A. COVER PAGE

Name of state: South Dakota

Cooperative agreement number: NCC5-588

Research project title: Leaf Area Index for Fire Chronosequences of the Black Hills and Southern Siberia: A Comparative Study

Lead investigator information:

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B. PROGRESS REPORT

1. Abstract of the original proposal.

Leaf area index (LAI, the leaf area per unit area of soil surface) is a fundamental biophysical parameter through which vegetation canopy physiological functioning can be related to remotely sensed observations. Canopy LAI can be highly correlated with the fraction of absorbed photosynthetically active radiation (FPAR) and, ultimately, net primary productivity and biosphere-atmosphere exchange of heat, momentum, and many important trace gases. However, quantifying LAI presents numerous challenges. Existing methods for quantifying LAI include direct measures via destructive harvesting techniques (accurate but prohibitively labor-intensive) and indirect derivations via ground-, aircraft-, and satellite-based remote sensing observations (rapid and appropriate for a wide range of measurement scales, but with varying and difficult-to-define accuracy due to complex interactions between canopy geometry, sensor resolution, and sun-sensor geometry). Although a large body of work has been done to establish baseline relationships between LAI and remote sensing measurements from various platforms, there is still a great need for comprehensive and novel field data to validate and improve remotely sensed LAI derivations.

Here, we propose to work in collaboration with Donald Deering and his research team at the Goddard Space Flight Center to collect and analyze comprehensive data sets at two coniferous forest canopies. These data will be used to evaluate and improve the accuracy of remotely derived LAI estimates. Two specific questions to be addressed in our research are *1) What is the spatial scale at which the LAI of a coniferous forest can be most accurately derived using above-canopy remote sensing?*, and *2) To what extent can bidirectional measurements be used to improve LAI (and FPAR) estimates using remote sensing?* We will collect field data at the boreal forest of southern Siberia and the ponderosa pine-dominated forest of the South Dakota Black Hills. Field sites will occur along forest fire and thinning chronosequences in order to capture a wide range of conifer LAI values. This project will build upon and assist in the analysis of two years of ground LAI measures already completed by Deering and colleagues near Krasnoyarsk, Russia, and provide comparison measurements in the Black Hills region to determine the broad scale applicability of satellite-based LAI derivations for conifer forests. Field measurements will include destructive sampling to establish allometric LAI relationships, and non-destructive optical sampling using established techniques. In addition to these within-canopy measurements, satellite remote sensing data at several scales will be analyzed using kriging methods to evaluate how well LAI can be scaled. Remote sensing imagery to be analyzed using kriging methods will include multispectral IKONOS, Landsat 7, and MODIS data. In addition, recently developed spectral indices that incorporate the bidirectional character of canopy reflectance will be applied to Multi-Angle Imaging Spectroradiometer (MISR) data in order to assess how such data may provide improved LAI estimates. At the Black Hills sites, additional spectral measurements will be made with the South Dakota School of Mines and Technology Short Wave Aerostat-Mounted Imager (SWAMI), a pointable hyperspectral instrument with an adjustable ground instantaneous field of view between approximately 1-500m. We expect that the novel observations acquired using the SWAMI will provide useful data for independently testing the results obtained using the various satellite remote sensing systems.

2. Accomplishments compared to original and revised metrics and milestone goals.

(Metrics and goals are not listed in any order of priority)

Metric/goal 1: Collect field data sets with which to validate/evaluate remote sensing measures of LAI, with the goal of improving the accuracy of remotely derived leaf area estimates across fire chronosequences in the Black Hills and Siberia.

Our research team has collected comprehensive field data sets in both the Black Hills and Siberia. In order to test LAI algorithm performance across the broadest possible range of forest conditions at these two sites, field data were collected in 1-3 year old burns of varying intensity, as well as at sites where burns had not occurred for approximately 13, 25, and >100 years. These field data were then used as ground 'truth' measurements for algorithm development using remotely sensed data from IKONOS, Landsat TM4, Landsat TM5, Landsat ETM+, ASTER, MODIS, and airborne discrete return lidar (laser altimetry) sensors. These data sets are available for future use in calibration or validation studies of other sensors. Furthermore, we have partnered with industry to collect ground-based, high resolution lidar data to improve ground-based measures of vegetation structure. This technique has the potential to revolutionize the way that surface vegetation canopy parameters are quantified and therefore is one of the keystones of our proposed future work.

Metric/goal 2: Determine the spatial scale at which conifer forest LAI can be most accurately derived using remote sensing.

Our research team investigated relations between conifer forest LAI and remote sensing measurements across a continuum of spatial scales ranging from the first sub-pixel validation effort of IKONOS data (1m length scale) to the level of the MODIS LAI product (1000 m length scale). A key finding of this work was that high resolution IKONOS data, when aggregated to the size of a 30x30m field plot (designed to approximate the size of a Landsat TM/ETM+ pixel), allowed for the best prediction of site-specific surface LAI. This result is most likely due to the decreased geometric errors associated with comparing high resolution satellite data with field plots. Scaling of IKONOS and Landsat pixels to the MODIS level revealed that the MODIS LAI algorithm overestimated LAI in sparse vegetation canopies and underestimated LAI in denser forests. Furthermore, our multi-scale work has led to the discovery of how canopy structural phenomena (e.g. shading effects) can be used to identify and quantify vegetation functional groups via sub-pixel analysis. This work has led us to the important result of partitioning woody LAI from herbaceous LAI in forested systems, a finding that has implications for mapping of biogeochemical pools of C, N, P, and other elements.

Metric/goal 3: Determine the extent to which bidirectional measurements using the Multi-Angle Imaging Spectroradiometer (MISR) can be used to improve LAI (and FPAR) estimates using remote sensing.

This was one of the original goals set forth in the initial proposal. However, MISR land surface data for vegetation canopy analysis has been available only at the "beta" level since early 2002. Beta level data has been made available by the MISR Science Team with the caveat that it is:

- Intended as a test bed to discover and correct errors.
- Minimally validated and still may contain significant errors.
- General research community is encouraged to participate in the QA and validation, but need to be aware that product validation and QA are ongoing.
- Parameter may be used in publications as long as beta quality is indicated by the authors. **Drawing quantitative scientific conclusions is discouraged.** (emphasis ours) Users are urged to contact science team representatives prior to use of the data in publications, and to recommend members of the instrument teams as reviewers. (http://www-misr.jpl.nasa.gov/mission/maturity.html)

Provisional data products from MISR are still not available as of this writing (May 2004). Because of the potential errors associated with these beta level data and because of the statement that "drawing quantitative scientific conclusions is discouraged", our team (with concurrence by Don Deering, our NASA Technical Monitor) made the decision to forego the MISR bi-directional reflectance analyses in favor of focusing our efforts upon further development of other aspects of the original proposal.

