A Lidar-Radar-Optical Data Fusion Approach for Estimating the Aboveground Carbon Stocks of North American Forests: Means and Uncertainties at Regional to Continental Scales

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SUMMARY

Forests are the most important terrestrial carbon reservoir and will influence and be influenced by climate change. For this reason, monitoring forest carbon stocks at regional and continental scales will be an important element of a future climate observing system. Such a forest carbon monitoring capability will also be a key input to new generations of coupled Earth system models and will provide a means of validating the large-scale performance of various adaptation and mitigation strategies. The proposed research will build on a methodology that we have developed in previous NASA-funded projects of combining data from the Geosciences Laser Altimetry System (GLAS), which has been flying on the ICESat satellite, with data from airborne lidar, ground plots, land cover classifications, and digital elevation models to predict aboveground forest carbon stocks. Whereas we have previously applied this approach only to northern forests, we adapt our methodology in the current proposal so that we can move our work to the next logical step and apply it to the entire North American continent. The field efforts will be concentrated on forests in the contiguous US and in Mexico.

The basic approach makes use of recently measured, geolocated forest inventory plots which are then over flown with a portable airborne lidar. This permits us to relate lidar heights to the aboveground carbon stocks and biomass of the plots. We then fly the airborne lidar over the GLAS ground tracks, allowing us to statistically relate the airborne laser data to the satellite data. The full set of quality-filtered GLAS data can then be extrapolated to larger spatial scales by combining this information with land cover classification and topographic data. Since our previous experience has shown that GLAS does not perform well for estimating biomass of open stands with aboveground biomass <20 Mg ha^{-1}, we will develop an image processing procedure that can integrate the GLAS information with L-band radar data from PALSAR and from the MODIS Vegetation Continuous Fields (VCF) canopy closure product. We will use the VCF optical product to establish a threshold below which PALSAR-based estimates start to replace the GLAS-based estimates. We will also develop a statistical framework for integrating the different satellite information sources into a coherent methodology for estimating the amount and the uncertainty of aboveground forest carbon stocks for all of North America as well as its principal ecoregions. The statistical framework will also allow us to quantify how future changes in land cover and land use in the different regions of North America are likely to impact aboveground carbon stocks. This project will make a significant contribution to the continental-scale components of the North American Carbon Program (NACP) as well as the US-Mexican-Canadian collaboration of the Carbo-NA Program, both high priority elements of NASA's and USDA's carbon cycle science programs.

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Scientific /Technical/Management Section

1.1 Objectives and Expected Significance of the Proposed Research

Quantifying the amount, uncertainties, and spatial distribution of carbon (C) pools in North American is a key objective of the North American Carbon Program (NACP) and its trilateral equivalent, Carbo - North America (Carbo-NA). An ability to assess these pools and their potential vulnerability to climate change is essential for developing a predictive capability of how these pools might feedback to, and be impacted by, a changing climate system. Furthermore, evaluating C-related mitigation and adaptation strategies requires the on-going development of new technologies and approaches for measuring and monitoring C stocks. Since forests are the largest aboveground terrestrial C pool in North America, it is logical to focus the development of a monitoring capability on forest ecosystems. NASA is proceeding along these lines in planning DESDynI, although the exact design and launch date of such a satellite has not been determined.

Feedbacks between terrestrial ecosystems and climate could easily nullify all human efforts to mitigate climate change. However, there is a great deal of uncertainty in our current estimates of global C pools in vegetation (Kauppi 2004). The aboveground component of forest C is the most easily impacted by human activities and natural disturbance and is the most readily observable. A major focus of this proposal is modifying and expanding an approach that we have developed in previous work for assessing large-scale forest C stocks using a combination of ground plots, airborne lidar, and the ICESat-GLAS spaceborne lidar so that it can be applied at the continental scale for North America. Since GLAS has been shown to be of limited utility in low biomass areas (Nelson 2010), we propose a fusion of GLAS with information from the PALSAR radar and from MODIS Vegetation Continuous Fields (VCF) percent canopy cover product. The approach is linked to a rigorous statistical framework that will allow us to assess how uncertainties are propagated through the scaling and data fusion procedures. The statistical component involves critical issues of how to assess variance when data are collected along transects such as we obtain for ground tracks of spaceborne lidars and how to apply a statistical framework when different satellite sensors are used to evaluate aboveground C stocks.

Researchers suspect significant C uptake occurs in northern temperate forests due to its age-class structure and in the southwest US due to hardwood encroachment into rangeland areas (CCSP 2007; Pacala et al. 2001). Myneni et al. (2001) and Goetz et al. (2005) reported enhanced photosynthetic activity in some areas of North American boreal ecosystems, although Kurz et al. (2007, 2008a,b) demonstrated that increased fires and insect epidemics have pushed the managed forest of Canada toward being a net C source. The atmospheric analysis reported in Stephens et al. (2009), on the other hand, suggests that tropical regions may be significant C sinks if land-use-related emissions are not considered and that the sink strength of temperate forests may therefore be overestimated. The uncertainty about the location, extent, and dynamics of these C sinks and their related C pools is driven, in part, by limitations associated with the use of optical sensors to estimate standing C stocks and changes to those stocks. Optical sensors, such as the Landsat-TM, AVHRR, or MODIS, can precisely define the location and extent of forested areas that have been cleared or burned, i.e., obvious land cover change, but the spectral measurements cannot generally be used to estimate accurately the amount of biomass or C lost from these converted areas. For example, Houghton et al. (2000, 2001) compared seven different estimates of biomass in the Brazilian Amazon and these estimates varied from 39 to 93 Gt C and were inconsistent even for locating areas of high and low biomass. The authors suggested that one way to improve the estimation of regional C stocks is to employ airborne or satellite observations that measure vertical canopy structure,, e.g., lidar (light detection and ranging) technology and/or synthetic aperture radar (SAR).

Objectives: The general objective of the proposed research is to develop estimates of the aboveground C in the forests of North America using a consistent methodology that combines ground plots, airborne lidar sampling, and a fusion of different lidar, radar, and optical satellite sensors. The proposed work is based using a hierarchical sampling approach that we have already employed successfully in Canada and Alaska (Figs. 1 and 2). Using this approach, we will attain the following specific objectives.

(a). We will fly a portable airborne lidar (PALS) in a single-engine fixed wing aircraft over forest inventory ground plots for the major forest ecozones in the USA and Mexico. This will allow us to develop regression equations relating the metrics from PALS to aboveground forest biomass and C at different levels of aggregation for the forests of North America. We have already acquired these data for Canada and Alaska.

(b). We will fly PALS along the ground track transects of the ICESat GLAS sensor (Geosciences Laser Altimetry System, described further below) whereby we can relate the PALS metrics to the GLAS waveforms for the same area of ground (Fig. 1). This allows us to calibrate the GLAS data to aboveground forest C stocks for the various ecozones and forest cover types.

(c). GLAS tends to not function well in low biomass areas where 75^{th} percentile heights are <7m, biomass is < 20 Mg ha-1 (Nelson 2010) and/or canopy closure is <20-40% (Neuenschwander, 2010). Given these limitations, we will use the L-band synthetic aperture radar data from the PALSAR sensor flying on the ALOS satellite in situations where the GLAS-PALS relationships fail. We will use the MODIS Vegetation Continuous Fields (VCF) percent canopy closure product to test various thresholds for the transition between GLAS and PALSAR estimates.

(d). We will develop an image processing procedure that can integrate the data from GLAS PALSAR and MODIS-VCF.

(e). The effects of topographical slope on the GLAS-PALS-PALSAR relationships will be assessed by overlying the ASTER 30-m digital elevation model. We can also use the SRTM (Shuttle Radar Topographic Mission) 30 to 90 m digital elevation model at latitudes below 60°N.

(f). We will scale the aboveground C stocks using >28 million quality-filtered GLAS pulses (Fig. 3a) as well as the complementary PALSAR / MODIS-VCF data. We will scale the biomass estimates for a given cover type within an ecozone by their surface area using Landsat-derived land cover maps and more general ecozone maps for Mexico, the US, and Canada (Fig. 3b).

(g). The biomass estimates will then be compared to forest inventory estimates of wood volume, biomass, and C in various regions and cover types. These inventory estimates tend to be higher than the remote sensing based estimates since inventories have a bias toward establishing plots where wood volumes are substantial (Boudreau et al. 2008, Nelson et al. 2009).

(h). We will develop a consistent statistical framework for integrating the different satellite data sources into a coherent analytical framework for estimating the amount and the uncertainty of aboveground forest C stocks for all of North America as well as its principal ecoregions.

This research is significant because it will furnish the first baseline estimates of aboveground C stocks for the North American continent based on a standardized methodology that links ground plots, small footprint airborne lidar, a full waveform satellite lidar, L-band radar, and an optical percent tree cover product. Much of the methodology has been tested during our recent projects. However, the current proposal reaches for the continental scale and thus the size and complexity of the data sets are greater than our previous studies. The proposed study also capitalizes on the expertise and team-building we have conducted over the last several years and we now wish to expand our team to include our Mexican collaborators. The integration of the different types of remote sensing products into a coherent image processing system and the building of a statistical framework for estimating means and variances from this methodology will be a significant scientific advance. The regional and continental scale C stock estimates will be valuable for constraining C cycle models and can serve as a foundation and point of reference for future remote sensing based estimates of forest biomass and C stocks once the DESDynI satellite, or its alternative, are ready for launch sometime over the next 5 to 10 years. We will analyze the robustness of the statistical relationships between the airborne and GLAS data (2004 through 2008 collections) as a function of productivity, i.e., how do the relationships in the tropical or sub-tropical areas differ as a function of the time gap between the airborne, GLAS, and PALSAR data? We will also determine whether areas having high rates of disturbance have significantly different PALS-GLAS-PALSAR relationships than areas of low disturbance.

