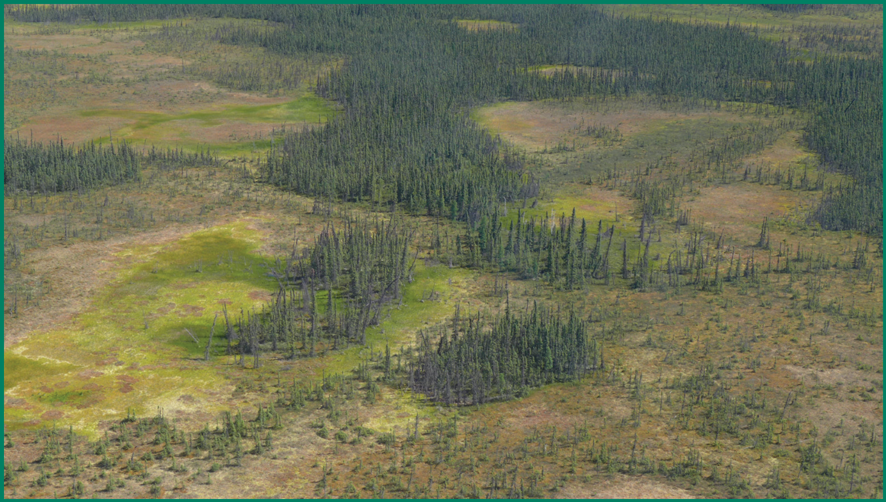
North American Boreal Terrestrial Ecosystem Biomass:

A Spatial Data Review



GKA GEOGRAPHIC SOLUTIONS

by Gregory Kehm
for Wildlife Conservation Society Canada

WCS Canada

Wildlife Conservation Society Canada
344 Bloor Street West, Suite 204
Toronto, Ontario. M5S 3A7 Canada
Telephone: (416) 850-9038
www.wcscanada.org

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Wildlife Conservation Society Canada

Wildlife Conservation Society Canada (WCS Canada) was incorporated as a conservation organization in Canada in July 2004. Its mission is to save wildlife and wildlands by improving our understanding of — and seeking solutions to — critical problems that threaten vulnerable species and large wild ecosystems throughout Canada. WCS Canada implements and supports comprehensive field studies to gather information on the ecology and behavior of wildlife. Then, it applies that information to resolve key conservation problems by working with a broad array of stakeholders, including local community members, conservation groups, regulatory agencies, and commercial interests. It also provides technical assistance and biological expertise to local groups and agencies that lack the resources to tackle conservation dilemmas. Already, WCS Canada has worked on design of protected areas (Nahanni National Park), monitoring and recovery of species (grizzly bear, lynx, wolverine, and woodland caribou), restoration of ecosystems, integrated management of large landscapes, and community-based conservation.

Although WCS Canada is independently registered and managed, it retains a strong collaborative working relationship with sister WCS programs in more than 55 countries around the world. The Wildlife Conservation Society is a recognized global leader in conservation, dedicated to saving wildlife and wildlands for species in peril, such as elephants, tigers, sharks, macaws and bears. For more than a century, WCS has worked in North America promoting conservation actions such as recovery of bison, establishment of parks, and legislation to protect endangered wildlife. Today, WCS Canada draws upon this legacy of experience and expertise to inform its strategic programs from Yukon to Labrador.

To learn more about WCS Canada, visit: www.wcscanada.org. To contact WCS Canada, write to: wcscanada@wcs.org.

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Gregory Kehm
Gregory Kehm Associates
3552 West 8th Avenue
Vancouver BC Canada V6R 1Y7
(604) 787-5000
gregory.kehm@gmail.com

Wildlife Conservation Society Canada
344 Bloor Street West, Suite 204
Toronto, Ontario M5S 3A7
(416) 850-9038
www.wcscanada.org

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Mike Oldham

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Summary

Boreal forests, wetlands, and soils hold substantial amounts of carbon in the form of plant material, alive and in various stages of decay (herein "biomass carbon"). Governments, scientists, industry, and civil society organizations are increasingly interested in identifying where and how much biomass carbon is held in North American boreal ecosystems to help prioritize stewardship actions, inform adaptive planning, proactively mitigate climate change, and harness new investments in ecosystem services. This report surveys publicly available spatial data quantifying biomass carbon in various subsets or pools (above-ground, below-ground, within soil, wetland, and permafrost) across the North American boreal.

Scientists and agencies have been busy working to develop, improve, and adequately quantify estimates of biomass carbon in each of these subsets of the ecosystem. This report provides recommendations on the most useful data sources and data sets for each of the pools of biomass carbon (with links to those sources) and discusses appropriate scale and consideration of error or variability in estimation. Care must be taken in recognizing the difference between mapped biomass (all organic material) and mapped carbon (just the carbon component of the organic matter). New technologies, especially those producing remotely sensed data from satellites, are also opening up new options. The findings of this review will therefore have to be revisited periodically to incorporate these new sources.

1.0 Introduction

Boreal forests, wetlands and soils hold substantial volumes of biomass carbon. Governments, industry and civil society organizations are increasingly interested in identifying where and how much biomass is held in North American boreal ecosystems to help prioritize stewardship actions, inform adaptive planning, proactively mitigate climate change, and harness new investments in ecosystem services.

This report is focused on surveying publicly available spatial data identifying terrestrial vegetation (forest focus) and soil biomass across the North American boreal[1]. In the last decade numerous global biomass data layers have been created including a few directly supporting UN treaties on the reduction of carbon emissions. The majority of these layers are the products of satellite-based instruments, including those aboard ALOS-2 (European Union), Copernicus (EU), JAXA (Japan), Landsat (United States), MODIS (US), and Sentinel-1 and Sentinel-2 satellites. The satellite-based instruments have differing resolution, ranging from 9x9 km (or coarser) ground equivalent areas (GEA) to as fine as 30m x 30m – 10m x 10m GEA. Regional and local layers supporting forest biomass quantification are available for some jurisdictions (e.g. British Columbia) and may be derived from fine-scale photo-interpreted vegetation inventories with forest stem, branch, and root biomass estimates.[2]

To fill a gap in monitoring biomass trends with increasingly finer-scale, global coverage and to provide a common reference layer, the European Space Agency is launching the Earth Explorer Biomass[3] satellite in 2021. This satellite will carry new synthetic radar to acquire accurate, fine-scaled tropical, temperate, and boreal above-ground forest biomass across the five-year mission time period.

Another data gap is a comprehensive ground-based biomass measurement (either long-term monitoring or LiDAR-based plots[4, 5]) to validate remotely sensed data and decrease uncertainty levels. Canada, in particular, does not appear to have a national, high quality, and compiled database of plot-level biomass measurements. Nevertheless, increased efforts at validation of remotely sensed data will aid in providing a consistent calibration and uncertainty calculation for both global and national remotely sensed biomass data layers.

Care is warranted in interpreting forest biomass density and carbon weights that are not site specific. Cross-platform quantitative biomass comparison is laden with challenges, including varied methodologies, different land-cover masking, time periods and sensor abilities. Global layers offer useful, consistent and relatively recent estimates for broad strategic decision making and cross-jurisdictional planning processes. Additionally, uncertainty in the spatial data -- whether in the spatial distribution or area densities – is comparable between distant jurisdictions. While this does not solve the need for greater accuracy, cross-jurisdictional comparisons can be reliably inferred. Sub-national layers will have higher biomass fidelity.

Comparisons of global biomass spatial data reveal variability in the reporting of error/ uncertainty. The best data sources create a spatial layer of per-cell error/ uncertainty. Different layers may be recording biomass in different ecosystems – some forests, others entire ecosystems depending on the land cover or forest inventory data applied as a mask. Advances in sensor technology and different space platforms and methods add an underlying condition, and perhaps an important caveat as to why per-pixel biomass values between different sources of data can be substantially different.

Any quantitative valuations of biomass carbon are best when including data and evaluations based on site-specific information analyzed with consistent methodologies. However, the availability of site-specific biomass data is often limited to small geographic areas and includes significant costs to develop. Projects requiring these intensive biomass data might include an investment in forest carbon inventory due diligence prior to buying or selling carbon credits.

Global biomass density coverage serves different needs. These data provide a cost-efficient and globally consistent comparison across large jurisdictional areas. These data are vital to monitoring International agreements on carbon reduction and remain cautiously useful when making areal and quantitative comparisons between large jurisdictions. Increasingly, these data are captured annually and provide a unique opportunity to monitor changes to biomass density over time.

These global data will continue to improve with new satellites, technology and methods advancement. For example, a recent paper by Spawn and Gibbs[6] describes an improved method in the integration of land-cover specific, remotely sensed maps of woody, grassland, cropland, and tundra above and below-ground biomass using data collected in 2010. There remains a catch-up between global remote data collection instruments and refinement of methods to generate annual, consistent data from them. An optimal solution would appear to be dynamically collected data with consistent methods applied in developing consistently low-error global data products.

2.0 Terrestrial Ecosystem Biomass

Biomass density is all living tissue of plants and measured in megagrams per hectare (Mg/ha) with a commonly used conversion factor to dry forest biomass carbon of 0.5[7]. Most of the spatial data collected for this report measure biomass density. Biomass density is mapped at two different temporal states: dynamic and static. Gross Primary Productivity (GPP) is dynamic and quantifies the total amount of carbon dioxide fixation by vegetation photosynthesis over a period of time. This includes carbon dioxide (CO_2) respired and converted into biomass at a rate of megagrams/hectare/day (Mg/ha/day). Net Primary Productivity (NPP) is also dynamic, quantifying the amount of CO_2 that vegetation takes in during photosynthesis minus how much CO_2 is released during respiration[8] (See Appendix F for GPP sources).

Static biomass is the amount of biomass in Mg/ha in above- and below-ground parts of a tree - including leaves, branches, trunk, bark, and roots, all at a single point in time. This report is focused on static terrestrial boreal ecosystem biomass including surveying for available spatial data mapping biomass in forests, herbaceous cover (moss), wetland/peatlands, soil organic density, and permafrost. The North American boreal contains substantial biomass reserves in soils and particularly in peatlands – the latter covering about 15% of its surface area. This is a sizable storehouse of global carbon, and vulnerable to drying up and burning, thereby releasing carbon and diminishing the role of wet peatlands as fire breaks in the larger matrix forest.

