0254-B2

ESTIMATING SUB-ARCTIC FOREST CARBON STOCKS: CONCEPTS, METHODS AND PRELIMINARY RESULTS

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Abstract

In the context of understanding the role of forests in the global carbon cycle, research interest is shifting from the wood volume of commercial forests to the carbon budget of both commercial and remote non-commercial forests. So far, there has been no structured attempt to assess the carbon stocks of Canada's non-commercial and remote sub-Arctic forests. As part of the project on improving Canada's national forest biomass inventory, this study outlines the concepts and methods for estimating carbon stocks throughout Canadian sub-Arctic forests by matching ground plots with remote-sensing data. The study also highlights the large difference between the carbon stocks in ground plot biomass estimates and the biomass predicted by an existing global carbon model, a type of model that could be used by third party observers to verify Canada's claims to forest carbon sequestration. Finally, it stresses the need to conduct coordinated biomass inventories at high latitudes to elucidate the interaction between environment, disturbance and carbon budget in sub-Arctic forests.

Introduction

According to current information (IPCC 2001), approximately 1 to 2 billion tons of carbon are sequestered in sinks located on land north of 30° N. However, the geographic distribution of these northerly land sinks remains unknown. Myneni et al. (2001) addressed the topic by proposing a global biomass model based on matching inventory plots with remote sensing. For Canada, where most of the wood biomass is stocked in boreal and sub-arctic forests, Myneni et al. (*op. cit*.) used inventory plots collected in boreal forests to extrapolate the wood biomass stock to sub-arctic forests. Through this extrapolation, and by merging sub-arctic forests with boreal forests, Myneni et al. (*op. cit*.) found that northern Canadian forests are losing carbon and explained this loss by increased incidences of fire and infestation in Canada. However, Myneni et al. (*op. cit*.) concluded that clear and exact reasons for this loss are unknown, and underlined the need for reducing the uncertainty of the biomass sinks estimated by monitoring with ground- based inventories and space-based sensors. In fact, as is eloquently explained in the Temperate and Boreal Forest Resources Assessment 2000 statistics, to data, forest inventory statistics have been collected in commercial forests only and have focused on the assessment of woody resources with carbon stock and other uses. This study represents a step forward in the assessment of carbon stocks in Canadian sub-arctic forests and highlights both the importance of these stocks and the need to improve their quantification so that we may be able to properly address claims such as those reflected by the work of Myneni et al. (*op. cit*.).

This paper first outlines the concepts and methods for estimating carbon stocks throughout Canadian sub-arctic forests by matching ground plots with remote sensing data. The paper presents in its second part preliminary sub-arctic woody biomass estimates and their comparison with those predicted by the global biomass model of Myneni et al. (*op. cit*.). It is presumed that this methodology would also be applicable in the boreal forests of Russia where reliable biomass estimates are also lacking (Gaveau et al. 2002).

Concepts

The extent and remoteness of the Canadian sub-arctic forests make field plot measurements costly. We therefore propose a three-step procedure to estimate total carbon stocks and their components. In this procedure, results from a minimum number of field plots are scaled up to the landscape through remote sensing inputs. The first step involves the stratification of ground cover through the classification of fine resolution satellite images (e.g. Landsat-TM) for the location and distribution of ground plots. The second step involves the field data collection in a nested design of three plot types. The third step consists in combining field data and remote sensing image classification into estimates of carbon stocks at the forest stand and landscape scales.

The sampling and scaling-up designs are five-levelled and fully nested, from intensive carbon stock field plots to remote sensing images. The ground portion of the design entails three levels of field plots: allometry plots, inventory plots and scaling-up plots. The plots are linked up to the two levels of remote sensing images: subsets of fine resolution images nested into coarse resolution images. Coarse (e.g. 1 km^2 pixels) resolution imagery is required at the national scale. The sole use of fine resolution images for mapping all of Canada's sub-arctic forests is impractical in the short term because of the area involved.

Methods

Sub-arctic forests have been very sparsely covered by aerial photography, the tool of choice for mapping stand distribution and interpreting stand attributes (cover type, cover density, stand height). Consequently, land-cover mapping of sub-arctic forests has to be based on a combination of a few fine resolution images within larger ecozones covered by coarse resolution images. The nested design also makes it possible to quantify the error involved in the use of a smaller number of ground cover classes in the coarse resolution image compared to the fine resolution image.

