FY17 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Development of Innovative Cost-Saving Methodology for Forest Inventory
PROJECT MANAGER: Dennis Kepler
AFFILIATION: Minnesota Department of Natural Resources
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WEBSITE: https://www.dnr.state.mn.us/forestry/resource-assessment.html
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 03o

APPROPRIATION AMOUNT: $800,000
AMOUNT SPENT: $796,117
AMOUNT REMAINING: $3,883

Sound bite of Project Outcomes and Results
The MNDNR's Resource Assessment Program studied using light detection and ranging (LiDAR) technology to innovate how forest inventory is conducted. The study found that using LiDAR can cut costs by as much as 55%, enables the collection of this valuable information across all lands, and makes data available much faster.

Overall Project Outcome and Results
Comprehensive forest inventory systems are a universal desire, but the costs of maintaining such a system with boots on the ground, especially considering Minnesota's extensive and diverse forest land base, continue to be a challenge. This project served as an important pilot to explore the accuracies achieved and cost savings gained with changing the way forest inventory is conducted. Two field sampling methods were tested in this project in over 300 plots, measuring over 9,000 trees: fixed radius plots placed in a gridded array (pre-stratification) and random plots placed proportionately within strata (post-stratification). Model results show that a gridded allocation performs better and has greater flexibility to reduce/expand the number of plots without risking model performance. Several forest inventory models (combined forest types, broadleaf only, and conifer only) were evaluated using numerous spatial predictors and two sources of LiDAR data: new high density and old low density. Model results show higher accuracies for conifers compared to broadleaf for both sources of LiDAR, and the combined models showed high density LiDAR performs much better. Another area of exploration was mapping cover types, since this is a crucial characteristic of a forest stand. The suite of remotely sensed data used and machine learning techniques applied have enabled cover type mapping with relatively good accuracy. The forest inventory and cover type mapping results in this project are incredibly encouraging and the methods developed are ready for statewide application once high density LiDAR data are available. Overall, the project results show that using remotely sensed data can cut inventory costs by about 55%, enables the analysis of this valuable information across all lands, makes data available much faster than traditional methods, and ultimately benefits the many agencies, organizations, and stakeholder groups who are hungry for an affordable change to how forest inventory is conducted.

Project Results Use and Dissemination
Analyses of the newly acquired high density LiDAR has resulted in several forest inventory metrics and cover type models created, utilizing more than 300 newly acquired field forest inventory plots with over 9,000 trees measured. All of the LiDAR and derived products will be provided free to the public and will be hosted as LiDAR point cloud files on an ftp server with other state LiDAR data holdings, as well as several web mapping services produced by the MNDNR and accessible via the Minnesota Geospatial Data Commons (https://gisdata.mn.gov/). The project team from DNR Resource Assessment has already and will continue to deliver the results of this project in a number of other ways, including presentations at regional and national conferences in the fields of

forestry, geographic information systems, and remote sensing, meetings and conference calls to share information directly with stakeholder groups, as well as the eventual submission of peer-reviewed manuscripts to scientific journals. In addition, DNR Resource Assessment has created a webpage that will be a central repository for all of the methods, reports, and links to access data.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan Final Report

Date of Report: August 16, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Development of Innovative Cost-Saving Methodology for Forest Inventory

Project Manager: Dennis Kepler

Organization: Minnesota Department of Natural Resources

Mailing Address: 483 Peterson Road

City/State/Zip Code: Grand Rapids, MN. 55744

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Email Address: dennis.kepler@state.mn.us

Web Address:

Location: Northern Cass County

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$800,000**
	Amount Spent:	**$796,117**
	Balance:	**$ 3,883**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03o

Appropriation Language:

$800,000 the second year is from the trust fund to the commissioner of natural resources to develop and pilot a new and more cost-effective methodology for an enhanced stand-based forest inventory, with the goal of extending the methodology statewide. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Development of Innovative Cost-Saving Methodology for Forest Inventory

II. PROJECT STATEMENT: Minnesota has an extensive and diverse forest land base important to multiple agencies and stakeholders, such as the U.S. Forest Service, DNR, counties, tribes, non-government organizations, and private citizens. **Using cutting-edge technologies, a less expensive and highly robust inventory of the forest land base will be developed through a pilot study across a diverse ecological landscape with multiple ownerships.** This pilot will assess methodology, accuracy, and costs, to evaluate the anticipated extension of this methodology statewide. After evaluation, we fully expect to establish and implement this cutting-edge inventory, thereby eliminating the need to return to the ENRTF for forest inventory funding.

- All agencies and stakeholders rely on forest inventory data for a wide variety of natural resource management purposes, including: assessing climate and landscape change, ecosystem fire and health risks, wildlife habitat, water resources, forest recreation, biomass estimations, and renewable timber assessments.
- Costs for accomplishing such forest inventories are increasingly expensive -- over $35 million is needed to inventory just the 5 million acres of DNR forest land, out of Minnesota's 17 million acres of forest land.
- Forest inventories are completed once every 10 to 20 years, making it difficult to respond to emerging issues.
- Technological advances in remote sensing and computing have now made it possible to rapidly collect, analyze, and characterize, in detail, ecological condition over large landscapes with very little ground data.
- Given these advancements, it is now possible to refine and apply these technological improvements to develop a revolutionary methodology for statewide forest inventory across diverse types of land ownerships.
- Ultimately, this project will demonstrate a highly effective, detailed, and robust method of achieving a comprehensive, accurate and regularly updated forest inventory at dramatically lower costs for the state.

The goal of this project is to create an updated, efficient, and revolutionary forest inventory technique by:

1. Developing a stand based forest inventory, including species composition, detailed attributes of the vegetation and forest structure, and characteristics that relate to wildlife and ecological habitat suitability.
2. Estimating a suite of tree attributes per stand (e.g., height, diameter at breast height (DBH), crown size, age, basal area, biomass, and volume) that relate to those ecological suitability characteristics.

Both the stand characteristics in (1) and the tree estimates in (2) are generated by acquiring cutting-edge, high density LiDAR data in concert with aerial and sub-meter satellite imagery and fewer, more detailed field reference information. The proposed work uses and builds on other recent ENRTF-funded projects such as Improved Rapid Forest Ecosystem and Habitat Inventory (Ek 2013), Mapping Landscapes for Better Land and Water Management (Knight et al. 2014), and the statewide light detection and ranging (LiDAR).

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 31, 2017:

- Purchased one eCognition license seat for object-based individual forest stand segmentation processing.
- Began preliminary forest plot design and metrics research and analysis.
- Began the research into the best type of sub-meter GPS unit and digital input devices for the field work.
- Wrote the LiDAR + Digital Aerial Photography bid specifications for fall 2017 flight. We've moved the LiDAR Acquisition from October 2016 to October 2017. This will not affect the final timeframe or outcomes of this project.

Project Status as of July 31, 2017:

- Began field data collection on forest plots on May 15, 2017.
  - DNR Interns and staff have collected field data on 114 - 1/10 acre plots.
  - County foresters have collected field data on 4 - 1/10 acre plots.
- Unmanned Aerial Systems (UAS) work has begun.
  - High resolution aerial imagery have been flown on 9 plots.
- Awarded the LiDAR bid to Quantum Spatial to be collected this fall.

- **Amendment request: July 31, 2017**
  - We were able to purchase two items for less than anticipated:
    - eCognition software – anticipated cost = $15,000, actual cost = $14,321.25, savings = $678.75.
    - LiDAR - anticipated cost = $375,000, actual cost = $371,409, savings = $3,591.
  - We over spent for the GPS data recorders by $883.66:
    - Anticipated cost = $30,000, actual cost = $30,883.66, over = ($883.66).
  - I request to move funding as follows:
    - $883.66 from the LiDAR acquisition in Activity 1, line item 20, to the purchase of GPS units in Activity 2, line item 26.
    - The remaining $2,707.37 from the LiDAR acquisition in Activity 1, line item 20, to the contract for segmentation in Activity 1, line item 21.
    - The $678.75 from the purchase of eCognition software in Activity 1, line item 25, to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR: August 29, 2017**

- **Amendment request (10/12/17):**
  - I request to move funding as follows:
    - Because the DNR has determined that Resource Assessment is exempt from direct and necessary costs, these dollars need to be moved to another activity. Moving the D&N dollars to the contract for segmentation with the UMN will enhance the LiDAR processing to include the classification after the stand boundary segments have been created. Classifying the new stand segmentations through the process the University proposes will provide significantly improved forest stand information we otherwise wouldn't have been able to complete.
    - $14,321 from Other: DNR's direct and necessary costs in Activity 1, line item 30 to the contract for segmentation in Activity 1, line item 21.
    - $9,215 from Other: DNR's direct and necessary costs in Activity 2, line item 30 to the contract for segmentation in Activity 1, line item 21.
    - $586 from Other: DNR's direct and necessary costs in Activity 3, line item 30 to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR 10-16/2017**

Project Status as of January 31, 2018:

- LiDAR + 30cm aerial photography has been acquired between September 20 and October 20, 2017 for 628,000 acres in northern Cass County by Quantum Spatial for $371,409. This data will be delivered during the winter months of 2018.
- Began field data collection on forest plots on May 15, 2017.
  - DNR Interns and staff have collected field data on 170 - 1/10 acre plots.
  - County foresters have collected field data on 21 - 1/10 acre plots.
- UAS aerial imagery, including pix4-D surface models work:
  - 44 plots visited, 37 had imagery acquired, and 7 plots were inaccessible via UAS.
- Wrote and entered into a contract with the University of Minnesota to create forest and non-forest delineated stand boundaries over the project area based on LiDAR, imagery, and other ancillary data; attempt to classify delineated stands into cover types mimicking CSA stands, and investigate the potential of species level classification with derived data attributes agreed upon by the State and the

Contractor: and use stand level object to investigate which relevant stand level metrics can be derived – Stand level metrics will include summaries for LiDAR-derived elevation and height, area and other relevant sub-stand metrics for $77,819.

