The Role of Land-Cover Change in High Latitude Ecosystems: Implications for Carbon Budgets in Northern North America

Annual Report for Second Year of NASA-LCLUC Project (NAF-11142) (Performance Period August 1, 2002 - July 31, 2003)

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Abstract

In our previous NASA LCLUC Project (NAG5-6275), we conducted change-detection studies of land-cover change in the Alaska region, and we developed a prototype spatially explicit modeling framework capable of using satellite-derived data on land-cover change to estimate how changes in land cover cause changes in ecosystem carbon storage. Our goals in our current NASA LCLUC Project are (1) to evaluate a key question about land-cover change that emerged from our previous project, and (2) to extend the application of our modeling framework to the entire Alaska-Canada region.

A key question that emerged from our previous studies pertains to whether lakes and wetlands are drying up in the Alaska region, which may be indicative of large-scale decreases in soil moisture across Alaska. We hypothesize that there has been a significant decrease in the number of lakes and ponds in regions of discontinuous permafrost. We proposed to test this hypothesis by comparing Digital Raster Graphics (DRGs) from the 1950's, Landsat TM imagery from the 1980's, and Landsat-7 ETM+ imagery from 2000. The comparisons will be made across an east-west and north-south climate gradient in Alaska. The areas we chose range from maritime to continental climate regimes: Kenai Peninsula, Copper River Basin, Seward Peninsula, Innoko Flats, Tanana Flats, Forty Mile Flats, and the Yukon Flats.

Our modeling framework is based on the Terrestrial Ecosystem Model (TEM), and in this study we will apply TEM to the entire Alaska-Canada region. In comparison to Alaska, a greater array of disturbances, which include fire, insects, agricultural land use, and timber harvest play a role in the carbon dynamics of Canada. Also, other factors besides disturbance such as increasing atmospheric CO_2, climate change, warming permafrost, and nitrogen deposition may be affecting carbon storage in both Alaska and Canada. Thus, the extension of our modeling efforts to simulate carbon dynamics for the Alaska-Canada region involves further development of TEM to consider multiple disturbances in the context of other multiple environmental changes and further development of spatially explicit data sets on land cover change in the Alaska-Canada region. We will evaluate our application of TEM to the Alaska-Canada region in the context of well-founded atmospheric inversion estimates, and in the context of other regional analyses of changes in carbon storage based on satellite-derived data (AVHRR) and forest inventory approaches.

Achievement of the objectives in the proposed study will improve our understanding of processes responsible for historical changes in carbon storage in high latitudes, will give us greater confidence in our ability to model those changes, and will give us the capability to evaluate how land-cover changes may affect carbon storage in high latitude regions in the future.

Key Words

Research Fields: Remote Sensing, Ecosystem Dynamics, Atmospheric Chemistry
Geographic Area/Biome: Alaska-Canada, Tundra, Boreal Forest
Remote Sensing: Change Detection, TM/ETM+, AVHRR
Methods/Scales: Ecological Modeling, Inversion Modeling, Forest Inventory Analysis

Questions, Goals, and Approaches

Relevance to NASA ESE Questions.

Our study is relevant to two NASA ESE questions: (1) What are the changes in land cover and land use change (LCLUC)?; and (2) What are the consequences of LCLUC? Our change detection study to evaluate whether lakes and wetlands are drying up in the Alaska region is directly related to the first question, while the application of our modeling framework to the entire Alaska-Canada region to evaluate the mechanisms responsible for changes in regional carbon storage is directly related to the second question. In our original proposal we did have a component of the study (approximately 25%) to evaluate whether human suppression of fire has affected the fire regime in Alaska (see Chapin et al., 2003, *Frontiers in Ecology*), a component that is related to the NASA ESE question on the causes of LCLUC. This component was eliminated from the study when we the budget was reduced, and we are currently attempting to leverage off of other funds to support this analysis. Thus, at this time we do not have an explicit human dimensions component in our NASA LCLUC Project. Themes covered in our project include carbon/nutrients (50%), water (25%), and GOFC (25%).

Overall Goals, Timeline, and Year-by-Year Objectives for the Project.