The sampling design is structured around the ecological stratification of northern latitudes in the Taiga Cordillera, Taiga Plains, Taiga Shield and Hudson Plain ecozones (Fig. 1). Within each ecozone, a sample of fine resolution images is used for the ground plot sampling design and for the extrapolation of carbon stock estimates from the plot to the coarse resolution pixel. Ground sampling uses three types of plots located in close proximity in a generally nested design: allometry plots, inventory plots and scaling-up plots. A small number of allometry plots provide raw above- and below-ground biomass data through harvest measurements for extending allometric equations to the tree forms of northern latitudes. The more numerous inventory plots are established using Canadian forest inventory standards, and are used in combination with the allometric equations to obtain estimates of plot-level biomass for a representative range of stand attributes. Finally, a larger number of scaling-up plots are established using a light protocol that centres on remotely-sensible attributes and the estimation of plot-level biomass, woody debris and soil carbon using simple local relationships derived from inventory plot measurements. This nested design makes field estimation of carbon stocks in a large number of field sites possible while maintaining costs to a minimum.

Data collection provides three types of data:

1. Stand attributes (cover type, cover density, stand height) and site attributes (latitude, longitude, slope, aspect);
2. Inventory data including tree diameter distribution, height of shrubs and herbs, percent coverage of shrubs, herbs, moss and lichen, and woody debris;
3. Tree above-ground biomass with its components (leaf, branch, wood and bark), understory biomass, coarse woody debris, litter, below-ground biomass data (coarse and fine roots), and soil carbon.

Type 1 data are measured in the three types of ground plots. Type 2 data are measured in inventory and allometry plots. Type 3 data are measured in allometry plots only and require laboratory measurements for completing their compilation. Biomass densities are reported on an oven-dry weight basis. Laboratory measurements are necessary for compiling data on woody debris, stem analysis, above-ground biomass, and below ground biomass.

Preliminary estimates and comparison with Myneni et al.'s (*op. cit.*) estimates

A first sampling effort was initiated during the summer of 2002 for benchmark sites across a Northern Quebec transect (Fig. 1). Dry biomass of diverse tree components and of diverse carbon stocks is currently still being processed in our laboratory. As a temporary alternative, an estimate of the woody biomass has been realized with the generalized allometric equation for black spruce based on data collected in the Taiga Shield ecozone of Northern Quebec by both Denis Ouellet in 1983 (*personal communication*) and by Moore and Verspoor (1973):

(1) $b=0.36d^{1.93}$

where b is tree total biomass in kg, and d is tree diameter at breast height outside bark (dbh) in cm (ranging from 1 cm to 29 cm). We used this equation to compute preliminary estimates of plot biomass from the ground plot inventory of tree dbh.

The normalized difference vegetation index (NDVI) is a commonly used metric of ecosystem level greenness and photosynthetic activity calculated as the difference between near infrared and red satellite reflectance divided by their sum. Myneni et al. (*op. cit*.) considered that NDVI magnitude and growing duration are representative variables of woody biomass in the north. They also found that seasonal signals of NDVI are closely related to seasonal patterns of temperature variation because temperature is the major controlling factor for growth of vegetation in northerly regions. Using ground plot data from six nations (Canada, USA, Finland, Norway, Russia, Sweden), Myneni et al. (*op. cit*.) established the relationship between the plot biomass B obtained from inventory data, and a combination of the cumulative growing season NDVI (N) and the latitude (L) of the centroid of the area sampled by forest inventory:

$$\frac{1}{B} = \alpha + \beta\left(\frac{1/N}{L^2}\right) + \gamma L$$

(2)

where α = -0.0557, ß = 5548.05, γ = 0.000854.

Dong (2002), a member of Myneni's research team, matched time series climate data with remotely-sensed NDVI across different latitudes and biome types. For the 30-60º North latitude band and for needle-leaved forest biome, the relation established is:

(3) NDVI(t) = 0.176646 + 0.010894Temp(t) + 0.002401Precip(t)

in which NDVI(t), Temp(t), and Precip(t) are the mean normalized difference vegetation index, mean air temperature (ºC), and precipitation (mm) in month t, respectively. We applied this equation to our plots by estimating the mean temperature and precipitation for each plot using the climate interpolation algorithm within the BIOSIM insect phenology simulator (Régnière 1996).

Equations 2 and 3 allow the superposition of the Northern Quebec transect plots on plots used by Myneni et al. (*op. cit*.). Figure 2a shows that the woody biomass in our northern plots is generally higher than the one found in the plots used by Myneni et al. (*op. cit*.). Figure 2a also shows that between a narrow magnitude of cumulative growing season NDVI, the range of the woody biomass in our northern plots is three times wider than in the plots used by Myneni et al. (*op. cit.*) to develop their global model. Consequently, it is likely that this global model will underestimate sub-arctic biomass, at least in Northern Quebec. Figure 2b illustrates the poor ability of Myneni et al.'s (*op. cit*.) global model to consider the great variability in the woody carbon stocks found at the stand scale and resulting from the interaction between climatic and edaphic factors, disturbances (particularly fire), and vegetation distribution. These results reinforce the need to further investigate and understand the interaction between NDVI and biomass, and general relations between remote sensing, canopy and ground surface. These results also show that these analyses are required for the validation of publicly-accessible global biomass models that can be used by third parties to assess the validity of national carbon sequestration estimates.