Project Status as of July 31, 2018:

- 413 out of 500 field plots have been completed.
  - DNR Interns and staff have collected field data on 333 - 1/10 acre plots.
  - County foresters have collected field data on 80 - 1/10 acre plots.
  - 55 1/10 acre plots deemed inaccessible.
  - Remaining 32 1/10 acre plots will be completed by September 1, 2018
- Unmanned Aerial Systems (UAS) work has continued.
  - 44 plots sites have been flown for high resolution aerial imagery.
  - Imagery processed using AgVault and Pix4D software and delivered:
    - Raw imagery in .tiff format.
    - Point Cloud files in .las format
    - Digital Surface Models (DSM) in .tiff format.
    - Digital Terrain Model (DTM) in .tiff format.
    - Ortho-Mosaics in .tiff format
  - All data uploaded to Northland OneDrive for DNR evaluation and use.
- Acquisition of high density LiDAR and 30cm imagery has been completed and delivered to the DNR by Quantum Spatial.
- University of Minnesota (UMN) has begun the process of creating both individual tree objects and subsequent stand boundaries in the project area.
- Resource Assessment Remote Sensing Analyst has also begun creating gridded stand metrics to impute CSA like attributes within each stand boundary created by UMN.

- **Amendment request (07/31/18):**
  - I request to move funding as follows:
    - Because field data collection has been more challenging and more difficult than first thought and intern wages have increased by $3.00 per hour, I request that funding be moved from the Personnel (Wages and Benefits in Activity 1 to in Activity 2:
    - $43,940 from Personnel (Wages and Benefits) in Activity 1 line item 12 to Personnel (Wages and Benefits) Activity 2 line item 12.
      - $16,940 from Remote Sensing Analyst – 1 in Activity 1 line item 15 to the Forester in Activity 2, line item 18.
      - $27,000 from Remote Sensing Analyst – 2 in Activity 1 line item 16 to the Interns in Activity 2, line item 19.
- **Amendment Approved by LCCMR 08/07/2018**

- **Amendment request (12/10/18):**
  - I request to move funding as follows:
    - $2,860 from Travel expenses in Minnesota in Activity 2 line item 28 to Travel expenses outside Minnesota (outstate) Activity 1 line item 30.

- Justification:
  - We're in our last FY of this project and would like to present it to the International LiDAR Mapping Forum, a major conference in Denver, Co. I realize Out of state transportation and travel expenses are generally ineligible, however, I'd like to ask approval for our Remote Sensing Consultant to go to the convention and present our project to the group.
  - The use of high density LiDAR to enhance and improve forest inventory is a significant paradigm shift from traditional forest inventory. Minnesota is a leader in this type of work and Resource Assessment's LCCMR pilot project's preliminary results have successfully shown that the State's investment will pay off. The International LiDAR Mapping Forum (ILMF) on January 28-30, 2019 in Denver, CO is a part of three joint national technical conferences. These conferences gather the practitioners, academics, and professionals in the field of remote sensing in a forum that is unlike any other to discuss and review airborne, terrestrial, and underwater LiDAR as well as emerging remote sensing and data collection tools and technologies. The conference content and vendors attending aim to emphasize on data acquisition, fusion, integration, processing and visualization, making it one of the most important events in this field for strategic networking, dissemination of results, and getting feedback from our colleagues. We've presented this project to many small groups within the region and plan to present to the Minnesota State Chapter of the Society of American Foresters (SAF) in Duluth this coming February. We also plan to utilize other funding to present this project at the National Society of American Foresters (SAF) in Louisville, Kentucky Next October/November. By sending the MNDNR Remote Sensing Program Consultant, Jennifer Corcoran to this conference, not only will we be sharing the great work that we have accomplished here in Minnesota, we will be learning how to maintain our innovative stance among our peers. Presenting at national meetings will also assist our efforts for improvements to the project outcomes through discussions and networking opportunities while attending such meetings.

- **Amendment Approved by LCCMR 01/08/2019**

Project Status as of December 10, 2018 for the January 31, 2019 update:

- UMN has completed both individual tree objects, stand boundaries, and forest metrics in the project area, however, they've not yet delivered results. RA expects delivery by January 1, 2019.
- Met with the UMN on a monthly basis for project updates and quality control checking
- Presented to more than 10 different stakeholder groups, regional and national conferences, and internal DNR meetings on the preliminary results from the UMN, field data, and the goals for the near future
- Clipped and processed several hundred statistics from the LIDAR point cloud for every field data plot
- In the process of developing imputation and regression models of several forest inventory metrics using the field data as well as the USFS Forest Inventory and Analyses (FIA) data, including diameter at breast height, volume, and site index
- In the process of comparing LIDAR-derived model results from stereo-derived model results.
- 432 out of 500 field plots have been completed.
  - Field work is complete and no more plots will be field visited.
- Unmanned Aerial Systems (UAS) work has continued.
  - 30 more plots sites have been flown for high resolution aerial imagery.

Overall Project Outcomes and Results:
Comprehensive forest inventory systems are a universal desire, but the costs of maintaining such a system with boots on the ground, especially considering Minnesota's extensive and diverse forest land base, continue to be a challenge. This project served as an important pilot to explore the accuracies achieved and cost savings gained with changing the way forest inventory is conducted. Two field sampling methods were tested in this project in over 300 plots, measuring over 9,000 trees: fixed radius plots placed in a gridded array (pre-stratification) and random plots placed proportionately within strata (post-stratification). Model results show that a gridded allocation performs better and has greater flexibility to reduce/expand the number of plots without risking model performance. Several forest inventory models (combined forest types, broadleaf only, and conifer only) were evaluated using numerous spatial predictors and two sources of LiDAR data: new high density and old low density. Model results show higher accuracies for conifers compared to broadleaf for both sources of LiDAR, and the combined models showed high density LiDAR performs much better. Another area of exploration was mapping cover types, since this is a crucial characteristic of a forest stand. The suite of remotely sensed data used and machine learning techniques applied have enabled cover type mapping with relatively good accuracy. The forest inventory and cover type mapping results in this project are incredibly encouraging and the methods developed are ready for statewide application once high density LiDAR data are available. Overall, the project results show that using remotely sensed data can cut inventory costs by about 55%, enables the analysis of this valuable information across all lands, makes data available much faster than traditional methods, and ultimately benefits the many agencies, organizations, and stakeholder groups who are hungry for an affordable change to how forest inventory is conducted.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Acquisition, processing, and utilization of remotely sensed and ground data
Description: We will use an object-based individual forest stand segmentation (polygon mapping) approach with newly acquired high density LiDAR (this proposal) and other remotely sensed imagery to identify a suite of forest stand attributes and tree estimates. Each stand will be populated with detailed forest metrics using a statistical imputation process developed by Dr. Alan Ek derived from newly collected and existing inventory data. The pilot project area will consist of 500,000 acres across multiple landowners in northern Cass County. The LiDAR cost estimate is based on information from several possible vendors currently acquiring this type of data. Because remote sensing technologies change very quickly, the cost of the LiDAR acquisition may be less than our current estimate. Therefore, if LiDAR acquisition costs are less than the expected $375K, we would ask that those dollars be reallocated, through the amendment process, to either additional remote sensing analysis (activity 1) or more outreach and analyses of the methodology (activity 3).

Summary Budget Information for Activity 1:		
	ENRTF Budget:	**$ 621,369**
	Amount Spent:	**$ 619,781**
	Balance:	**$ 1,588**

Outcome	**Completion Date**
1. Acquire high density LiDAR data for 500,000 acres in the pilot study area ($0.75/acre)	October 2017
2. Segment the forested land-cover data to individual stand polygons	April 2017
3. Develop forest stand metrics based on imputation with existing plots	June 2018
4. Develop stand metrics based on new LiDAR data	February 2019

Activity Status as of January 31, 2017:
- In preparation of the segmentation process needed to produce forest stands and to work with the University of Minnesota one eCognition license seat has been purchased for object-based individual forest stand segmentation processing.
- We've also began working on preliminary forest plot design research and analysis.

- Research into the best type of sub-meter GPS units and digital input devices for the field work is almost completed and ready for purchase.
- Finally, Resource Assessment has completed writing the LiDAR + Digital Aerial Photography bid specifications for the fall 2017 acquisition. Due to weather and timing complications, we've moved the LiDAR Acquisition date from October 2016 to October 2017. This will not affect the final timeframe or outcome of this project.
- Awarded the fall 2017 acquisition of LiDAR bid to Quantum Spatial on 728,000 acres for $445,086:
  - Cass County – 628,000 acres for $371,409.00

Activity Status as of July 31, 2017:

- Awarded the LiDAR bid to Quantum Spatial to be collected this fall
  - Reassessed RFP contract.
- **Amendment request: July 31, 2017**
  - We were able to purchase two items for less than anticipated:
    - eCognition software – anticipated cost = $15,000, actual cost = $14,321.25, savings = $678.75.
    - LiDAR - anticipated cost = $375,000, actual cost = $371,409, savings = $3,591.
  - I request to move funding as follows:
    - $883.66 from the LiDAR acquisition in Activity 1, line item 20, to the purchase of GPS units in Activity 2, line item 26.
    - The remaining $2,707.37 from the LiDAR acquisition in Activity 1, line item 20, to the contract for segmentation in Activity 1, line item 21.
    - The $678.75 from the purchase of eCognition software in Activity 1, line item 25, to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR August 29, 2017**

- **Amendment request (10/12/17):**
  - I request to move funding as follows:
    - $14,321 from Other: DNR's direct and necessary costs in Activity 1, line item 30 to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR 10-16/2017**

Activity Status as of January 31, 2018:

- LiDAR + 30cm aerial photography has been acquired (September 20 and October 20, 2017 for 628,000 acres in northern Cass County by Quantum Spatial for $371,409.
  - Because the cost of LiDAR has reduced substantially over the last year, Resource Assessment was able to increase the overall size of the area of acquisition to 628,000 acres for the same price listed in the approved budget.
  - A partial payment has been made for the acquisition of the entire area.
  - This data will be delivered during the winter months of 2018.