3.0 Method

The identification and collection of biomass spatial data available for the study area occurred primarily using keyword-based discovery searches input into several different web services and data portals representing regional, national, and global data libraries summarized in Table 1. Keywords included: geographic scale [global, North America, Canada], terrestrial, biomass, GIS data, and maps. The search process iterated through identification of good sources with data, checking availability and access, and email/phone call communication back to further refinement of keywords and search engines. A list of individuals contacted is in Appendix A. The search results in this report are not exhaustive, nor complete. New data are regularly appearing online with projects mid-way in their data development process and new satellites launching regularly.

3.1 Search Criteria

A rapid assessment approach was taken using sets of keywords including: biomass, boreal, carbon, wetlands, permafrost, soil, and spatial data. This was a starting point to identify the most relevant and useful data for landscape scales and for the entire area of the North American boreal. An emphasis was placed on identifying global datasets, although national and regional data were examined for their potential to more accurately support through ground-truthing the tabulating of biomass density in several regional landscape areas. The following criteria were used to further filter data sets of interest:

- Are the spatial data recent or within the last ten years (since 2010)?
- Is the spatial resolution of the data between 10 m and 1000 m?

- Is an uncertainty data layer available and/or sensor driven spatial error visible to aid in assessing relative error?
- Are the data inclusive of a North American boreal extent?

The temporal range included data developed since 2010 with a more focused investigation to identify the recently developed spatial data taking advantage of advances in satellite sensor technology and specific satellite launch missions targeting global biomass mapping in support of international conventions.

The range of spatial resolution was important, as a simple metric, to examine the range of scale of applicability both in quantifying ecosystem biomass carbon estimates for the entire North American boreal as well as landscape-level conservation areas in the Yukon Territory and Northeast British Columbia. Data including the entire North American boreal enable calculation of estimates of forest above-ground biomass density and often are developed as global data layers useful for multinational comparisons.

Uncertainty layers are the per-pixel standard error in Mg/ha as the biomass density value for a single pixel may have large uncertainty when making validation comparisons with field plot data measurements. Depending on the data set, a best practice is to provide aggregated density estimates for areas of 5,000 to 10,000 ha areas along with regional spatial distribution patterns. These patterns are likely systemic in the data and driven by satellite sensor errors often appearing as artificial data value breaks between raster cell values and over large areas created from either temporally different data scene mosaics or other signal errors. One example of signal errors is found in the high resolution binary wetlands mapping in the southern Yukon Territory where mosaics between satellite path scenes display poor edge-matching[9]. Similarly, patterns of no data result when satellite sensors fail (e.g. Landsat 7 that is to be replaced by Landsat 9 in late 2020[10]).

3.2 Search Spatial Scales

Searching regional, national and global data catalogues identified data that may best support quantifying terrestrial biomass estimates at various scales, including landscape conservation areas, while also capturing the approximately six-million square kilometre area of the North American boreal forest.

3.3 Literature Search

Literature searches and keyword using Google Scholar and Google captured recent scientific papers and spatial data not otherwise available. Authors of data of interest were contacted by email and/or phone. Finally, organizations and colleagues provided answers and contact information.

3.4 Data Collection, Preparation and Review

Data sources identified in the search discovery process meeting the criteria were downloaded and documented. Raster data were mosaicked in their native coordinate system to create a seamless single coverage. These data were then clipped to a North American boreal classification shapefile and projected to the Canadian Lambert Conformal Conic – NAD83 datum coordinate system displaying good directional and shape relationships for mid-latitude regions having a predominant east-west extent. Raster projection applied the

ArcGIS bilinear interpolation approximation method. Output raster cell sizes matched the published resolution.

Each data layer was qualitatively reviewed for errors by theming using a quantile classification in seven biomass density classes and excluding values = 0. Quantile classification is a data classification method that groups the same number of raster cells into each of whatever number of biomass density classes is selected. This classification is helpful to display higher biomass density values that occupy a smaller area, a common characteristic of these data. The choice of seven classes is subjective and selected to highlight areas with the greatest biomass density and the overall biomass patterning and distribution across the region.

Variability in the biomass density per cell is high among the data sets. This might be explained by many factors including satellite sensor differences, methodology and algorithm differences, resolution, land cover masking, and type of biomass being targeted. Such variability makes numeric comparisons between layers challenging and not advisable.

4.0 Gaps and Opportunities in Spatial Data and Knowledge

- Upcoming satellite missions will offer exciting new opportunities to fill gaps in terrestrial biomass estimation at finer scales, increased accuracy (spatial and attribute) and annual updates.

- Public access to a Canadian wetland mapping layer that is current and complete (e.g. including peatland complexes).

- Advances in cloud computation enabling automated model processes using Big Data to achieve rapid terrestrial biomass spatial analytics and trend reporting. This is important for automating terrestrial biomass data development and reducing time gaps.

- Updated models projecting potential carbon sequestration for subsoil (FAO) and terrestrial forest biomass in 2050 and 2100 under various global climate model scenarios.

- The United Nations World Conservation Mapping Centre published a global harmonized biomass and biodiversity layer in 2020 (using 2010 data[11]) useful for land planning.

- Biomass carbon in the North American boreal is held within a variety of ecosystem types (forest, moss, wetlands/peatlands, permafrost, and other organic soils). From this report's survey of available spatial data, forest biomass layers are produced/updated disproportionately more often compared to soil and non-forested ecosystems layers. Current and complete ecosystem biomass mapping is needed, with consistent and connected models, to enable a full picture of terrestrial biomass carbon reservoirs.

- Biomass data for Canada's long-term forest monitoring plots appear to be limited – at least publically and within global databases[12] – inhibiting ground validation of remotely sensed biomass data.

- Accuracy reporting for satellite-derived biomass spatial data needs consistent uncertainty/error reporting. Sensor failures, limited cloud-free days, satellite path, time and sensor angle to the earth's surface, and topographic distortion all combine to complicate generating a consistent, accurate layer. It is an effective practice to use only those data layers accompanied with a per-pixel uncertainty layer of the biomass density per cell.

5.0 Proxy Options for Estimating Biomass Carbon

Where boreal ecosystems have been mapped (e.g. wetlands), but are missing quantified biomass values (remotely sensed), a reasonable coarse estimation approach might include extrapolating field-based measurements of biomass density, or sub-regional mapping efforts, to the land cover types across the region of interest, or even across the full extent of the boreal such as by applying an extrapolation method using LiDAR plots in Canada's boreal forests[13] Alternatively, another approach for estimating biomass carbon in peatland, permafrost, etc. is applying a zonal stats function across select ecosystem types using data circa 2010 in Spawn et al. (2020).

6.0 Recent Advances and Recommendations

Several opportunities for new data, new analysis approaches, and new projects supporting advances in biomass mapping were identified for this report. These initiatives will support the increasing need for higher resolution, temporarily consistent spatial data collection focused on dynamic and static biomass. Application of the Google Earth Engine cloud computing infrastructure is enabling researchers to create automated processes attached to big data analyses. A recent Canadian example is the 2019 Canadian Wetland Inventory[14] at 10m resolution which will be very helpful in providing the cross-country ability to identify wetland ecosystems, including peat complexes, when released in late 2020. Biomass density values were not included in the scope of this project but might be reasonably estimated based on type and size of wetland complex.

6.1 New Data

Two notable new satellites launching in 2021 include:

i) European Space Agency (ESA) Earth Explorer - Biomass[15] satellite mission with five-year duration covering at least eight growth cycles. This mission has the following objectives:

  - Improved understanding and quantification of land contribution to global carbon cycle
  - Quantify flux of carbon from land use change
  - Greatly improved modelling of **terrestrial carbon cycle**
  - Gridded high-resolution global estimates of **above ground biomass**
  - Monitoring and quantification of forest disturbance and recovery
  - Monitoring and **quantification of wetland areas** and forest inundation
  - Mapping **subsurface structures, polar regions**

ii) ESA Earth Explorer – Fluorescence Explorer (FLEX)[16] dynamic carbon cycles including mapping gross primary productivity (GPP). This is a planned 2022 mission launch to map vegetation fluorescence to quantify photosynthetic activity. Currently, photosynthetic activity cannot be measured accurately from space with greenness indices (NDVI), but FLEX novel instrumentation will be capable of achieving this.

iii) An innovative satellite named The Global Ecosystem Dynamics Investigation (GEDI)[17] LiDAR mission launched December 2018 and is installed on the International Space Station with a two-year mission timeline. The first data were released to the public in late fall 2019. This mission has the following objectives:

- Produce the first high resolution laser ranging observations of the 3D structure of the Earth.
- Make **precise measurements of forest canopy** height, canopy vertical structure, and surface elevation.
- Significantly improve our ability to **characterize important carbon and water cycling processes**, biodiversity, and habitat.

6.2 Innovative Projects

A select example of ongoing innovative projects to track for new methods and data include:

i) World Wildlife Fund and McMaster University are planning a Canada-wide satellite-derived, repeatable mapping process documenting carbon density for soils, peat bogs, and forest biomass. The first results are expected in December 2020[18].

ii) The Arctic Boreal Vulnerability Experiment (ABoVE)[19] is actively producing data at a variety of scales in the boreal. Ongoing monitoring of the website and attendance at the regular webinars will aid in tracking thematic work at scales of Yukon/Northwest Territory or North American boreal; including biomass and GPP, permafrost, peatlands, etc.

iii) The Cascadia Partner Forum Spatial Priorities Tool 'TerrAdapt'[20] is partnering with World Wildlife Fund International to develop a dynamic, automated, cloud-based (using Google Earth Engine) static above-ground terrestrial biomass carbon module. It is expected to be completed by late 2021 for two regions: British Columbia and Washington state Cascadia region and the Dawna Tenasserim Transboundary area straddling the Myanmar/Thailand border. This module will integrate with existing ones currently dynamically tracking land cover, landscape integrity, habitat connectivity, and biome area shifts based on climate model future projections.

6.3 Recommendations

A primary goal of this spatial data survey is to examine publically available information layers supporting the calculation and comparison across multiple jurisdictions of estimates of terrestrial ecosystems static biomass carbon. Wildlife Conservation Society Canada and its international partners collaborate on ecosystem biomass carbon initiatives and investments and benefit from having a consistent biomass reference layer to make decisions with. Applied conservation actions (e.g. land investment, acquisition, management) have similar needs for assessing biomass carbon data but require a higher confidence in the mapping and quantification of biomass densities. These data are needed for regional scale or smaller, such as Indigenous Protected Conservation Areas and protected areas.