1.2 Technical Approach and Methodology

1.2.1 General Approach

The proposed study will employ a small, inexpensive, transportable airborne LiDAR profiler (Nelson et al. 2003a) that was designed specifically as a large-area sampling tool (e.g., state, province, ecoregion) for estimating forest volume, biomass, and C stocks. The laser system, which in this study will act as an intermediate data product to extend ground observations to ICESat/GLAS and PALSAR measurements, has been used previously to estimate aboveground biomass and C stocks regionally (e.g., Nelson et al 2003b; Nelson et al. 2004, Boudreau et al. 2008, Nelson et al. 2009). We fly the portable instrument on for-hire, single-engine aircraft. In the proposed study, we will further develop robust sampling procedures that report unbiased estimates of aboveground biomass and C stocks as well as unbiased estimates of their variances for all of North America. This study serves three purposes: 1) it will provide a spatially-explicit baseline of aboveground C stocks; a baseline which may change as the climate warms; 2) it will provide the statistical basis for generating unbiased C stock estimates and the *actual* variance associated with those estimates; and 3) it will serve as a significant step in the direction of

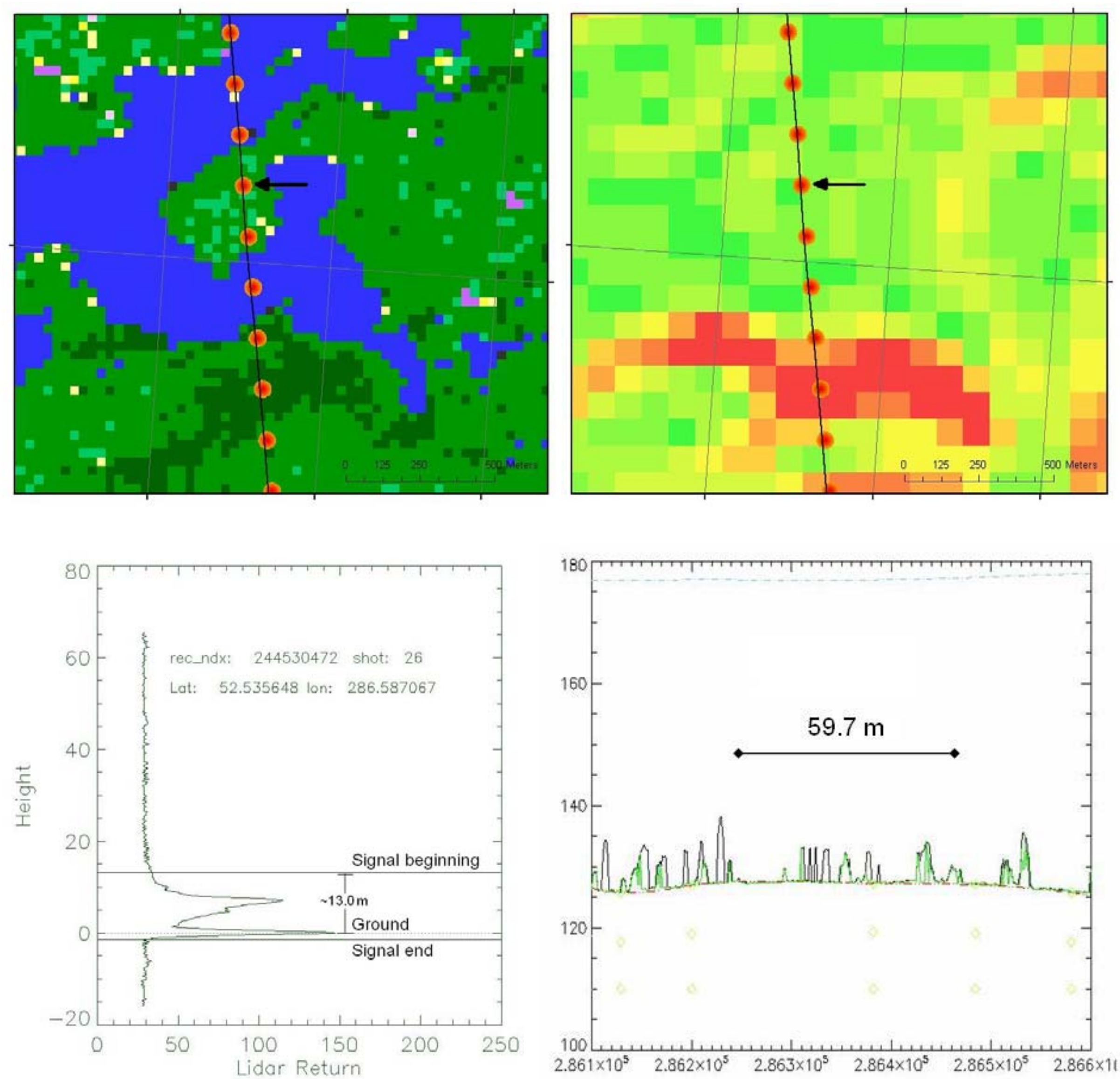

Figure 1. (Upper left) A GLAS and PALS transect laid over a cover type map of an open, coniferous boreal forest in Quebec. The distance between pulses is 170 m. (Upper right) SRTM slope map showing the GLAS and PALS transect. The pulse is located on slopes <3 degrees – green. (Lower left) The spaceborne GLAS waveform for the ground pulse located at the point of the black arrow in the upper images. (Lower right) The comparable airborne PALS measurements for the GLAS pulse.

perfecting procedures to measure and re-measure C stocks at the continental scale by combining satellite remote sensing with airborne and ground-based information.

1.2.2. Using Lidar to Estimating Forest Structural Properties

Airborne lidars have been used to measure forest structure – canopy height, height variability, and canopy closure – and to estimate forest biophysical properties – stem counts, basal area, stem

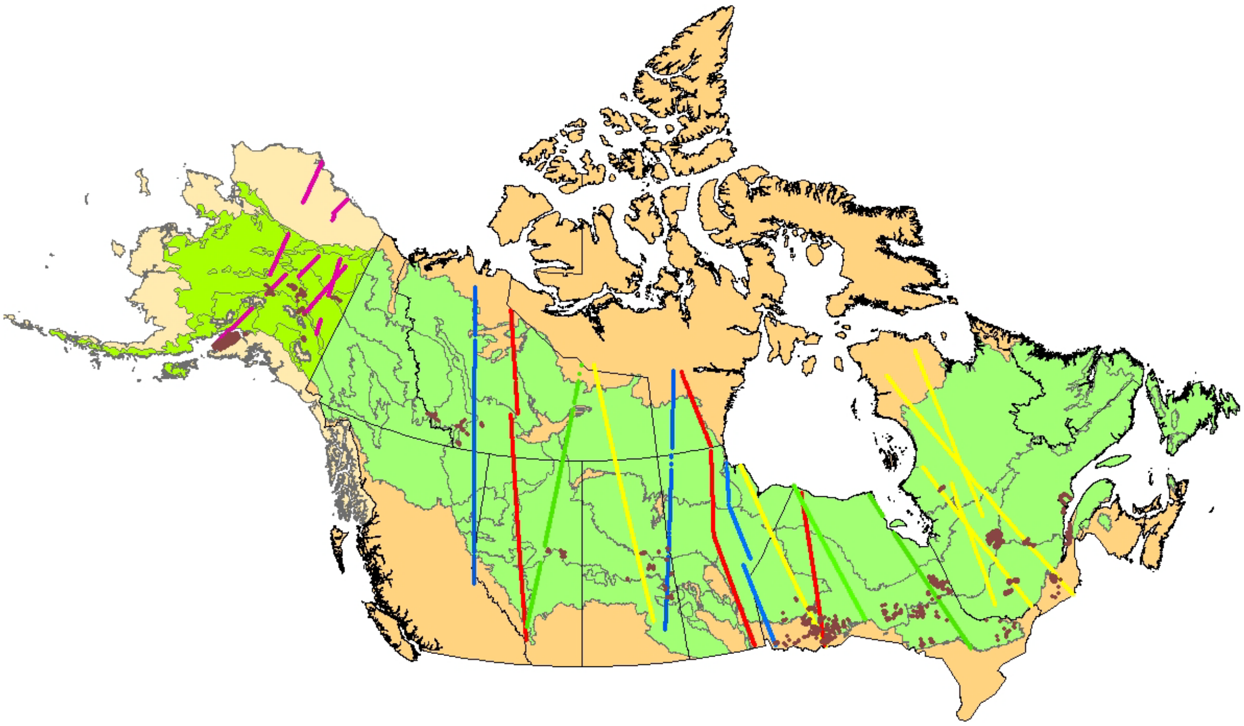

Figure 2. GLAS ground tracks flown by PALS airborne lidar in Canada in 2005 and 2009 and in Alaska in 2008. More than 100,000 GLAS footprints were sampled by PALS. Different color GLAS lines indicate different dates of acquisition. Red dots show the >1400 ground plots that were sampled by PALS. Green areas show the boreal forest ecozone.

volume, total above-ground dry biomass, and C stocks – since the early 1980's (Wulder et al. 2008, Wulder et al. 2009). Nelson et al. (1984) used an airborne profiling lidar to quantify changes in canopy structure due to insect defoliation in central Pennsylvania. Maclean and Krabill (1986) and Nelson et al. (1988a,b) developed models to predict stem volume and dry biomass based on forest canopy height and crown closure as measured by an airborne lidar. Maclean and Krabill (1986), working on the Delmarva Penisula, concluded that the inclusion of tree species information strengthened their regressions. Nelson et al. (1988a) found that species stratification in the southern pines yielded no appreciable improvement. Since that time, numerous researchers have employed a variety of increasingly complex lidar systems to develop models and sampling techniques to better quantify timber volume, aboveground dry biomass, and C stocks. We integrated airborne lidar sampling with ICESat GLAS measurements for the first time in a pilot study in the Province of Quebec and obtained precise estimates of aboveground biomass (4.9±0.3 Pg, Boudreau et al. 2007) and C (2.57 ± 0.33 Pg, Nelson et al. 2008).

Much of the lidar-based sampling work has been done by the PI in concert with investigators from Norway, Sweden, Canada, and the USA. Nelson et al. (2003b) reports results based on 1300 km of airborne profiling lidar measurements systematically acquired across Delaware (14

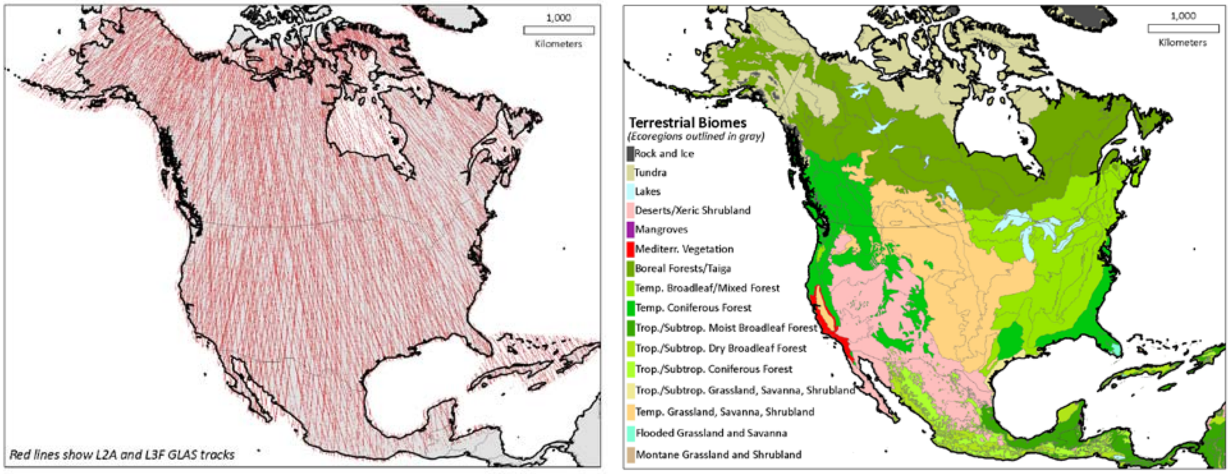

Figure 3. (a) GLAS orbital ground tracks over North America for Acquisitions 2a (autumn 2003) and 3f (spring 2006). We will have access to >20 million GLAS pulses for North America. (b) Ecozones of North America developed by the World Wildlife Federation.

flight lines spaced 4 km apart). They developed estimates of forest merchantable volume, total aboveground dry biomass, impervious surface area, and open water area based on profiling heights and interception lengths. They compared their biomass estimates to USFS-FIA ground-based results and found that county-level lidar estimates were within 19% of Forest Inventory Assessment (FIA) estimates at the regional level and within 16% at the State level.