We have two overall goals for this project: (1) to evaluate whether lakes and wetlands are generally drying up in the Alaska region, and (2) to extend the application of our modeling framework to the entire Alaska-Canada region for the purpose of elucidating the mechanisms responsible for changes in regional carbon storage. Our timeline for the first goal was to refine methodology by September 2002 by focusing our efforts on the Kenai Peninsula and Copper River Basin focus areas, to complete analyses on all ten focus areas (Kenai Peninsula, Copper River Basin, Seward Peninsula, Innoko Flats, Tanana Flats, Forty Mile Flats, Yukon Flats, North Slope, Alma Lakes, and the Denali Region) by September 2003, and to write and submit manuscripts during the final year of the project. Our timeline for the second goal is to make progress in model development and to obtain data sets during the first year of the project, to fully develop the spatially explicit data sets required for model application and to apply the fully developed model during the second year of the project, and to evaluate model simulations and to write manuscripts during the third year of the project.

With respect to the first goal, during the first year we recruited a graduate student to conduct the change detection study, we obtained most of the imagery needed for the change detection study, and we made progress in refining the methodology for conducting the change detection study. Our specific objectives for the second year of the project (performance period of August 1, 2002 - July 31, 2003) were (1) minimize errors in base images used for the change detection analysis and (2) to continue to refine the methodology of the change detection analysis for the Copper River Basin, the Yukon Flats, and the North Slope focus areas. Mr. Brian Riordan, who is a M.S. graduate student in Forest Science at the University of Alaska Fairbanks, identified errors of over 20% when comparing digital raster graphics (DRGs) to the black and white aerial photographs from with the DRGs were derived. This error needed to be minimized because the DRGs were initially envisioned as providing the baseline for the change detection analysis. To minimize the error we replaced the DRGs with the original black and white aerial photographs and attempted to obtain multiple images per focus area to minimize error associated with inter-annual variability in lake area. The black and white aerial photographs for the ten regions (over 200 photos) have been obtained and georectified. The rest of the methods we developed during the first year remain intact. We are currently completing our change detection analyses for three focus regions (Copper River Basin, Yukon Flats, and North Slope). The results for the Yukon Basin are very significant and indicate substantial loss of surface water in that region (Figure 1). Mr. Riordan is on track for completing the analysis for all ten focus areas in fall 2003, and completing his thesis and submitting manuscripts during the final year of the project.

With respect to the second goal, during the first year of the project we made progress in developing the modeling framework, in conducting some preliminary simulations for the Alaska-Canada region based on data sets we had already organized, in recruiting a student at Boston University to assist us with comparing results of simulations to data sets derived from analyses of remote sensing and forest inventory data, and in obtaining data sets from the Canadian Forest Service. Our specific objectives for the second year of the project were (1) to finalize a model version based on our efforts to enhance the representation of freeze-thaw and permafrost dynamics in the modeling framework, (2) to conduct simulations for the Alaska-Canada region with the new version of model with data sets that we have already organized, (3) to develop and organize the spatially explicit data sets required by the modeling framework for simulating how the full array of disturbances and other factors influence carbon storage in the Alaska-Canada region, and (4) to begin a study to evaluate how climate and disturbance influence changes in NDVI for the Alaska-Canada region over the last two decades.

With respect to objective 1, we have made substantial progress in developing the modeling framework. First, we have developed a version of the Terrestrial Ecosystem Model (TEM) that fully considers soil thermal dynamics (Zhuang et al., 2001), and have used the model in a study of carbon dynamics along a fire chronosequence in interior Alaska (Zhuang et al., 2002), and in a study of the role of soil thermal dynamics in carbon dynamics of northern terrestrial ecosystems (Zhuang et al., 2003). The seasonal dynamics of CO_2 exchange simulated by the version of the model applied to northern terrestrial ecosystems was validated based on atmospheric data (Figure 2). Spatial patterns of simulated changes in vegetation carbon storage during recent decades were compared with an analysis of changes in carbon storage based on remote sensing and inventory data (e.g., see Myneni et al., 2002, *PNAS* 98:14784-14789). This version of the model is the version we are using for objectives 2 and 3.

Related to objective 1, we have also made new progress in developing the capability to simulate methane dynamics in high latitudes and have applied the model to simulate historical and future methane dynamics for the Alaska region (Zhuang et al., submitted). Our application of the model estimates that the current net emissions of CH_4 (emissions minus consumption) from Alaskan soils are about 3 Tg CH_4 yr^{-1} (Figure 3) and projects that net CH_4 emissions will approximately double by the end of the century in response to high-latitude warming and associated climate changes. If CH_4 emissions from soils of the circum-boreal region respond to climate changes the way we project the Alaskan soils will, the net increase in high latitude CH_4 emissions could lead to a major positive feedback to the climate system.