Metric/goal 4: Develop and use the Short Wave Aerostat Mounted Imager (SWAMI) to acquire spectral measurements that can be used to independently test the results obtained using satellite remote sensing systems.
The SWAMI instrument is mounted to the tether line of a tethered balloon to allow spectral and visible analysis of landscapes with very good geometric registration. The SWAMI has been used to further investigate linear and non-linear spectral mixture models for use in quantifying vegetation cover and LAI. This work has demonstrated the great need for using non-linear spectral unmixing approaches in forest canopies, particularly in distinguishing tree cover from the shadows they cast. Two manuscripts describing this work are currently in review at the journal *Remote Sensing of Environment*.

Metric/goal 5: Establish relationships between spectral vegetation indices and LAI for the Black Hills and Siberia across fire chronosequences.
Several vegetation indices were investigated in this work, including the reduced simple ratio (RSR), the Enhanced Vegetation Index (EVI), the Normalized Difference Vegetation Index (NDVI), and several other indices that use short wave infrared (SWIR) spectral bands. We established that in these forests, the RSR performed the best regardless of vegetation type (deciduous or coniferous) and demonstrated a near-linear relationship with LAI even when all sites were compiled for the two experimental locations.

Metric/goal 6: Use LAI datasets to gain further insights to vegetation structure and function in forested ecosystems using satellite remote sensing.
We accomplished this goal along several lines of research. First, we learned that by using LAI to scale site moisture content (SMC; i.e. the amount of water contained in the

leaf biomass at a particular site), significant relationships between satellite image-derived spectral indices and forest ecosystem SMC could be established. This result is particularly important in conifer forests, where needle LAI can become decoupled from SMC over the course of a season (needle LAI can remain high during drought periods of low SMC). This work lays the foundation for comparisons of ecosystem-level water fluxes with spectral data at flux towers. Second, we learned that the EVI was quite sensitive to canopy shading effects and can be used to differentiate conifer forests (which exhibit high amounts of self-shading), deciduous forests, and understory deciduous species. NDVI did not exhibit such sensitivity to shadowing. These findings have implications for vegetation structure mapping and LAI partitioning among vegetation functional groups from the sub-pixel level to the landscape level.

Metric/goal 7: Strengthen collaboration between SD and NASA scientists.
Our team has worked diligently to strengthen collaborations with NASA partners throughout the NASA-EPSCoR project. In addition to disseminating our research results at conferences frequented by NASA scientists, we have initiated several project workshops and other team meetings to discuss and further develop our research with NASA personnel. Specific project meetings include:

Date	Site	NASA Personnel	SD Personnel	Key outcome(s)
December 2000	Washington, DC	A. Conley (GSFC)	L. Vierling	Development of initial proposal
July 2001	Russia	A. Conley D. Deering (GSFC)	L. Vierling	Collection of field data
November 2001	Rapid City, SD	A. Conley D. Deering N. Kozhoukhovskaya (NASA contractor from Sukachev Forest Institute)	All SD project participants (approximately 14 in total)	Development of detailed project work plan; SD field site visits by NASA personnel
January 2003	Rapid City, SD	D. Deering	All SD project participants	Preliminary results discussion and planning of publications; invitation of SD scientist C. Peng to become member of NASA's Northern Eurasia Earth System Science Partnership Initiative (NEESPI) science team; additional opportunities for SD scientists identified within NEESPI.
March 2003	Greenbelt, MD	A. Conley D. Deering	R. Smith X. Chen	Presentation/discussion of results
April 2003	Suzdal, Russia	D. Deering (GSFC) G. Gutman (HQ) J. Masek (GSFC) J. Ranson (GSFC) B. Yurchak (GSFC)	C. Peng	NEESPI Science Plan Workshop
September 2003	Rapid City, SD	J. Masek	L. Vierling, D. Swets, and others	J. Masek presented NASA Earth System Science research overview at the

				Western Regional Space Grant Consortium at the invitation of L. Vierling; Discussion of future collaboration
November 2003	Honolulu, HI	A. Braverman	D. Swets	Held further discussions regarding availability of MISR data for multi-angle portion of study
January 2004	Washington, DC	A. Conley	L. Vierling	Discussion/revision of paper by Conley et al. (including Vierling) prior to submission
March 2004	Greenbelt, MD	A. Conley D. Deering	L. Vierling X. Chen R. Smith	Third year internal review of project; presentation of advanced research results; preparation for NASA HQ site review of D. Deering's research program
May 2004	Moscow, ID	R. Nelson (GSFC) M. Kramer (NASA-Ames)	L. Vierling E. Rowell	Presentation of research results, discussion of future collaboration

Table 1. Meetings between NASA and SD scientists regarding this project.

Metric/goal 8: Establish/strengthen collaboration between SD scientists and industry partners at the local, regional, and national scales.
We have established several contacts along these lines. Locally, we have partnered with Horizons, Incorporated, a Rapid City-based photogrammetry and lidar remote sensing firm, and entered into a formal agreement whereby Horizons provided three lidar data flights over our Black Hills field sites for incorporation into our research and development program. In addition, Horizons paid for one year of salary for a graduate student (Eric Rowell) to develop his MS thesis, which includes elements of LAI algorithm development. We co-authored an SBIR proposal with Horizons, entitled "*Development of Analysis Utilities for Forestry Applications Employing Airborne Scanning LiDAR, High Resolution Hyperspectral Imaging and Ground Based Inventory Data",* which was awarded $1500 within South Dakota at the "Phase Zero" level. In total, this collaboration represents approximately $60,000 in industry investment. Second, we have teamed with Lamp-Rynearson Associates (LRA), Omaha, NE. LRA is a surveying and engineering company with expertise in ground-based lidar remote sensing. LRA employees traveled to the Black Hills to acquire ground lidar scans of several Black Hills plots as an experimental (i.e. very low cost) joint research venture. These data represent approximately $10,000 in industry investment, and serve as a cornerstone for our continued project work. Third, as a result of discussions with Don Deering (NASA GSFC) to suggest video-controlled stabilization of the Short Wave Aerostat-Mounted Imager (SWAMI), we have established a cooperative agreement with Pyramid Vision Technologies (a division of Sarnoff Corp., Princeton, NJ) and have been granted a no-cost use of approximately $45,000 of computer vision hardware and software from that company. Fourth, due in part to this project we have received a donation of one 100m tall research tower for installation at a site in the Black Hills for future remote sensing and biosphere-atmosphere exchange research from Basin Electric

Corporation. This tower represents a gift of approximately $15,000. Finally, our work has attracted the attention of scientists at the Science Applications International Corporation (SAIC), and the SAIC is now employing one graduate student (Kurtis Nelson) full time in order that he can complete work relating to pre/post-fire vegetation health in the USGS/DOI LANDFIRE project. This contribution represents approximately $30,000 of investment into the project thus far.