Nelson et al. (2004) explain the statistical framework that provides the basis for lidar sampling and report estimates of standing C for Delaware, using the 0.5 t C/1 t dry biomass conversion suggested by Houghton et al. (2000). A subsequent study that employed the entire 56 flight line Delaware data set (Nelson et al., 2007) where parallel lidar profiles are spaced 1 km apart indicate that (1) the inflationary effects of spatial autocorrelation between closely-spaced flight lines <6 km apart on cover type biomass variances can be mitigated by using alternative variance estimators, and (2) inclusion of regression error in the variance estimate increases biomass standard errors, on average, by approximately one t/ha (8-15%). This latter finding generally agrees with results reported by Phillips et al. (2000) who found inclusion of regression error in his ground-based forest inventory increased regional volume variances by 0.7 – 10.3%.

In summer 2005, we conducted our first hierarchical ground-PALS-GLAS sampling in a pilot project in Quebec. We successfully flew 207 ground plots and obtained an R^2 for ground plot biomass versus lidar height metrics of 0.65 (Boudreau et al. 2008). We then flew 4 GLAS transects and related GLAS waveform parameters to PALS height metrics with a R^2 of 0.59 (n=1325). This allowed us to use the >100,000 GLAS pulses available for Quebec to scale aboveground biomass to the entire province (4.9±0.3 Pg) and analyze its distribution by region. Nelson et al. (2009) determined that a simple random sampling estimator, with covariance terms added, could be used to quantify the variability of regional GLAS biomass estimates where inter-orbit distances are, on average, ~15 km apart. Prediction error increased standard errors, on average, 24.4%, 4.6%, and 2.8% at the cover type, vegetation zone, and provincial levels, respectively. Inclusion of the covariance term in the calculation of grouped cover type variances increased the vegetation zone standard errors up to 3.7 times and the provincial standard errors 15.6 times. Approximately 25% of the C was found to be located in two southern vegetation zones (northern hardwood and mixedwood), another 25% in two northern vegetation zones (taiga and treed tundra), and the remaining 50% in the boreal zone (Nelson et al. 2009). However, the ability of GLAS to predict biomass for areas with <20 Mg C ha^{-1} was weak (Nelson 2010).

In 2008, we expanded our study design to cover the entire boreal forest of North America (Fig. 2). We conducted flights over >486 ground plots and four GLAS ground tracks in Alaska. We flew an additional 970 ground plots and eleven GLAS ground tracks in Canada during 2009. We are in the process of analyzing these data. The analyses should be largely completed before the beginning of the work described in the current proposal.

After almost 30 years of research by a number of researchers in Norway, Sweden, Finland, Canada, Japan, and the United States, the following generalities emerge:

(a) *Volume and biomass can be reliably estimated using airborne lidar data.*
(b) *Conifers are more easily measured than hardwoods.*
(c) *Systematically acquired lidar data can be used for regional inventories.*
(d) *Robust relationships can be found for relating airborne lidar to GLAS data if care is taken to filter for low biomass areas and/or very steep topography.*

1.2.3. Airborne PALS Laser

The PALS instrument serves as an intermediate sampling tool to extend the spatially limited ground measurements to the continental-scale GLAS observations. PALS is a small, transportable (2 suitcases), relatively light-weight (~20 kg), inexpensive (~30k USD) Lidar profiler which can be carried to remote study areas and bolted onto local, for-hire, small single or two-engine fixed wing or rotary aircraft. The system is made up of 4 subsystems – laser transmitter/receiver (t/r), differential GPS (dGPS), video camera and recorder, and data acquisition computer. The system records the lidar range/amplitude data stream interleaved with GPS location information, and also records a GPS-annotated video of targets overflown. We will upgrade the system for the work described in the current proposal so as to integrate an Inertial Measurement Unit (IMU) to record pitch, roll and yaw of the aircraft and to improve the data acquisition system, e.g., USB versus serial port. The IMU was given to us recently by Wallops at no cost. Flight readiness reviews for our missions are conducted by NASA Wallops.

The airborne system has been used to measure forest height and canopy closure along GLAS orbital transects 1000's of kilometers in length in Canada and Alaska in 2008 and 2009 (Fig. 2). Flying at 200 m above ground level (AGL), at a ground speed of 97 knots, (180 km/hr, or 50 m/s), with a beam divergence of 1.8 mr, a lens diameter of 10 cm, a pulse rate of 2000 range measurements/second, and a sampling ratio of 10:1, the system was recording a first/last ranging measurement every 25 cm along the flight transect (post-spacing) and illuminating the target with a 37 cm spot. Frequently, one or more pulses hit ground, even in dense forest canopies, and post-flight processing is done to identify these ground returns. A spline is fit to the ground points to define a ground line, and once the ground line is identified, then a canopy height can be calculated for every pulse. The PALS data stream contains ranging information that can be used to calculate canopy height, top-of-canopy height variation, and canopy cover. The system worked well in Canada and Alaska but some system upgrades for geolocation and data transfer are desirable before the next major mission. PALS measurements can be related to ground-measured forest biomass and C stocks using linear models. The operational envelope of the system is from ground level up to 600 m above terrain. Above 600 m, data dropout rates increase to over 20% and data quality is compromised; below 350 m AGL, dropout rates fall to zero. We plan to fly the field sites and GLAS transects at 200 m AGL; the sampling rate will be tailored to the nominal speed of the host aircraft so that pulses along a flight transect are contiguous.

PALS data will be collected on ~1400 ground plots and along ~15,000 km of GLAS transects to cover the major forest biomes of the US and Mexico. Since we will be flying essentially the same PALS sensor and flight profile as previous missions, we can also include the >1400 ground plots we have already flew in Canada and Alaska. We expect to fly 14 north-south GLAS transects spaced across the US and Mexico and >1200 plots, an endeavour similar in scope to our Canada-Alaska campaigns. Flight costs are estimated at $165,000 for approximately 550 hours in the air at $300/hour. We expect to complete all of the aircraft sampling in the first and second years. With 170 m post spacing between the ~70 m GLAS spots, we should overfly ~100,000 GLAS pulses. Based on our experiences in Canada and Alaska, more than half of the pulse locations should provide useful, usable GLAS data. A for-hire, single-engine aircraft, e.g., Cessna 172 of Piper 32A, will be used, as was done for our previous GLAS airborne campaigns.

1.2.4. Availability of Ground Plots

We will fly our airborne PALS sensor over a sample of ground plots located in the major forest regions of the U.S. and Mexico. The exact sampling design will be determined at project planning meetings once funding is obtained. We have ready access in both the US and Mexico to recent geolocated ground plots where biomass and aboveground C estimates can be derived. Our USDA Forest Service co-investigator, Hans Anderson, is a part of the Forest Inventory and Analysis Division and is highly knowledgeable and experienced about the procedures for accessing the large quantity of plot data available in the US and flying lidar missions.

Our Mexican collaborators (Ben De Jong and Fernando Paz-Pellat) are part of the Forest Carbon Tracking Task (GEO-FCT) which was established by GEOS to support countries wanting to establish forest C estimation and reporting systems. The GEO-FCT effort facilitates access to long-term satellite, airborne and *in situ* data**,** provides the associated analysis and prediction tools, and creates the appropriate framework and technical standards for a global network of national forest C tracking systems. As part of this initiative, a network of intensively measured biomass plots have been established in various regions of Mexico (Fig. 4a). We will fly as many of these plots as possible. These plots can be supplemented by the abundant supply of recently measured ground plots from Mexico’s National Forest Inventory (Fig. 4b).

1.2.5. ICESat-GLAS Data

The ICESat mission was launched in January 2003 with the Geoscience Laser Altimeter System (GLAS) on-board. GLAS has three lasers which are meant to be used sequentially to extend mission life, hence the instrument is a space-based lidar profiler which lays down a pulse of

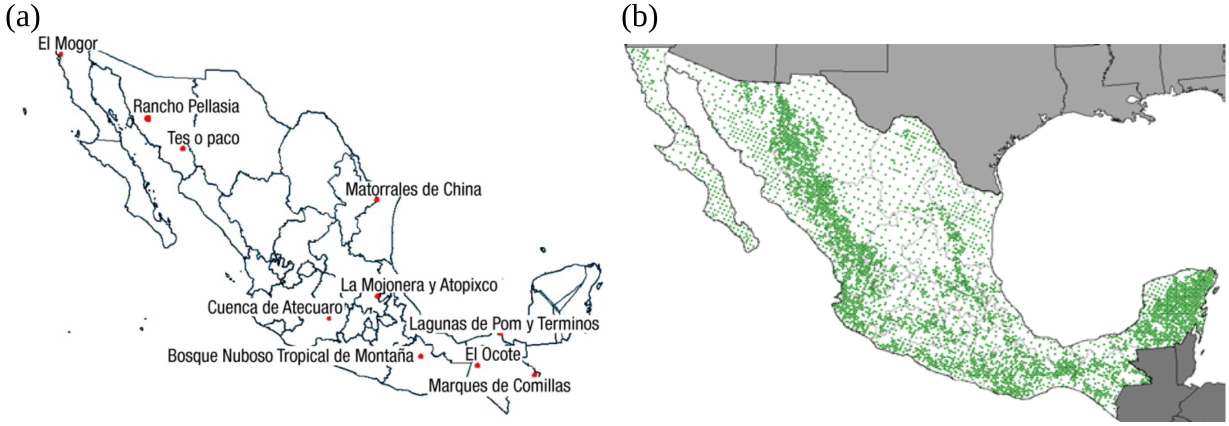

Fig. 4. (a) Locations of 10 km x 10 km calibration-validation sites for GEO Forest Carbon Tracker (FCT) (2009-10) in Mexico where intensive biomass sites have been established. We intend to fly as many regions as logistically possible. The exact flight plan will be decided during project planning meetings. (b) The 5,000 conglomerate sampling units (4 sampling sites of 400 sq. m each) that were remeasured in 2009. The same number of conglomerates (different locations) will be resampled in 2010 and again in 2011 for the 25,000 conglomerates established for Mexico's National Forest Inventory in 2004-2007. The large quantity of FIA ground plots available in the US are not shown due to space constraints.

approximately 53 by 97 m every 170 m along the ground track of the spacecraft when one of the lasers is firing (Abshire et al. 2005). The primary objective of the ICESat mission is to measure and remeasure the thickness of the polar and circumpolar ice sheets, and the lasers are turned on and off to conserve firing resources and to pick up targets of interest.