Conclusion

Sub-arctic forests represent 40% (Lowe et al. 1994) of all the Canadian forests. Besides their important extent, progress in understanding the carbon stocks and the carbon fluxes of sub-arctic forests is hindered by the limited existing field data and the lack of consistent spatial information on vegetation biomass. Existing Canadian biomass data have been restricted to commercial forests. As a result, Canadian forest biomass may be significantly underestimated by existing global carbon stock models. A preliminary field study for benchmark sites in Northern Quebec shows substantial biomass in sub-arctic forests. This double move from commercial to sub-arctic forests, and from woody biomass to total site carbon, will require substantial investments in field work and in satellite-based scaling-up methodologies. However, without such an effort, great uncertainty will remain with respect to the magnitude of Canadian sub-arctic carbon stocks and to the factors that control their distribution, thereby hindering our ability to verify global results of terrestrial carbon models and develop coherent policies with respect to our northern forests.

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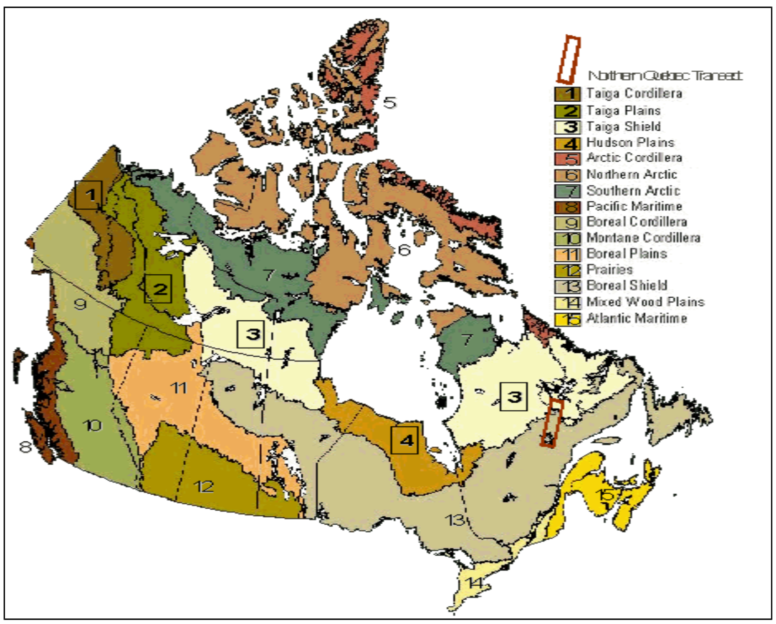

Figure 1. Canadian ecozones (Ecological Stratification Working Group 1996) and the Northern Quebec transect.

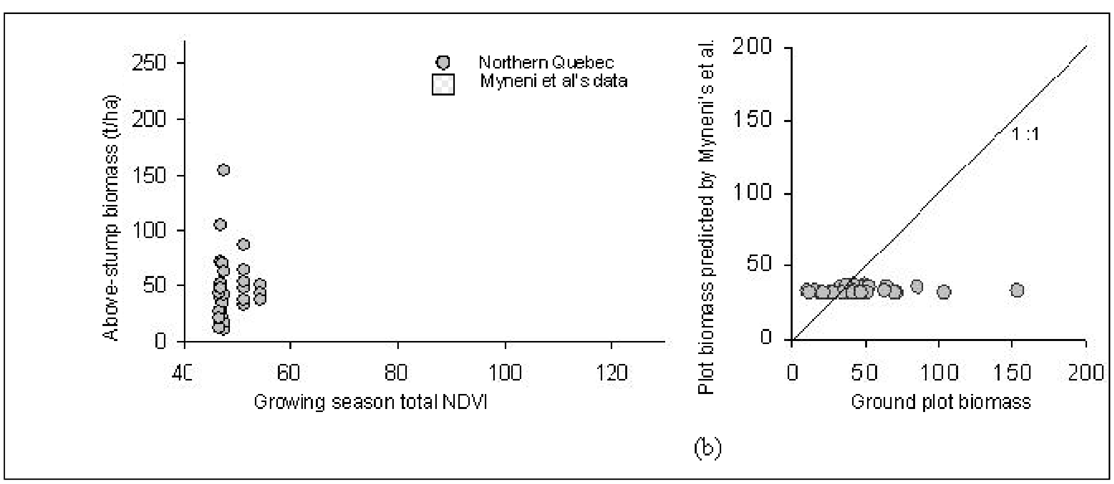

Figure 2. (a) Superposition of the ground plot biomass of the Northern Quebec transect on an adaptation of Fig. 1 in Myneni et al. (*op. cit.*) showing the range of plot biomass and NDVI used in model adjustment. (b) Ground plot biomass related to the biomass predicted by Myneni et al.'s (*op. cit.*) global model.

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