Metric/goal 9: Strengthen collaboration among SD university scientists and scientists at other institutions in the area of terrestrial remote sensing.
We are accomplishing this goal in several ways. Notable examples include our involvement with the SpecNet consortium of scientists, headed by Dr. John Gamon of the Virtual Center for Spatial Analysis and Remote Sensing (*http://vcsars.calstatela.edu/SpecNet/*) whereby we are applying knowledge gained through the NASA EPSCoR project to better scale ecophysiological measurements quantified at the Black Hills Ameriflux tower using remote sensing approaches. Secondly, in relation to this work we have established the Forest Public Access Resource Center (ForestPARC), led by scientists at SDSM&T, the University of Idaho, and the University of Montana in collaboration with the Upper Midwest Aerospace Consortium. ForestPARC is actively seeking grant moneys so as to improve the chances that our research program will be sustainable over the long-term. Thirdly, we have partnered with Dr. Zhiliang Zhu and Mr. Donald Ohlen at the EROS Data Center to become team members on the USGS/DOI LANDFIRE project, an effort with goals that overlap in many ways with the research done in the current NASA EPSCoR project.

Metric/goal 10: Provide research and educational opportunities for students interested in remote sensing-related careers.
Graduate and undergraduate students have served central roles in all phases of this project. Numerous students have also had the opportunity to interact with NASA scientists throughout this project. Please see the "personnel" section below for further detail. One MS thesis has already been completed, and three additional MS theses will be completed in August 2004. A Ph.D. dissertation will be completed in September 2004. In addition, an undergraduate minor in remote sensing has been instituted by this project's PIs at Augustana College in consortium with the USGS EROS Data Center.

Metric/goal 11: Organize outreach activities to educate K-12 students and the general public about remote sensing and earth system science.
We take to heart the effort put forth by NASA to develop a workforce "pipeline" of scientists and engineers for the 21st century. Therefore, our research team has organized and participated in more than twenty outreach programs to educate students, teachers, and the general public about work related to this project. Outreach events have ranged from 20-minute long seminars to the Rapid City business community, to day-long Black Hills field trips for teachers to participate in forest measurement activities, to an afternoon-long remote sensing workshop with Native American high school students, to a three-day remote sensing field experiment with pre-service teachers at the Rosebud Sioux Reservation.

3. List of articles submitted to or published in refereed journals.

Note: because a large number of papers resulting from this project are in the final stages of preparation, we include manuscripts that will be submitted by August 31, 2004, the end of the current project period.

Toomey, M., and Vierling, L. Comparison of ASTER and Landsat for Equivalent Water Thickness Derivation in the Black Hills of South Dakota, *International Journal of Remote Sensing*, to be submitted.

Toomey, M. and Vierling, L. Remote sensing of ponderosa pine forest foliar moisture using Landsat TM imagery. *Canadian Journal of Forest Research*, to be submitted.

Chen, X., Vierling, L.A., Deering, D.W., and Conley, A.H., Remote monitoring of post-fire vegetation dynamics in Siberian Boreal Forests using MODIS and Landsat. International Journal of Remote Sensing, to be submitted.

Chen, X., Vierling, L.A., Deering, D.W., and Conley, A.H.,. Local clustering of invariant features: a new relative radiometric normalization method for detecting landscape change. *Remote Sensing of Environment*, to be submitted.

Smith, R. and Vierling, L.A. Improving remotely sensed LAI estimates in a burned ponderosa pine ecosystem. *Remote Sensing of Environment*, to be submitted.

Chen, X., and Vierling, L.A., Seasonal variability in the Enhanced Vegetation Index and its relation to forest canopy LAI in Siberia and the Black Hills of South Dakota. *Remote Sensing of Environment*, to be submitted.

Conley, A.H., Deering, D.W., Nelzina, A.G., Kharuk, V.I., Leblanc, S.G., Kofman, G.B., Chen, J.M., and Vierling, L.A. Leaf area index across post-fire Siberian boreal forests. *Agricultural and Forest Meteorology*, in review.

Vierling, L., Fersdahl, M., Chen, X., and Zimmerman, P. The Short Wave Aerostat-Mounted Imager (SWAMI): A novel platform for acquiring remotely sensed data from a tethered balloon. *Remote Sensing of Environment,* in review.

Chen, X. and Vierling, L. Spectral mixture analyses of hyperspectral data acquired using a tethered balloon. *Remote Sensing of Environment,* in review.

Chen, X., Vierling, L., Rowell, E., and DeFelice, T. 2004. Using lidar and effective LAI data to evaluate IKONOS and Landsat 7 ETM+ vegetation cover estimates in a ponderosa pine forest. *Remote Sensing of Environment,* 91(1): 14-26.

4. List of patents (pending and awarded).

None.

5. List of talks, presentations, or abstracts at professional meetings.

Note: in addition to the professional meeting presentations listed below, we have also presented findings relating to this work at lectures at the EROS Data Center and universities outside of SD on 7 different occasions.

Chen, X., Vierling, L., Rowell, E., and DeFelice, T. "Using Lidar and Effective LAI to Evaluate Vegetation Cover Estimates from IKONOS and Landsat 7 in a Ponderosa Pine Forest." ForestPARC Lidar User's Conference, Moscow, ID. May, 2004.

Chen, X., Vierling, L., Deering, D., and Conley, A. "The Temporally Invariant Cluster (TIC) Method: a New Relative Radiometric Normalization Scheme for Detecting Landscape Change Using Multi-temporal Images." American Society for Photogrammetry and Remote Sensing Annual Meeting, Denver, CO. May 2004.

Smith, R., Chen, X., Conley, A., and Vierling, L. "Using MODIS and ETM+ to examine the effect of spatial scale on leaf area index estimates in forest burn chronosequences." Tenth Biennial USDA Forest Service Remote Sensing Applications Conference, Salt Lake City, UT. April 2004.

Rowell, E., Vierling, L., and Shepperd, W. Using Lidar Remote Sensing to Supplement Forest Inventory Variables and to Characterize Canopy Fuels in the Black Hills Experimental Forest." Tenth Biennial USDA Forest Service Remote Sensing Applications Conference, Salt Lake City, UT. April 2004.

Toomey, M. and Vierling, L. "Remote Sensing of Landscape Level Foliar Moisture Using Landsat TM SWIR Reflectance." Tenth Biennial USDA Forest Service Remote Sensing Applications Conference, Salt Lake City, UT. April 2004.