GLAS is a waveform instrument (Zwally et al. 2002). Unlike PALS, which records a first-last return range measurement from aircraft to target for each pulse, GLAS records the brightness of the 1.064 um, near-infrared return in one ns increments as the pulse traverses from the top of the target to the ground. Each nanosecond of travel corresponds to 15 cm vertical penetration into a porous target such as a forest canopy. Over snow and ice, the waveform for a single laser pulse would produce a very obvious peak return at the level of the snow or ice surface, providing a ranging measurement from spacecraft to target accurate to within 5 cm (Zwally et al. 2002). Over trees, the multiple returns recorded for a single pulse will provide an initial return from the top of the canopy and also provide secondary returns from subcanopy layers and the ground as the pulse traverses vertically from top to bottom (Ranson et al. 2004). Each individual waveform is analyzed to extract a number of measurements related to the biophysical characteristics of the forest canopy (Yong et al. 2004). Such measurements include total canopy height, height to subcanopy layers, heights associated with different percentages of pulse energy return, height of median energy (HOME), canopy density (if assumptions are made concerning ground/canopy reflectivity ratio), and canopy height variability (Yong et al. 2004). These structurally related measurements can, in turn, be related to forest biophysical characteristics of interest such as basal area, timber volume, above-ground biomass, and C stocks (Lefsky et al. 2002a,b).

GLAS data is also potentially useful for interpreting the vertical structure of forest ecosystems (Sun et al. 2007). For example, GLAS data has been successfully correlated to aboveground biomass in the Amazon with an R^2 of 0.73 and an RMSE of 58.3 Mg ha^{-1} (Lefsky et al. 2005). GLAS waveform data was also correlated to canopy height in tropical broadleaf forests in Brazil, temperate broadleaf forests in Tennessee, and temperate needleleaf forests in Oregon with R^2 values between 0.59 and 0.68 and RMSE between 4.8 and 12.7 m (Lefsky et al. 2005). However, when the GLAS pulse interacts with vegetation on topography having a significant slope, pulse broadening can occur, thus confounding the interpretation of the influence of the vegetation alone on the waveform (Harding and Carabajal 2005). In our Quebec study, topography was not a major confounding factor. The jury is still out for the boreal North America analysis.

Pflugmacher et al. (2008) related regional biomass estimates derived from forest inventory plots to GLAS estimates for two regions in the eastern and western US and obtained differences between 39.7 and 58.2 Mg ha-1. Baccini et al. (2008) used a regression tree model of MODIS spectral data to derive aboveground biomass of Africa and these estimates correlated well with GLAS height metrics. Nelson et al. (2009b) used a two-phase ground plot – GLAS pulse sampling design to attribute timber volume estimates to 16 forest cover classes in 10° x 12° study area in south-central Siberia. However, the robustness of the statistical analyses is much greater when a three phase sampling strategy is employed, i.e., when airborne lidar is used as an intermediate sampling tool. This is what we propose for North America.

We have ready access to GLAS data through NASA Goddard. While we do make use of the GLAS 14 tree height product, we mostly use the GLAS-01 raw waveforms and build our own processing algorithms. In addition to the 14 GLAS orbits that will be sampled by our airborne PALS system, the scaling of the relationships to the entire forest of North America will be conducted using the >28 million GLAS pulses in Collections 2A through 3H taken either in the spring or autumn of 2004-2008. However, we will not use acquisitions obtained when snow cover is present. We will also examine any apparent differences that may be present between the autumn and spring acquisitions and changes over time. Our team has developed considerable expertise in the processing and analysis of GLAS data for analysis of terrestrial ecosystems in North America and Siberia. The current project allows us to take what we have learned during our efforts in Quebec and boreal North America and apply them to a continental-scale analysis.

1.2.6. PALSAR Data

Synthetic aperature radar (SAR) has shown potential for estimating biomass of young or sparsely vegetated forests (Dobson et al. 1992). The Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) was launched in January 2006. It has a 23.6 cm wavelength and provides HH (horizontal transmit and horizontal receive) and HV (horizontal transmit and vertical receive) data. PALSAR, and other L-band systems, respond to the aboveground biomass of tropical savannas and open forests (Mitchard et al. 2009, Podest and Saatchi, 2002) and some global biomass mapping projects using PALSAR are in progress. Biomass estimates saturate at around 100 to 150 Mg C ha^{-1}, suggesting that it should be useful to combine these data with our hierarchical PALS-GLAS sampling to estimate a wide range of biomass levels for North America. The HV backscatter had stronger sensitivity than the HH and VV backscatter for unfrozen boreal forests in Sweden (Santoro et al. 2009). We will obtain

PALSAR data for low biomass areas of North America through the Alaskan Satellite Facility via existing NASA agreements. We will compare the PALSAR estimates with our airborne and plot data and use this as a basis to compare the GLAS and PALSAR C stock estimates.

1.2.7. MODIS Vegetation Continuous Fields – Percent Canopy Cover

The MODIS sensor, part of NASA's Earth Observation System (EOS) onboard the Terra and Aqua satellites, is designed for moderate-resolution global monitoring of the Earth. The Vegetation Continuous Fields (VCF) product is derived from multiple temporal composites and provides a percent canopy cover value for each 500 m pixel. This continuous value (0–100%) is related to the amount of skylight obstructed by tree canopies equal to or greater than 5 m in height. We believe that this continuous value approach can be combined with other satellite data (GLAS and PALSAR) to more reliably estimate aboveground forest C stocks, particularly for areas with sparse canopies where GLAS tends to fail. The heterogeneous nature of forest cover lends itself well to the continuous mapping method of the VCF. There have been other efforts to map tree cover using VCF around the world, our group has worked extensively with VCF data as part of a project to map the taiga-tundra ecotone (e.g., Montesano et al. 2009). We intend to use the VCF product to define contours of threshold percent tree cover below which we will rely primarily on the PALSAR estimates of aboveground C.

1.2.8. Landsat Land Cover Products

For Canada, we use a high-quality land cover product constructed by the Earth Observations for Sustainable Development (EOSD) project, a 30-m land cover product based on Landsat-7 Enhanced Thematic Mapper (ETM+) data that was released in 2006 (Wulder et al. 2003).

For the US, we will use the 30-m 2006 National Land Cover Data (NLCD) classification. This would provide a consistent, up-to-date land cover layer for the US that will be used for stratification. NLCD land cover is available through the Multi-Resolution Land Characteristics (MRLC) Consortium (http://www.mrlc.gov). The MRLC purchased three dates of Landsat 7 imagery for the entire United States and coordinated the production of a comprehensive NLCD land cover database (Homer et al. 2007). The MRLC consortium is specifically designed to meet the current needs of Federal agencies for nationally consistent satellite remote sensing and land-cover data. We will use Landsat-derived disturbance products from the NASA funded LEDAPS project to flag areas where there have been recent changes in cover type status.

For Mexico, we will use the Landsat land use and land cover product developed at INEGI (Instituto nacional de estadistica y geografia). A 2007 land cover mapping was performed using ETM+ data. INEGI will complete an update in 2010. Our Mexican colleagues have great deal of experience working with these products.

1.2.9. ASTER and SRTM Digital Elevation Models

The ASTER Global DEM was produced using ASTER data on the Terra satellite acquired from the start of observation to the end of August, 2008 in cooperation with the Japan-US ASTER Science Team. Accuracies in the range of 7 to 15 m are achieved when ASTER stereo image data is of good quality as it generally is for North America. The Global DEM was created by stereo-correlating the 1.3 million scene ASTER VNIR archive, covering the Earth's land surface between 83°N and 83°S latitudes. It was produced with 30 meter postings, and is formatted in 1 x 1 degree tiles as GeoTIFF files. Each GDEM file is accompanied by a Quality Assessment file, either giving the number of ASTER scenes used to calculate a pixel's value, or indicating the source of external DEM data used to fill the ASTER voids. Slope can be calculated from this data using topographic modeling features in the ENVI software.

Shuttle radar (SRTM) data can also be used to mask and/or classify areas of significant slope where the GLAS waveform returns convolve topography and forest structure. The SRTM mission, flown in February of 2000, collected topographic data over almost all land surfaces between 60°N and 54°S latitude. The 30 m data in the US and 90 m elsewhere have ≤ 16 m absolute vertical height accuracy, ≤ 10 m relative vertical height accuracy, 90% of the time. The data are available through the EROS Data Center and may be downloaded for free via the web. We used SRTM data successfully during the Quebec Carbon Lidar Project while our North American boreal analysis is based more on the ASTER DEM.

1.2.10. Exploring Variance Calculations

Several investigators on this proposal have been involved in studies to identify appropriate lidar-based sampling procedures and to refine the associated variance estimators. Defining and refining the appropriate statistical framework is a work in progress, with the most recent advances reported by Andersen et al. (2009), Ståhl et al (2010) and Gregoire et al. (2010). Andersen et al. (2009) and Gregoire et al. (2010) report on model-assisted, design-based statistical approaches that are similar to those described by Särndal et al. (1992). These frameworks rely on a relatively intensive, design-unbiased allocation of reference observations, typically ground plots, that are used to adjust laser-based estimates to ground. Ståhl et al. (2010), on the other hand, proposes a model-based procedure that incorporates both sampling error and model-based error. The model-based approach rests on the assumption that the predictive model (e.g., biomass = f(laser ht)) is true and unbiased. This assumption tends to make lidar investigators nervous since most/all models have some level of bias. However, the extent of the bias can be quantified by comparing lidar-based results with ground inventory data compiled on selected areas throughout the study area of interest. We will use both the Gregroire et al. (2010) and Ståhl et al. (2010) frameworks to generate stratum, ecosystem, national, and continental estimates in this study.

