Adaptation to rapid land-use and climate changes on the Yamal Peninsula, Russia: Remote sensing and models for analyzing cumulative effects

2010 Annual Report to NASA

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Abstract
This report summarizes the first and second year of research for the NASA-LCLUC project entitled “Adaptation to rapid land-use and climate changes on the Yamal Peninsula, Russia: Remote sensing and models for analyzing cumulative effects”. The report includes summaries of field work conducted in the summers of 2009 and 2010, a project workshop in Rovaniemi, Finland in March 2010, work completed on the major components of the study, and a list of publications to date.

Study objectives and significance
Our principal goal is to develop better, more far-looking tools to predict the cumulative effects of resource development, climate-change, and traditional land use. To accomplish this we will employ a combination of analyses and models of climate/vegetation change with social-ecological analyses.

The Yamal Peninsula in northern Russia has undergone extensive anthropogenic disturbance and transformation of vegetation cover over the past 20 years due to gas and oil development and overgrazing by the Nenets reindeer herds. It has been identified as a “hot spot” for both Arctic climate change and land-use change. The complex interactions between a rapidly changing climate, expanding resource development, and constantly evolving social, economic and political environments make it clear that more sophisticated models and approaches are needed to help in planning for the future of the Yamal. The tools developed here will also serve to examine similar changes that are occurring elsewhere in the Arctic and help the indigenous people adapt to the impending changes.

We are using remote-sensing technologies to examine how the terrain and anthropogenic factors of reindeer herding and resource development, combined with the climate variations on the Yamal Peninsula, affect the spatial and temporal patterns of vegetation change and how those changes are in turn affecting traditional herding by indigenous people of the region.

Major Accomplishments during the first two years of funding

Field work in 2009 and 2010
One of the goals of the Greening of the Arctic project is to examine the trends in vegetation, soils, permafrost characteristics and surface spectral properties along a complete Arctic transect in Russia. The transect stretches from Nadym at 65° 19’ N to Krenkel Station in Franz Josef Land at 80° 38’ and consists of seven study locations in all five of the Arctic bioclimate
subzones and the forest-tundra transition (Fig. 1). This work is comparable to the work recently published for the North America Arctic Transect (Walker D. A. et al. 2008).

Field research was done at Ostrov Belyy and Kharp in July 2009 and near the Krenkel Hydro-meteorological Station in Franz Jozef Land in August 2010 (Fig. 1). Data reports from all four NASA-GOA Russia EAT expeditions in 2008-2010 are available online at http://www.geobotany.uaf.edu/yamal/reports.

The 2010 expedition to Hayes Island in the Franz Josef Land Archipelago completed the Eurasia Arctic Transect (EAT). The 2011 Krenkel and data report presents the vegetation, remote sensing and environmental data collected in 2010 near Krenkel Station. The studies followed the same basic procedures used at the locations visited in 2007-2009. The data report includes: (1) a general description of the location and study sites with photographs, (2) maps of the study sites, study plots, and transects at each location, (3) tabular summaries of the vegetation, site factors, and soils at each relevé, (4) summaries of the Normalized Difference Vegetation Index (NDVI) and leaf area index (LAI) along each transect, (5) detailed soil descriptions and photos of the large soil pits at each study site, (6) contact information for each of the participants. The expedition also established permafrost and active-layer monitoring sites at the zonal site. The data from the permafrost studies will be presented in another report that will be included in the next annual report. The appendices to the report include: Appendix A — Names and addresses of the participants in all four expeditions; Appendix B — Plot and soil photographs from all study sites; and Appendix C — List of birds observed at Krenkel Station and along the route of the ship during 28 Jul to 2 Aug. (available at the web site: http://www.geobotany.uaf.edu/library/reports/yamal_2009_dr091212embDRAFTa.pdf. The most recent data report is attached to show the nature of these reports.