Vierling, L.A., Chen, X., Fersdahl, M., and Zimmerman, P. "Research and Outreach with the Short Wave Aerostat-Mounted Imager (SWAMI)." National Science Foundation CAREER Conference, Arlington, VA, January 2004.

Vierling, L.A., Chen, X., Fersdahl, M., and Zimmerman, P. "The Short Wave Aerostat-Mounted Imager (SWAMI): A Novel Hyperspectral Remote Sensing Instrument Platform." American Geophysical Union Fall Meeting, San Francisco, CA. Invited presentation. December 2003.

Swets, D., Stavenger, T., and Peterson, J., "Parallel NDVI Smoothing Algorithm Comparison: A Study using a Windows-based PVM cluster and a multithreaded implementation," in *Proceedings, 30th International Symposium on Remote Sensing of Environment*, Honolulu, HI, 2003.

Smith, R., and Vierling, L. "Improved ground- and satellite-based methods for deriving LAI in a burned ponderosa pine ecosystem." Presentation at the Ecological Society of America annual meeting, Savannah, GA, August 2003.

Derr, K. and Matzner, S. "Effects of Different Fire Intensities on Understory Vegeatation Diversity in the Jasper burn Area of the Black Hills." Ecological Society of America Annual Meeting, Savannah, GA, August 2003.

Chen, X., Conley, A. and Vierling, L. "Remotely sensed estimates of Leaf Area Index in forests of Central Siberia using MODIS Data." South Dakota Academy of Sciences annual meeting, Rapid City, SD, April 2003. Poster presentation.

Derr, K. and Matzner, S. "Effects of Different Fire Intensities on Understory Vegeatation Diversity in the Jasper burn Area of the Black Hills". South Dakota Academy of Sciences Annual Meeting, Rapid City, SD, April 2003.

Vierling, L., Chen, X., Conley, A., Deering, D., Derr, K., Matzner, S., Rowell, E., Smith, R., Swets, D., and Toomey, M. "Remote Determination of Leaf Area Index Along Fire Chronosequences in the Black Hills and Southern Siberia." Presented at the NASA EPSCoR Annual Conference, Washington, DC, March 2003.

Vierling, L., Rowell, E., Smith, R., Chen, X., and Toomey, M. "From surface to satellite: using remote sensing to measure and monitor forest ecosystems." South Dakota Association of Environmental Professionals 6th Annual Conference, Rapid City, SD, October, 2002.

Chen, X., Vierling, L., Dykstra, D., Rowell, E., and Capehart, W. "Assessing fractional tree coverage using IKONOS, Landsat 7, and LiDAR data in a ponderosa pine forest via sub-pixel interpretation." Presented at the Ecological Society of America annual meeting, Tucson, AZ, August, 2002.

Rowell, E., Vierling, L., Dykstra, D., and Chen, X. "Small footprint LiDAR estimates of canopy gap structure in a ponderosa pine forest." Presented at the Ecological Society of America annual meeting, Tucson, AZ, August, 2002.

Vierling, L., Rowell, E., and Dykstra, D. "LIDAR: A promising approach to estimating Western forest fire susceptibility." Presented at the ESRI User's Conference, San Diego, CA, July, 2002.

Vierling, L., Rowell, E., Chen, X., Dykstra, D., and Vierling, K. "Relationships Among Airborne Scanning LiDAR, High Resolution Multispectral Imagery, and Ground-Based Inventory Data in a Ponderosa Pine Forest." Presented at the IEEE International Geoscience and Remote Sensing Symposium, Toronto, Canada, June, 2002. Poster presentation.

Chen, X., Vierling, L., Rowell, E., Dykstra, D., Capehart, W., and DeFelice, T. "Relationships Among IKONOS Imagery, Airborne Scanning LIDAR, and Ground-Based Tree Inventory Data in a Ponderosa Pine Forest: A Multiple Endmember Approach." USGS/NIMA/NASA High Spatial Resolution Commercial Imagery Workshop, Reston, VA, March, 2002. Oral presentation.

6. List of follow-on grant proposals submitted and funded (including NASA awards).

Funded Projects:

1. Source of Support:	National Center for Landscape Fire Analysis
Project Title:	Incorporating Ground-Based Laser Measurements of Forest Properties into a Collaborative Lidar Research Program
Award Amount:	$30,000
Period of Award:	May 2004-May 2005
Lead Investigator:	L. Vierling

2. Source of Support:	South Dakota Center for Biocomplexity Studies (NSF EPSCoR)
Project Title:	Quantification and Scaling-up of the Coupled Biogeochemical Cycles of Carbon and Water in Grassland Ecosystems of South Dakota: Synthesis of Flux Tower Measurements, Modeling, GIS, and Remote Sensing
Award Amount:	$50,207
Period of Award:	February 2004 through February 2005
Lead Investigators:	L. Vierling, P. Zimmerman

3. Source of Support:	Subcontract: from University of Idaho (Prime: NASA)
Project Title:	Forest Public Access Resource Center (ForestPARC)
Award Amount:	$45,000
Period of Award:	July 1, 2003 through March 31, 2004
Lead Investigator:	L. Vierling

4. Source of Support:	USDA Forest Service
Project Title:	Lidar Remote Sensing for Precision Forest Management
Award Amount:	$12,424 (SDSM&T portion)
Period of Award:	August 8, 2003 through June 30, 2005
Lead Investigator:	L. Vierling

5. Source of Support:	Subcontract: from University of North Dakota (Prime: NASA)
Project Title:	Developing Forestry Applications of LIDAR
Award Amount:	$30,000
Period of Award:	March, 2002 through March, 2003
Lead Investigator:	L. Vierling

6. Source of Support:	South Dakota SBIR Office
Project Title:	Phase Zero: Development of Analysis Utilities for Forestry Applications Employing Airborne Scanning LiDAR, High Resolution Hyperspectral Imaging and Ground Based Inventory Data
Award Amount:	$1,500
Period of Award:	Spring 2002

Lead Investigators: L. Deibert (Horizons Inc.), E. Rowell, L. Vierling

In addition to these government agency grants, we have received approximately $160,000 in data, equipment, and personnel services through five separate agreements with industry partners (see Metric/goal #8, above). We have included these figures in the attached metrics spreadsheet.