The Gregoire et al. (2010) and Stahl et al. (2010) estimators are not ideal for our work because they are designed to handle two-stage or two-phase sampling frameworks. As done for our Quebec and North American Boreal Carbon-Lidar Projects, the work proposed here employs three sampling layers – ground plots, airborne lidar, and satellite lidar. To integrate the Gregoire and Ståhl sampling frameworks with our three-phase data collection, PALS estimates of biomass will serve as the secondary sampling unit, supplanting ground-based estimates as described by Greogoire and Ståhl, and the systematic GLAS measurements will serve as the primary sampling unit. Nelson will continue to work with Gregoire, Ståhl, as well as Næsset and Gobakken (Norwegian co-I's on previous NASA-funded investigations) to further refine these estimators and to extend them to include three sampling phases. There is common interest among these parties to work together to develop robust statistical frameworks. This statistical framework will allow us to quantify how future changes in land cover and land use in the different regions of North America are likely to impact aboveground C stocks.

1.2.12. Validation

PALS/GLAS estimates of biomass will be compared with other biomass estimates available from the US, Mexico, and Canada. For instance, on the Kenai Peninsula of Alaska, an area completely sampled by the USFS-FIA, our study results can be compared to regional USFS estimates. Similar checks can be made for any US state in the lower 48. Mexico also has a national forest inventory framework, and regional ground estimates will be compared to our lidar-based estimates in those areas where observations are temporally coincident. Canada is somewhat more problematic given (1) the lack of access to most of their 4 million square kilometers of forest, (2) the autonomy of provincial forest inventories and (3) a provincial trend to inventory only commercial forests. Of all provinces polled in our recent boreal North America study, the commercial forests of Ontario seems best suited to serve as a test bed for lidar comparisons.

We envision the development of generic equations to estimate biomass using PALS and GLAS data across land cover types, although we will test to see if stratification is merited between strata (i.e., land cover types) within ecozones. Such generic equations functioned well in our previous studies. However, this current study proposes to develop predictive equations across vastly different cover types, ecozones, and GLAS data acquisitions. A stratified design will be implemented if it becomes apparent that there is an advantage to developing regressions for each land cover type. We will report our biomass estimates by cover type, ecozone, and various political boundaries that may be of interest (countries, regions, large-scale watersheds, etc.).

1.3 Perceived Impact

This study will provide a baseline aboveground C inventory of the forests of North America using a standardized, consistent methodology across all three countries derived from a hierarchical sampling approach. The research will be conducted by a team of leading forest C cycle scientists in the US, Mexico, and Canada. Our group is unique in that, to our knowledge, we are the only group with experience integrating GLAS biomass analyses with an airborne field campaign and ground plots. We also use state-of-the-art statistical approaches and uncertainty estimates to estimate variances, particularly those based on transect data. This research should have a significant impact on how satellite-based C stock monitoring will be conducted in the future. It should also be useful for constraining C cycle models since parameterization of biomass pools is critical to most of these models. This study will make a significant contribution to future national and continental-scale assessments such as SOCCR (State of the Carbon Cycle Report) and the IPCC. Our research will help form a solid methodological and statistical foundation for future biomass satellite missions. It will also provide a foundation for satellite data fusion activities via our efforts to integrate GLAS, PALSAR and MODIS VCF information. The C stock estimates for Mexico will be useful for validating other estimates such as those obtained through GEO-FCT and should be pertinent to Reduced Emissions from Deforestation and Forest Degradation (REDD) initiatives. Management activities or policies in one region of North America may affect C budgets of other regions. Robust estimates of continental-scale forest C stocks and their spatial distribution will provide a quantitative framework these types of analyses.

1.4. Relevance of the Proposed Work to NASA Programs and Interests

NASA's Earth Science Program has a keen interest in designing and applying satellite technologies for developing a climate observation system and a new generation of coupled Earth system models that can provide decadal forecasting capability. Developing a capability to monitor aboveground C stocks at a continental scale is a high priority in this regard. Such research is crucial for determining the size and dynamics of the reservoirs of C in North America. It is important to make use of existing technologies to provide a pathway for NASA's future biomass missions. This proposal integrates a number of key NASA assets (ICESat, MODIS, ASTER, SRTM, Landsat, PALS) and data sources (GLAS waveform data, digital elevation models, canopy cover fraction, land cover class) to provide continental scale estimates of forest C stocks. While it is centered on the use of space technology for estimating C stocks, it also has strong links to the USDA Forest Service's Forest Inventory Assessment and to equivalent efforts in Mexico. NASA is a key player in the North American Carbon Program and the closely-related trilateral Carbo-NA effort. The proposed research will be a significant and concrete contribution to these multi-agency and multi-lateral efforts.

1.5 General Work Plan

1.5.1 Key Milestones

Year 1 – Develop flight plans for airborne lidar flights of ground plots and GLAS lines in Mexico and U.S. Upgrade PALS system to improve georeferencing of pulse locations. Obtain relevant PALSAR data and begin processing. Process biomass estimates of ground plots. Fly the eastern US portion in first summer. Begin processing other satellite data sets. Examine VCF product for determining different thresholds for where GLAS versus PALSAR estimates will be applied.

Year 2 – Major year for field campaign in Mexico and middle and western US. Process PALS data from first field season. Begin statistical analyses of new data sets.

Year 3 – Finish data processing and complete statistical analyses. Write articles.

1.5.2 Management Structure for Proposal Personnel

The project involves a collaborative team of scientists based primarily out of NASA Goddard as well as new members that will allow us to expand our efforts to a truly continental scale study. The core Goddard team (Nelson, Cook, Sun, Margolis, and Montesano) has been working together for several years on various aspects of the remote sensing of forest structure and C stocks using lidar, radar, and optical approaches. Recently, members of our core group have worked together on projects aimed at estimating aboveground C stocks of Quebec, boreal North America, and boreal Eurasia using GLAS, ground plots, airborne lidar when feasible, and various optical remote sensing products. We have also worked on mapping the northern taiga-tundra ecotone, the development of models that simulate the interaction of radar and lidar pulses within forest canopies, the development of data fusion algorithms for forest biomass mapping using both lidar and radar data, and a number of research activities in support of the development of two planned satellite lidar missions, DESDynI and ICESat-2 (e.g., view angle effects, impacts of different instrument designs, etc.). Nelson has been a member of the ICESat-2 Science Team and Cook is on the DESDynI Development Team. Our core group has developed good collaborations with Andersen and Wulder including the NASA-supported North American Boreal Carbon-Lidar

Project which focuses on aboveground C stocks in Canada and Alaska. The current proposal will build on these collaborations as it moves our focus to the continental scale. A key feature of the current proposal is the enhancement of our research collaborations to integrate two prominent C cycle scientists from Mexico, Fernando Paz-Pellat and Ben de Jong. Both are members of the steering committees of the Mexican Carbon Program and the trilateral Carbo-NA group. Margolis is Program Leader through mid-2011 of the Canadian Carbon Program and is also a member of the Carbo-NA steering committee. He has been integrated into the NASA Goddard research program since the early 1990's. Overall, the team has a unique blend of expertise in plot sampling, airborne lidar, processing and understanding GLAS and other satellite data, combined with a very robust and rigorous statistical approach.

Nelson is the PI for the current proposal and will have overall responsibility for the scientific direction and management of the project as well as the development of the statistical framework for the integration of all data sources. ***Nelson and Margolis*** will share responsibility for lidar flight planning and execution as well as the post-processing of the lidar data and the statistical analysis. As well, ***Margolis*** holds both a US and Canadian private pilot license which are useful for flight planning and operations in support of the professional pilot(s) who will fly the missions. He will spend the equivalent of 3 to 4 months per year in residence at NASA Goddard.

Guoqing Sun will be the primary interface with the ICESat and PALSAR data systems and their initial processing as well as serve as our senior software and image processing expert. ***Sun and Bruce Cook*** will have the primary responsibility for processing and analyzing the PALSAR data. ***Cook*** will also be the primary person responsible for assembling and testing the improved PALS system including the integration of the Inertial Measurement Unit (IMU) navigation capability. ***Paul Montesano*** will provide key technical and scientific support to all aspects of the project including the fusion of the lidar, radar, and VCF data and all GIS work related to the planning, execution, and analysis phases of the project.

Andersen will provide scientific and technical input regarding the FIA plots in the US to fly with our airborne lidar and related flight planning. He will also provide statistical advice about plot-related matters such as allometric equations. ***De Jong*** and ***Paz-Pellat*** will be our primary collaborators in Mexico and will provide logistic support and advice on the selection of plots to fly with our airborne lidar, GIS planning, flight planning, and support with other information sources from Mexico such as land cover maps and ecozone maps. One of their institutions will serve as the site for an initial project management meeting and both will serve as an important base of operations during the airborne campaign. ***Wulder*** will continue to provide support as needed for interpreting the remote sensing and plot data for Canada that we used in the previous North American boreal effort, particularly in regard to how they can best be integrated with the rest of the North American data set. All project participants will attend project meetings and will participate and provide intellectual input for scientific manuscripts

1.6 Data Sharing Plan

We will share our airborne data with any people who express an interest. The satellite data and data products are already publicly available except for PALSAR. We will follow the established agreements between NASA and JAXA for the PALSAR data. We will also follow all laws and agreements relative to the confidentiality of ground plot data in both the US and Mexico.

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2007 "Investigating RaDAR-LiDAR Synergy in a North Carolina Pine Forest", Nelson, R., P. Hyde, P. Johnson, B. Emessiene, M. Imhoff, R. Campbell, and W. Edwards. *Remote Sensing of Environment* 110(1): 98-108.

2005 "Locating and Estimating the Extent of Delmarva Fox Squirrel Habitat Using an Airborne LiDAR Profiler", Nelson, R.F., C. Keller, and R. Ratnaswamy, *Remote Sensing of Environment* 96(3-4): 292-301.

2004 "Measuring Biomass and Carbon in Delaware Using an Airborne Profiling LiDAR", Nelson, R.F., A. Short, and M. Valenti, *Scandinavian Jour. of Forest Research*, 19: 500-511. [Erratum. 2005, 20: 283-284.]

2003 "A Multiple Resource Inventory of Delaware Using Airborne Laser Data", Nelson, R.F., M.A. Valenti, E.A. Short, and C. Keller, *BioScience* 53(10): 981-992.

2003 "A Portable Airborne Laser System for Forest Inventory", Nelson, R. F., G. Parker, and M. Hom, *Photogrammetric Engineering and Remote Sensing* 69(3): 267-273.

2000 "Secondary Forest Age and Tropical Forest Biomass Estimation Using Thematic Mapper Imagery", Nelson, R.F., D.S. Kimes, W.A. Salas, and M. Routhier, *BioScience* 50(5): 419-431.

2000 "Canopy Height Models and Airborne Lasers to Estimate Forest Biomass: 2 Problems", Nelson, R., J. Jimenez, C.E. Schnell, G.S. Hartshorn, T.G. Gregoire, and R. Oderwald, *International Journal of Remote Sensing,* 21(11): 2153-2162.