A second goal is to identify the most recent data and trends to visualize and quantify the amount of existing boreal ecosystems biomass. Increasing human pressures on forests around the world indicate an immediate need for current and repeatable data development processes to monitor threats and take pre-emptive conservation actions with new data and analyses.

Identifying a perfect dataset (scalable, full ecosystem, recent) is not possible. Global datasets share in common a large geographic coverage but differ in almost every other aspect of their development including sensor sensitivity to biomass signatures, temporality, vegetation masks and definitions (e.g. forest types), methods/algorithms applied, spatial resolution, and error assessment. International requirements from governments and institutions for carbon accounting, and routine annual data releases supporting biomass monitoring, are being implemented and will help support the need for an annually updated biomass layer with consistent assumptions and hardware.

Global biomass density data generally do not scale down well to regional and sub-regional applications. Although the spatial resolution may be small enough to enable a clear view, the specific relevance to the smaller area may be limited. Some layers map all of the vegetation biomass, while others are focused on forest, but in both cases the land cover masks may not provide adequate distinction between vegetation classes to be accurate. Density units vary between layers – most are measuring total biomass [Mg/ha], and some measure biomass of carbon alone [MgC/ha].

Uncertainty error is perhaps the most systemic limitation on the scalability of the data. Error for the boreal forest, in particular the western portion of Canada is, in some cases such as the European Space Agency's Climate Change Initiative (CCI) biomass estimates, at the higher range of global values. Not all biomass spatial data are accompanied with uncertainty estimates spatially, leaving a worrisome gap of information to interpret. At best, global data sets might be applied to large multi-jurisdictional regions (e.g. boreal ecozones or larger) while discussing quantitative values in terms of regional means, avoiding pixel-specific attributes.

The United Nations World Conservation Mapping Centre Harmonized above and below-ground biomass map compiled in 2020 (data circa 2010), using the reliable publically-available global datasets on biomass carbon[21], is a good applied example of synthesizing layers together to aid in quantifying a more complete picture of terrestrial ecosystem biomass, including linkages to biodiversity, risk, and conservation priorities. A few of these layers are available from the authors and are useful when seeking a quantification of biomass combining together terrestrial ecosystems and soils. Santoro et al. (2020)[22] applied updated methodologies to 2010 data to create global harmonized above and below-ground ecosystem biomass carbon density data at 300m resolution. These data are included for reference although published too late to be given full consideration in this report. Although useful these data inputs are a decade old.

Recommendation summaries are below and detailed data descriptions, including maps, are located in the appendices.

6.3.1 Recommendation: Above-ground forest biomass density (Appendix B)

Above-ground forest biomass (AGB) includes tree stems, bark, branches, twigs. Recommend adopting the European Space Agency Climate Change Initiative (ESA_CCI) above-ground forest biomass maps (2017) as a WCSC **global** standard to map, quantify and compare boreal forest biomass across broad jurisdictional areas over time. The above-ground biomass and standard error spatial data will be annually updated and CCI AGB change maps are forthcoming with the next annual update. If quantifying current global biomass density over time defines important needs at this scale, the ESA_CCI data are currently unmatched. Note: comparisons between the 2017 AGB layer with the earlier 2010 GlobBiomass AGB dataset are discouraged as they are different methodologies. See Appendix B for a description and maps. Within Canada, smaller **regional** biomass comparisons are better suited to the National Forest Inventory [NFI 2011) biomass layer [see Appendix F in Table for Forest Vegetation].

6.3.2 Recommendation: Below-ground forest biomass density (Appendix C)

Below-ground includes tree roots estimated by using root-to-shoot ratios published in 2006 IPCC guidelines for National Greenhouse Gas Inventories. Recommend including below-ground terrestrial forest biomass density estimates to complement above-ground estimates. Although the boreal forest biome has a lower root to shoot ratio than other biome types (mean 0.205 compared with a mean of 0.900 for all biomes)[23], the significant size of the boreal forest and its global importance in terms of carbon stores strongly suggests that below-ground biomass is an important factor in understanding Boreal biomass carbon. Data from the Oak Ridge National Laboratory (2010) provide a strong option although at 300m cell resolution with data collected over a decade ago. A 2020 paper applying a new harmonized methodology and forest/non-forest land cover with an improved methodology using 2010 data is interesting and potentially useful when realizing ecosystems, not just forests, were mapped with biomass **carbon** density units [MgC/ha][24].

6.3.3 Recommendation: Soil organic carbon density (Appendix D)

Soil organic carbon data may be confused with below-ground biomass layers – the latter referring to tree roots. Recommend adopting the recently upgraded version (2017) of the top and subsurface SOILGrids by Hengl et al.[25] as a standard reference for soil organic carbon density. Total soil organic carbon includes the following attributes: top and subsoil bulk density; top and subsoil organic carbon content; and, a dilution factor (see Appendix D). These data are based on a repeatable automated process from soil profile and covariate data that is ongoing. The mapping accuracy of each targeted soil property and classes is limited with an amount of variation explained by the model in ranges between 30 and 70%[26].

6.3.4 Recommendation: Wetland (peatlands, fen, bog) biomass density

Revise as necessary and when new data are available update the WCSC peatlands map product. An excellent data compilation, assessment[27] , and story map have been completed by Meg Southee, WCSC. Additional work includes identifying the biomass density distribution of peatlands across Canada and to expand to include the Alaskan boreal areas.

New data include interesting methods using Cloud Computing on the Google Earth Engine platform and 10m satellite imagery to generate a new wetlands map of Canada. A map shared by the author (Figure 1) displays pre-validation wetland data for the Canadian boreal compiled by ecoregion.

A release date for these 10-m wetlands data is planned for late 2020. This methodology allows for repeatability and rapid temporal data update as new imagery is added into the Google infrastructure (M. Mahdianpari et al. 2019)[28]

A new global peatlands layer is included in work underway by Dr. Alexandra Barthelmes 'Developing a new global soil map (incl. peatlands) based on available data sets'.[29] The author shared a preliminary map for this report (Figure 2.)

6.3.5 Recommendation: Permafrost extent (Appendix E)

Limited mapping of northern boreal permafrost has occurred and current estimates of soil organic carbon do not explicitly identify permafrost-affected soils[30]. Recommend tracking the changing distribution and change trends for permafrost with ESA_CCI permafrost programme data (circa 2013-2017), even though this is a first generation product where the spatial distribution of the southern extent of the Boreal in North America appears too restricted for immediate use. A recent product from GlobPermafrost[31] uniquely looks at thermal changes in soil surface temperatures to map permafrost. There is still a need to evaluate how these two products may be used, perhaps in an integrative fashion, to benefit a full ecosystem biomass accounting, including identifying some estimation of an average biomass density per permafrost class.

Figure 1. Pre-validation map of first generation Canadian wetland map using cloud computing and Google Earth Engine. (M. Mahdianpari et al. 2019)

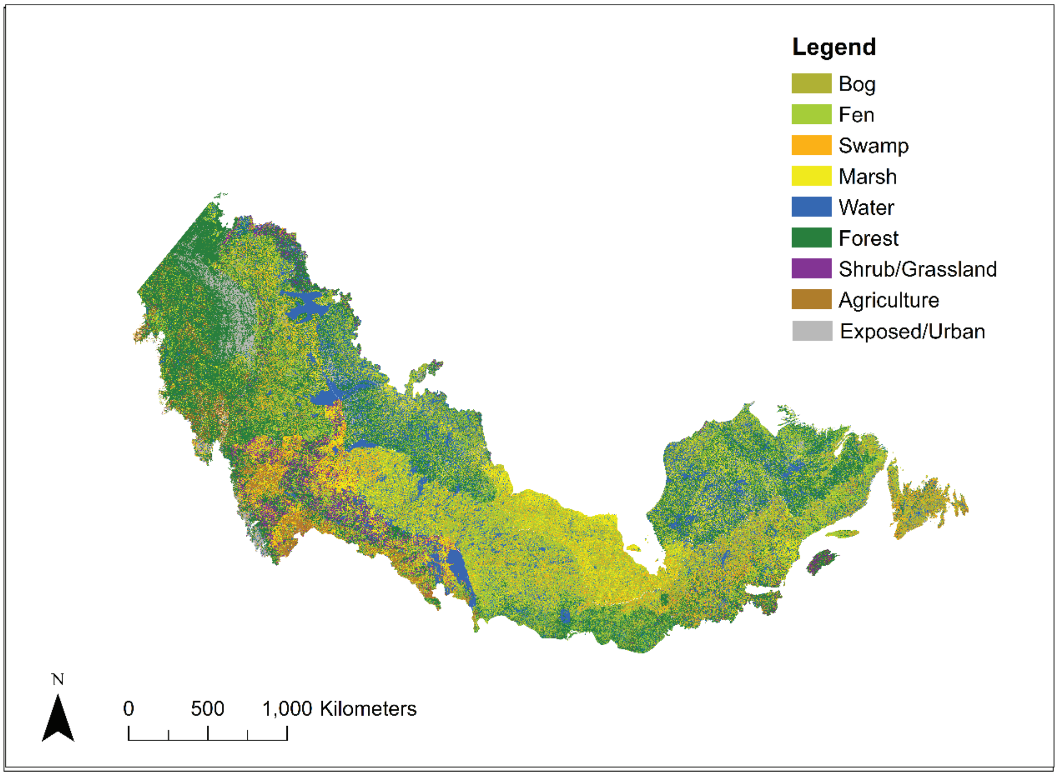
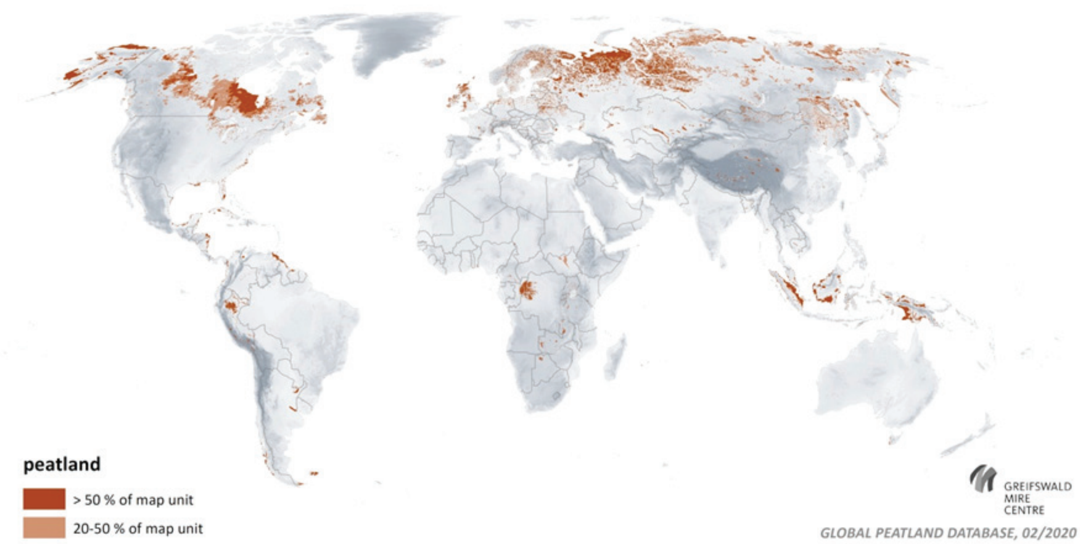


Figure 2. An unpublished draft map of peatlands developed by Global Peatlands Database in partnership with the Greifswald Mire Centre, Germany as part of a new global soil map initiative. Map shared by author, June 2020.