Figure 1. Eurasian Arctic Transect. Bioclimate subzones are according to CAVM Team (2003). The seven EAT study locations are also shown.
Second Yamal Land-Cover Land-Use Change Workshop, Rovaniemi, 8-10 Mar 2010, and other conferences and workshops

The Second Yamal Land-Cover Land-Use Change Workshop was attended by 22 participants at the Arctic Centre, Rovaniemi, Finland, 8-10 March 2010. The agenda for the meeting is on the project web site http://www.geobotany.uaf.edu/yamal/rovMtg/agenda. The overall objectives of the workshop were to (1) review the goals of the project; (2) discuss the progress of each of the individual parts of the project; (3) adjust the goals in light of new discoveries, changing funding situation, and changing personnel; (4) discuss the 2010 and 2011 summer field seasons; (5) plan new publications and research; and take advantage of the special opportunity to meet with collaborators in NASA (Joey Comiso and Jorge Pinzon). A total of 30 presentations were made at the meeting (See “Publications, Unpublished talks and posters, citations 1-30, and the Yamal LCLUC website (http://www.geobotany.uaf.edu/yamal/rovMtg/posters).

In addition, we have made presentations at several other conferences and workshops including the 2009 and 2010 LCLUC All Scientists meetings (unpublished talks and posters citations 31-43), the Fall AGU meetings in San Francisco (Dec 2009 and 2010), the State of the Arctic Meeting in Miami (Mar 2010), and the IPY Oslo Science Conference (Jun 2010).

Summaries from the each component of the project:

a. Human dimensions and analysis of shrub growth (Bruce Forbes)

A major publication regarding the resilience and adaptation of the Yamal Nenets to change was published and featured on the front cover of the Proceedings of the National Academy of Science (Forbes et al. 2009). The Yamal peninsula encompasses a tightly integrated arctic social-ecological system (SESs). In contrast to northern Alaska and Canada, most terrestrial and aquatic components of West Siberian oil and gas fields are seasonally exploited by migratory herders, hunters, fishers, and domesticated reindeer (Rangifer tarandus L.). Despite anthropogenic fragmentation and transformation of a large proportion of the environment, recent socioeconomic upheaval, and pronounced climate warming, the team found the Yamal Nenets SES highly resilient according to a few key measures. The paper details the remarkable extent to which the system has successfully reorganized in response to recent shocks and evaluates the limits of the system's capacity to respond. However, expansion of infrastructure, concomitant terrestrial and freshwater ecosystem degradation, climate change, and a massive influx of workers underway present a looming threat to future resilience.
Another part of this project component examined the correspondence between the growth rings of shrub willows and the summer air temperatures in the vicinity of the Yamal Peninsula (Forbes et al. 2010). Annual ring growth of an abundant and nearly circumpolar erect willow (\textit{Salix lanata} L.) from the coastal zone of the northwest Russian Arctic (Nenets Autonomous Okrug) were correlated with station data from numerous sites in northwestern Siberia and Europe. The resulting chronology is strongly related to summer temperature for the period 1942–2005. Remarkably high correlations occur at long distances (1600 km) across the tundra and taiga zones of West Siberia and Eastern Europe. There is a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981–2005, confirming a parallel ‘greening’ trend reported for similarly warming North American portions of the tundra biome. The standardized growth curve suggests a significant increase in shrub willow growth over the last six decades. These findings are in line with field and remote sensing studies that have assigned a strong shrub component to the reported greening signal since the early 1980s. Furthermore, the growth trend agrees with qualitative observations by nomadic Nenets reindeer herders of recent increases in willow size in the region. The quality of the chronology as a climate proxy is exceptional. Given its wide geographic distribution and the ready preservation of wood in permafrost, \textit{S. lanata} L. has great potential for extended temperature reconstructions in remote areas across the Arctic. These results were summarized in an invited talk at the 2010 NASA LCLUC All Scientists Meeting in Bethesda, MD (Forbes et al. 2010 unpubl.) and presented at the Fall 2010 AGU meeting in San Francisco.