1998 "The Effects of Fixed-Area Plot Width on Forest Canopy Height Simulation", Nelson, R.F., T.G. Gregoire, and R.G. Oderwald, *Forest Science* 44(3): 438-444.

1997 "Separating the Ground and Airborne Laser Sampling Phases to Estimate Tropical Forest Basal Area, Volume, and Biomass", Nelson, R.F., R. Oderwald, and T.G. Gregoire, *Remote Sensing of Environment* 60(3): 311-326.

1997 "Modeling Forest Canopy Heights: The Effects of Canopy Shape", Nelson, R.F., *Remote Sensing of Environment* 60(3): 327-334.

1994 "Two-Stage Forest Sampling: A Comparison of Three Procedures to Estimate Aggregate Volume", Nelson, R. and T.G. Gregorie, *Forest Science*, 40(2): 247-266.

1993 "AVHRR-LAC Estimates of Forest Area in Madagascar, 1990", Nelson, R.F. and N. Horning, *International Journal of Remote Sensing*, 14(8):1463-1475, also journal cover 1445-1446.

1988 "Estimating Forest Biomass and Volume Using Airborne Laser Data", Nelson, R., W. Krabill, and J. Tonelli, *Remote Sensing of Environment* 24:247-267.

1988 "The Use of Airborne Lasers for Estimating Forest Canopy and Stand Characteristics", Nelson, R., R. Swift and W. Krabill, *Journal of Forestry* 86(10):31-38.

1984 "Determining Forest Canopy Characteristics Using Airborne Laser Data", Nelson, R.F., W. Krabill, and G. MacLean, *Remote Sensing of Environment*, 15:201-212

HANK A. MARGOLIS

Affiliations: Faculty of Forestry, Geography, and Geomatics, Laval University
Quebec City, Quebec Canada
and
University of Maryland, Baltimore County, Goddard Earth Sciences and Technology Center (GEST) / Caelum Research Corporation, NASA Goddard Space Flight Center, Code 614.4, Greenbelt, Maryland, USA

Degrees

Doctor of Science (Honorary). 2010. University of Lethbridge, Lethbridge, Alberta
Ph.D. 1985. Oregon State University, Corvallis, Oregon. Discipline: Ecosystems & Silviculture
Master of Forestry 1980. Yale University, New Haven, Connecticut. Discipline: Ecophysiology
B.Sc. 1977. University of Vermont, Burlington, Vermont. Discipline: Forest Management

Work Experience

Faculty of Forestry, Geography, and Geomatics, Laval University, Quebec City, Canada
Full Professor (1998 – now); Assoc Prof (1993-98); Asst Prof (1991-93); Res Prof (1986-91).
Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland
Intermittent/Sabbatical Visiting Scientist (2004-2011, 1995); NRC Research Assoc. (1996).

Career Summary

I have conducted research on the terrestrial carbon cycle since the early 1990s. I have led several large research networks (BOREAS 1992-97, Fluxnet-Canada 2002-07, the Canadian Carbon Program for 2007-11) and subsequently managed and led integrated field projects involving dozens of scientists working in the areas of ecosystem ecology, remote sensing, biometeorology carbon cycle modeling, and biogeochemistry. This included setting up a national-scale flux tower network for Canada which now integrates other carbon cycle measurements into a robust modeling framework. I have conducted research in many of these fields. I have a long history of working with the Biospheric Sciences Branch at NASA-Goddard from 1992 that is focused on remote sensing of biosphere-atmosphere interactions. I am on the steering committee of the Joint North American Carbon program (now Carbo-NA) and on the science committee of the La Thuile global Fluxnet synthesis effort. I have directed 35 grad students and 9 postdocs since 1986. The research networks that I have led have trained over 180 grad students and postdocs. Refereed publ = 97.

SELECTED PUBLICATIONS

Nelson, R., Boudreau, J., Gregoire, T.G., **Margolis, H.A.,** et al. 2009. Estimating Québec provincial forest resources using ICESat/GLAS. *Canadian Journal Forest Res.* **39**: 862–881.
Boudreau, J., R.F. Nelson, **H.A. Margolis**, et al. 2008. Regional aboveground forest biomass using airborne and spaceborne LiDAR in Québec. *Remote Sensing of Environment* 112: 3876-3890.
Piao, S., P. Ciais, P. Friedlingstein, P. Peylin, M. Reichstein, S. Luyssaert, **H. Margolis,** et al. 2008. Net CO_2 losses of northern ecosystems in response to autumn warming. *Nature* 451:49-53.
Zhang, Q.-Y., E.M. Middleton, **H.A. Margolis,** et al.. 2009. Can a satellite-derived estimate of the fraction of PAR absorbed by chlorophyll improve predictions of light-use efficiency and ecosystem photosynthesis for a boreal aspen forest? *Rem. Sens. Environ.* 113: 880–888.
Montesano, P.M., R.F. Nelson, G. Sun, **H.A. Margolis**, A. Kerber, and K.J. Ranson. 2009. MODIS tree cover validation for the northern circumpolar taiga-tundra transition zone. *Remote Sensing of Environment* 113: 2130–2141.
Drolet, G.G., E.M. Middleton, (**H.A. Margolis & others)**. 2008. Regional mapping of gross light-use efficiency using MODIS spectral indices. *Rem. Sens. Environ.* 112: 3064-3078.

Bruce D. Cook, PI
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Current Position/Research: Physical Scientist focusing on LiDAR remote sensing and carbon/nutrient cycling in wetland and upland ecosystems, with expertise in flux tower measurements, satellite remote sensing of plant communities, and terrestrial ecology.

NASA Mission Affiliation: Member of the **DESDynI** Science Team; Deputy Project Scientist, Landsat Data Continuity Mission (**LDCM**).

Education:

PhD	Natural Resources - Assessment, Monitoring, and Geospatial Analysis, University of Minnesota, St. Paul, MN (2008)
MS	Soil, Water, and Climate, University of Minnesota, St. Paul, MN (1990)
BS	Biology, Huntington College, IN (1985)

Selected Professional Positions and Experiences:

2009-	Physical Scientist, NASA's Goddard Space Flight Center, Code 614.4
2008-2009	Research Associate, Forest Resources, University of Minnesota, St. Paul
2001-2007	Research Fellow, Forest Resources, University of Minnesota, St. Paul
2000-2001	Research Assistant, Meteorology, Penn State University, University Park
1991-2000	Research Fellow, Soil, Water and Climate, University of Minnesota, St. Paul

Professional Memberships: American Geophysical Union, American Society for Photogrammetry & Remote Sensing, Soil Science Society of America

Selected Publications:

Cook, B. D., P. V. Bostad, E. Næsset, R. S. Anderson, S. Garrigues, J. Morisette, J. Nickeson, and K. J. Davis. 2009. Using LiDAR and Quickbird data to model plant production and quantify uncertainties associated with wetland detection and land cover generalizations. *Remote Sensing of Environment* 113:2366-2379.

Sulman, B. N., A. R. Desai, **B. D. Cook**, N. Saliendra, and D. S. Mackay. 2009. The impact of a declining water table on observed carbon fluxes at a northern temperate wetland. *Biogeosciences* 6:1115–1126.

Ollinger, S. V., A.D. Richardson, M. E. Martin, D. Y. Hollinger, S. Frolking, P. B. Reich, L. C. Plourde, M -L. Smith, P. V. Bolstad, **B. D. Cook**, G. G. Katul, T. A. Martin, R. K. Monson, J. W. Munger, R. Oren, K. T. Paw U, and H. P. Schmid. 2008. Canopy nitrogen, carbon assimilation and albedo in temperate and boreal forests: functional relations and potential climate feedbacks. *Proceedings of National Academy of Sciences of the United States of America* 105:19335-19340.

Cook, B. D., P. V. Bolstad, J. G. Martin, F. A. Heinsch, K. J. Davis, W. Wang, A. R. Desai, and R. M. Teclaw. 2008. Using light-use and production efficiency models to predict forest production and carbon exchange during canopy disturbance events. *Ecosystems* 11:26-44.

Desai, A.R., A. Noormets, P.V. Bolstad, J. Chen, **B.D. Cook**, K.J. Davis, E.S. Euskirchen, C.M. Gough, J.M. Martin, D.M. Ricciuto, H.P. Schmid, J. Tang, and W. Wang. 2008. Influence of vegetation type, stand age and climate on carbon dioxide fluxes across the Upper Midwest, USA: Implications for regional scaling of carbon flux. *Agricultural and Forest Meteorology* 148:288-308.

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EDUCATION

B.S. Physics, University of Science and Technology of China 1970
M.S. Remote Sensing, Nanjing University, China 1981
Ph.D. Geography, University of California, Santa Barbara, USA 1990

ACTIVE RESEARCH AREAS

Radar Backscatter and Lidar Waveform Modeling of Vegetated Surface
Data Fusion for Vegetation 3D Structure and Ecosystem Studies
Land Cover and Land Use Change from Remote Sensing

MEMBERSHIP

Senior member, IEEE, IEEE Geosciences and Remote Sensing Society
Member, American Geophysical union

PROFESSIONAL SERVICE

April 2006 – present: Member of ORNL DAAC's User Working Group
Jan. 2007 – present: Associate Editor of Canadian Journal of Remote Sensing
Sept. 1998 – present, Guest professor, Institute of Remote Sensing Applications, Chinese Academy of Science
July 5, 2001 – present, Guest professor, Beijing Normal University

PUBLICATIONS (selected)

<u>Reviewed Literature</u>

Liu, D., **G. Sun**, Z. Guo, K. J. Ranson and Y. Du, 2010, Three-Dimensional coherence radar backscatter model and simulations of scattering phase center of forest canopies, IEEE Transactions on Geoscience and Remote Sensing, Vol. 48, No. 1, pp 349-357.

G. Sun, K.J. Ranson, D. S. Kimes, J.B. Blair, and K. Kovacs , 2008, Forest Structural Parameters From GLAS: an Evaluation Using LVIS, SRTM Data and Field Measurements, *Remote Sensing of Environment*. 112(1): 107-117.

G. Sun, K.J. Ranson, J. Masek, Z. Guo, Y. Pang, A. Fu, and D. Wang, 2008, Estimation of Tree Height and Forest Biomass from GLAS Data, Journal of Forest Planning, 13:157-164.

Koetz, B., **G. Sun**, F. Morsdorf, K. J. Ranson, M. Kneubuhler, K. Itten, and B. Allgower, 2007, Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization, *Remote Sensing of Environment*, Vol. 106 (4), pp. 449-459.

Sun, G., K. J. Ranson and Z. Zhang, 2006, Forest vertical parameters from lidar and multi-angle imaging spectrometer data, *Journal of Remote Sensing (in Chinese)*, 10(4): 523-530.