- Wrote and entered into a contract with the University of Minnesota to complete the following:
  - Use eCognition to perform object based image analyses (OBIA) over the LiDAR study area to develop meaningful 'stand level objects', including objects that are forest and non-forest classes, defined as homogeneous areas based on attributes such as, LiDAR-derived elevation data (such as all returns and/or first returns, normalized digital surface models (nDSM), and digital elevation models (DEM),

spectra, texture, geometry, and contextual information. Through OBIA, forested 'stands' will be segmented (aka delineated) and classified through an iterative process using those representative attributes and reference data. The deliverable will be polygons of non-forested and forested stands.

- Attempt to classify forested stand objects, where the scheme will be determined by iterative trial and error, field validated data from stand level forest inventory plots, and discussions between The State and The Contractor. Stand classification should be at the cover type level and not be interpreted as a representation of the mix or dominant tree species within any given stand, as species classification requires additional data and observations beyond those provided by aerial imagery and LiDAR. The classification scheme should mimic the Cooperative Stand Assessment (CSA) as close as possible. The Contractor will investigate the potential of species level classification, as defined by trial and error with the derived data attributes and conversations with The State and The Contractor.

- Use the stand level objects to investigate which relevant stand level metrics can be derived and discuss these findings with The State throughout the project. Stand level metrics will include summaries for LiDAR-derived elevation and height area, and other relevant sub-stand metrics. These metric may include, but are not limited to: statistics of all LiDAR point cloud returns and first returns using agreed upon categories of height strata (such as mean, median, mode, skewness and standard deviation). size class, density class, site index, topographic code, canopy closure/gap percentage) volume of vegetation (i.e. biomass and/or basal area), estimates of mortality and/or damage, understory related metrics, and crown width/diameter and/or height to base of crown.

Activity Status as of July 31, 2018:

- Acquisition of high density LiDAR and 30cm imagery has been completed and delivered to the DNR by Quantum Spatial.
- University of Minnesota (UMN) has begun the process of creating both individual tree objects and subsequent stand boundaries in the project area.
- Resource Assessment Remote Sensing Analyst has also begun creating gridded stand metrics to impute CSA like attributes within each stand boundary created by UMN.

- **Amendment request (07/31/18):**
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Activity Status as of December 10, 2018 for the January 31, 2019 update:

- UMN has completed both individual tree objects, stand boundaries, and forest metrics in the project area, however, they've not yet delivered results. RA expects delivery by January 1, 2019.
- Met with the UMN on a monthly basis for project updates and quality control checking
- Clipped and processed several hundred statistics from the LIDAR point cloud for every field data plot
- In the process of developing imputation and regression models of several forest inventory metrics using the field data as well as the USFS Forest Inventory and Analyses (FIA) data, including diameter at breast height, volume, and site index
- In the process of comparing LIDAR-derived model results from stereo-derived model results

Final Report Summary:

<u>LiDAR Acquisition:</u>
The original 500,000 of LiDAR acquisition in Cass County increased to 628,000 acres for $371,409 ($0.59/acre)

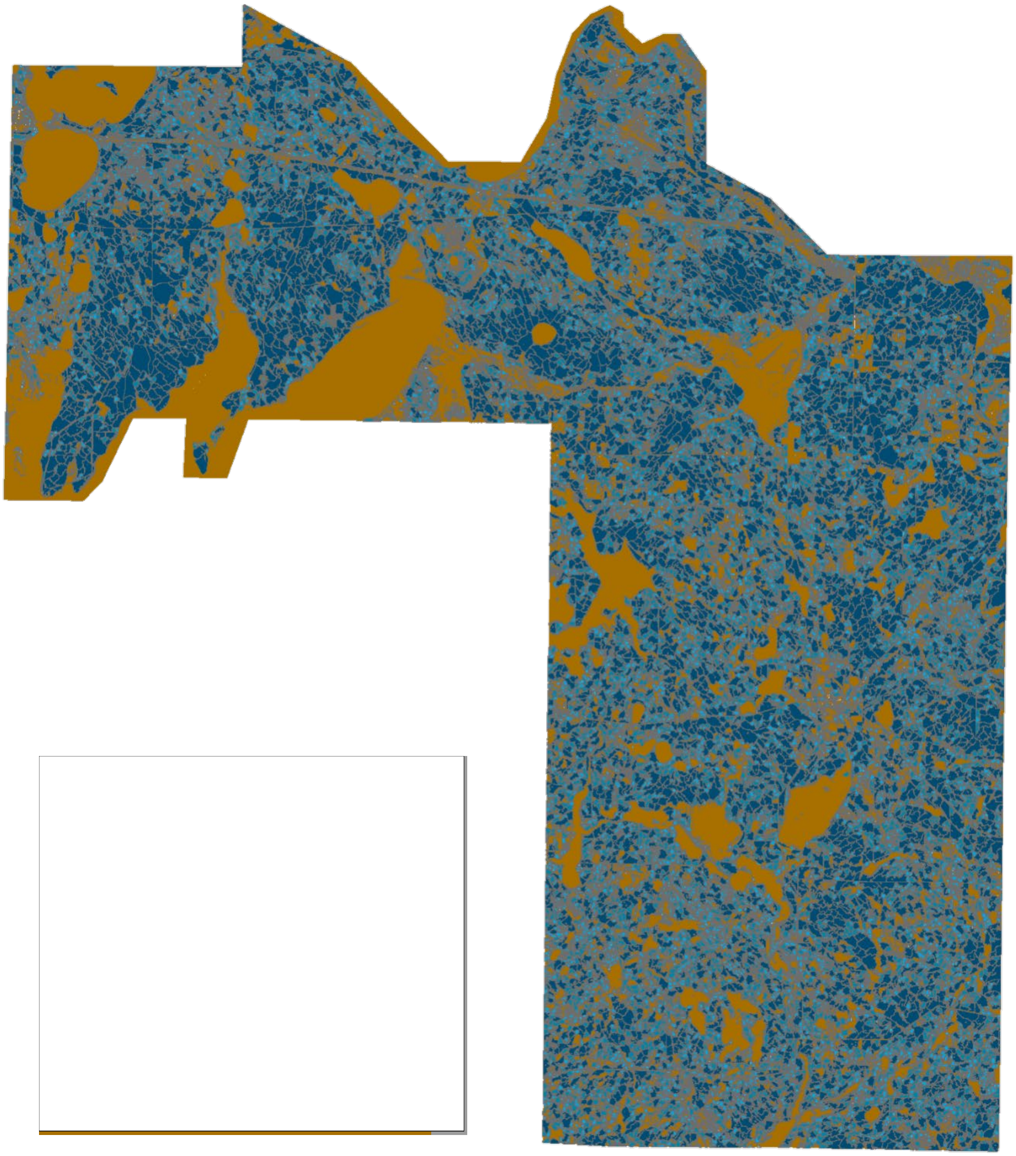
<u>Object-based (segmentation) Image Analysis for stand and sub-stand mapping completed by UMN:</u>
The object-based approach used a divide and conquer approach to identify sub-stands and stands. The approach used multi-threshold segmentation and the CHM to create large objects consisting of tall features (> 1.37m) and low features such as ground and water. The tall features are then segmented using multi-resolution segmentation to differentiate buildings and trees and were classified as such using spectral information and building footprints. The forest objects were then segmented using watershed segmentation to identify individual canopies or sub-stand objects. Watershed segmentation inverts the canopy height model and uses the low areas as seeds to fill the objects until it reaches the high values thus creating the sub-stand objects. These objects were then classified as coniferous and deciduous based on the difference between summer and fall normalized difference vegetation indices (NDVI) where coniferous trees have higher values and deciduous trees have lower values. The updated Minnesota National Wetland Inventory (NWI) was then used to assign overlapping sub-stand objects to upland and wetland classes.

Stands were created by aggregating sub-stand objects and assigning then to area-based classes. Sub-stand objects were aggregated using multiresolution region grow, a merging segmentation algorithm that merges neighboring objects with similar spectral, textural, and height values. Canopy gaps and other small ground areas (< 0.2 ac) were merged with the stand objects. Stands were then assigned to five area categories using area metrics derived from the distribution of forest inventory management (FIM) plots: < 5ac, 5ac <= 10ac, 10ac <= 20ac, 20ac <= 30ac, and > 30ac. Stand attributes were then calculated and included percent canopy cover, percent cover type, mean, max, and median height. A complete list of algorithms with parameters and attributes are attached to this document.

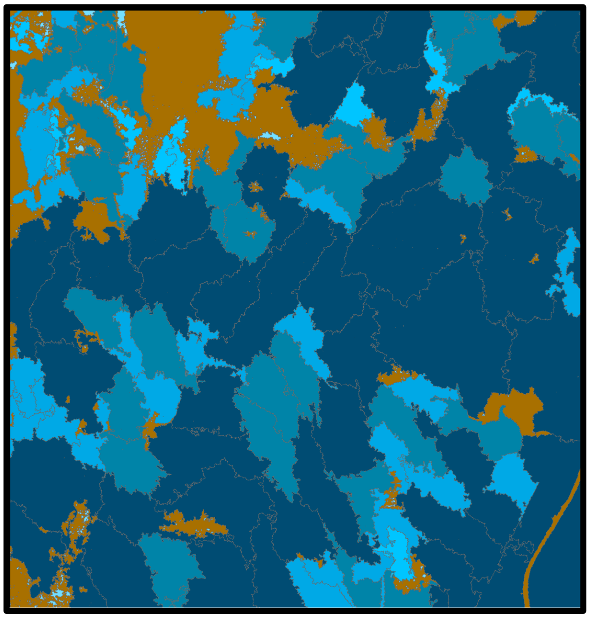
Attribute	Description
Class	Cover class
PerConif	Percent Coniferous Cover
PerDecid	Percent Deciduous Cover
PercCanopy	Percent Canopy Cover (Classification)
NoConif	Number of Deciduous Sub-Objects
NoDecid	Number of Coniferous Sub-Objects
acres	Area in acres
conif_AC	Deciduous Cover in Acres
decid_AC	Coniferous Cover in Acres
max_hgt	Maximum Height Value (CHM)
mean_hgt	Mean Height Value (CHM)
med_hgt	Median Height Value (CHM)
min_hgt	Minimum Height Value (CHM)
q10_hgt	10th percentile of height (CHM)
q25_hgt	25th percentile of height (CHM)
q95_hgt	95th percentile of height (CHM)
sd_hgt	standard deviation of height (CHM)
skew_hgt	skewness of height (CHM)

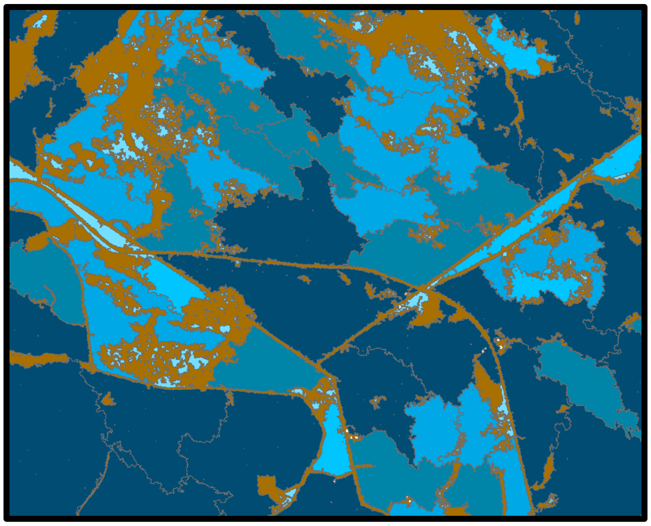
Stand geodatabases contain the sub-stand objects and super-stand polygons.