Appendix A – Individuals Contacted

Joyce Arabian, Specialist, GIS & Spatial Analysis WWF – Canada. Call regarding status of McMaster/WWF remote sensing of Canada-wide biomass carbon.

Dr. Alexandra Barthelmes - DUENE e.V. (Partner in the Greifswald Mire Centre, Germany) inquiry regarding 'Developing a new global soil map (incl. peatlands) based on available data sets'.[32] Although these data are not yet available the author has shared am example map included in this report.

Gwen Bridge (Independent, Y2Y) – Unpublished 2019 report for the Yellowstone to Yukon Conservation Initiative by M. Mitchell "Ecosystem Service Provision in the Canadian Y2Y Region".

Dr. Gary Bull – Professor and Head of Department, Forest Resources Management, University of British Columbia. Forest biomass, carbon and atmospheric CO_2.

Dr. Ron Hall – Emeritus Scientist, Natural Resources Canada. Canada Satellite Vegetation Inventory.[33]

Dr. Masoud Mahdianpari – lead author "Big Data for a Big Country: The First Generation of Canadian Wetland Inventory Map. 2020.[34]

Corinna Ravilious – Senior GIS Officer, UN Environment Programme, World Conservation Monitoring Centre [WCMC]. Data request from the paper "Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. 2020".[35]

Alain Richard and Darrel Kovacz – Ducks Unlimited. Inquiry on the status of a Canada Wetland Inventory, peatlands ongoing mapping project.

Meg Southee – Wildlife Conservation Society Canada (WCSC). Data sources for a WCSC Peatlands Story Map.[36]

Dr. Dave Thau – Data and Technology Global Lead Scientist, World Wildlife Fund (WWF). WWF Global, and Canadian carbon initiatives including spatial data.

Dr. Dan Thompson – Scientist, Natural Resources Canada. Email inquiry regarding treed boreal peatlands in Canada.[37]

Appendix B – Recommendation for Above-ground Forest Biomass Density

The European Space Agency (ESA) Climate Change Initiative (CCI) Biomass programme dataset comprises estimates of forest above-ground biomass for the year 2017.

The ESA-CCI Programme functions to provide systematic monitoring of the global climate system using earth observation spatial data archives[38]. These data are critical to monitoring, evaluating progress and making decisions within the multinational actions agreed to under the United Nations Framework Convention on Climate Change. The objective is to provide public access and increased use of remotely sensed global data to users around the world.

Included in CCI is the Biomass team providing global maps of above-ground biomass for four epochs (mid 1990s, 2007-2010, 2017/2018, 2018/2019) at 100m cell resolution. Biomass is defined as the mass, expressed as live woody parts (stem, bark, branches and twigs) of all living trees excluding stump and roots. This report recommends applying these data to map and quantify above-ground biomass for the North American boreal forest. The AdaptWest Climate Resilience Data Explorer[39] include the previous version data from 2010.

Data lineage includes: PALSAR-2 instrument on the ALOS-2 satellite, and data from the Sentinel-1 satellite. A separate data layer is provided with per-pixel uncertainty expressed as standard error in Mg/ha. These data are the first to integrate multiple acquisitions from the Copernicus Sentinel-1 mission and Japan's ALOS mission. Introducing data from these satellites' sensors improves the accuracy of forest biomass detection across different biomes, and is a significant advance on the previous 2010 map generated by the GlobBiomass project (currently loaded into the Adaptwest Climate Resilience Data Explorer tool).

Citation: Santoro, M.; Cartus, O. (2019): ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the year 2017, v1. Centre for Environmental Data Analysis, 02 December 2019. http://dx.doi.org/10.5285/bedc59f37c9545c981a839eb552e4084

Spatial data and user guide: https://catalogue.ceda.ac.uk/uuid/bedc59f37c9545c981a839eb552e4084

Units : Mg/ha (biomass density, live weight)

Figure 3. ESA_CCI boreal forest above-ground biomass density estimates (Mg/ha). Quantile classification exclusing zero values.

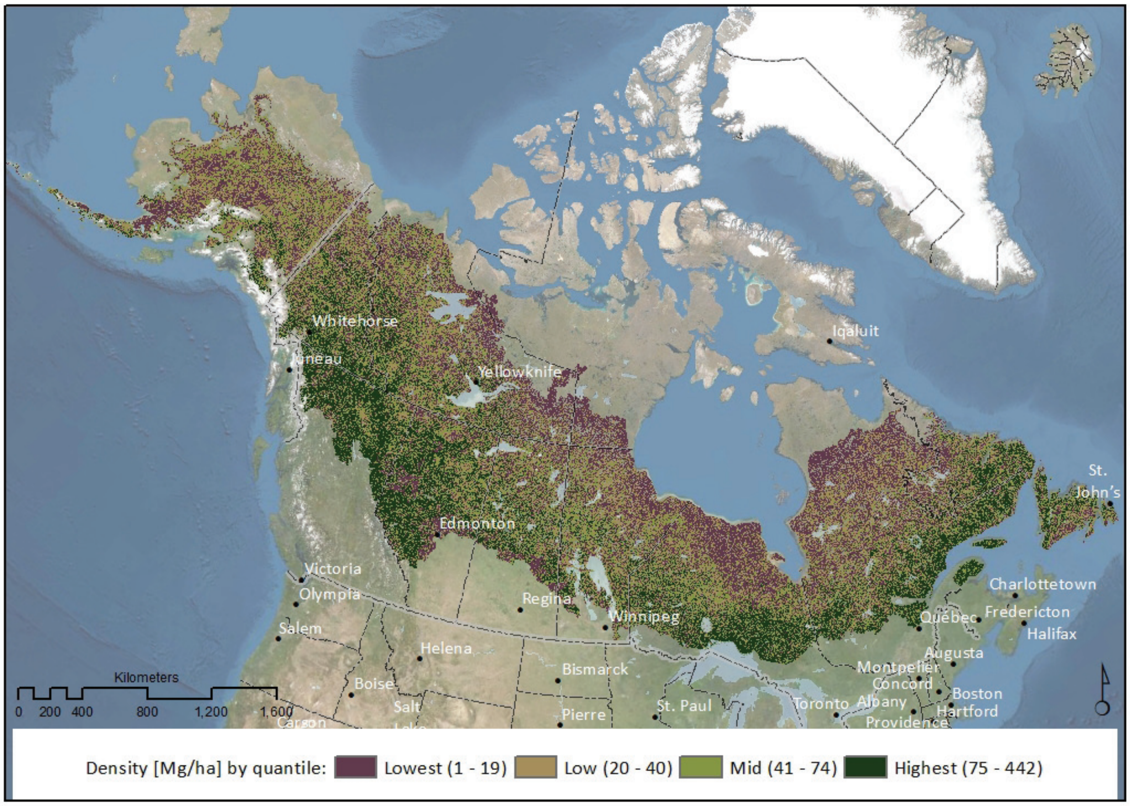
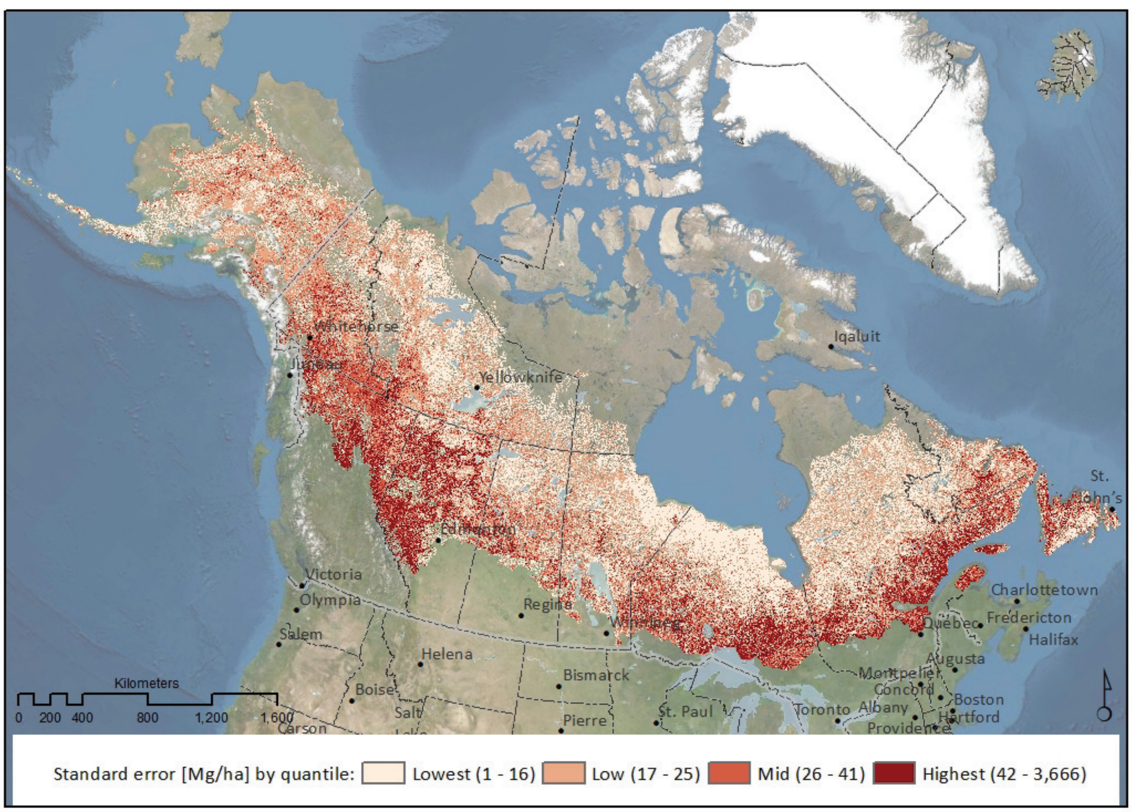


Figure 4. ESI_CCI boreal forest per pixel uncertainty calculated as a density (Mg/ha).