Sun, G., K. J. Ranson, V. I. Kharuk, and K Kovacs, 2003, Validation of surface height from Shuttle Radar Topography Mission using Shuttle Laser Altimeter, Remote Sensing of Environment, Vol. 88, Iss. 4, pp. 401-411.

Sun, G., K. J. Ranson, and V. I. Kharuk, 2002, Radiometric slope correction for forest biomass estimation from SAR data in Western Sayani mountains, Siberia, *Remote Sensing of Environment, Vol. 79:279-287*.

Sun, G. and K. J. Ranson. 2000, Modeling lidar returns from forest canopies *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, pp.2617-2626.

Sun, G. and K. J. Ranson, 1998, "Radar modeling of forest spatial structure", *Int. Jour. of Remote Sensing*, Vol. 19, No. 9, 1769-1791.

Ranson, K.J. , **G. Sun**, J. F. Weishampel, and R. G. Knox, 1997, Forest biomass from combined ecosystem and radar backscatter modeling, *Remote Sensing of Environment*, 59:118-133

Sun, G. and K. J. Ranson, 1995, A three-dimensional radar backscatter model of forest canopies, *IEEE Transaction on Geoscience and Remote Sensing*, Vol. 33, No. 2, pp. 372-382.

Ranson, K.J. and **G. Sun,** 1994, Mapping biomass for a northern forest ecosystem using multifrequency SAR data, IEEE Transaction on Geoscience and Remote Sensing, Vol. 32, No. 2, pp. 388-396.

Sun, G., D. S. Simonett, and A. H. Strahler, 1991, A radar backscatter model for discontinuous coniferous forests, IEEE Transaction on Geoscience and Remote Sensing, Vol. GE-29, No. 4, pp. 639-650.

Paul Mannix Montesano

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Interests: Advance the application of remote sensing data fusion and geo-spatial tenchnology to document, quantify and monitor changes of forest carbon stocks.

Recent Experience

Support Scientist, November 2006 – Present
Science Systems and Applications, Inc. / Sigma Space Corp. – NASA Goddard Space Flight Center, Greenbelt, MD

Project Assistant, June 2005 – August 2006
Nelson Institute of Environmental Studies, University of Wisconsin - Madison

Project Assistant / Teaching Assistant, September 2004 – August 2005
Department of Geography, University of Wisconsin - Madison

GIS Coordinator/Research Technician, September 2001 – June 2004
Grant F. Walton Center for Remote Sensing and Spatial Analysis, Cook College, Rutgers University

Technical Skills

Analysis/Scripting/Presentation:	ArcInfo, Definiens eCognition, ENVI/IDL, GIS - Google Earth integration, ERDAS Imagine, Python
Application Areas:	Remote sensing, data visualization, spatial analysis, landscape change analysis, cartography
Instruments/Data Types:	High-moderate resolution multispectral / microwave / LiDAR airborne and spaceborne sensors

Education

Nelson Institute of Environmental Studies, University of Wisconsin - Madison
M.S.(Research option) Environmental Monitoring, May 2006
Master's Thesis: Estimating chl-*a* in lakes with MODIS: A regional assessment

Rutgers College, Rutgers University
B.A. with High Honors, May 2001 Major: Geography Minor: Biology
Senior Honors Thesis: Examining relationships between snow coverage and wildfires in the western U.S.

Selected Publications

1. Montesano, P.M., Ranson, K.J., Nelson, R.F. Mapping the circumpolar taiga-tundra ecotone with MODIS tree cover data. (In Preparation).
2. Montesano, P.M., Nelson, R., Sun, G., Margolis, H., Kerber, A., Ranson, K.J. (2009). MODIS tree cover validation for the circumpolar taiga-tundra transition zone, Remote Sensing of Environment, vol. 113, pp. 2130-2141.
3. D. Kimes, A. Ullah, G. Sun, K.J. Ranson, V. Kharuk, P. Montesano (2009). The Potential of Mapping Timber Volume using MISR Multi-Angle Spectral and GLAS Lidar Data. (In Preparation).
4. Nelson, R., Ranson, K. J., Sun, G., Kimes, D., Kharuk, V., Montesano, P. (2009). Estimating Siberian timber volume using MODIS and ICESat/GLAS, Remote Sensing of Environment, vol. 113, pp. 691-701.
5. Ranson, K. Jon; Kimes, Daniel; Sun, Guoqing; Nelson, Ross; Kharuk, Vyatcheslav; Montesano, Paul. Using MODIS and GLAS data to develop timber volume estimates in Central Siberia. Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International 23-28 July 2007 Page(s):2306 - 2309.
6. Lathrop, R., Montesano, P., Haag, S. 2005. A multi-scale segmentation approach to mapping seagrass habitats using airborne digital camera imagery. *Photogrammetric Engineering and Remote Sensing* 72(6): 665-675.
7. Lathrop, R., Montesano, P., Tesauro, J., Zarate, B. 2005. Statewide mapping and assessment of vernal pools: A New Jersey case study. *Journal of Environmental Management* 76: 230-238.
8. Lathrop, R.J, Windham, L.M, Montesano, P. 2003. Does Phragmites expansion alter the structure and function of marsh landscapes? Patterns and processes revisited. Estuaries 26:423-435.
9. Medler, M.J., Montesano, P., Robinson, D. 2002. Examining the relationship between snowfall and wildfire patterns in the western United States. Physical Geography 21:335-342.

HANS-ERIK ANDERSEN

EDUCATION:

University of Washington, Seattle, Washington
Ph.D., Quantitative Resource Management (Forest Biometrics), February, 2003
M.S., Forest Resources, August, 1997
International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands
Professional Master *with distinction*, Forest Survey, August, 1998
Williams College, Williamstown, Massachusetts
B.A. *cum laude*, History, June, 1994

PROFESSIONAL EXPERIENCE:

USDA Forest Service Pacific Northwest Research Station, Anchorage, Alaska USA
Research Forester, September, 2006 – present
University of Washington College of Forest Resources, Seattle, Washington USA
Affiliate Assistant Professor, October, 2006 – present
Research Scientist, March, 2003 – September, 2006

SELECTED RECENT PUBLICATIONS:

Kim, S., R.J. McGaughey, H.-E. Andersen, and G. Schreuder. 2009. Tree species differentiation using intensity data derived from leaf-on and leaf-off airborne laser scanner data. *Remote Sensing of Environment* 113(8): 1575-1586.

Andersen, H.-E. 2009. Using airborne lidar to characterize forest stand condition on the Kenai Peninsula of Alaska. *Western Journal of Applied Forestry* 24(2): 95-102.

Andersen, H.-E., R.J. McGaughey, and S.E. Reutebuch. 2008. Assessing the influence of flight parameters, interferometric processing, slope, and canopy density on the accuracy of X-band IFSAR-derived forest canopy height models. *International Journal of Remote Sensing* 29(5): 1495-1510.

Li, Y., H.-E. Andersen, and R.J. McGaughey. 2008. A comparison of statistical methods for estimating forest biomass from light detection and ranging data. *Western Journal of Applied Forestry* 23(4): 223-231.

Pang, Y., M. Lefsky, H.-E. Andersen, M. Miller, and K. Sherrill. 2008. Validation of the ICESat vegetation product using crown-area-weighted mean height derived using crown delineation with discrete return lidar data. *Canadian Journal of Remote Sensing*, Vol. 34, Supplement 2, pp. S471-S484.

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. A rigorous assessment of tree height measurements obtained using airborne lidar and conventional field methods. *Canadian Journal of Remote Sensing* 32(5): 355-366.

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2006. Chapter 3: Active remote sensing. In: Shao, G., and K. Reynolds, eds., *Computer Applications in Sustainable Forest Management*, Springer-Verlag, Dordrecht.

Andersen, H.-E., S.E. Reutebuch, and R.J. McGaughey. 2005. Accuracy of an IFSAR-derived digital terrain model under a conifer forest canopy. *Canadian Journal of Remote Sensing* 31(4):283-288.

PRIOR RESEARCH PROJECT EXPERIENCE:

• *Co-Investigator* on NASA ROSES project “Using the ICESAT-GLAS Lidar to Estimate the Amount, Spatial Distribution, and Statistical Uncertainty of Aboveground Carbon Stocks of the North American Boreal Forest.” Assist in obtaining, processing, and compiling plot-level biomass data in Alaska collected by DoD, UAF, NPS, USDA FIA. Andersen allocation of grant award $43,000. Provide statistical support and assist in analyzing the ICESAT-GLAS data and airborne profiling lidar data acquired over plots in Alaska.

• *Principal investigator* on JFSP-funded “Investigation of pre-fire fuels loading and burn intensity using pre-fire IFSAR combined with multi-spectral imagery for 2003 southern California fires.”(2004-2009). Grant award $532,000. Co-author of the grant proposal. Co-developed the experimental design and supervised the field data collected in southern California in 2004 and 2005.

• *Principal investigator* on federally-funded investigation of the utility of LIDAR as a source of information for the nationwide Forest Inventory and Analysis (FIA) program (2004-2009). Grant award $350,000. Co-wrote the proposal and managed analysis and data collection for the project.

CURRICULUM VITAE : BEN H.J. DE JONG

1. Current Position:

- Senior Researcher (full-time research staff member), El Colegio de la Frontera Sur (ECOSUR); September 1992 to present;

2. University education:

- Candidate (B.Sc level) in Forestry Science (1976), Agricultural University Wageningen, Wageningen, The Netherlands (September 1972-January 1976).
- Doctoral Exam (M.Sc. level) in Forestry Science (1979, with Honours), Agricultural University Wageningen, Wageningen, The Netherlands (January 1976-June 1979).
- Doctor in Science (October 2000), Wageningen University, Wageningen. Title dissertation: Forestry for Mitigating the Greenhouse Effect: An ecological and economic assessment of the potential of land-use to mitigate CO2 emissions in the Highlands of Chiapas, Mexico.