ChippewaStands.gdb
> Superstands_2017_chippewa
> Substands_2017_chippewa



Examples:





LiDAR-derived spatial forest inventory models (forest stand metrics):

LiDAR applications in forestry have been continuously expanding since the past few decades because of recognized accuracy in inventory predictions and cost-effectiveness compared to the traditional approach (design-based) based solely on field measurements. LiDAR is an active remote sensing technology that are highly sensitive to structural attributes and provide accurate three-dimensional coordinates of the pulse returns from intercepting canopy and terrain elements. While the cost of acquisitions is declining and the resolution of data is continuously improving with the development of new sensors and technology, LiDAR has become an affordable and reliable tool for both public and private agencies involved in natural resource management. Consequently, spatial and temporal monitoring of resources (i.e., status and trend) have become feasible in operational forest management as various agencies are involved in periodic acquisition of data, also supplemented by satellite data. For example, MN DNR completed a state-wide LiDAR (of density 1 to 1.5 points per m^2) baseline between 2007 and 2012 and is preparing further plans for statewide and periodic collections of high density LiDAR while already piloting few large-area acquisitions in Cass and Lake Counties with different modes of LiDAR. This documentation describes inventory modeling work in Cass County, Minnesota where high density data were acquired using Single Photon LiDAR (SPL) instrument from Leica/Hexagon. The SPL are considered to be efficient for large scale projects as the sensor operates at a faster speed with a wider track coverage and captures data using 100 outlet beams; it requires only one detected photon per ranging measurement as opposed to hundreds or thousands of detected photons per ranging measurement in conventional airborne LiDARs. MN DNR Forestry Resource Assessment Program intends to supplement and/or substitute the ground-based measurements via cutting-edge remote sensing technology such as LiDAR because the traditional field-based estimates are costly and quickly become outdated with stand growth and disturbances (natural or anthropogenic). The purpose of SPL together with simultaneously collected high resolution aerial photography was to produce forest inventory, and ultimately to update regional forest cover type maps and to evaluate forest condition and trends for timber production, wildlife habitat, forest health, and land managers.

The Quantum Spatial Inc. was contracted to acquire the SPL data and 30-cm color-infrared (CIR) aerial imagery simultaneously in fall of 2017. Field sample plots were also measured in summers of 2017 and 2018, and the inventory data were integrated with SPL- and CIR-derived metrics to produce spatial inventory models for several attributes including standing volume and aboveground biomass. The remotely sensed metrics were combined with the field inventory to produce eight different models in R statistical software using the Random Forest machine learning algorithm. In addition, tree objects and stand objects were produced from LiDAR point cloud. Ram Deo, Senior Remote Sensing Analyst of MN DNR Resource Assessment, was responsible for the processing of SPL and analysis of field inventory data. The SPL processing was done using FUSION software of the US Forest Service (McGaughey, 2018) and some publicly available tools from the LAStools software suite (https://rapidlasso.com/lastools/).

Field data analysis

Field data for model training was collected in the Cass AOI (Figure 1) during the summers of 2017 and 2018 using one-tenth acre fixed radius plots that were distributed systematically in a grid sample design with a density of about one plot per 920 acres. The x,y coordinates of the plot centers were estimated using Trimble R2 GNSS Receiver and differential correction post-processing that resulted in an average horizontal error of less than a meter; the average horizontal accuracy of plot locations after post processing was 0.23m. Altogether 418 sample plots were established and measured, however, only 362 plots contained trees while the other 56 plots were in open (non-forest) areas. Every tree with 5-inch minimum diameter at breast height (DBH) was measured in the plots and DBH, total height, foliate height, crown class, azimuth and distance from plot center and other tree size variables along with species were recorded (using Survey123 field app on mesa2 devise).

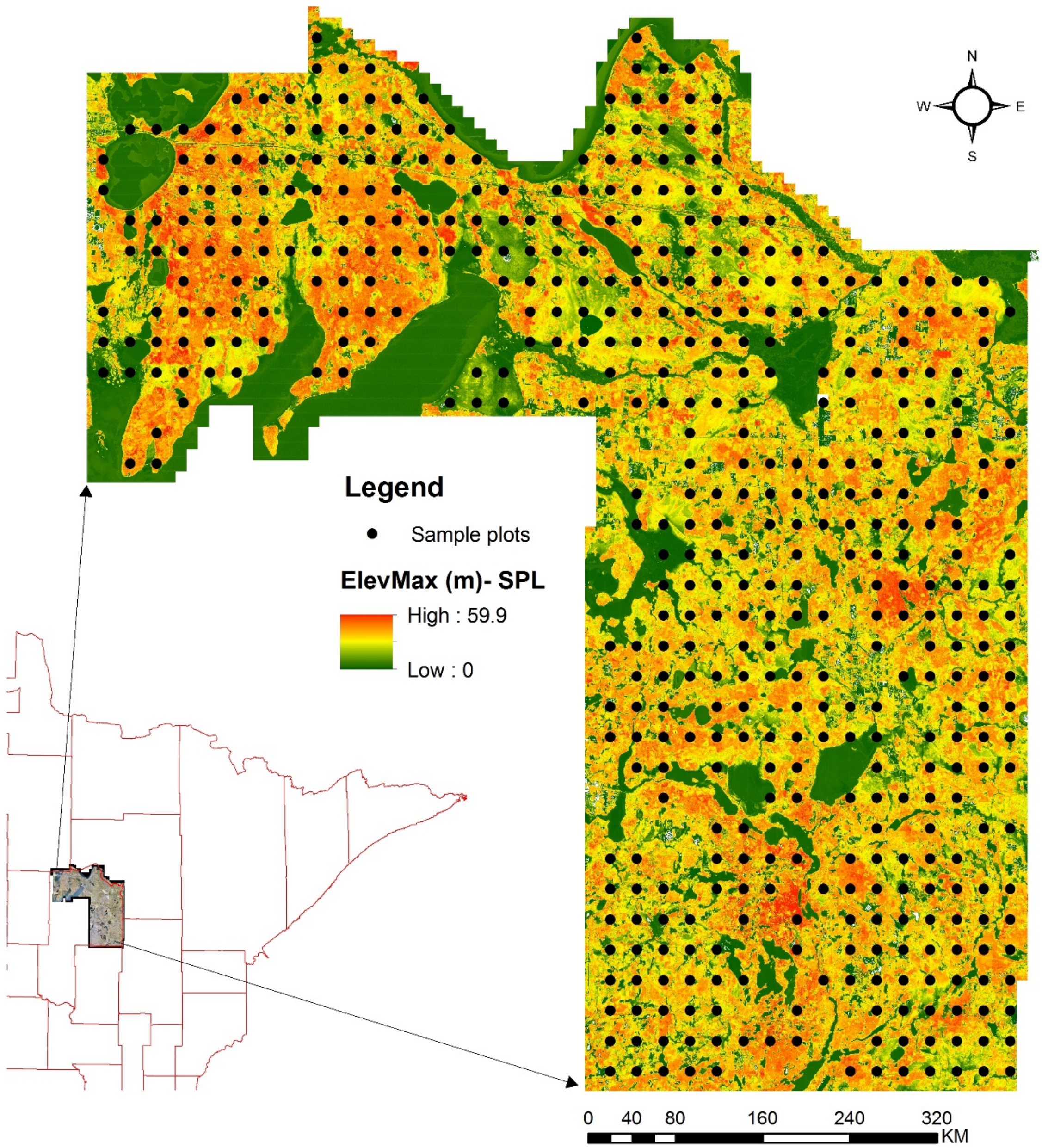


Figure 1. Cass County Areas of Interest.

Using the species-specific standard allometric models and the techniques adopted by the FIA program of the USDA Forest Service Northern Research Station, tree-level metrics were calculated and summed to obtain the plot-level inventory. The following plot-level inventories were calculated as combined and separately by softwood and hardwood.

- Aboveground biomass
- Standing volume
- Maximum height
- Basal area weighted height
- Stand basal area
- Trees per are
- Quadratic mean diameter
- Site index

LiDAR data and processing

Quantum Spatial Inc. (QSI) was the main contractor for simultaneously acquiring the high density SPL and 4-band (RGB NIR) aerial imagery in southwestern Chippewa National Forest site (663,293 acres) in Cass County. The data was collected between September 30, 2017 and October 16, 2017, during peak fall foliage color using a laser system operating at 532 nm wavelength, from an aircraft flying at an altitude of 3750-m above ground level with a speed of 160 knots, scan angle (field-of-view) of 30 degrees, effective scan rate of 6Mhz (PRR: 60kHz, 100 beamlets per laser pulse), beam divergence of 0.08 mrad/beamlet, swath width of 2000-m, and side overlap 50%. The data was acquired during peak fall color with an anticipation that canopy conditions will enhance forest species discrimination. Since single photon are considered to be sensitive to solar noise, QSI performed solar noise removal processing (prior to flightline calibration) by applying a kernal density estimation to the data.