\textit{b. Sea-ice, climate, land-surface temperatures, and NDVI characterization (Uma Bhatt, Skip Walker, Martha Raynolds, Jiong Jia, Howie Epstein, Jorge Pinzon, Joey Comiso).}

\textit{Figure 2. Percentage changes in land-surface summer warmth index (the sum of the annual mean monthly temperatures $>$0 °C (1982-2010).}
Bhatt et al. (2010) found using satellite observations from 1982-2010 that land warming is more pronounced in North America than in Eurasia (Fig. 2) and that changes in the NDVI on land are associated with areas of greatest changes in the early-summer distribution of sea ice (Fig. 3). Changes in MaxNDVI have proceeded at a similar rate in North America and Eurasia (Fig. 4a), but there are clear differences in the rate within smaller regions. For example, MaxNDVI has increased 24% on land areas adjacent to the Beaufort Sea, but only 4% in the W. Kara Sea region (Fig. 4b).

c. **Ground measurements of NDVI-LAI-Biomass (Howie Epstein, Skip Walker, G.V. Frost)**

NDVI, LAI, and biomass trends have now been determined for the entire Eurasia transect. We have developed a comprehensive, synthetic dataset of field observations for vegetation and soil properties along the full bioclimate gradient in North America and Eurasia. Information from the North America transect has been accepted for publication in *Applied Vegetation Science* (Walker et al. 2011). Information from the Eurasia transect will be presented at the European Vegetation Survey Workshop in Rome, April 6-8, 2011.

![Figure 3. Circumarctic pattern of changes in open early-summer open sea-water distribution and integrated NDVI on land portions of the Arctic (1982-210).](image)

![Figure 4. Percentage increases in MaxNDVI. (a) for Eurasia, Northern Hemisphere and North America, and (b) land areas adjacent to the Beaufort and Kara seas (1982-2010).](image)
Among the findings is a remarkably similar relationship between zonal landscape-level aboveground biomass and AVHRR-derived NDVI along both transects (Fig. 5). However, despite the almost identical relationships between biomass and NDVI, the Eurasia transect has distinctly higher hand-held NDVI values for equivalent biomass and LAI (Fig. 6a and b). Similarly, the hand-held NDVI values are higher for equivalent AVHRR NDVI values along the EAT than along the NAAT (Fig. 6c). Most interesting is the diverging regression lines of LAI vs. biomass along the two transects, with higher LAI values along the NAAT. The differences in the trend lines are attributed to differences in plant canopy structure caused by a variety of factors including different precipitation regimes, glacial histories, soils and grazing regimes, which alter the relative proportions of different plant growth forms (Raynolds et al. 2010 in preparation, Walker et al. 2010).

d. Modeling (Howie Epstein, Jed Kaplan, Qin Yu)

We are using the ArcVeg arctic tundra vegetation dynamics model (Epstein et al. 2007) to simulate the combined effects of temperature increases and different grazing regimes on the tundra vegetation biomass, productivity, and species composition. In a recently published paper (Yu et al. 2009), we simulated seven sites on the Yamal Peninsula that differ in their soil organic nitrogen (SON) quantities and that are found across three different bioclimate subzones (Fig. 7). A
A 2°C increase in temperature led to aboveground biomass increases ranging from ~150 g m\(^{-2}\) to 665 g m\(^{-2}\) depending on the subzonal climate and the SON. Increased grazing frequency from every 10 years to every 2 years reduced the effects of climate change on tundra vegetation, yielding aboveground biomass increases ranging from ~100 g m\(^{-2}\) to ~370 g m\(^{-2}\).

**Fig. 7.** Comparison of tundra biomass and net primary production (NPP) to low and high grazing regimes in three tundra subzones and different levels of soil organic nitrogen (SON). LV-1 = subzone E, loamy soil; LV-2 = subzone E, sandy soil; VD-1 = subzone D, loamy soil; VD-2, subzone D, mixed loamy and sandy soil; VD-3, subzone D, sandy soil; KH-1, subzone C, loamy soil; KH-2, subzone C, mixed loamy and sandy soil.

We have more recently used the ArcVeg model to examine in more detail the plant functional type (PFT) compositional changes in response to warming and altered grazing regimes on the Yamal Peninsula. We modified the ArcVeg model so that it was parameterized with available reindeer diet data, and grazing in the model is now a function of both foliar nitrogen concentration and plant type preferences. We simulated 11 sites on the Yamal Peninsula (subzones C-E), Belyy Ostrov (subzone B) and Hayes Island (subzone A) across a variety of SON quantities. A total of 132 simulation runs (variations of the 11 sites, three warming scenarios, and four grazing regimes) were analyzed using non-metric multi-scaling (NMS) ordination, and the results indicated that grazing can be as important as latitudinal climate gradient for controlling tundra community structure (Fig. 8). Most PFTs responded to a 2°C increase in temperature with increased biomass with a few exceptions: rushes in the High Arctic (~2%), non-vascular plants (~5%) and dwarf prostrate shrubs (~20~10%) in the Low Arctic. Increasing grazing frequency from every 10 years to every 2 years had a greater impact on PFT biomass than changing the annual percentage eaten from 25% to 50%, and most PFT biomass declined in response to increasing grazing intensities except for evergreen shrubs and mosses (Yu et al. in prep.).