3. Professional experience:

- Coordinator National Inventory of Greenhouse Gas Emissions in the LULUCF sector. 2005-2009.
- Project Coordinator: ECOSUR/US-EPA project "Landscape Characterization, Vegetation Analysis, and Carbon Storage Assessment for Chiapas, México", funded by US-EPA (1993-1996). ECOSUR/University of Edinburgh projects: Sustainable Forest Management and Conservation in Chiapas, funded by Darwin Inititiative (1995-1997); Evaluation of the Cost of Large-Scale Forestry Projects for Carbon Sequestration, funded by International Energy Agency (1996-1997); International Pilot Greenhouse Gas Bubble for Forests - Chiapas, México, funded by The Forestry Research Programme , UK (1998-2001). Ecological and socio-economic assessment of Land-use/Land-cover change in the humid tropics of eastern Tabasco and Selva Lacandona, Chiapas, funded by CONACyT, Mexico (2001-2004). Land Use, Land-Use Change and Forestry (FUMEC); 2004-2005; GHG emissions estimations from Land Use Land-use Change and Forestry in Mexico 1993-2002; financed by PNUD (2005-2006); Strengthening of CDM Projects in the Forestry and Bio-energy sectors in Ibero-America, financed by the Government of Spain (2005-2007);
- ECOSUR/INE/SEDESOL/PAJAL YA CAK'TIK project "Sustainable Forestry Development: Carbon Sequestration" (1994-1995). UNAM/ECOSUR project "Land-Use Change and Carbon Emissions in the Humid Tropics of Mexico: Current Situation and Mitigation Scenarios", financed by US-EPA (2000-2001). LCLUC-SYPR Project "Land-Cover and Land-Use change in the Southern Yucatán Peninsular Region (SYPR)", funded by NASA (2001-2003). UNAM/ECOSUR/INE project: Land Use, Land-Use Change and Forestry; financed by US-EPA through The United States-Mexico Foundation for Science (2004-2005).
- Consultant for British American Tobacco on Carbon sequestration potential of fuelwood plantations in Brazil.
- Member of the National Council on Climate Change;

- Member of the Scientific Steering Comission of the Mexican Carbon Program.
- Expert of UNFCCC-CDM methodologies in the LULUCF sector.

Recent publications

- Ordoñez, J.A.B., B.H.J. de Jong, F. García-Oliva, F.L. Aviña, J.V. Pérez, G. Guerrero, R. Martínez, O. Masera. 2008. Carbon content in vegetation, litter, and soil under 10 different land-use and land-cover classes in the Central Highlands of Michoacan, Mexico. Forest Ecology and Management 255: 2074-2084.
- M. Skutsch, N. Bird, E. Trines, M. Dutschke, P. Frumhoff, B. de Jong, P. van Laake, O. Masera, and D. Murdiyarso. 2007. Clearing the way for reducing emissions from tropical deforestation. Environmental Science and Policy 10: 322-334.
- De Jong Ben H., Omar Masera, Marcela Olguín, Rene Martínez. 2007. Greenhouse gas mitigation potential of combining forest management and bioenergy substitution: A case study from Central Highlands. Forest Ecology and Management 242: 398-411.
- Sandra Brown, Myrna Hall, Ken Andrasko, Fernando Ruiz, Walter Marzoli, Gabriela Guerrero, Omar Masera, Aaron Dushku, Ben DeJong, Joseph Cornell. 2007. Baselines for land-use change in the tropics: application to avoided deforestation projects. Mitigation and Adaptation Strategies for Global Change 12: 1001-1026.
- De Jong, B.H.J., Esquivel-Bazán, E., S. Quechulpa-Montalvo. 2007. Application of the "Climafor" baseline to determine leakage: the case of Scolel Té. Mitigation and Adaptation Strategies for Global Change 12: 1153-1168.
- Castillo-Santiago, MA; Hellier, G.; Tipper, R.; De Jong, B.H.J. 2007. Carbon emissions from land-use change: a regional analysis of causal factors in Chiapas, México. Mitigation and Adaptation Strategies for Global Change 12: 1213-1235

Villahermosa, Tabasco, May 2, 2010

Bernardus H.J. de Jong, Senior Researcher, ECOSUR

Fernando Paz Pellat, biographical sketch

Dr. Fernando Paz Pellat (FPP), Ph.D. in Water Sciences and Remote Sensing from Colegio de Postgraduados, Mexico, in 2005. FPP has been full Research Professor in the University of Sonora, Mexico, 1982-1991, and Director of the Research Center in Engineering, 1983-1987, University of Sonora. FPP was Director of Research and Development with several private firms, consulting related to natural resources development and advanced technology. In 1991-2002, FPP was an Associated Researcher in the Colegio of Postgraduados. From 2005 is a research professor in the Colegio of Postgraduados, Mexico. Actually, he is member of the Mexican System of Researchers, chairman of the Science Steering Committee of the Mexican Carbon Program, member of the Science Steering Committee of CarboNa, leader of the MRV component of Mexico REDD strategy, coordinator of Mexican Unified Terrestrial and Remote Sensing Monitoring System (a multi-institutional program, member of Mexican GHG inventories group (soil and remote sensing components), member of the Mexican modeling of C dynamics (joint collaboration between Canada and Mexico), Mexican coordinator of the GEO-FCT. His research activities has been directed to the development of insurance products based in remote sensing technology (AVHRR and MODIS), irrigation assistance with remote sensing (SPOT, LANDSAT, ASTER), yield forecasting using remote sensing, optical and radar technology, uncertainty analysis of spatial geodata, including multi-scale approaches, disturbance analysis of C dynamics, fusion of remote sensing and ground data, development of active technologies for ground sampling, national C inventories standards, advanced modeling approaches. Some of the publications related to remote sensing and uncertainty characterization are:

Paz, F., Palacios, E., Bolaños, M., Cano, A., Zarco, A., Pascual, F., Palacios, L.A. y Martínez, M., 2006, Design of a country scale livestock insurance in grasslands using AVHRR sensor, In: Sobrino, J.A. (Ed.), Recent Advances in Quantitative Remote Sensing, Universitat de Valencia, Valencia, Spain, pp. 683-685. Paz, F., Palacios, E., Bolaños, M., Palacios, L.A., Martínez, M., Mejía, M. y Huete, A., 2007, Design of a vegetation spectral index: NDVIcp. Agrociencia 41, 539-554. Paz, F., Bolaños, M., Palacios, E., Palacios, L.A., Martínez, M., y Huete, A., 2008, Optimization for the spectral vegetation index NDVIcp. Agrociencia, 42: 925-937. Paz, F., Odi, M., Cano, A., Bolaños, M.A. y Zarco, A., 2009, Environmental equivalence in vegetation productivity, Agrociencia 43:635-648. Palacios-Sánchez, L.A., F. Paz-Pellat, J. L. Oropeza-Mota, B. Figueroa-Sandoval, M. Martínez-Menes, C.A. Ortiz-Solorio y A. Exebio-García. 2006. Generic object classificator in ETM+ images, Agrociencia 40:613-626. Bolaños, M., F. Paz, E. Palacios, E. Mejía, y A. Huete. 2007. Modeling the sun-sensor geometry in the vegetation canopy. Agrociencia 41: 527-537. Zarco, A, Paz, F., Palacios, E., Cano, A., Bolaños, M, Pascual, F. Palacios, L.A., Palacios, O. y Oropeza, J.L., 2008, Modeling of the spectral scale effect in the soil-vegetation system, Agrociencia, 42: 193-204. Paz, F., A. Zarco, A. Cano, M.A. Bolaños, y M. Odi. 2009. Balbontin, C., C. Cruz, F. Paz., J.D. Etchevers. 2009. Soil Carbon Sequestration in Different Ecoregions of Mexico. In: Soil Carbon Sequestration and the Greenhouse Effect. 2nd ed. SSSA Spec. Publ. 57. R. Lal and R.F. Follett (ed.) SSSA, Madison, WI. Cano, A., F. Paz, M. Bolaños, E. Palacios, E. Mejia, J.L. Oropeza, R. Valdez, J. Chavez, and A. Zarco. 2009. On the classification of tree systems using multi-angular spectral information. Agrociencia 43:279-290. Paz, F., C. Balbontin, J. Etchevers, M. Martinez. C. Ortiz. 2009. Multifractal analysis of soil organic carbon. 1. Universal scaling function. Terra Latinoamericana 26:183-191.

Dr. Michael A. Wulder. Research Scientist – Canadian Forest Service

Biographical Sketch.
Friday, April 23, 2010

Bio-sketch:
Mike Wulder received his B.Sc. degree from the University of Calgary (1995), and his M.E.S. (1996) and Ph.D. (1998) degrees from the Faculty of Environmental Studies at the University of Waterloo. Dr Wulder joined the Canadian Forest Service, Pacific Forestry Centre, in Victoria, British Columbia as a Research Scientist in 1998. Dr Wulder's major research publications include the book Remote Sensing of Forest Environments: Concepts and Case Studies (2003, KAP) and Forest disturbance and spatial pattern: Remote sensing and GIS approaches (2006, Taylor and Francis). He has produced more than 150 refereed papers in the top remote sensing, forestry, environmental science, and GIS journals. Dr Wulder is an adjunct professor in the Department of Geography at the University of Victoria and the Department of Forest Resources Management of the University of British Columbia. Dr. Wulder is on the NASA/USGS Landsat Science Team and the GOFC-GOLD Land Cover Implementation Team. Dr. Wulder leads a science, applications, and product development program, from which a land cover map of the forested area of Canada was produced.

Select citations:

Wulder, M.A., White, J.C., Gillis, M.D., Walsworth, N., Hansen, M.C, Potapov, P., (2009). Multi-scale satellite and spatial information and analysis framework in support of a large-area forest monitoring and inventory update. Environmental Monitoring and Assessment. (DOI: 10.1007/s10661-009-1243-8)

Falkowski, M.J., M.A. Wulder, J.C. White, and M.D. Gillis (2009). Supporting large-area, sample-based forest inventories with very high spatial resolution satellite imagery. Progress in Physical Geography. Vol. 33, No. 3, pp. 403–423.

Wulder, M.A., J.C. White, G. Stinson, T. Hilker; W.A. Kurz, N.C. Coops, B. St-Onge, and J.A. Trofymow (2009). Implications of differing input data sources and approaches upon forest carbon stock estimation, Environmental Monitoring and Assessment. Published online 11 June 2009. (DOI 10.1007/s10661-009-1022-6).

Hilker, T., Wulder, M.A., Coops, N.C., Seitz, N., White, J.C., Gao, F., Masek, J., & Stenhouse, G.B. (2009). Generation of dense time series synthetic Landsat data through data blending with MODIS using the spatial and temporal adaptive reflectance fusion model (STARFM). Remote Sensing of Environment. Vol. 113, No. 9. pp. 1988-1999.

Hilker, T., Wulder, M.A., Coops, N.C., Linke, J., McDermid, G., Masek, J., Gao, F., and White, J.C. (2009). A new data fusion model for high spatial- and temporal- resolution mapping of forest disturbance based on Landsat and MODIS. Remote Sensing of Environment. Vol. 113, No. 8, pp. 1613-1627.

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Wulder, M.A., J.C. White, T. Han, N.C. Coops, J.A. Cardille, T. Holland, and D. Grills, 2008. Monitoring Canada's forests. Part 2: National forest fragmentation and pattern. Canadian Journal of Remote Sensing. Vol. 34, No. 6, pp. 563-584.