The vendor delivered classified LiDAR point cloud data (in las 1.4 format) in 4772 tiles, each of 750×750-m size, and some derived products such as digital surface model (DSM) and bare-earth digital elevation models (DEM) at 30-cm spatial resolutions. However, QSI used only the first return of LiDAR pulses to derive DSM and so the full potential of LiDAR was not used to fully capture the canopy structure. Hence, we reproduced the DSM and canopy height model (CHM) in FUSION which also required production of DEM in PLAN's DTM format. The LiDAR point cloud was separated into ground and non-ground returns and DEM (in DTM format) was created for each tile using ground returns only. The DEM was next subtracted from the DSM to obtain CHM. Orthorectified and radiometrically corrected 4-band imagery were also delivered by QSI as 8 bit GeoTiffs (total 398 tiles, each of 2418×3505-m dimensions).

The LiDAR system captured up to five returns per pulse and generated point cloud data with average return density of 27.8 points/m^2 (ranging from 2.9 to 44.8 points/m^2) and vertical accuracy RMSE was 0.067 m. The point density was examined using Catalogue command in FUSION. The LiDAR datasets were processed following FUSION commands to obtain more than 150 grid metrics at 20-m spatial resolutions that matches the size of field inventory plots. However, only 36 metrics (Table 1) were found to be important in inventory models when evaluated using Random Forest model selection algorithm. The heights of aboveground pulse returns were also summarized to obtain the grid metrics for canopy cover and vertical strata density as described in Deo et al. 2017.

Inventory modelling

In order to obtain a training data frame consisting of response and predictor variables, SPL and CIR-derived predictors were attached to the field plot measurements in a GIS environment. The SPL point cloud was clipped (e.g., Figure 3) for each plot location and numerous LiDAR metrics describing canopy height distribution, vertical strata density, and canopy cover were produced in FUSION software. The training data frame included more than 100 SPL-derived grid metrics and two CIR-derived metrics (namely, normalized difference vegetation index (NDVI) and near-infrared band). Random Forest (RF) and ordinary least-square multiple linear regression methods were used to formulate the spatial inventory models based on the integration of remotely sensed and field sample data. Spatial inventory models were developed separately for softwood- and hardwood- plots and also combined (Table2).

Before fitting the models, firstly multi-collinear predictors were identified and removed using a multivariate variable screening process based upon QR-matrix decomposition (Deo et al. 2017). Subsequently, a RF-based model selection procedure was applied to obtain a parsimonious set of predictor variables. The set of predictors identified in the RF model selection procedure were further subjected to both forward and backwards elimination methods of stepwise regression to remove statistically insignificantly predictors that did not improve model fits. The optimal sets of predictors thus selected were used separately in multiple-linear regression (MLR) and RF modeling frame works. RF have the ability to rank importance of predictors, and was used to plot importance of predictors for each model. RF also gives an unbiased estimate of mean square error through internal cross-validation, and hence does not require separate validation dataset. In fact, RF creates an ensemble of multiple regression tree models (for continuous variables), each constructed from a bootstrap subsample (about 66%) of the training data frame, and estimates model mean square error (MSE) as the average value of the errors met with the out-of-bag data corresponding to approximately 33% of the plots that are withheld from the bootstrap subsample.

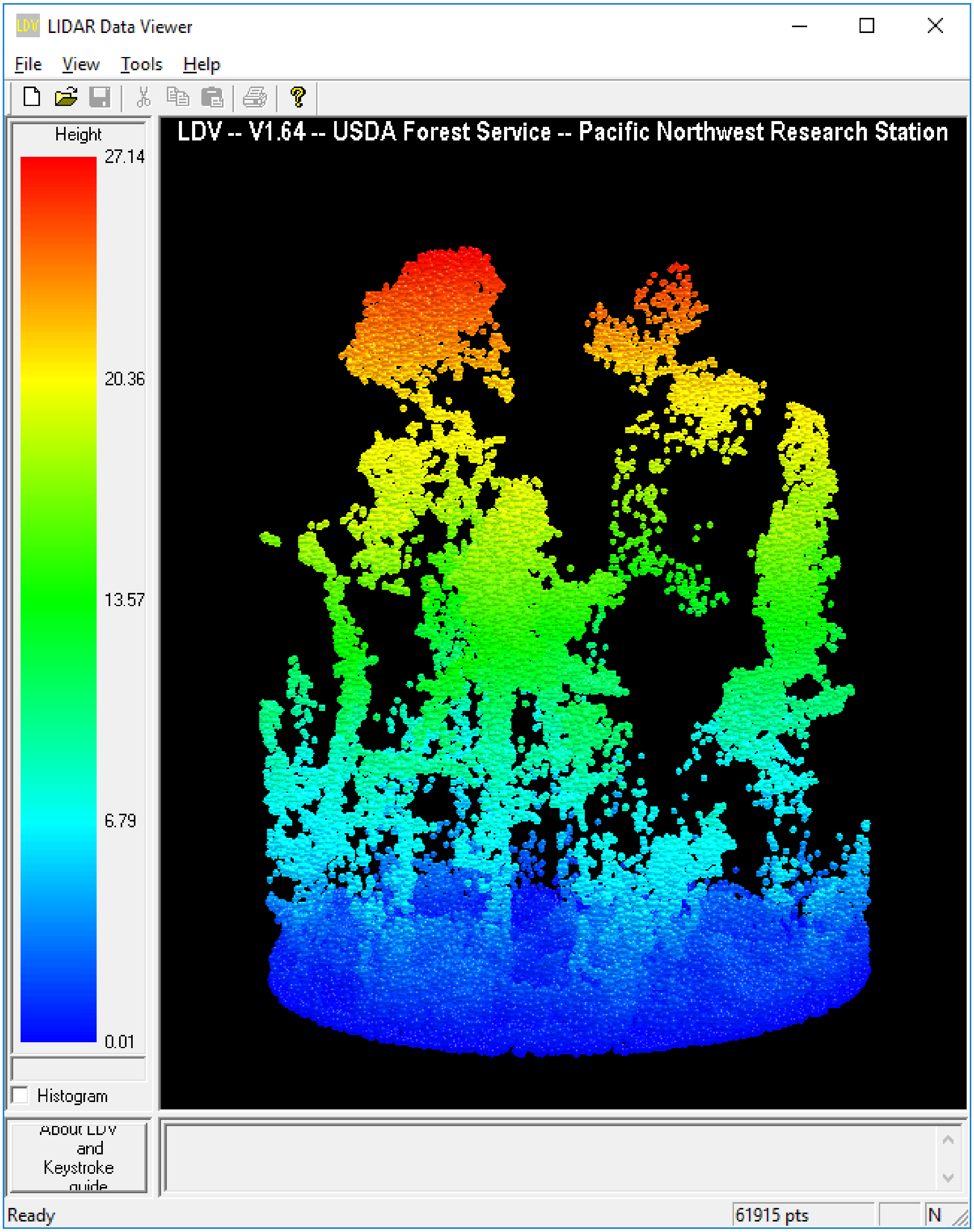


Figure 2. LiDAR point cloud clipped for one of the plots measured in summer 2018.

Finally, the models were extended spatially (wall-to-wall) using the LiDAR-derived grid metrics. Few samples of the inventory metrics are shown in Figure 3.

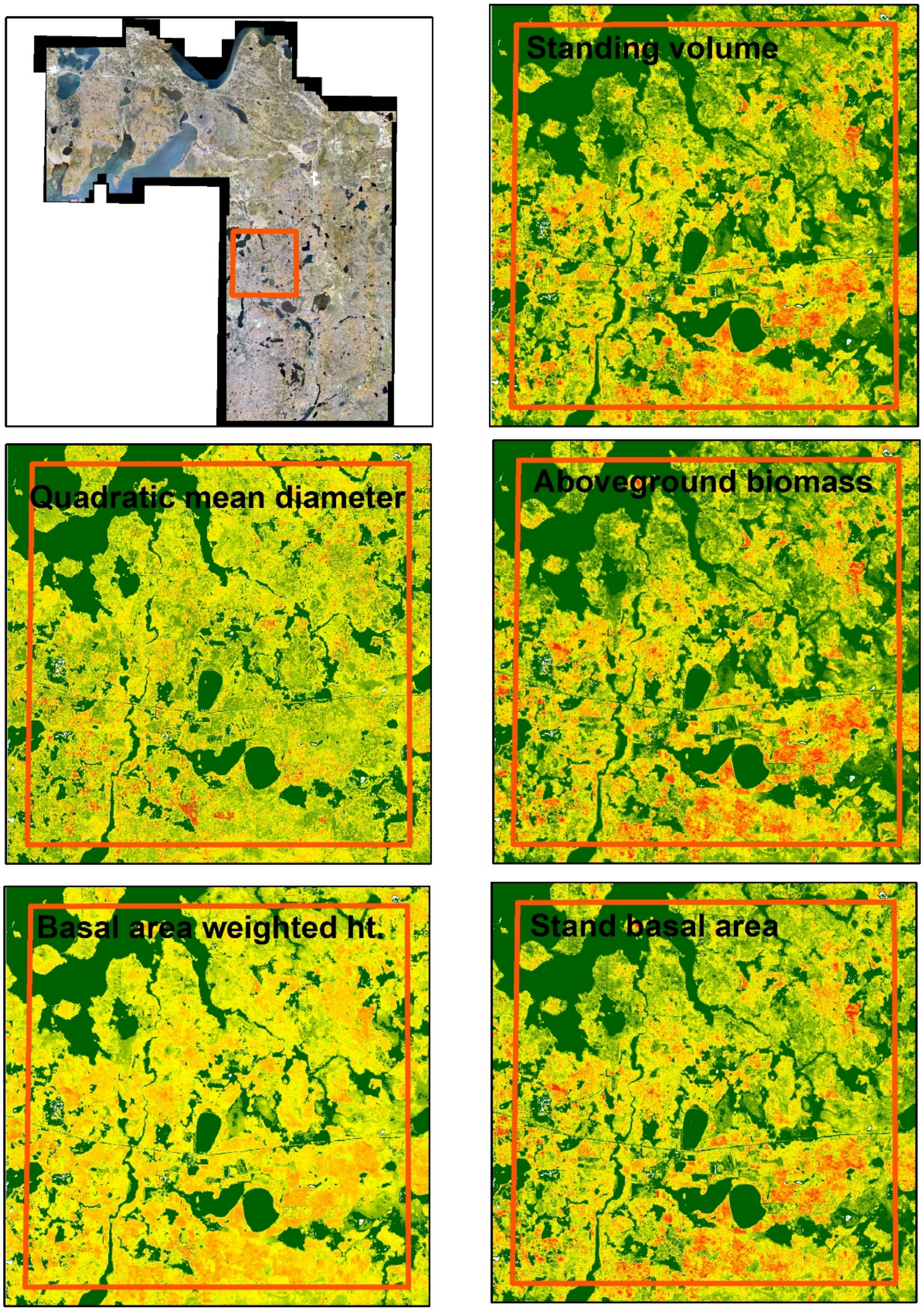


Figure 3. Some sample inventory metrics derived from Single Photon LiDAR in the Cass County.