With respect to objective 2, during the last year we have now conducted a full set of simulations for the Alaska region with the version of the model that was applied in the northern hemisphere study of Zhuang et al. (2003). These simulations consider the effects of historical changes in atmospheric CO_2, climate, and fire (Figure 4). We have also conducted simulations for the Alaska region with the new version of the model to evaluate (1) the role fire history and (2) interactions between annual area burned and fire severity. We are in the process of putting together a manuscript for the study on the role of fire history. The fire severity study is being conducted with collaborators Drs. Eric Kasischke and Nancy French, and we are interacting with them on next steps for this study.

With respect to objective 3, we have obtained over 100 Landsat Images over Canada for the 1970's and 1980's to identify the exact boundaries of fires that occurred between 1960 and 1980 based on fire scars in the images. We have provided these images to another of our collaborators in the Canadian Forest Service, Dr. Brian Stocks, who is using them to improve the spatial representation of fires in the Canadian Fire Scar Database. McGuire has made two trips to Victoria, British Columbia (one in late July and one in October) to interact with two of our collaborators from the Canadian Forest Service (Drs. Kurz and Apps) with respect to the use of data on fire, insect disturbance, and salvage logging in our study. These discussion have led to a study in which we are comparing the results of simulations for Canada that consider only changes in fire between our modeling framework and the Carbon Budget Model of the Canadian Forest Sector. This study allows us to compare the results of our models for a single disturbance type without changes in atmospheric CO_2 and climate in our modeling framework and without insect disturbance and salvage logging in the Canadian Carbon Budget Model. We have also made progress in developing a version of TEM that considers multiple disturbances, and we have evaluated the performance of this version for spatial data sets on agriculture and forest harvest that we already have organized for the conterminous U.S. We are currently preparing data sets for our multiple-disturbance version of the modeling framework to simultaneously consider fire, insect, logging, and agricultural disturbance in the Alaska-Canada region. We expect to have these data sets completed in early fall 2003 with application of the modeling framework for the entire region by the end of the year.

With respect to objective 4, we have begun a study to analyze the response of 8 km NDVI Pathfinder data to climate and historical wildfire scars in interior Alaska from 1950 to present. Specifically, the modeled rates of change in NDVI for areas that burned since 1950 will be compared to rates of change in areas that have not burned in that period. For areas that have not burned we will evaluate whether changes in temperature and precipitation are associated with changes in NDVI during recent decades. A Ph.D. graduate student, Mr. Michael Bashi, is currently processing data for this study.

Besides the two main goals of our project, we have also contributed substantially to the synthesis book for the NASA LCLUC Program. McGuire is lead author on the Alaska-Canada chapter of the book (chapter 9) and he has organized the sections on carbon dynamics and on fire in high latitudes for the fire chapter of the LCLUC synthesis book (chapter 19).

Approaches/Methods

The research directed at our first goal is focused on detecting changes in the area of ponds and water bodies that have no inlet or outlet. We have acquired the majority of the images that we need to perform this study. The key change in approach is that we have replaced digital raster graphics with aerial photographs to generate base images. This provides us with the oldest possible visual record of the presence of ponds. We will then co-register each Landsat image or recent aerial photograph to base images. By toggling between the images we can visually detect the presence or absence of a water body. We will then create separate polygon themes, which will be composed of ponds, for each image. These polygon themes can then be compared in order to calculate surface water loss or gain. We will then determine whether seasonal variability can account for changes in water area by evaluating variability in precipitation and temperature records between the years associated with the images.

In comparison to Alaska, a greater array of disturbances, which include fire, insects, agricultural land use, and timber harvest play a role in the carbon dynamics of Canada. Also, other factors such as increasing atmospheric CO_2, climate change, warming permafrost, and nitrogen deposition may be affecting carbon storage in Canada. Thus, the extension of our modeling efforts to simulate carbon dynamics for the Alaska-Canada region involves further development of TEM to consider multiple disturbances in the context of other multiple environmental changes and further development of spatially explicit data sets on land cover change in the Alaska-Canada region. A key focus of our modeling development efforts is to provide the model with the capability to consider the effects of interactions between soil thermal dynamics, climate variability, and disturbance. We have a number of data sets that are available to support application of the modeling framework to the Alaska-Canada region. In addition, access to some recently developed data sets will allow us to better address the effects of spatial and temporal variations in the distribution of plant functional types, forest harvest and regrowth, and atmospheric nitrogen deposition across the globe on terrestrial carbon, nitrogen and water dynamics. Similar to other studies we have conducted with the modeling framework, we will conduct simulations in a factorial fashion to identify the role of various factors that we are considering (atmospheric CO_2, climate, nitrogen deposition, and disturbance) on the historical carbon dynamics simulated for the Alaska-Canada region. With respect to disturbance regimes, we will conduct analyses that identify how simulated carbon dynamics varies with respect to uncertainty in assumptions made in the modeling framework, particularly assumptions about the severity of disturbance and about the frequency of disturbance prior to the availability of historical information on the frequency of disturbance. We will evaluate our application of TEM to the Alaska-Canada region in the context of well-founded atmospheric inversion estimates (e.g., Dargaville et al., 2002; Schimel et al., 2001, *Nature* 414:169-172), and in the context of other regional analyses of changes in carbon storage based on satellite-derived data (AVHRR) and forest inventory approaches (e.g., Myneni et al., 2001, *PNAS* 98:14784-14789; Goodale et al., 2002, *Ecological Applications* 12:891-899).