Appendix C – Recommendation for Below-ground forest biomass density

The Oak Ridge National Laboratory generated both an above and below-ground biomass carbon (living roots) density data set for the year 2010. These are compilations of multiple peer reviewed inputs. The below-ground biomass layer combines matching maps derived from each aboveground biomass map (woody and tundra biomass) and land-cover specific empirical models.

Below-ground biomass of trees was generated using a multiple regression model that considers root-to-shoot covariance with above-ground biomass density, mean annual temperature, the stand's regenerative origins (planted or natural), and the stand phylogeny[40].

Maps reporting the accumulated uncertainty of pixel-level estimates were created. Uncertainty represents the cumulative standard error that has been propagated through the harmonization process.

Citation: Spawn, S.A., and H.K. Gibbs. 2020. Global Above and Below-ground Biomass Carbon Density Maps for the Year 2010. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1763

Spatial Data: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763

Units : MgC/ha (biomass carbon density)

Figure 5. ORNL bleow-ground boreal forest biomass carbon density (MgC/ha).

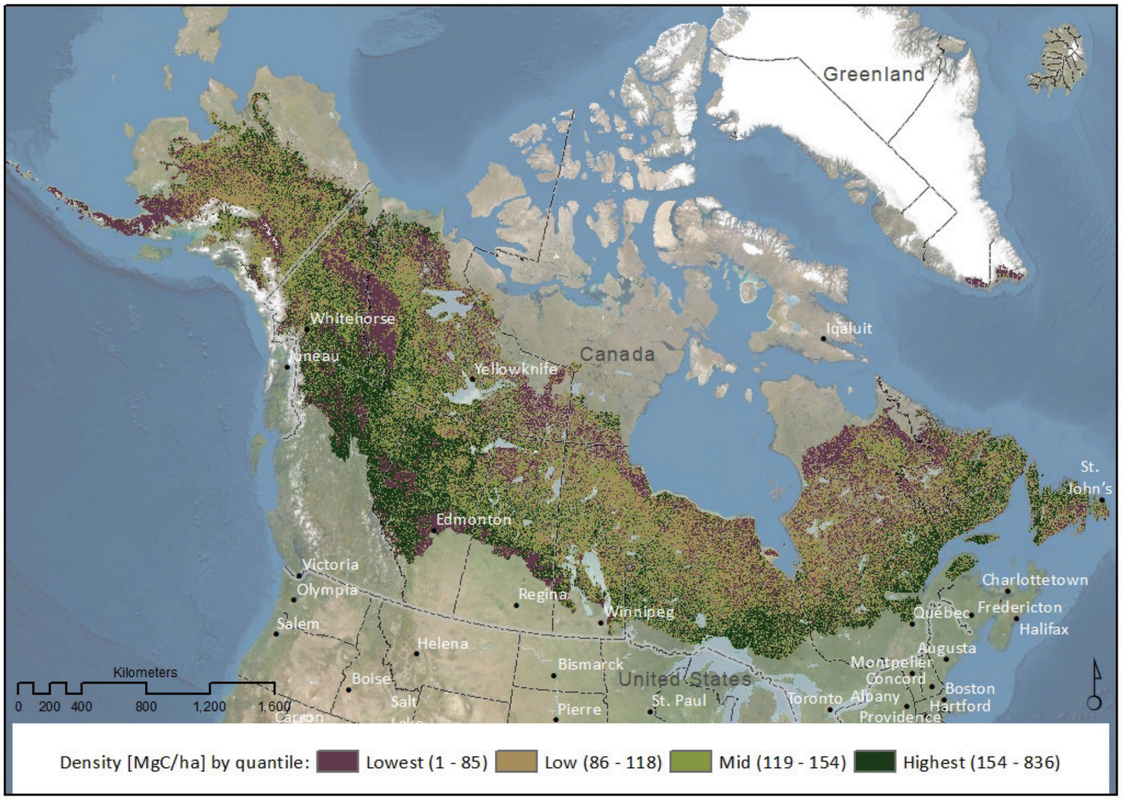
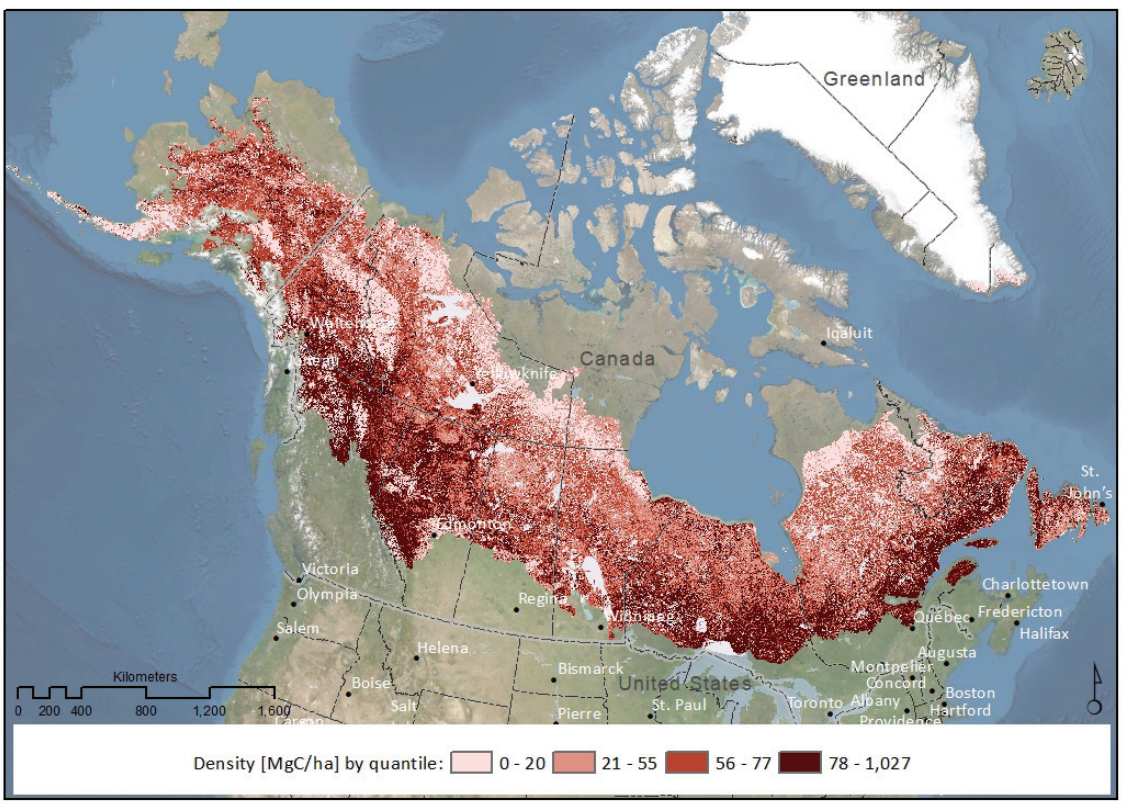


Figure 6. ORNL below-ground boreal forest biomass carbon uncertainty as pixel density (MgC/ha).



Appendix D – Recommendation Soil Organic Carbon Density

The International Soil Reference and Information Centre (ISRIC) has a mission to serve the international community as a custodian of global soil information[41]. The World Soil Information Service (WoSIS) collects soil geographical and taxonomical information from various global data providers and completes quality assessments and standards. The North American sources include:

- Canadian Soil Information Service (CanSIS), Agriculture and Agri-Food Canada, Government of Canada (https://sis.agr.gc.ca/cansis).
- Canadian Upland Forest Soil Carbon Database (May 2016 version), Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.
- United States Department of Agriculture (with Universities, State and Federal agencies, and private members) hosts a large collection of soil profile data shared by the National Cooperative Soil Survey, National Cooperative Soil Characterization Database (NCSS, NRCS, for data see here); includes some 1100 'international profiles').

Current data in WoSIS are from 2017. The soil organic carbon density mapping units are in kg per m^3 and compiled across seven standard depths. These data are created using a global compilation of soil ground-based observations (about 150,000) for model fitting. Accuracy assessments of the maps are available. The spatial resolution is 250m.

