhite M 2017 Billion dollar boreal woodland caribou and the biodiversity impacts of the global oil and gas industry *Biol. Conserv.* **206** 102–11
Hély C, Bergeron Y and Flannigan M D 2000 Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest *J. Veg. Sci.* **11** 813–24
Hember R A, Coops N C and Spittlehouse D L 2017 Spatial and temporal variability of potential evaporation across North American forests *Hydrology* **4** 5
Hermosilla T, Bastyr A, Coops N C, White J C and Wulder M A 2022a Mapping the presence and distribution of tree species in Canada's forested ecosystems *Remote Sens. Environ.* **282** 113276
Hermosilla T, Wulder M A, White J C, Coops N C and Hobart G W 2015a An integrated Landsat time series protocol for change detection and generation of annual gap-free surface reflectance composites *Remote Sens. Environ.* **158** 220–34
Hermosilla T, Wulder M A, White J C, Coops N C and Hobart G W 2015b Regional detection, characterization, and attribution of annual forest change from 1984 to 2012 using Landsat-derived time-series metrics *Remote Sens. Environ.* **170** 121–32
Hermosilla T, Wulder M A, White J C, Coops N C and Hobart G W 2018 Disturbance-informed annual land cover classification maps of Canada's forested ecosystems for a 29-year Landsat time series *Can. J. Remote Sens.* **44** 67–87
Hermosilla T, Wulder M A, White J C, Coops N C, Hobart G W and Campbell L B 2016 Mass data processing of time series Landsat imagery: pixels to data products for forest monitoring *Int. J. Digit. Earth* **9** 1035–54
Hermosilla T, Wulder M, White J and Coops N 2022b Land cover classification in an era of big and open data: Optimizing localized implementation and training data selection to improve mapping outcomes *Remote Sens. Environ.* **268** 112780
IPCC 2023 Climate change 2023: synthesis report *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H Lee and J Romero (Core Writing Team)
Johnson C A, Sutherland G D, Neave E, Leblond M, Kirby P, Superbie C and McLoughlin P D 2020 Science to inform policy: linking population dynamics to habitat for a threatened species in Canada *J. Appl. Ecol.* **57** 1314–27
Johnson C J and Rea R V 2024 Response of moose to forest harvest and management: a literature review *Can. J. For. Res.* **54** 366–88
Kauppi P E, Tomppo E and Ferm A 1995 C and N storage in living trees within Finland since 1950s *Nutrient Uptake and Cycling in Forest Ecosystems: Proc. CEC/IUFRO Symp. Nutrient Uptake and Cycling in Forest Ecosystems (Halmstad, Sweden, 7–10 June 1993)* ed L O Nilsson, R F Hüttl and U T Johansson (ed) (Springer) pp 633–8
Kristensen J Å *et al* 2024 Tree planting is no climate solution at northern high latitudes *Nat. Geosci.* **17** 1087–92
Kurz W A (ed) 1992 *The Carbon Budget of the Canadian Forest Sector: Phase 1* (Northern Forestry Centre)
Kurz W A *et al* 2009 CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards *Ecol. Modelling* **220** 480–504
Lacerte R, Leblond M and St-Laurent M-H 2021 Determinants of vegetation regeneration on forest roads following restoration treatments: implications for boreal caribou conservation *Restor. Ecol.* **29** e13414
Landsberg J J and Waring R H 1997 A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning *For. Ecol. Manage.* **95** 209–28
Landsberg J J, Waring R H and Coops N C 2003 Performance of the forest productivity model 3-PG applied to a wide range of forest types *For. Ecol. Manage.* **172** 199–214
Latta G, Temesgen H, Adams D and Barrett T 2010 Analysis of potential impacts of climate change on forests of the United States Pacific Northwest *For. Ecol. Manage.* **259** 720–9
Lesmerises R, Ouellet J-P, Dussault C and St-Laurent M-H 2013 The influence of landscape matrix on isolated patch use by wide-ranging animals: conservation lessons for woodland caribou *Ecol. Evol.* **3** 2880–91
Lesven J A, Druguet Dayras M, Cazabonne J, Gillet F, Arsenault A, Rius D and Bergeron Y 2024 Future impacts of climate change on black spruce growth and mortality: review and challenges *Environ. Rev.* **32** 214–30
Maltman J C, Coops N C, Rickbeil G J M, Hermosilla T and Burton A C 2024 Quantifying forest disturbance regimes within caribou (Rangifer tarandus) range in British Columbia *Sci. Rep.* **14** 6520
Mansuy N, Burton P J, Stanturf J, Beatty C, Mooney C, Besseau P, Degenhardt D, MacAfee K and Lapointe R 2020 Scaling up forest landscape restoration in Canada in an era of cumulative effects and climate change *For. Policy Econ.* **116** 102177
Mazziotta A, Lundström J, Forsell N, Moor H, Eggers J, Subramanian N, Aquilué N, Morán-Ordóñez A, Brotons L and Snäll T 2022 More future synergies and less trade-offs between forest ecosystem services with natural climate solutions instead of bioeconomy solutions *Glob. Change Biol.* **28** 6333–48
Molina R, Costello C and Kaffine D 2024 Sharing and expanding the co-benefits of conservation *Ecol. Econ.* **218** 108113

Mulverhill C, Coops N C, Wulder M A, White J C, Hermosilla T and Bater C W 2024 Multidecadal mapping of status and trends in annual burn probability over Canada's forested ecosystems *ISPRS J. Photogramm. Remote Sens.* **209** 279–95