**Fig. 8.** NMS ordination of effects of different grazing frequency and intensity.
In addition to work specific to the Yamal, we are also in the process of conducting circumpolar simulations of tundra vegetation change, using circumpolar maps of tundra subzones, soils, grazing herds, and general circulation model (GCM) output. Jed Kaplan has recently developed a module for his BIOME4 model that simulates the temporal dynamics of soil temperatures and the active layer, which we hope to link with ArcVeg (Kaplan et al. 2010). Finally, we have begun the process of developing a daily version of the ArcVeg model to simulate the effects of changing seasonality on tundra vegetation and carbon cycling. The daily version will include a daily weather generator for climates in all five subzones of both North America and Eurasia, a daily module for the mineralization of nitrogen and the growth of competing plants, empirical equations for the starts and ends of growing seasons, and seasonality of plant functional type activity as well as grazer activity.

**e. Remote sensing of land use land cover change (Howie Epstein, Skip Walker, TimoKumpula, Bruce Forbes, Gerald Frost, Qin Yu, Hilmar Maier)**

We have several efforts related to the remote sensing of land-use land-cover change on the Yamal Peninsula and other regions of Siberia and North America. Kumpula et al. (2011), using Quickbird, ASTER, SPOT, and Landsat imagery to examine the social and environmental impacts of development at the Bovanenkovo gas field in central Yamal on the tundra and its relation to the Nenets reindeer herders. We are continuing with this effort to use high and very high resolution satellite imagery to examine the effects of development on surface properties of the adjacent tundra, including surface temperatures, albedo, normalized difference vegetation index (NDVI) and normalized difference water index (NDWI). In addition to conducting further analyses of Bovanenkovo (Kumpula 2010, unpub.), we have expanded the scope of this effort to include gas extraction sites at Nadym and Kharasavey as well as oil development sites near Prudhoe Bay, Alaska (Yu et al. 2011 in prep., Kumpula et al. 2010unpub.; Forbes et al. 2010unpub.). We have also begun to use the Landsat Decadal Survey imagery to develop land cover change maps for the entire Yamal Peninsula, (Maier and Walker 2010a, b, unpub.).

High level pre-processing of Landsat images in the Nadym region was performed. We derived NDVI, albedo, surface temperature, NDVI for years 2007 and 1988. The composite images of differences in NDVI, albedo and either surface temperature or NDWI (Fig. 9) offer a unique approach to change evaluation and interpretation. Expanded gas facilities and new roads are detected with increased albedo. Vegetation appears to have recovered to some degree along old roads. More detailed vegetation change analysis will be based on the higher resolution image analysis.
Changes detected near the field sites

**Fig. 9.** Composite image of difference map based on derived NDVI, albedo, surface temperature and NDWI between year 2007 and 1988.

**Fig. 10.** Remote sensing images of the Tazovskiy Peninsula study site, ~60 km east of the southern Yamal. (Left) 1968 Corona image showing extent of alder shrublands on shallow hillslopes (most dark areas in the image). (Right) Co-registered 2002 IKONOS-2 image showing infilling of alders, for examples note the areas in the vicinity of the letters A, B, C, and D.