Tree and stand objects

Tree objects (polygons) were produced for individual tiles in FUSION which employs watershed segmentation algorithm to canopy height model and outputs tree crown boundaries. A height threshold of 7-m was used in the process with an assumption that 7-m tall trees have an average DBH of 5-inch. Each tree objects are attributed with crown area, and locations of maximum elevations. The tree objects of individual tiles are combined into a big shape file for the entire AOI. An example of tree objects along with CIR imagery is shown in Figure 4.

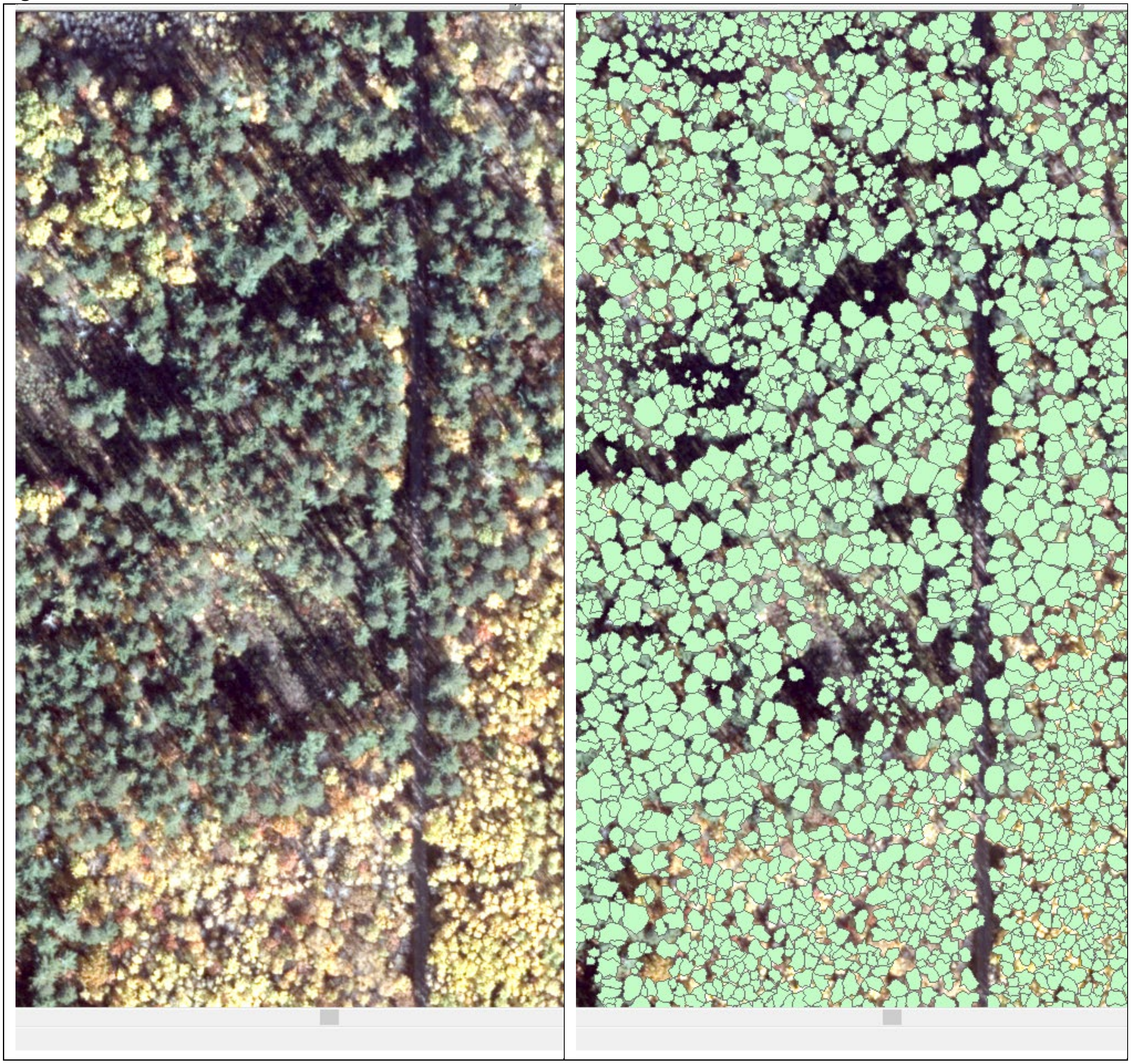


Figure 4. Color-infrared fall imagery (left) and LiDAR-derived tree objects (right).

Stand segments were produced using mean shift segmentation tool in ArcMap. The tool was applied to biomass, volume, basal area weighted height, and maximum height raster's and found that maximum height raster produced better objects compared to others. A minimum area threshold of 5-acre was set in the process of segmentation. An example of stand objects is shown in the Figure 5 below:

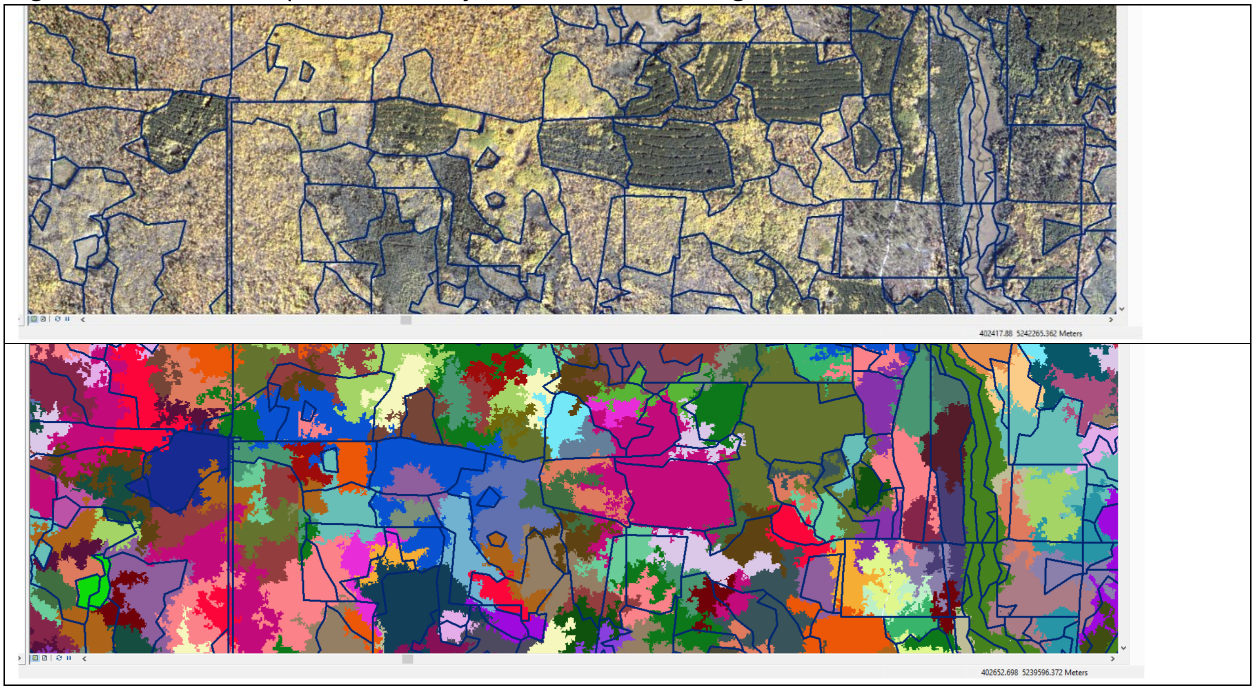


Figure 5. DNR managed FIM stands overlaid on CIR imagery (top) and on the stand segments (below) produced from LiDAR.

Results

- Only 36 LiDAR metrics were found to be useful in the inventory models, and none of the CIR-derived variables were significant in the model.
- Maximum canopy height and basal-area weighted height models provided the best fit statistics while site index and trees per acre models performed poor (Table 2). Further, softwood models were always stronger than hardwood models.
- The site index model can be improved if actual field measurements of tree age are done. In this study, tree age was predicted based on a formulated model depending on DBH and height data from FIA online database.
- Single photon LiDAR did not properly capture deciduous canopy as segmentation of canopy height model did not produce comparable number of tree objects as field counts.
- Stand objects can be reliably produced using high density LiDAR and CIR imagery from full leaf-on condition.