Pending Proposals:

Source of Support:	South Dakota Office for Tourism and Economic Development (2010 Initiative)
Project Title:	Center for Applied Research in Biogeosciences
Award Amount:	$5,000,000
Period of Award:	Five Years
Lead Investigator:	P. Zimmerman

Source of Support:	NASA
Project Title:	Enhanced NDVI/NPP in the Northern Great Plains 1982-98—is it still occurring and what are the consequences on the ground for carbon and greenhouse gases?
Award Amount:	$500,000
Period of Award:	Three years
Lead Investigators:	S. Frolking (UNH), P. Zimmerman, R. Harriss (NCAR)

Source of Support:	NASA
Project Title:	Carbon dynamics of the Great Plains: Quantification and Trends
Award Amount:	$160,584
Period of Award:	Three years
Lead Investigators:	B. Wylie (EDC); P. Zimmerman

Declined Proposals:

Our research group has submitted 6 major (>$200,000 each) proposals (2 NSF, 2 NASA, 1 USFS, 1 NCSSF) as specific follow-on grants to this particular project that have been declined over the past 24 months.

7. <u>Name(s) and frequency of contact with Technical Monitor(s).</u>

Dr. Don Deering is the Technical Monitor of this project. As shown in Table 1 above, our project team has had face-to-face meetings with Dr. Deering on 6 separate occasions since the beginning of the project. We have also met to work with Alexis Conley (NASA-SSAI), Dr. Deering's project scientist, 6 times. In addition, we routinely communicate with Dr. Deering and Ms. Conley via phone and email. Table 1 spells out other contacts that have been made between NASA and SD scientists as a direct consequence of this project.

Our collaboration with Dr. Deering has been extremely fruitful. As a result of this project, Dr. Deering has assisted members of our group to become directly involved with NASA projects (e.g. the NEESPI). Furthermore, Dr. Deering has donated a research-quality pneumatic boom from under his jurisdiction at NASA-GSFC to SDSM&T for use in this and other remote sensing studies relating to forest canopies. Finally, L. Vierling and D. Deering have discussed the formation of an MOU between SDSM&T and GSFC to facilitate collaboration and visiting appointments of SD students and faculty at that NASA center.

8. Personnel information – numbers, gender distribution, and ethnic distribution of faculty, post-docs, graduate and undergraduate students.

Name	Gender	Position	Ethnic Background
Lee Vierling, PI	M	Assistant Professor, SDSM&T	Caucasian
Steven Matzner	M	Assistant Professor, Augustana	Caucasian
Daniel Swets	M	Associate Professor, Augustana	Caucasian
William Capehart	M	Associate Professor, SDSM&T	Caucasian
Changhui Peng	M	Associate Professor, SDSM&T	Chinese
Patrick Zimmerman	M	Professor, SDSM&T	Caucasian
Kathryn Derr	F	B.S. Student, Augustana	Caucasian
Meghan Calhoon	F	B.S. Student, Augustana	Caucasian
Olga Degtyaryova	F	B.S. Student, Augustana	Ukranian
Mark Lindgren	M	B.S. Student, Augustana	Caucasian
Andrew Reinartz	M	B.S. Student, Augustana	Caucasian
Shane Hansen	M	B.S. Student, SDSM&T	Caucasian
Beth Hansen	F	B.S. Student, SDSM&T	Caucasian
Bruce Hoon	M	B.S. Student, SDSM&T	Caucasian
Denise Dykstra	F	M.S. Student, SDSM&T	Caucasian
Rachel Smith	F	M.S. Student, SDSM&T	Native American
Michael Toomey	M	M.S. Student, SDSM&T	Asian American
Eric Rowell	M	M.S. Student, SDSMT&T	Caucasian
Xuexia Chen	F	Ph.D. Student, SDSM&T	Chinese
Angela Belote	F	Project Assistant, SDSM&T	Caucasian
Karl Lalonde	M	System administrator and Ph.D. student, SDSM&T	Caucasian

9. Progress towards achieving self-sufficiency beyond the award period of this grant (limit: 1/2 page).

Several details regarding the progress towards achieving self-sufficiency have been mentioned previously in this document. In sum, we have made strides towards achieving self-sufficiency in the following ways:

a) Stengthening collaborative ties with NASA scientists and strategic research initiatives.
b) Building key intellectual and research equipment infrastructure via collaborative partnerships with industry.

c) Partnering with highly regarded university and non-NASA governmental scientists on a wide range of collaborative projects relating to this proposal.
d) Increasing the number of proposals submitted to NASA and NSF in areas relating to remote sensing and earth system science.
e) Preparation, submission, and publication of scientific results in highly regarded scientific journals to establish our group as one with demonstrated expertise in remote sensing science.

10. A summary of research results (limit: five pages)

Major findings of our research work can be categorized into six main sub-studies, as described below:

Study 1: Remote monitoring of post-fire vegetation LAI dynamics in Siberian Boreal forests using MODIS, Landsat and IKONOS data

A large body of research has been conducted to characterize leaf area index (LAI) using remotely sensed observations acquired at the surface and above the canopy. However, because local-to-global scale biogeochemical and climate studies have different resolution requirements with respect to LAI quantification, and due to the fact that spectral data from many sensors of varying resolution are now available, it is important that LAI derivation accuracy be quantified using multiple study sites, sensors, and surface characteristics across a range of scale.

The research sites were centered in the central Siberian region of Krasnoyarsk (57.3˚N, 91.6˚E). Mixed coniferous forest is the dominant land cover, while deciduous forests occur occasionally. Four postfire sites were selected based on their difference of dominant species and postfire age. Canopy LAI was measured in the field during the summers of 1999, 2000, and 2001, and were calculated following theory established by Chen and Cihlar (1996).

Landsat 7 ETM+ images were acquired on 20 June 2000 and 26 August 2001, and one IKONOS image was collected on 23 June 2000. These images were radiometrically calibrated, dark object subtraction corrected, and co-registered based on the 2000 ETM+ image. NDVI, EVI (Enhanced Vegetation Index) and RSR (Reduced Simple Ratio) were calculated for these images respectively. In addition, the NDVI and EVI of two ETM+ images were normalized to a common radiometric scale using the TIC method (See Study 2, below). MODIS MOD09 and MOD15 data products of 2000 were ordered over the study site through EOS data gateway (EOS 2004) and reprojected using the MODIS reprojection tool.

Dynamics of the MODIS LAI product for the year 2000 provided seasonal dynamic changes and also indicated that the MODIS LAI product significantly underestimated the LAI of coniferous forest in the winter. This result may be due to influences of background snow or due to the high-angle illumination effects prevalent at high latitude sites in the winter. ETM+ derived EVI performed better than NDVI to separate the deciduous and coniferous forest due to its sensitivity to canopy shadows and the better correction of atmospheric influences. Field LAI data contained significant correlation with ETM+ derived EVI (logarithmic, r^2=0.61) and NDVI (linear, r^2=0.69). IKONOS derived EVI and NDVI of coniferous forests also indicated good correlation with field LAI (logarithmic, r^2=0.56, and linear r^2=0.82, respectively). RSR can normalize the difference between deciduous and coniferous forests, and this advantage significantly increases the LAI interpretation for mixed forests (r^2=0.89). LAI regression functions derived from ETM+ and IKONOS vegetation indices including EVI, NDVI and RSR were used to scale up the fine resolution images for evaluating the 1-km resolution MODIS LAI product. The results showed that MODIS LAI overestimated the low LAI deciduous forests and underestimated the high LAI coniferous forests. Additionally, field measures of forest in various postfire ages were presented to provide a picture of the postfire dynamics.