Progress During the Second Year

In general, we are making good progress on the second-year objectives for both goals of the project, and we expect to have all second year objectives met in fall 2003. With respect objectives related to the first goal to test whether the areas of ponds and lakes in Alaska are shrinking, we have further refined our methods and have obtained results of changes in lake area for three focus areas (the Copper River Basin, the Yukon Flats, and the North Slope). Results of the change detection analysis for these areas suggests that the area of ponds and lakes have substantially shrunk in the Copper River Basin and the Yukon Flats, areas of discontinuous permafrost were permafrost temperature is near thawing, but have not changed substantially on the North Slope, an area of continuous permafrost where permafrost temperature is substantially below freezing. Climate data have been organized to evaluate whether changes in lake area can be explained by precipitation and evapotranspiration or whether the changes in the Copper River Basin and Yukon Flats appear to be associated with thawing of permafrost and subsequent drainage.

With respect to the objective related to the second goal to extend the model framework to the Alaska Canada region, we have (1) finalized a version of the model for use in the project, (2) conducted a variety of simulations for the Alaska-Canada region with this version of the model, (3) and met with collaborators in the Canadian Forest Service and are conducting studies to compare the results of our simulations with equivalent simulations conducted by the Carbon Budget Model of the Canadian Forest Sector. We are currently (1) organizing data so that we can conduct simulations for the region that consider the full array of disturbances for the region, and (2) we are conducting an analysis to partition trends in NDVI over Alaska between climate and disturbance.

New Findings

- **Results of the change detection analysis in Alaska for regions of discontinuous permafrost, i.e. permafrost near thawing, indicate that lake area has substantially shrunk during the latter half of the 20th Century, but that lake area has not changed in regions of continuous permafrost, i.e. permafrost substantially below freezing.**

- **Our methane simulations for Alaska estimate that the current net emissions of CH_4 (emissions minus consumption) from Alaskan soils are about 3 Tg CH_4 yr^{-1} (Figure 3) and projects that net CH_4 emissions will more than double by the end of the century in response to high-latitude warming and associated climate changes. If CH_4 emissions from soils of the pan-Arctic region respond to climate changes the way we project the Alaskan soils will, the net increase in high latitude CH_4 emissions could lead to a major positive feedback to the climate system.**

New Potential

- **The capability to consider interactions among permafrost dynamics, water table dynamics, methane dynamics, and changes in carbon storage represents a new capability among global biogeochemical models.**

New Products

We have no new products at this time. We will be making spatial data sets available as we organize and develop new data sets through the course of this project. However, the research on changing lake areas was highlighted in a recent issue of Agroborealis, which is the outreach publication of the University of Alaska Fairbanks Agricultural Experiment Station. Also, both Dave McGuire and Dave Verbyla were interviewed by personnel from Scientific American Frontiers, which is producing a television program for PBS on the effects of climate change in Alaska. Filming for the television program is to occur in August 2003.

Conclusions

The progress during the second year of our study indicates that we are on track with respect to achieving the two goals of the study. Results of the change detection analysis in Alaska for regions of discontinuous permafrost, i.e. permafrost near thawing, indicate that lake area has substantially shrunk during the latter half of the 20th Century, but that lake area has not changed in regions of continuous permafrost, i.e. permafrost substantially below freezing. We have added a new capability to consider how interactions of permafrost and water table dynamics influence methane dynamics and changes in carbon storage. We are making good progress towards conducting simulations for the Alaska-Canada region that consider the full array of disturbance that affect carbon storage in the region.

Publications

(includes submitted manuscripts and publications from our previous NASA LCLUC Project)

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