Table 1. Some LiDAR-derived grid metrics that were used in inventory modeling

LiDAR grid metrics	Description
ElevCV	Coefficient of variation of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevIQ	Interquartile range of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevKurtosis	Kurtosis of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevL3	Third L-moment of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevL4	Fourth L-moment of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevLCV	L-moment coefficient of variation of all returns above 15cm, per 20-m by 20-m grid cells
ElevLkurtosis	L-moment kurtosis of all returns above 15cm, per 20-m by 20-m grid cells

ElevLskewness	L-moment skewness of all returns above 15cm, per 20-m by 20-m grid cells
ElevMADmedian	Median of the absolute deviations from the overall median of elevations, per 20-m by 20-m grid cells
ElevMADmode	Mode of the absolute deviations from the overall mode of elevations, per 20-m by 20-m grid cells
ElevMax	Maximum of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevMean	Average of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevMode	Mode of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP01	First percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP05	5th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP10	10th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP20	20th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP30	30th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP80	80th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP90	90th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevP95	95th percentile of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevSD	Standard deviation of elevations of all returns above 15cm, per 20-m by 20-m grid ells
ElevSkewness	Skewness of elevations of all returns above 15cm, per 20-m by 20-m grid cells
ElevVar	Variance of elevations of all returns above 15cm, per 20-m by 20-m grid cells
IntCV	Coefficient of variation of all returns intensity, per 20-m by 20-m grid cells
IntL2	Second L-moment of all returns intensity, per 20-m by 20-m grid cells
IntMax	Maximum intensity per 20-m by 20-m grid cells
IntMin	Minimum intensity per 20-m by 20-m grid cells
Ist_rtns_ab_mean	Total first returns (count) above the mean
Perc_all_returns_above_3m	Percent of all returns above 3m from ground (i.e., all returns above 3m * 100/ total count of all returns); this is proxy metric for canopy cover
Perc_all_returns_above_mode	Percent of all returns above mode elevation of 0-m by 20-m grid cells (i.e., all returns above mode * 100/ total count of all returns)
Stratum1	Proportion of total returns in the vertical interval from ground to 1.37m above ground per 20-m by 20-m grid cells
Stratum2	Proportion of total returns in the vertical interval from 1.37 to 5m above ground per 20-m by 20-m grid cells
Stratum3	Proportion of total returns in the vertical interval from 5 to 10m above ground per 20-m by 20-m grid cells
Stratum4	Proportion of total returns in the vertical interval from 10 to 15m above ground per 20-m by 20-m grid cells
Stratum5	Proportion of total returns in the vertical interval from 15 to 20m above ground per 20-m by 20-m grid cells

Table 2. Fit statistics of SPL-dependent spatial inventory models

	Model fit statistics: R^2 (%) and RMSE			Cross-validation: R^2 (%) and RMSE		
Forest Inventory Attributes	Softwoods	Hardwoods	Combined	Softwoods	Hardwoods	Combined
Maximum height (ft)	83.17 (8.85)	60.8 (10.25)	71.39 (9.97)	80.67 (9.59)	60.11 (10.27)	71.15 (10.01)
Standing Volume (ft^3/ac)	82.12 (789.41)	66.95 (864.59)	67.5 (932.29)	74.94 (957.91)	64.98 (899.44)	66.17 (955.45)
Aboveground biomass (US tons/ac)	80.83 (14.88)	70.59 (17.57)	69.56 (18.23)	79.43 (15.55)	66.86 (18.87)	67.99 (18.69)
Basal area weighted height (ft)	80.25 (8.93)	56.11 (8.73)	67.79 (9.03)	78.96 (9.42)	55.44 (8.99)	67.32 (9.09)
Stand basal area (ft^2/ac)	64.63 (37.48)	58.17 (34.26)	55.82 (37.61)	60.65 (39.97)	55.16 35.65	53.75 (38.63)
Quadratic mean dia. (inch)	71.5 (1.76)	44.31 (1.77)	51.48 (1.90)	65.73 (1.91)	34.44 (1.94)	46.44 (1.99)
Stem density (trees per acre)	29.64 (104.80)	38.54 (90.64)	34.11 (96.54)	31.05 (100.19)	37.58 (91.45)	31.37 (98.63)
Site index (ft)	48.45 (20.80)	27.41 (12.20)	29.9 (17.12)	46.17 (21.75)	26.18 (12.46)	29.39 (17.21)

Forest Cover Type Mapping:

Cover type and stand species composition are crucial stand parameters. They are the "What" in forest inventory. Given their importance, it is a necessity that timely and accurate data be collected. Current forest inventory methods used to collect stand species composition consist of a timber cruise, where given the size of the stand, X number of plots are established (i.e. a 50 acre stand would have 6 plots established). At each plot tree characteristics are recorded (see MN DNR CSA manual for detailed field protocols). Plot data are averaged for the stand and the majority tree species (based on volume) is selected as the cover type for that stand. While the CSA methods have proven effective there are three major limitations: 1) Stand cruising is time consuming and a complete state inventory can take decades, 2) The potential for rare species to be missed due to sampling design, 1) The potential for rare species to be missed due to sampling design, 3) The shape and size of the stand plays a large role in cover type determination. Resource Assessment created a study to investigate if remote

sensing can be used to accurately determine cover type and species composition while also addressing the CSA limitations.
For this study we employed Sentinel-1 radar imagery, Sentinel-2 multi-spectral imagery, Single Photon Lidar (SPL), and Peak Fall Color (PFC) 4 band aerial imagery along with Random forest Classification methods and MN DNR Forest Inventory (FIM), USFS Forest Stands, and 356 20m field collected inventory plots.

Imagery
Sentinel-1 and Sentinel-2 are satellite constellations launched and managed by the European Space Agency. Sentinel-1 consists of two satellites, Sentinel-1A and Sentinel-1B that carry identical C-band synthetic-aperture radars that collect in a single (HH or VV) polarization at a 5x20 meter pixel size. The revisit time is 12 days. Sentinel-2 consists of two satellites, Sentinel-2A and Sentinel-2B that carry identical multi-spectral sensors that collect 12 bands in varying wavelengths at 10 m, 20m, and 60m bands (Table 1). The revisit time is 5 days. For this project Google Earth Engine (GEE) was used to process the Sentinel-1 and Sentinel-2 data. GEE leverages the processing power of unused Google servers to conduct remote sensing analysis. Processes that would weeks to compile and run on a single desktop, take minutes on GEE. Four Sentinel-1 and six Sentinel-2 composites were processed and downloaded from GEE. Composites area created by first selecting a date range, then all images that were collected during the date range are gathered into an image collection, a median filter is then passed over each pixel in the image collection, calculating the median value for that pixel from the all the images in the image collection. The median filter removes speckle from the radar imagery and clouds from the multispectral imagery. Sentinel-1 VV and VH images were downloaded for the following image collection dates: 5/1/2017 – 5/15/2017, 7/1/2017 – 7/15/2017, 9/15/2017 – 10/30/2017, and 5/1/2017 – 10/30/2017.Sentinel-2 bands 2,3,4,5,6,7,8,11, and 12 were downloaded for the following image collection dates: 5/1/2018 – 6/1/2018, 6/10/2017 – 7/15/2017, 6/1/2018 – 7/10/2018, 10/1/2017 – 11/1/2017, 9/1/2018 – 11/1/2018, and 11/1/2017 – 3/31/2018.
SPL data and PFC imagery were collected by Quantum Spatial for the study area (627,722 acres) from September 30, 2017 - October 16, 2017. SPL data were collected using a Leica – SPL100 and were processed and height filtered by Quantum Spatial resulting in ~60 points/meter. For this project Fusion was used to process the SPL data into 92 LiDAR metric.

Sentinel-2 bands	**Central wavelength (nm)**	**Bandwidth (nm)**	**Spatial resolution (m)**
Band 1 – Coastal aerosol	442.7	21	60
Band 2 – Blue	492.4	66	10
Band 3 – Green	559.8	36	10
Band 4 – Red	664.6	31	10
Band 5 – Vegetation red edge	704.1	15	20
Band 6 – Vegetation red edge	740.5	15	20
Band 7 – Vegetation red edge	782.8	20	20
Band 8 – NIR	832.8	106	10
Band 8A – Narrow NIR	864.7	21	20
Band 9 – Water vapour	945.1	20	60
Band 10 – SWIR – Cirrus	1373.5	31	60
Band 11 – SWIR	1613.7	91	20
Band 12 – SWIR	2202.4	175	20

Training Data
MN DNR FIM polygons, USFS forest stand polygons, and 356 20m field collected inventory plots were analyzed for viability to be used as training data for forest cover training data. Early model results revealed that MN DNR FIM polygons and USFS forest stand polygons were too large spatially to be used to train a classifier, while the 356 20m inventory plots were too small. Therefore the PFC imagery along with the MN DNR FIM polygons, USFS

forest stand polygons, and 356 20m field collected inventory plots were used to generate 260 “pure” cover type points. Cover type points were buffered with a 40m buffer to create 260 cover type polygons.

Random Forest Classifier

Mean pixel values for each band of Sentinel-1 and Sentinel-2 imagery were extracted for each cover type polygon using R. SPL Lidar data for each cover type polygon were extracted and the mean value for each LiDAR metric was calculated for each polygon. Resulting mean values from each dataset were compiled into a training dataset consisting of a response, i.e. cover type, and predictor variables, i.e. mean band values. Training data were used for Random forest Classification. A total of 3 Random forest classification models each predicted cover type but with varying input predictor variable were produced: a Sentinel-1 and Sentienl-2 model (SS), a LiDAR only model (L) , and a Sentinel-1, Sentinel-2, and LiDAR model (SSL). Random forest models require variables to be removed or trimmed in order to achieve best model results. To this end a variable importance metric, Mean Decrease in Gini was used to remove variables between model iterations until model accuracies began to decrease. Model accuracies were 78%, 65%, and 78% for the SS, L, and SSL models respectively. The SS and SSL models performed similarly, therefore, the SS model was selected as the final model given the applicability of the model to areas that lack LiDAR.

The SS model was imputed using the caret package in R. The resulting 20m cover map was analyzed for accuracy visually using FIM and FS Veg polygons. It was found that there was confusion between upland and lowland coniferous cover types. To address this issue a hybrid classification scheme was developed that consisted of three additional Random forest cover maps : one that classified just the lowland coniferous cover types, one that classified just the upland coniferous cover types, and one that classified the remaining cover types along with compressed upland and lowland coniferous cover types. The resulting maps were combined using raster calculator in ArcMap to produce a 20m cover type map with the same classes as the SS model. Given that the resulting map was a combination of three Random forest models and independent dataset was needed to assess model accuracy. Ecological Land Classification System (ECS) site classification data are collected by division foresters while in the field. These data are spatial in nature and one of the attributes collected is dominate tree species. Therefore, ECS site classification data were extracted for the cover type mapping area, were filtered to remove those sites that had mixed dominate/no dominate tree species, and were compared with a disturbance layer to ensure no changing classes. The resulting ECS dataset was buffered using a 20m buffer to convert the point locations into polygons. Zonal statistics as table in ArcGIS was used to extract the majority cover type within each ECS polygon. ECS cover type was compared to the map cover type using a confusion matrix to assess map accuracies. The resulting map accuracy was also 78%, however, confusion between upland and lowland conifers has been reduced. It should be noted that there were no water, non-forest, and balsam fir ECS points, therefore accuracies for those cover classes are taken from the Random forest models.