The above results provided valuable information about the influence of forest fire and the scaling issue between fine resolution and coarse resolution satellite remote sensing data. In addition, RSR was demonstrated as a promising vegetation index to interpret surface LAI, and has been further applied to datasets acquired in the Black Hills (overall compilations of Black Hills and Siberia data show the important result that RSR-LAI relations are linear across the wide range of vegetation type and density of these systems). Further study will focus on the performance of RSR in multi-temporal images for surface change detection.

Study 2: Developing a new relative radiometric normalization scheme, the temporally invariant cluster (TIC) method, for detecting vegetation canopy change using multi-temporal satellite images

The quality of satellite data is well developed for monitoring changes in vegetation, but radiometric consistency among multi-temporal imagery of the same area is difficult to maintain due to variation in satellite sensors, the atmosphere, and other effects. To detect accurate landscape changes using multi-temporal Landsat images, a new relative radiometric normalization scheme, the temporally invariant cluster (TIC) method, was developed. In this study, we assumed that: (1) the temporally invariant cluster (TIC) centers can be separated from other variant pixels; (2) at least two TIC centers can be found within the point density map; and (3) the radiometric relationships of NDVI (Normalized Vegetation Index) and EVI (Enhanced Vegetation Index) among multi-temporal images are linear (after Myneni and Asrar 1994, Gao et al. 2000).

Landsat TM4 on June 9, 1990, Landsat 7 ETM+ on June 20, 2000 and August 26, 2001 were acquired over the boreal forests near Siberian city of Krasnoyarsk. Both NDVI and EVI were calculated for each image. ETM+ 2000 imagery was used as base image for georegistration and radiometric normalization. TIC centers were identified by a point density map of the base image and the target image. The normalization regression line then was created by following all TIC centers. The target images were then recalculated using the normalization regression function, bringing all images into a common scale.

During normalization, the NDVI and EVI were compared across multi-temporal images of different summer periods. The EVI point density maps showed three TIC centers, including water, cities and high density coniferous forests. The analyses of density maps of NDVI and EVI indicated that NDVI was a very effective vegetation index to reduce cloud shadowing influences, while EVI was very sensitive to cloud shadows. This can explain the ability of EVI values to delineate coniferous forests from deciduous forests: coniferous forests contain high levels of self shadowing while deciduous forests do not due to their different canopy structures. In the point density map, significantly variant pixels due to land cover changes were separable from pixels exhibiting seasonal changes.

After normalization, coefficients of determination (r^2 value) of NDVI and EVI with field collected total LAI in 2000 and 2001 were significantly improved from 0.49 to 0.69, and 0.46 to 0.60, respectively. NDVI and EVI of post-fire sites were also presented along time series using image data in 1990, 2000 and 2001 to interpret the post-fire forest dynamics.

Compared with previous relative normalization methods, this new method avoids the need for subjective selection of a normalization regression lines (e.g. Du et al. 2002), high levels of programming and statistical skills (e.g. Chavez 1996), and adjustments for seasonal influences due to changes in vegetation phenology (e.g. Song et al. 2001).

Study #3: Multiscale analysis of Leaf Area Index estimation from Landsat ETM+ and MODIS LAI product data in a burned ponderosa pine ecosystem

This study utilized a series of field measurements collected in a recently burned ponderosa pine-dominated forest to investigate the accuracy and potential improvements of leaf area index (LAI) estimates from satellite sensors. Our field data collection methods, as well as the satellite image processing and analysis, were based on an associated study conducted in the Siberian boreal forest (Conley et al, in review, Chen X., et al, Study #1). The main objectives of this study were:

1) To establish a range of post-fire LAI values based on relationships developed between ground-based LAI estimates and Landsat TM/ETM+ derived spectral vegetation indices (SVI).
2) To determine which SVI provided the best correlation with field LAI estimates and to use the resulting regression model to construct a high resolution (30 m) LAI map.
3) To scale up the Landsat LAI (to ~1 km map) to evaluate the MODIS LAI product.

As a result of 100 years of fire suppression in the Black Hills, our study utilized fire severity/canopy damage to provide a range of LAI values in this ecosystem, while the post-fire chronosequence (years post-fire) was the basis of the Siberia analysis. Permanent field sites (14 sites with at least 4 plots/site for a total of 64 plots) were established within and around the 33,800 hectare Jasper fire (burned September 2000) in the southwestern Black Hills. Sites were chosen to represent a continuum of LAI values. Sites were classified according to canopy damage, which included burns of high severity (trees are devoid of needles, 27% of total fire area); medium severity (partial crown scorching, 48% of fire area); low severity (ground fire only with no canopy damage, 25% of fire area); and 3 unburned sites served as our control. Field LAI measurements were collected three times throughout the summer growing season in 2002 and 2003, for a total of 6 collections. Nine of the original 14 sites were sampled in 2003. Additionally due to the malfunction of the Landsat ETM+ sensor, Landsat 5 (TM) data were used for the

2003 analysis. The theory and methods for estimating LAI followed Chen (1996) and Chen et al. (1997).

Canopy structural changes resulting from fire (medium severity sites only) suggested that adjustments of the calculated field LAI should be considered. *Thus, a necessary improvement to the LAI product algorithm in burned areas is to utilize site-specific estimates of the woody/needle area ratio based on burn severity.* Tuning of the woody/needle ratio, especially in areas experiencing large-scale disturbance, will serve to improve the quality and utility of satellite-based LAI (Figure 1).

The reduced simple ratio (RSR) SVI had the highest correlation with canopy LAI for both years (r^2= 0.67, normalized 2002 data). Other studies have shown RSR correlates well with field LAI measurements especially over heterogeneous land cover (Brown et al. 2000, Chen et al. 2002, Chen X., et al, Study #1). For overall LAI measurements, the three SVIs evaluated in this study (NDVI, EVI, RSR) performed similarly (r^2 = 0. 57, normalized 2002 data). A LAI map was created for the three Landsat ETM+ 2002 images using the overall NDVI-LAI regression. The main MODIS LAI algorithm utilizes red and near-infrared reflectance to create possible LAI values. When this initial algorithm fails, a back-up algorithm is implemented to produce LAI values based on general NDVI-LAI regressions. With this in mind we evaluated the MODIS LAI product using the high resolution LAI map and found that the MODIS LAI output overestimated surface LAI, particularly in unburned control sites.