Calculation of the full profile organic carbon density uses the following formula. The SoilGRID layers appear to have generated the needed inputs. Additional methods in BC Strategic Priorities [2014][42]

$$\mathrm{COS}_t = \sum_{\mathrm{horizon}=i}^{\mathrm{horizon}=n} \left(\left[\left(\mathrm{BD}_i \times \mathrm{TH}_i \times \left[1 - \frac{\mathrm{CR}_i}{100} \right] \right) \times \mathrm{C}_i \right] \times 100 \right),$$

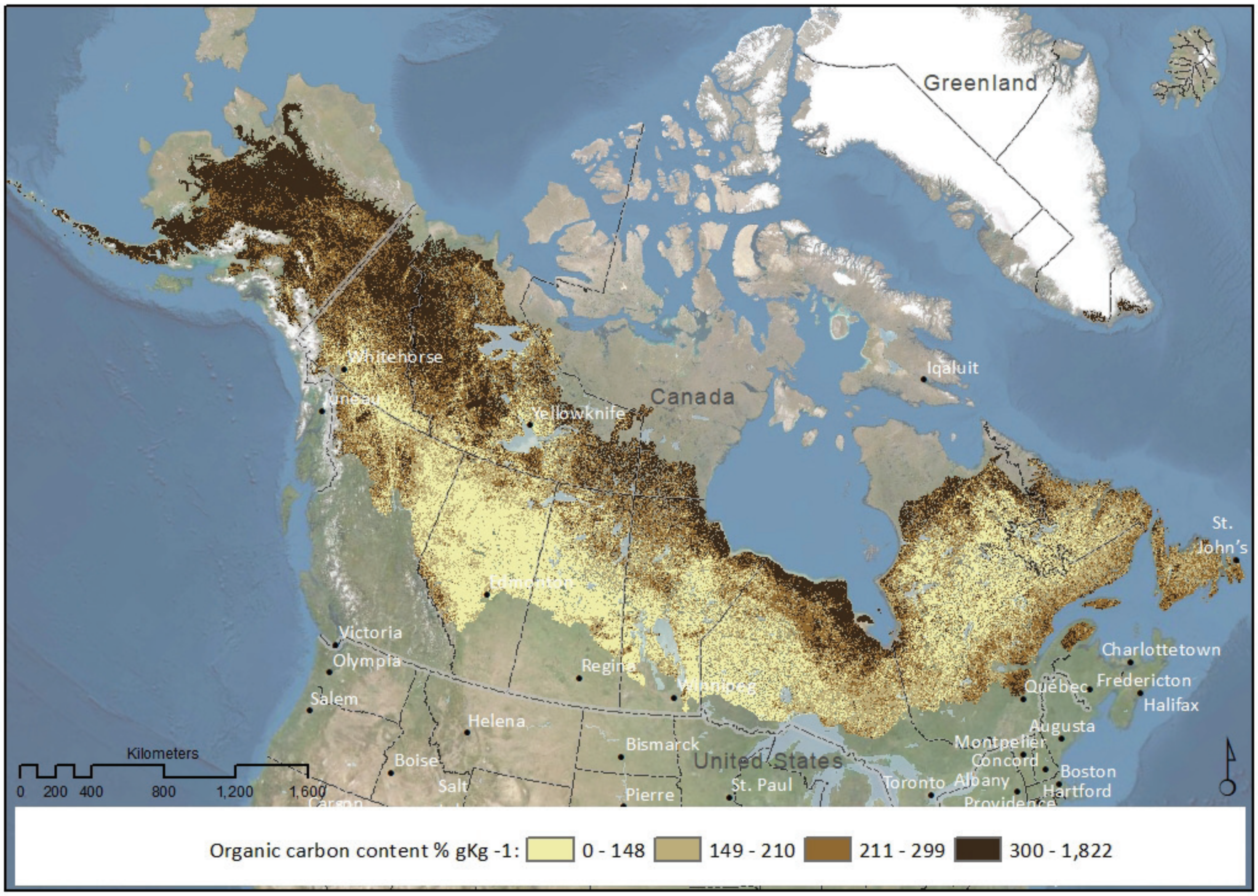
where COS**t** = Full profile organic carbon (Mg/ha); BD**i** = Bulk density of horizon **i** (g/cm3); TH**i** = Thickness of horizon **i** (m); CR**i** = Volume of thick fragments of the horizon **i** (vol. %); C**i** = % of organic carbon in **i** horizon (%).[43]

Citation: Hengl T, Mendes de Jesus J, Heuvelink GBM, Ruiperez Gonzalez M, Kilibarda M, Blagotić A, et al. (2017) SoilGrids250m: Global gridded soil information based on machine learning. PLoS ONE 12(2): e0169748. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0169748

Spatial data: https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c02ddf8b-cbfb-4533-a9c3-7bf0790fd042

Accuracy assessments of the maps: Hengl et at. (2017) DOI: 10.1371/journal.pone.0169748

Figure 7. ISRC boreal soil organic carbon content (%g/Kg) displayed with a quantile classification.



Appendix E – Recommendation for Permafrost Extent

These permafrost extent data are produced as a part of the European Space Agency's (ESA) Climate Change Initiative (CCI) Permafrost project. Raster data are released annually following the Julian year beginning and end to correspond to average annual ground temperatures. This period is the basis for the retrieval of yearly fraction of permafrost-underlain and permafrost-free area within a pixel. The IPA (International Permafrost Association) classification is followed to capture the permafrost zones: isolated (0-10%), sporadic (10-50%), discontinuous (50-90%) and continuous permafrost (90-100%). These data appear to be too limited in the southern extent, although appealing for the potential of annual updates and improvements.

Figure 8 Citation: Obu, J.; Westermann, S.; Barboux, C.; Bartsch, A.; Delaloye, R.; Grosse, G.; Heim, B.; Hugelius, G.; Irrgang, A.; Kääb, A.M.; Kroisleitner, C.; Matthes, H.; Nitze, I.; Pellet, C.; Seifert, F.M.; Strozzi, T.; Wegmüller, U.; Wieczorek, M.; Wiesmann, A. (2019): ESA Permafrost Climate Change Initiative (Permafrost_cci): Permafrost Extent for the Northern Hemisphere, v1.0. Centre for Environmental Data Analysis, 19 December 2019. http://dx.doi.org/10.5285/c7590fe40d8e44169d511c70a60ccbcc

Figure 8 Spatial data:
https://catalogue.ceda.ac.uk/uuid/c7590fe40d8e44169d511c70a60ccbcc

A recent larger coverage permafrost layer by Obu. J. et al. [2019] is generated by "an equilibrium state model for the temperature at the top of the permafrost (TTOP model) for the 2000–2016 period, driven by remotely-sensed land surface temperatures, down-scaled ERA-Interim climate reanalysis data, tundra wetness classes, and landcover map from the ESA Landcover Climate Change Initiative (CCI) project." Note the broader spatial distribution of the permafrost classes and southward extending boundary.

Figure 9 Citation: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km scale. Jaroslav Obua, Sebastian Westermann, Annett Bartsch, Nikolai Berdnikov,Hanne H. Christiansen, Avirmed Dashtseren, Reynald Delaloye, Bo Elberling,Bernd Etzelmüllera, Alexander Kholodov, Artem Khomutovc, Andreas Kääba, Marina O. Leibmanc, Antoni G. Lewkowiczi, Santosh K. Pandah, Vladimir Romanovskyh, Robert G. Wayk, Andreas Westergaard-Nielseng, Tonghua Wum, Jambaljav Yamkhine, Defu Zou. Earth Sciences Review. April 2019. DOI: 10.1016/j.earscirev.2019.04.023

Figure 9 Spatial data: https://doi.pangaea.de/10.1594/PANGAEA.888600

Figure 8. ESA_CCI permafrost extent for the northern hemisphere boreal forest region.

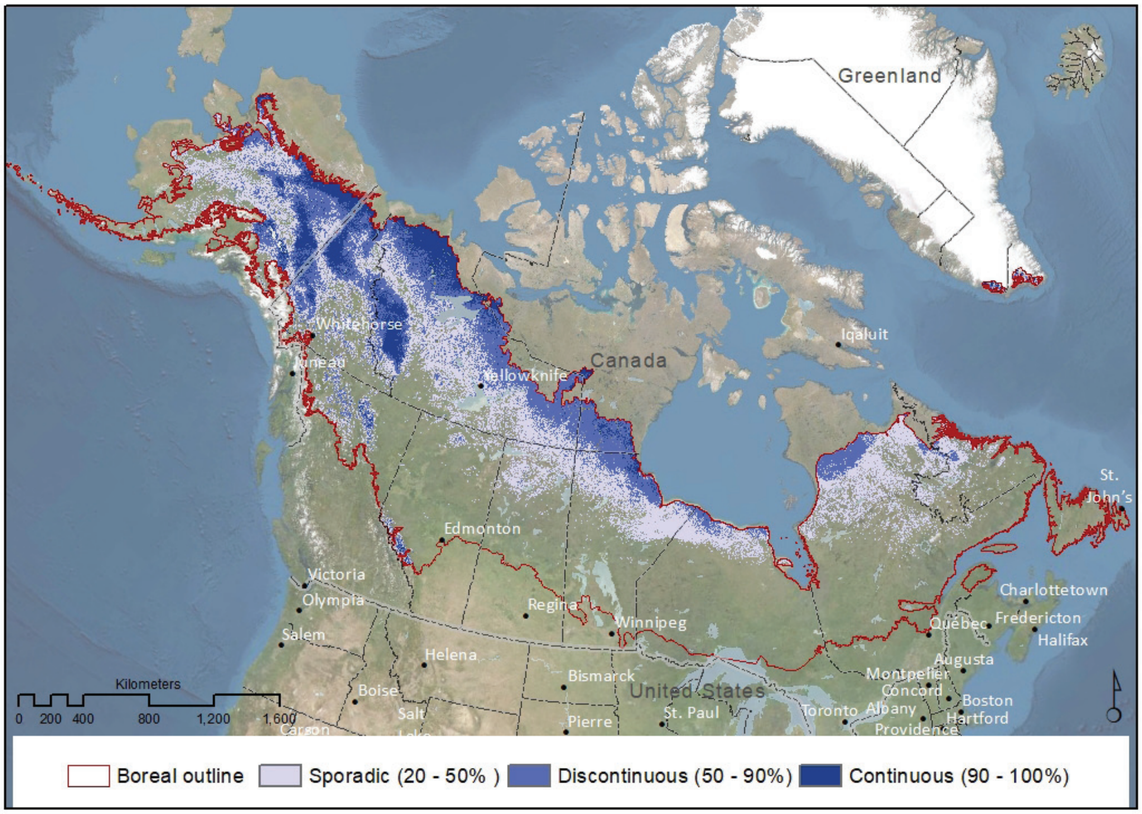
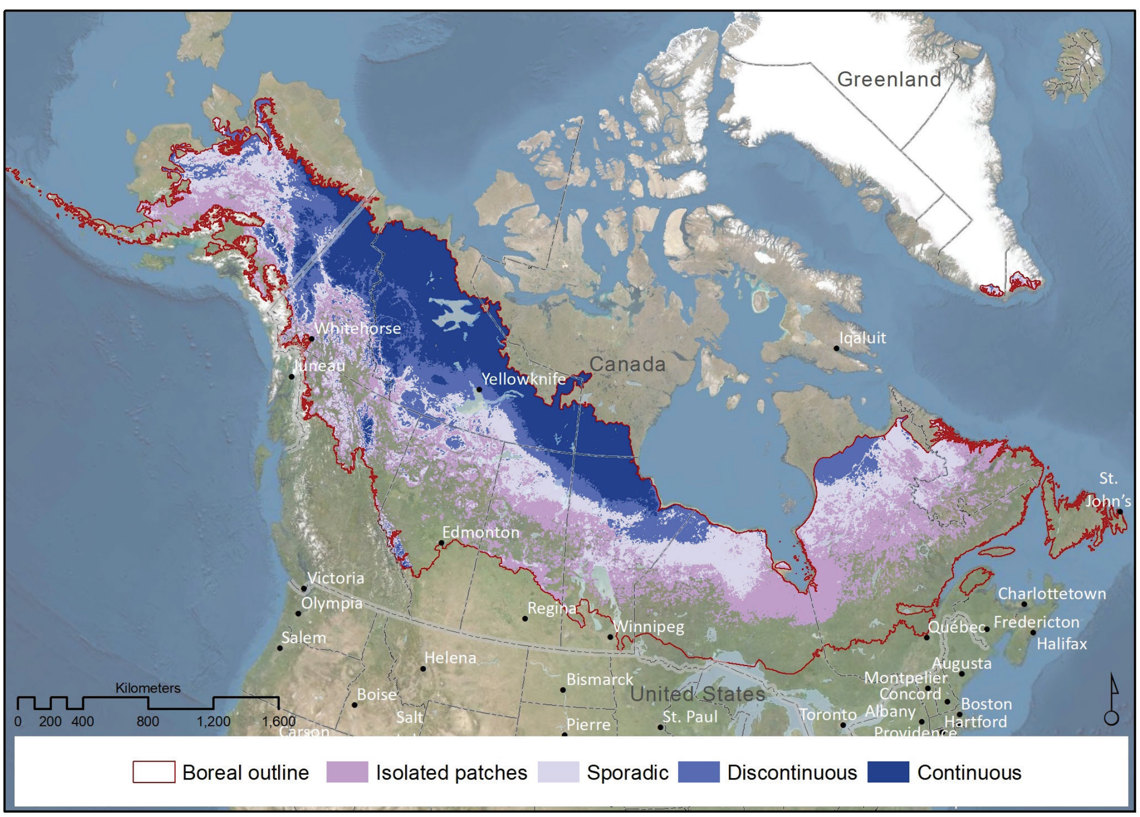