We also are examining recent vegetation dynamics in forest-tundra ecotones across the Russian Arctic using imagery from the 1960s-era Corona high-resolution satellite missions (Frost et al.)
Corona images are co-registered with recent images and analyzed for changes in the extent and abundance of trees and tall shrubs. Dramatic changes in vegetation cover are evident at several sites over a ~40 year period, including two sites near the southern Yamal. On the Tazovskiy Peninsula, erosion of sandy marine deposits from shallow hillslopes has exposed clayey soils that are nutrient-rich and support highly-productive shrub vegetation (Fig. 10). The surficial geology and disturbance regime of the Tazovskiy site appears to be similar to that of the Vaskiny Dachi field site on the central Yamal, but Tazovskiy is in bioclimate subzone E and alder is a dominant shrub on landslide-affected slopes. The other site is in the foothills of the Polar Urals near the town of Kharp. We visited Kharp in summer 2009 and discovered that an old (~100 YBP), high-intensity fire probably initiated the rapid alder shrub advancement in the area. We observed that alders have established most readily on mineral soils that were exposed either by fire, or by cryogenic processes associated with small patterned-ground features (frost boils, non-sorted circles). Cryogenic disturbance is thought to lead to regularly-spaced “shrub savannas” that are common in the Low Arctic, and which up until now have not been fully explained. The fire/frost-boil/shrub savanna hypothesis is being examined in more detail by Frost as part of his Ph.D. thesis research along the Dalton Highway in Alaska, where there are extensive areas that were burned in 2007-2008, as well as at the Kharp site (planned for 2011).

In a related project looking at land cover changes in the North Slope of Alaska, we analyzed Landsat imagery over a 22-year period using the Normalized Difference Vegetation Index (NDVI) (Raynolds et al. 2010). Six Landsat scenes covering the areas of the Toolik Field Station were compared: 1985, 1989, 1995, 1999, 2004, and 2007 (TM and ETM, 30-m pixels). All scenes had minimal cloud cover and were collected during the peak of the growing season. Average NDVI of the study area increased significantly over the time period, at a rate of 0.0006 NDVI units/year, showing a 3.2% increase in NDVI over the 22 years. This was less than one-fifth the rate seen for the entire Bioclimate Subzone E on the North Slope using AVHRR data (0.0035 units/year, 1981-2001, Jia et al. 2003). This may be partly because the study area includes higher elevations and steeper slope angles in the southern portion than are characteristic of the entire Subzone E area, areas which were shown to have smaller than average increases in NDVI. Climate data during this time period (1988-2007) from within the

![Significant Trend in NDVI](image)

**Fig. 11.** Areas of significant NDVI change within the Toolik Lake Field Station region, AK (1985-2007). Most of the change has occurred on younger glacial surfaces, and in areas of disturbance, including areas with massive ground ice. Raynolds et al. 2010)
study area show no local increase in temperature, an increase in total precipitation, and increased variability between years (Wahren et al. 2005). The strongest increases in NDVI were on revegetating abandoned gravel pads and material pits, and stabilizing river terraces. The strongest decreases in NDVI were on eroding river terraces and new gravel pits. General greening occurred along the Dalton Highway. Field work is planned for 2011 to collect ground data from areas with large changes in NDVI.

Plan for 2011 field seasons
The project will complete field work along the Eurasian transect in summer 2011, with an intensive study of azonal habitats at Vaskiny Dachi in the central Yamal Peninsula. We will examine the shrub vegetation, lichen heathlands, and a wetland to help in the remote sensing interpretations of the peninsula and to examine disturbed habitats. We will also have a study in the Bovanenkovo gas field to update the extent of land-use changes during the past few years. We will also spend a week in the field at the Kharp site to elucidate the relationship between post-1968 shrub expansion and disturbance at the landscape-scale (fire) and the meter-scale (cryogenic processes).

Publications (includes publications from the first round of funding)
2011

2010
Alcaraz, J.D., Cabello, J., Epstein, H.E., Jia, G.J. 2010. Trends in the surface vegetation dynamics of the tundra and taiga network of protected areas in Eurasia as observed by satellite sensors. in prep.