This work leads to a better understanding of how post-fire plant damage and regeneration can be best monitored with satellite imagery. Adjustments to canopy structure parameters (alpha) improved relationships between satellite and field measurements, which has implications for retrieving LAI in areas affected not only by fire but also other disturbances such as drought and insect/pathogen infestations. This analysis also demonstrates that RSR is best correlated to our field estimated LAI data. This supports published work by Wang et al. (2004), which suggests the use of RSR in the MODIS LAI algorithm could improve estimates of coniferous forests, and as this research has shown, of disturbed coniferous forests as well. A comparison of MODIS LAI and ETM+ derived LAI demonstrates an overestimation of the low coniferous LAI sites of the Black Hills.

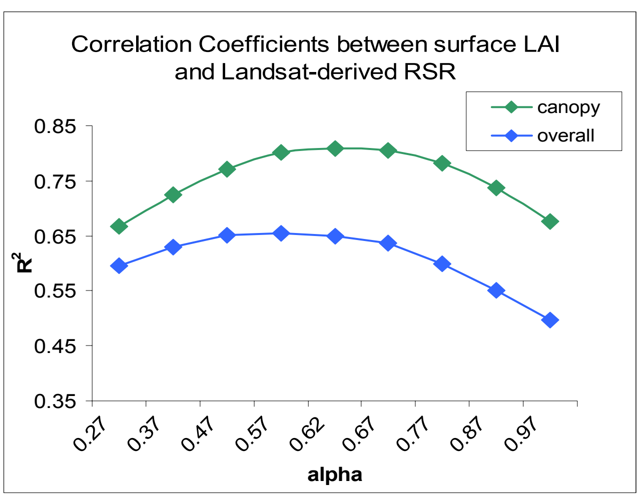

Figure 1. The goodness-of-fit between LAI and satellite derived Reduced Simple Ratio for medium severity sites reflects how critical alpha value assessments are for disturbed forests. As alpha values increase, indicating more wood exposure, the regression model in this particular case peaks at an alpha value of ~0.67.

Study #4: Using LAI to understand ecosystem function: remote sensing of landscape level foliar moisture using SWIR reflectance and image transformation

Monitoring the varying moisture levels in plants has ramifications for understanding fire potential, botany, ecosystem dynamics, and boundary layer meteorology. Studies of the spectral response to changes in plant water content have been conducted for several decades (e.g. Al Abbas et al., 1974), but the majority of this work has been conducted in the laboratory. Despite the relevance of foliar moisture and the advances within this area of study, the remote sensing of plant moisture at the landscape level is largely unexplored.

Shortwave infrared (SWIR; 1400-2500nm) reflectance is strongly correlated with the leaf water content, exhibiting low to moderate reflectance (15-30%) for a single leaf. This spectral characteristic makes SWIR ideal for investigating the primary effects of moisture variations in leaves. We utilized five SWIR-derived spectral indices (three novel and two older indices), principal component analysis (PCA), and Tasseled Cap Transformation (TCT) with Landsat TM data to quantify landscape level foliar moisture in a ponderosa pine-dominated ecosystem.

In situ foliar moisture calculations were conducted at the leaf level; the Leaf Area Index was estimated to scale moisture to the landscape level, yielding site moisture concentration (SMC). Comparisons between SMC calculations and TM data revealed that the Normalized Difference Infrared Index (NDII; Hardisky et al., 1983), with a two-fold weighting of the near infrared reflectance, exhibited the strongest correlation with ground data (r^2=0.627). Ceccato et al. (2002) found that a very similar index was most accurate for estimating chaparral moisture levels. The strongest correlation was found between SMC and the second principal component (r^2=0.765). Tasseled Cap Transformation wetness also showed strong correlation with SMC (r^2=0.638). The weighted NDII (wNDII) and TCT wetness are more practical for fire and ecosystem monitoring, because of the data dependence of PCA. It is suggested that the wNDII serve as an alternative index for the departure from average NDVI (Burgan et al., 1996) fire potential monitoring system implemented by the Forest Service and US Geological Survey, since the NDVI senses only secondary effects of moisture variations. Current research entails the use of canopy reflectance modeling to develop physically-based SMC derivation for ASTER and Landsat data.

Study #5: Biodiversity assessments of understory foliar regrowth in post-fire environments

Fire has become an increasingly important issue in western states because of the frequency and severity of many recent wildfires. Years of fire suppression policy have resulted in higher fuel loads that cause fires to burn more intensely (Bock 1984). The effect of fire intensity on the understory vegetation recovery was studied within the 2000 Jasper Burn area in the Black Hills of South Dakota during the summer of 2002. It was hypothesized that high intensity fires would be more damaging to forest understory recovery, while low intensity fires, which are thought to be more typical of pre-settlement times, might lead to increased diversity by stimulating the growth of more fire tolerant native species (Bock 1984, Fisher 1985). The results however did not conform to our original hypotheses. Species richness and diversity were not significantly different between high and low intensity burn sites. In fact, the unburned sites had significantly higher species richness and diversity compared to either the low or high intensity burns. Analysis of individual species changes revealed that fire of any intensity resulted in the loss of fire intolerant species, but that fire did not appear to be stimulating growth of fire tolerant native species. The absence of an increase in fire tolerant natives may be due to a lack of seed source or individuals to resprout. Recovery of natives in this system may occur more slowly than originally thought and may require additional burn events before recovery is complete.

Study #6: Using lidar and effective LAI data to evaluate IKONOS and Landsat 7 ETM+ vegetation cover estimates in a ponderosa pine forest.