Figure 9. Northern hemisphere permafrost based on TTOP modelling for 2000-2016 [Obu, J. et al. 2019].



Appendix F – Table of Compiled Ecosystem Biomass Spatial Data Sources

This table documents all spatial data discovered during the search process for static and dynamic terrestrial forest biomass, wetlands, soil organic carbon, and harmonized layers. Harmonized layers include collecting various input spatial layers with different scales and sources, creating crosswalks and a standard resolution (coarser). These projects require costly and substantial effort to generate outputs and are useful where a more complete and standardized summary of biomass carbon is needed (e.g. for multi-national and global analyses). National and sub-national analyses may be better off custom-building a harmonized layer to maintain finer resolutions.

Forest vegetation (above and below-ground): estimates of stored static carbon

Spatial Data Sources Reviewed as a part of the report, Kehm G. 2021. "North American Boreal Ecosystem Biomass: A Spatial Data Review".

Note: green cells denote preferred layers referenced in the report

Thematic Area	Reference Name	Entity	Geographic Coverage	Reference Year	Unit	Resolution	Reference	Comment	URL
1) Dynamic Ecosystem Carbon									
Net ecosystem carbon (CO_2) ecosystem exchange	SMAP L4	NSIDC (National Snow and Ice Center)	Global	2015-present		9kmx9km	Kimball, J. S., L. A. Jones, T. Kundig, and R. Reichle. 2018. SMAP L4 Global Daily 9 km EASE-Grid Carbon Net Ecosystem Exchange, Version 4. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/9831N0JGVAF6. [Date Accessed].	-	https://nsidc.org/data/search/#keywords=SOIL+ORGANIC+CARBON+SOC/sortKeys=score,,desc/facetFilters=%257B%257D/pageNumber=1/itemsPerPage=25
2) Gross Primary Productivity [GPP]									
GPP Density by Ecozones	MODIS	USGS	Global	Circa. 2017	kg C/m²	500m	MOD17A2H Version 6 is a cumulative 8-day composite. MOD17A2HGF will be generated at the end of each year when the entire yearly 8-day MOD15A2H is available.		https://modis.gsfc.nasa.gov/data/dataprod/mod17.php
GPP Long-term Density Variation		Zheng	Global	1982-2017	g C m-2 day-1	1000m	From paper by Zheng et al. 2019		https://www.earth-syst-sci-data-discuss.net/essd-2019-126/
GPP Boreal Evergreen Needleleaf forest - site level validation	BIGFOOT (MODIS)	NASA Terrestrial Ecology Program	NA Boreal Forest	2001-2003		25m	Turner, D.P., W. D. Ritts, and M. Gregory. 2006. BigFoot GPP Surfaces for North and South American Sites, 2000-2004		https://daac.ornl.gov/BIGFOOT_VAL/guides/bf_gpp_surf_guide.html
Gross Dry Matter Productivity	CGLOPS-GDMP	Copernicus Global Land Service	Global	2014-	kgDM/ha/day	300m	This dataset provides temporally consistent and harmonized global maps of aboveground and belowground biomass carbon density for the year 2010 at a 300-m spatial resolution. The aboveground biomass map integrates land-cover specific, remotely sensed maps of woody, grassland, cropland, and tundra biomass. Input maps were amassed from the published literature and, where necessary, updated to cover the focal extent or time period. The belowground biomass map similarly integrates matching maps derived from each aboveground biomass map and land-cover specific empirical models. Aboveground and belowground maps were then integrated separately using ancillary maps of percent tree cover and landcover and a rule-based decision tree. Maps reporting the accumulated uncertainty of pixel-level estimates are also provided.		https://land.copernicus.eu/global/products/dmp
				Planned (2015-2019)			1 km maps of daily CO2 fluxes (GPP, NPP, Reco, NEE), wetland CH4 emissions, Net Ecosystem Carbon Balance; annual surface SOC stocks (2003 to > 2016 for towers sites and the ABoVE domain) >>		-

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Thematic Area	Reference Name	Entity	Geographic Coverage	Reference Year	Unit	Resolution	Reference	Comment	URL
3) Terrestrial Biomass Density except where noted. Above-ground carbon density values can be estimated as 50 percent of biomass density values.									
Above-ground biomass forested vegetation density	GEOCARBON	European Union FP7 GEOCARBON Project	Global	2000	Mg/ha	1000m	Based on Boreal forest map by Santoro et al. (2014). Covers forested areas (tree dominant) in Global Landcover Data (2000)	Course scale, over twenty years old	http://www.geocarbon.net/index3ff6.html?option=com_content&view=category&layout=blog&id=31&Itemid=135
Above-ground live woody biomass density	GFW	Global Forest Watch	Global	2000	Mg/ha	~30m	These data expand on the methodology presented in Baccini et al. (2012)		http://data.globalforestwatch.org/datasets/8f93a6f94a414f9588ce4657a39c59ff_1?geometry=135.625%2C38.698%2C-2.363%2C71.362&page=7
Above-ground forest biomass	Biomass_cci	European Space Agency Biomass Climate Change Initiative	Global	2017	Mg/ha	100m	Santoro, M.; Cartus, O. (2019): ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the year 2017, v1. Centre for Environmental Data Analysis, 02 December 2019. This dataset comprises estimates of forest above-ground biomass for the year 2017. The data has been produced as part of the European Space Agency's (ESA's) Climate Change Initiative (CCI) programme by the Biomass CCI team. Data lineage: PALSAR-2 instrument on the ALOS-2 satellite, and data from the Sentinel-1 satellite. A separate data layer is provided with per-pixel uncertainty expressed as standard error in Mg/ha.	Very recent data time stamp; planned annual updates for trend analysis; very high per-pixel biomass density uncertainty in northern regions (i.e. boreal); methods and results likely to improve with future iterations; some questions on data gap areas - see in report zoomed-in study areas.	https://catalogue.ceda.ac.uk/uuid/bedc59f37c-9545c981a839eb552e4084

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Thematic Area	Reference Name	Entity	Geographic Coverage	Reference Year	Unit	Resolution	Reference	Comment	URL
Above-ground forest biomass - all stock	GlobBiomass	European Space Agency	Global	2010	Mg/ha	100m	Santoro, Maurizio (2018): GlobBiomass - global datasets of forest biomass. PANGAEA, consist of four (4) global layers that include estimates of: growing stock volume, above ground biomass and two uncertainty layers. The mass, expressed as oven-dry weight of the woody parts (stem, bark, branches and twigs) of all living trees excluding stump and roots. A separate data layer is provided with per-pixel uncertainty expressed as standard error in Mg/ha.	A precursor to Biomass_ CCI and not similar or compatible for trend analysis to this newer layer. Used in AdaptWest Climate Explorer tool (2020).	https://doi.pangaea.de/10.1594/PANGAEA.894711
Above and below-ground all vegetation	GlobBiomass and various products	ESA and others	Global	2010	MgC/ha	300m	Seth A . Spawn, Clare C. Sullivan, Tyler J. Lark & Holly K. Gibbs. (2020). Harmonized global maps of above and below-ground biomass carbon density for the year 2010.	Useful as forested and non-forested vegetation combined together for an ecosys-tem biomass summary (useful to combine with permafrost, peatlands, etc.); note the units are density of biomass carbon (most others are in biomass density alone - pre-conver-sion to car-bon); unfor-tunate the data used are over a decade old, and unclear if will be upated.	https://doi.org/10.1038/s41597-020-0444-4