Kelley, A.M., Epstein, H.E. 2009. Effects of nitrogen fertilization on plant communities of nonsorted circles in
moist nonacidic tundra, Northern Alaska. *Arctic, Antarctic, and Alpine Research.* 41:(1):119-127.  PDF


2007


Stammerl, F., Forbes, B.C. 2007. Declaration on coexistence of oil & gas activities and indigenous communities on
Nenets and other territories in the Russian North. *Symposium on Oil and Gas Development in NAO and YNAO, Rovaniemi, Finland, 10-11 December*. PDF


**Talks (without published abstracts):**

2010


Forbes, B.C., Murray, M.S., Walker, D.A. 2010. Human dimensions of land-cover and land-use change in the Arctic with a focus on the Yamal Peninsula, Russia. *Presented at: Land Cover, Land Use Change Spring Science Team Meeting Bethesda, MD April 20-22*. PDF


Khomutov, A.V., Leibman, M.O. 2010. Relation between active-layer depth, NDVI and LAI along the Yamal Transect. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF

Kumpula, T., Forbes, B.C., Stammler, F. 2010. Land-use and land-cover changes in Yamal peninsula. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF


Orekhov, P., Leibman, M.O. 2010. Yamal Peninsula, climate, zonation, physiography, geology, permafrost. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF

Pinzon, J.E., Tucker, C.J. 2010. GIMMS 3g NDVI set and global NDVI trends. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF


Ukrainsteva, N.K. 2010. High Willow Shrubs in Yamal: Reasons of Their Wide Expansion and Methods of Biomass Assessment. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF

Walker, D.A. 2010. Welcome, goals of the workshop, and overview of the project. Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland 8-10 March. PDF


2008


2008


Comiso, J.C. 2008. Decadal Changes in the Arctic Sea Ice Cover and Surface Temperature with especial focus on Yamal, Alaska and the Canadian Peninsula. Presented at: Yamal Land-Cover Land-Use Change Workshop Moscow, Russia January 28-30. PDF


Forbes, B.C., colleagues, w.m.d. 2008. Effects of petroleum development on reindeer herding in Northwest Siberia: Combining scientific and traditional knowledge. Presented at: 2008 Yamal Land Cover and Land Use Workshop Moscow, Russia January 28-30. PDF


Khomutov, A.V., Leibman, M.O. 2008. Landscape structure in natural and disturbed conditions of Yamal Peninsula, field results and local GIS. Presented at: Yamal Land-Cover Land-Use Change Workshop Moscow, Russia January 28-30. PDF


Matyshak, G.V. 2008. Soils at Nadym and Yamal area. Presented at: Yamal Land-Cover Land-Use Change Workshop Moscow, Russia January 28. PDF

Moskalenko, N.G. 2008. Overview of vegetation dynamics, disturbance and recovery studies in Nadym and Yamal areas. Presented at: Yamal Land-Cover Land-Use Change Workshop Moscow, Russia January 28-30. PDF

Orekhov, P.T. 2008. Lake ecosystems in different landscapes in the Nadym region. Presented at: Yamal Land-Cover Land-Use Change Workshop Moscow, Russia January 28-30. PDF


Walker, D.A. 2006. Application of space-based technologies and models to address landcover/land-use change problems on the Yamal Peninsula, Russia. Presented at: NEESPI-CLAC meeting Fairbanks, AK April 6-8.


Posters 2010


Khitun, O., Rebristaya, O. 2010. Concrete Flora Concept as a Base for Floristic Investigations in the Russian Arctic. Presented at: Yamal Land-Cover land-Use Change Workshop Rovaniemi, Finland March 08-10. PDF


Maier, H.A., Walker, D.A. 2010. OstrovBelyy (White Island), Yamal Peninsula region, Russia: Landsat ETM+ false color image, land-cover map, and NDVI map (1:200K scale). Presented at: Second Yamal Land-Cover Land-Use Change Workshop Rovaniemi, Finland March 08-10. PDF


Moskalenko, N.G. 2010. Vegetation Dynamics at the Nadym and Kharasavei sites in the West Siberia North. Presented at: Yamal Land-Cover land-Use Change Workshop Rovaniemi, Finland March 08-10. PDF
along a 900-km Arctic transect. Presented at: Land Cover, Land Use Change Spring Science Team Meeting Bethesda, MD 20-22 April. PDF


2009


2008


NASA Carbon Cycle and Ecosystems Joint Science Workshop, Adelphi, MD, April 28 - May 2. PDF


address land-cover/land-use change problems on the Yamal Peninsula, Russia: 2007 field studies along the bioclimate gradient. 

*Presented at: 2008 NASA Carbon Cycle and Ecosystems Joint Science Workshop Adelphi, MD April 28 - May 2.* [PDF](#)


2007


2006


2005