Structural and functional analyses of ecosystems benefit when high accuracy vegetation coverages can be derived over large areas. In this study, we utilized IKONOS, Landsat 7 ETM+, and airborne scanning light detection and ranging (lidar) to quantify coniferous forest and understory grass coverages in a ponderosa pine (*Pinus ponderosa*) dominated ecosystem in the Black Hills of South Dakota. Linear spectral mixture analyses of IKONOS and ETM+ data were used to isolate spectral endmembers (bare soil, understory grass, and tree/shade) and calculate their subpixel fractional coverages. We then compared these endmember cover estimates to similar cover estimates derived from lidar data and field measures. The IKONOS-derived tree/shade fraction was significantly correlated with the field-measured canopy effective leaf area index (LAI_e) (r^2=0.55, p<0.001) and with the lidar-derived estimate of tree occurrence (r^2=0.79, p<0.001). The enhanced vegetation index (EVI) calculated from IKONOS imagery showed a negative correlation with the field measured tree canopy effective LAI and lidar tree cover response (r^2=0.30, r=−0.55 and r^2=0.41, r=−0.64, respectively; p<0.001), and further analyses indicate a strong linear relationship between EVI and the IKONOS-derived grass fraction (r^2=0.99, p<0.001). We also found that using EVI resulted in better agreement with the subpixel vegetation fractions in this ecosystem than using normalized difference of vegetation index (NDVI). Coarsening the IKONOS data to 30 m resolution imagery revealed a stronger relationship with lidar tree measures (r^2=0.77, p<0.001) than at 4 m resolution (r^2=0.58, p<0.001). Unmixed tree/shade fractions derived from 30 m resolution ETM+ imagery also showed a significant correlation with the lidar data (r^2=0.66, p<0.001). These results demonstrate the power of using high resolution lidar data to validate spectral unmixing results of satellite imagery, and indicate that IKONOS data and Landsat 7 ETM+ data both can serve to make the important distinction between tree/shade coverage and exposed understory grass coverage during peak summertime greenness in a ponderosa pine forest ecosystem.

C. REQUEST FOR CONTINUATION

1. Two-year program plan and budget (section D).

Years 4 and 5 of this project will build upon knowledge learned during the first three years of the award period. During these final years, less emphasis will be placed upon gathering field data with more emphasis on data analysis, algorithm development, and extrapolation of results to other areas. We will continue to pursue working with multi-angle MISR data for LAI evaluation if and when that data becomes available as a provisional product. Furthermore, we will pursue the use of ground lidar as a means to derive canopy values of foliar clumping and foliar/woody biomass ratios, two metrics of great import in the derivation of surface LAI in needleleaf systems. We will continue our work of partitioning LAI estimates among vegetation functional groups, an important step in improving remotely sensed estimates of biogeochemical pools of N, P, and C. Finally, we will be very active in continuing to pursue outside funding so as to make our research program sustainable after NASA EPSCoR funding is complete. Specific milestones are listed in the timeline (Figure 2).

2. Metrics to be used for tracking and evaluating program progress.

We propose the following classes of metrics to be used for tracking and evaluating progress of this program:

Scientific metrics will include:

- the number of papers that are published in peer-reviewed scientific journals;
- the number of undergraduate and Master's level theses as well as Ph.D. dissertations written in conjunction with this project;
- the number of presentations at scientific meetings relating to this research; and
- the inclusion of NASA scientists as co-authors on journal articles.

Administrative metrics will include:

- timely budget spending;
- maintenance of communications with NASA collaborators;
- maintenance of collaborative interactions with participating schools; and
- strengthening NASA collaborations over the long term.

Programmatic metrics will include:

- achievement of scientific goals;
- the number of K-12 students and laypersons exposed to remote sensing science via this project; and
- adherence to the project timeline shown in Figure 2.

3. Milestones and timetables for achievement of specific objectives during the award period.

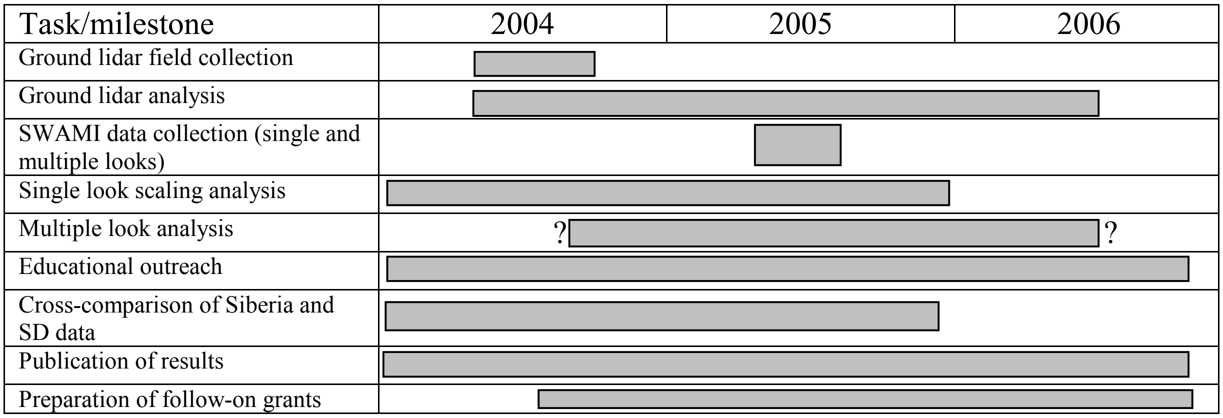

Figure 2. Timeline of significant research efforts and milestones within this project

4. Potential towards achieving self-sufficiency beyond the award period of this grant (limit: 1/2 page).

We feel that given our performance during the first three years of the award, the likelihood that our research team can achieve self-sufficiency beyond the award period is high. The ability of this research program to enable long term scientific research self-sufficiency within the state continues to depend greatly upon the strengths of the collaborative relationships we will be able to make across the state, region, and nation, as well as at NASA field centers. This proposed work will continue to provide our research team with a solid framework on which to build these collaborations. We have already made significant progress to link our research with that of scientists at the Goddard Space Flight Center Biospheric Sciences Branch, and have begun discussions with scientists at NASA-Ames. Furthermore, we have established the ForestPARC consortium with the Universities of Montana and Idaho, entered the SpecNet consortium, built a collaboration with the National Center for Landscape Fire Analysis, begun work on the USGS/DOI LANDFIRE project in collaboration with that project's PI at the EROS Data Center, and may have future possibilities to collaborate in the NASA Northern Eurasia Earth Science Partnership Initiative (NEESPI). We have partnered with multiple industrial affiliates with the goal of further research and development of products or techniques that may be commercialized, and will continue to do so. Through this program we feel that we will be able to develop the necessary technical skills to be able to provide valuable resources for future NASA goals.

5. Potential for the proposed research area to continue to grow in importance in aerospace fields in the future (limit: 1/2 page).

Among the highest of research priorities in earth system science today is the need to identify and quantify pools and fluxes of C and other biogeochemically important materials (e.g. N, P, S, H_2O) in the terrestrial biosphere. Furthermore, it is of critical importance to understand how these pools and fluxes change through time so that we may continue to improve our ability to model and predict future changes in primary production, albedo, and, ultimately, climate. LAI products produced by global-viewing sensors (e.g. MODIS) are likely to contain biases that must be further understood in order to better constrain such parameters. Not only will these issues continue to be of pure scientific importance; they are rapidly becoming geopolitically important as climate change and greenhouse gas regulation become ever more tangible. We hope to contribute to these important lines of investigation as our collaborative research work continues to grow.

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