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Thematic Area	Reference Name	Entity	Geographic Coverage	Reference Year	Unit	Resolution	Reference	Comment	URL
Above and below ground (not soil) biomass carbon density (a synthetic layer using multiple peer-reviewed inputs)		Oak Ridge National Lab.	Global	2010	MgC/ha	300m	Above and below-ground biomass carbon density in the year 2010.		https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763
Above-ground total forest biomass		Canada's National Forest Inventory (NFI)	Canada	2011	Mg/ha	250m	Beaudoin A, Bernier PY, Villemaire P, Guindon L, Guo XJ. 2017. Species composition, forest properties and land cover types across Canada's forests at 250m resolution for 2001 and 2011. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Quebec, Canada	Although dated, the use of plot-based truthing data and the national Forest Inventory make these data useful for quantitative comparisons. Some questions on whetehr forests are spatially overestimated.	https://doi.org/10.23687/ec9e2659-1c29-4ddb-87a2-6aced147a990
Above-ground total forest biomass (note: data set has significant spatial error)	Landsat	Natural Resources Canada	Canada	2015	Mg/ha	30m	Matasci, G., Hermosilla, T., Wulder, M.A., White, J.C., Coops, N.C., Hobart, G.W., Bolton, D.K., Tompalski, P., Bater, C.W., 2018b. Three decades of forest structural dynamics over Canada's forested ecosystems using Landsat time-series and lidar plots. Remote Sensing of Environment 216, 697-714. Matasci et al. 2018)Geographic extent: Canada's forested ecosystems (~ 650 Mha)Time period: 1985–2011	Significant satellite scene error over large portions of the western study area prevent these data from being useful.	https://open.canada.ca/data/en/dataset/8268d8ad-4c09-4bb0-a6a0-f4ef5eb748fc
Static terrestrial above and below-ground forest biomass	BC Strategic Opportunities		British Columbia	2014	Mg/ha	100m	Holt and Kehm. 2014. Strategic Priorities in BC. Based on BC Vegetation Resource Inventory and the biomass attributes		
Moss and lichen	CGLS-LC100 collection 2	Copernicus Global Land Cover Service	Global	2015	Percent	100m	Various land cover classes by percent cover, updated regularly and based on the EU Copernicus satellite		https://land.copernicus.eu/global/products/

Wetlands: mapping wetland extent

Spatial Data Sources Reviewed as a part of the report, Kehm G. 2021. "North American Boreal Ecosystem Biomass: A Spatial Data Review".

Thematic Area	Reference Name	Entity	Geographic Coverage	Data Date	Unit	Resolution	Comment	URL
High Resolution Binary Wetland Map (forested ecosystems)		Natural Resources Canada	Canada	2001-2016			Wulder, M.A., Z. Li, E. Campbell, J.C. White, G. Hobart, T. Hermosilla, and N.C. Coops (2018). A National Assessment of Wetland Status and Trends for Canada's Forested Ecosystems Using 33 Years of Earth Observation Satellite Data. Remote Sensing.	
First Generation of a Canada Wetland Inventory	CWI	NR-CAN/C-Core	Canada	2016-2018		10m	M. Mahdianpari et al. 2019. Big Data for a Big Country: The First Generation of Canadian Wetland Inventory Map at Spatial Resolution of 10-m Using Sentinel-1 and Sentinel-2 Data on the Google Earth Engine Cloud Computing Platform.	https://doi.org/10.1080/07038992.2019.1711366

Soils, peats, wetlands, and permafrost: estimates of stored static carbon

Spatial Data Sources Reviewed as a part of the report, Kehm G. 2021. “North American Boreal Ecosystem Biomass: A Spatial Data Review”.

Thematic Area	Reference Name	Entity	Geographic Coverage	Data Date	Unit	Resolution	Reference	URL
Top and Subsurface Soil (multiple depths)	SOILGrids	ISRIC - World Soil Info.	Global	2020 (May)	Kgm^3 x 10	250m	Hengl et at. (2017) DOI: 10.1371/journal.pone.0169748 Accuracy assessement of the maps is availble in Hengl et at. (2017) DOI: 10.1371/journal.pone.0169748 **Used in AdaptWest Climate Explorer tool	https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c02ddf8b-cbfb-4533-a9c3-7bf0790fd042
Total organic soil carbon	GSOCmap	UN FAO	Global	2017?	t/ha	1000m	FAO and ITPS. 2018. Global Soil Organic Carbon Map (GSOCmap) Technical Report. Rome. 162 pp.	http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/
North American Soil Map	Unified North American Soil Map	NACP MsTMIP	North America	1993-2010		0.25 degree (~28 km)	Liu, S., Y. Wei, W.M. Post, R.B. Cook, K. Schaefer, and M.M. Thornton. 2014. NACP MsTMIP: Unified North American Soil Map. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1242	https://daac.ornl.gov/NACP/guides/NACP_MsTMIP_Unified_NA_Soil_Map.html
Total organic soil carbon	HWSD	UN FAO Harmonized World Soil Database	Global (BC analysis)	2014		100m	Holt and Kehm. 2014. Strategic Opportunities in BC.	
Peatland	Global Peatland Database (GPD)	Greifswald Mire Centre					Not yet publically available	https://www.greifswaldmoor.de/global-peatland-database-en.html
Treed Boreal Peatlands in Canada	NFI Treed Peatlands		Canada	2016		250m	Using forest structure to predict the distribution of treed boreal peatlands in Canada. 2016. Thompson, D.K.; Simpson, B.N.; Beaudoin, A. Forest Ecology and Management 372(2016):19-27	https://www.sciencedirect.com/science/article/abs/pii/S0378112716301463?via%3Dihub
Peatlands of Canada	Peatlands of Canada V3	Geological Survey of Canada	Canada	2011	n/a		Tarnocai, C., I.M. Kettles and B. Lacelle. 2011. Peatlands of Canada; Geological Survey of Canada, Open File 6561 (digital database); CD-ROM.	https://geoscan.nrcan.gc.ca/text/geoscan/metadata/of6561-e.pdf
Permafrost Northern Hemisphere	Permafrost_CCI	ESA Climate Change Initiative	Global - northern hemisphere	2013-2017		0.9 km	ESA Permafrost Climate Change Initiative (Permafrost_cci): Permafrost Extent for the Northern Hemisphere, v1.0. Centre for Environmental Data Analysis, 19 December 2019	https://catalogue.ceda.ac.uk/uuid/c7590fe40d8e44169d511c70a60c-cbcc
Northern permafrost	Northern Circumpolar Soil Carbon	NCSCD	North American northern latitudes	2016			Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D. K.: The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, Earth Syst. Sci. Data, 5, 3–13, https://doi.org/10.5194/essd-5-3-2013, 2013.	https://essd.copernicus.org/articles/5/3/2013/
Permafrost (AK)	NoAK	Northern Alaska Landscape/Permafrost characterization	Alaska	2014			This 2014 dataset is an update to the ecological landscape mapping first compiled in 2006 and later updated in 2012. This update includes permafrost mapping that provides the following new layers: permafrost extent, massive ice, thaw settlement potential, segregated ice and thermokarst landforms.	http://arcticlcc.org/products/spatial-data/show/northern-alaska-landscape-permafrost-gis-files

Harmonized or integrated ecosystem scale: estimates of stored static carbon

Spatial Data Sources Reviewed as a part of the report, Kehm G. 2021. "North American Boreal Ecosystem Biomass: A Spatial Data Review".

Thematic Area	Reference Name	Entity	Geographic Coverage	Reference Year	Unit	Resolution	Reference	URL
3) Combined above and below-ground total biomass carbon with soil								
Biomass carbon density	Nature Map Earth	UNEP-WCMC	Global	2010	Mg/ha	1000m (with finer scale inputs)	Soto-Navarro C., Ravilious C., Arnell A., de Lamo X., Harfoot M., Hill S. L. L., Wearn O. R., Santoro M., Bouvet A., Mermoz S., Le Toan T., Xia J., Liu S., Yuan W., Spawn S. A., Gibbs H. K., Ferrier S., Harwood T., Alkemade R., Schipper A. M., Schmidt-Traub G., Strassburg B., Miles L., Burgess N. D. and Kapos V. (2020) Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. Philosophical Transactions of the Royal Society B. 375 http://doi.org/10.1098/rstb.2019.0128	https://explorer.naturemap.earth/methods https://data-gis.unep-wcmc.org/portal/home/item.html?id=2444626e38a04573b3a52904f2a050d9
Carbon density for soils, peat bogs and forest biomass	WWF	WWF	Canada	2020 (Dec.?)		250m	Nature-Based Solutions: Indigenous-led Conservation and Carbon Storage in Canada. Reproducable. Soil organic carbon stocks and above-ground biomass carbon.	Greg spoke with Joyce Arabian (WWF) about rationale, inputs and timing
Above-ground and soil biomass	Y2Y ES	Y2Y	Canada/ US-regional	2010	Mg/ha	100m	M. Mitchell. 2019. "Ecosystem Services Provision in the Y2Y Region" (unpublished)	

Endnotes

1 Brandt, J.P. 2009. The extent of the North American boreal zone. Environmental Reviews 17: 101-161.

2 Holt R., Kehm G. 2014. Conservation and Adaptation in British Columbia: Strategic Opportunities in a Climate Changing World. https://databasin.org/groups/a6389ad9835642ed8b1d1dd-bf8663aa7

3 European Space Agency Earth Explore. https://earth.esa.int/web/guest/missions/esa-future-missions/biomass. Google Search. Accessed June 20, 2020

4 Xu, Q. et al. 2018. Quantification of uncertainty in aboveground biomass estimates derived from small-footprint airborne LiDAR. Remote Sensing of the Environment 216: 514-528. https://doi.org/10.1016/j.rse.2018.07.022. Google Search. Accessed August 5, 2020.

5 Matasci, G. et al. 2018. Large-area mapping of Canadian boreal forest cover, height, biomass and other structural attributes using Landsat composites and Lidar plots. Remote Sensing of the Environment 209: 90-106. https://doi.org/10.1016/j.rse.2017.12.020. Google Search. Accessed August 5, 2020.

6 Spawn, S.A., and H.K. Gibbs. 2020. Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1763. Google Search. Accessed November 30, 2020.

7 Smith, J et al. 2013. Carbon Factors and models for forest carbon estimates for the 2005-2011 National Greenhouse Gas Inventories of the United States. https://www.ncrs.fs.fed.us/pubs/jrnl/2013/nrs_2013_smith-j_001.pdf

8 NASA Earth Observatory. https://earthobservatory.nasa.gov/global-maps/MOD17A2_M_PSN . Google Search. Accessed June 26, 2020.

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WCS Canada

344 Bloor Street West, Suite 204
Toronto, Ontario M5S 3A7
(416) 850-9038

wcscanada.org