Nagy-Reis M *et al* 2021 Habitat loss accelerates for the endangered woodland caribou in western Canada *Conserv. Sci. Pract.* **3** e437
NASA, METI, AIST, Japan Spacesystems, U.S./Japan ASTER Science Team 2019 ASTER Global Digital Elevation Model V003 (https://doi.org/10.5067/ASTER/ASTGTM.003)
Neilson E W, Castillo-Ayala C, Beckers J F, Johnson C A, St-Laurent M H, Mansuy N, Price D, Kelly A and Parisien M A 2022 The direct and habitat-mediated influence of climate on the biogeography of boreal caribou in Canada *Clim. Change Ecol.* **3** 100052
Nole A, Law B, Magnani F, Matteucci G, Ferrara A, Ripullone F and Borghetti M 2009 Application of the 3-PGS model to assess carbon accumulation in forest ecosystems at a regional level *Can. J. For. Res.* **39** 1647
Osaka S, Bellamy R and Castree N 2021 Framing "nature-based" solutions to climate change *WIREs Clim. Change* **12** e729
Palm E C, Fluker S, Nesbitt H K, Jacob A L and Hebblewhite M 2020 The long road to protecting critical habitat for species at risk: The case of southern mountain woodland caribou *Conserv. Sci. Pract.* **2** e219
Parisien M-A *et al* 2023 Abrupt, climate-induced increase in wildfires in British Columbia since the mid-2000s *Commun. Earth Environ.* **4** 1–11
Peng C, Zhang L, Zhou X, Dang Q and Huang S 2004 Developing and evaluating tree height-diameter models at three geographic scales for black spruce in Ontario *North. J. Appl. For.* **21** 83–92
Peris-Llopis M, Mola-Yudego B, Berninger F, Garcia-Gonzalo J and González-Olabarria J R 2024 Impact of species composition on fire-induced stand damage in Spanish forests *Sci. Rep.* **14** 8594
Rana P and Varshney L R 2023 Exploring limits to tree planting as a natural climate solution *J. Cleaner Prod.* **384** 135566
Ray J C 2014 *Defining Habitat Restoration for Boreal Caribou in the Context of National Recovery: a Discussion Paper*
Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68
Sands P J and Landsberg J J 2002 Parameterisation of 3-PG for plantation grown *Eucalyptus globulus For. Ecol. Manage.* **163** 273–92
Seddon N 2022 Harnessing the potential of nature-based solutions for mitigating and adapting to climate change *Science* **376** 1410–6
Serrouya R *et al* 2021 Trophic consequences of terrestrial eutrophication for a threatened ungulate *Proc. R. Soc.* B **288** 20202811
Serrouya R, Dickie M, DeMars C, Wittmann M J and Boutin S 2020 Predicting the effects of restoring linear features on woodland caribou populations *Ecol. Modelling* **416** 108891
St-Pierre F, Drapeau P and St-Laurent M-H 2021 Drivers of vegetation regrowth on logging roads in the boreal forest: implications for restoration of woodland caribou habitat *For. Ecol. Manage.* **482** 118846
Tattersall E R, Burgar J M, Fisher J T and Burton A C 2020 Mammal seismic line use varies with restoration: applying habitat restoration to species at risk conservation in a working landscape *Biol. Conserv.* **241** 108295
Trotsiuk V, Hartig F and Forrester D I 2020 r3PG—an r package for simulating forest growth using the 3-PG process-based model *Methods Ecol. Evol.* **11** 1470–5
van Rensen C K, Nielsen S E, White B, Vinge T and Lieffers V J 2015 Natural regeneration of forest vegetation on legacy seismic lines in boreal habitats in Alberta's oil sands region *Biol. Conserv.* **184** 127–35
Veldman J W, Overbeck G E, Negreiros D, Mahy G, Le Stradic S, Fernandes G W, Durigan G, Buisson E, Putz F E and Bond W J 2015 Where tree planting and forest expansion are bad for biodiversity and ecosystem services *BioScience* **65** 1011–8
Wang T, Hamann A, Spittlehouse D and Carroll C 2016 Locally downscaled and spatially customizable climate data for historical and future periods for North America *PLoS One* **11** e0156720
White J C *et al* 2014 Pixel-based image compositing for large-area dense time series applications and science *Can. J. Remote Sens.* **40** 192–212
White J, Wulder M, Hermosilla T, Coops N and Hobart G 2017 A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series *Remote Sens. Environ.* **194** 303–21
Wittmer H U, Mclellan B N, Serrouya R and Apps C D 2007 Changes in landscape composition influence the decline of a threatened woodland caribou population *J. Animal Ecol.* **76** 568–79
Wulder M A, Hermosilla T, Stinson G, Gougeon F A, White J C, Hill D A and Smiley B P 2020 Satellite-based time series land cover and change information to map forest area consistent with national and international reporting requirements *For. Int. J. For. Res.* **93** 331–43
Wulder M A, Hermosilla T, White J C, Bater C W, Hobart G and Bronson S C 2024 Development and implementation of a stand-level satellite-based forest inventory for Canada *For. Int. J. For. Res.* **97** 546–63
Wulder M A, White J C, Cranny M, Hall R J, Luther J E, Beaudoin A, Goodenough D G and Dechka J A 2008 Monitoring Canada's forests. Part 1: completion of the EOSD land cover project *Can. J. Remote Sens.* **34** 549–62
Zhang L 1997 Cross-validation of non-linear growth functions for modelling tree height–diameter relationships *Ann. Bot.* **79** 251–7
Zheng D, Hunt E R and Running S W 1996 Comparison of available soil water capacity estimated from topography and soil series information *Landscape Ecol.* **11** 3–14