Aspen	Balsam Fir	Black Ash	Black Spruce	Cedar	Jack Pine	Non-Forested	Northern hardwood	Oak	Red Pine	Tamarack	Water	White Pine	White Spruce
0.758	0.533	0.822	0.839	0.722	0.632	0.95	0.808	0.718	0.761	0.794	1	0.617	0.830

Conclusion

The use of passive remote sensing i.e. satellite multispectral imagery, for cover type mapping has never been easier to implement. Cloud based platforms along with machine learning techniques, like Google Earth Engine and Random forest , make processing and training large amounts of satellite data trivial. The low cost of handheld GPS units and the improvement in location accuracies make ground truth data collection easier and more accurate. Therefore the time has never been better to explore the potential for cover mapping at large scales.

ACTIVITY 2: Relating field plot data to remotely sensed data for tree level forest metrics
Description: Extensive plot information will be collected (~300 plots) across the project pilot area to build a strong relationship between ground reference data and high density LiDAR and other imagery. We will use this large dataset to examine the use of Alan Ek's imputation methodology to populate stand inventory with detailed tree attributes pertinent to wildlife and ecological applications. A sample of these plots will also be assessed with very high resolution aerial photography taken from an unmanned aerial system (UAS) provided by partners at Northland Community and Technical College (NCTC) to assess the cost savings for such a data collection method. Additional plots will be collected by County, Forest service, and other DNR Division personnel for in-kind contributions.

Summary Budget Information for Activity 2:

ENRTF Budget:	**$ 167,574**
Amount Spent:	**$ 165,280**
Balance:	**$ 2,294**

Outcome	Completion Date
1. Establish and collect field plot data for use with LiDAR and imagery data (Fig. 1)	September 2017
2. Training and verification of new and existing LiDAR data and imputation on new field data	June 2018
3. Acquisition of very high resolution photography via UAS, including training, verification, and analysis of this imagery with LiDAR and imputation from field data (performed by NCTC)	December 2017

Activity Status as of January 31, 2017:
- No work completed on this activity to date.

Activity Status as of July 31, 2017:
  - 15 plots have been photographed remotely using UAS.
- **Amendment request: July 31, 2017**
  - We over spent for the GPS data recorders by $883.66:
    - Anticipated cost = $30,000, actual cost = $30,883.66, over = ($883.66).
  - I request to move funding as follows:
    - $883.66 from the LiDAR acquisition in Activity 1, line item 20, to the purchase of GPS units in Activity 2, line item 26.
- **Amendment Approved by LCCMR: August 29, 2017**

- **Amendment request (10/12/17):**
  - I request to move funding as follows:
    - $9,215 from Other: DNR's direct and necessary costs in Activity 2, line item 30 to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR 10-16/2017**

Activity Status as of January 31, 2018:
- DNR Interns and staff have collected field data on 170 - 1/10 acre plots.
  - County foresters have collected field data on 21 - 1/10 acre plots.
- UAS aerial imagery, including pix4-D surface models work:
  - 44 plots visited, 37 had imagery acquired, and 7 plots were inaccessible via UAS.

Activity Status as of July 31, 2018:

- 413 out of 500 field plots have been completed.
    - DNR Interns and staff have collected field data on 333 - 1/10 acre plots.
    - County foresters have collected field data on 80 - 1/10 acre plots.
    - 55 1/10 acre plots deemed inaccessible.
    - Remaining 32 1/10 acre plots will be completed by September 1, 2018
- Unmanned Aerial Systems (UAS) work has continued.
    - 44 plots sites have been flown for high resolution aerial imagery.
    - Imagery processed using AgVault and Pix4D software and delivered:
        - Raw imagery in .tiff format.
        - Point Cloud files in .las format
        - Digital Surface Models (DSM) in .tiff format.
        - Digital Terrain Model (DTM) in .tiff format.
        - Ortho-Mosaics in .tiff format
    - All data uploaded to Northland OneDrive for DNR evaluation and use.

    - I request to move funding as follows:
        - $43,940 from Personnel (Wages and Benefits) in Activity 1 line item 12 to Personnel (Wages and Benefits) Activity 2 line item 12.
            - $16,940 from Remote Sensing Analyst – 1 in Activity 1 line item 15 to the Forester in Activity 2, line item 18.
            - $27,000 from Remote Sensing Analyst – 2 in Activity 1 line item 16 to the Interns in Activity 2, line item 19.
- **Amendment Approved by LCCMR 08/07/2018**
- **Amendment request (12/10/18):**
    - I request to move funding as follows:
        - $2,860 from Travel expenses in Minnesota in Activity 2 line item 28 to Travel expenses outside Minnesota (outstate) Activity 1 line item 30.
- **Amendment Approved by LCCMR 01/08/2019**

Activity Status as of December 10, 2018 for the January 31, 2019 update:

- 432 out of 500 field plots have been completed.
    - Field work is complete and no more plots will be field visited.
- Unmanned Aerial Systems (UAS) work has continued.
    - 30 more plots sites have been flown for high resolution aerial imagery.

Final Report Summary:

<u>Field Sampling</u>

The literature supports using a fixed radius plot methodology for developing models relating remotely sensed auxiliary variables to field measurements. Fixed radius is considered an area based approach. Within the 37.2 foot radius of the sample plot used, all trees down to a specified DBH are measured. Other authors have identified this 1/10 acre circular plot as the smallest plot size that corresponds well to a 20m pixel, and reduces edge effects. These studies utilized lower density LiDAR, other plot sizes may be possible with higher density LiDAR, which is under investigation. The literature is unclear if variable radius plots using a 10 BAF prism could be utilized, this is ongoing research in the forestry community, but currently the literature does not support this methodology for sampling. In total sample plots, approximately one mile apart, were allocated in an evenly spaced grid over the 628,000 acres of the study area. Sample plots that fell on privately-owned land, were excluded from the study. Plots on Federal, State, County and Industrial ownerships, with agreements for access, were selected to visit and for data collection. 501 plots met this criteria and were identified as Sample plots to be included in the study.

Using a custom measurement protocol, plot center was monumented with a sub-meter GPS coordinates using a Trimble R2 high-precision GPS. Careful consideration was given to ensuring measurements were made accurately and referenced to the plot's center. Distance and azimuth from plot center to each stem was measured. Tying on-the-ground data to the correct location is important to ensure it's matched to the LiDAR signature. Inventory metrics were measured on each tree within the plot area. Trees >= 5 in DBH were measured for height, diameter at breast height (DBH), as well as crown position, relative to the other trees. Within each plot, we assessed the densities of vegetation in the volume of cylinders of varying heights, encompassing the footprint of the 1/10th acre plot. Ocularly estimated densities of the grasses and forbs, shrubs and tree species were assessed within the strata of 0-2 feet, 2-6 feet, 6-16 feet and 16 feet and higher. Capturing this measurement was an attempt to quantify the amount of vegetation present in understory strata that LiDAR returns may pick up, to better fit to measured field data. All measurements were electronically recorded on a Juniper Mesa tablet using a custom Survey 123 (ESRI), data entry form. Data sheets were uploaded each time the tablet was connected to Wi-Fi. A total of 400 plots were conducted this way at a cost of approximately $40 per plot.

In total there were 356 plots, of the 400 accessible plots, that were forested. Nominal plot densities within the study area were 1 plot per 1,459 acres, which roughly corresponds to 333 plots, which were used for modeling. While in total there were 356 forested plots, 23 plots were reserved for validation exercises. The non-forested plots were used for other processes such as cover type mapping, however they were not used to develop forest inventory metrics.

<u>Model Assisted Yield Estimation and Sampling Size Evaluation</u>

Introduction

Models relating remotely sensed variables to other natural resource variables of interest are developed using either multivariate least squares regression, machine learning (e.g Random Forest), or other model based estimation approach. Once developed models can be leveraged to derive estimates of attributes being measured, in this case forest inventory attributes. While all metrics provide useful information to managers, estimated yield information is often desired. Yield metrics provide crucial information which typically informs a management direction, whether to enhance, harvest, or defer management within a stand. Likewise planners and economist are interested in yield information for resource planning and exploitation.

Models were developed relating LiDAR metrics to field measured plot data using multivariate least squares regression. Upon completion of this effort, the models were applied to other downstream analysis, including yield and other attribute estimation for the area, as well as an evaluation of sampling intensity, and finally a cost benefit analysis. Details of this analysis are detailed.

Methods:

Model Assisted vs. Simple Random Sample

Upon completion of model development, regression models were used to estimate a number of forest yield variables. Using a regression estimator has been termed a model assisted (MA) approach, while using a simple random sample, as in only the field plots, has been termed a simple random sample or SRS approach (Strunk *et al*. 2012). The MA approach may be utilized when the LiDAR based auxiliary variables are measured for the complete study area or entire population being measured (Lohr 1999, Särndal *et al* 2003). Equation 1 and equation 2 represent the total population estimate and the total variance respectively for the MA.

(1) $\widehat{\mathrm{T}}_{\boldsymbol{y}.\mathrm{re}\boldsymbol{g}} = \mathrm{N} * (\widehat{\mathrm{B}}\mu_{\mathrm{x}})$

(2) $SE_{\widehat{\mathrm{T}}_{y.reg}} = \sqrt{N^2 \frac{s^2{}_{reg}}{n}}$

Where $\widehat{\mathrm{T}}_{\mathrm{y.reg}}$ is the regression based estimate of the mean. N is the area sampled (i.e. the forested region of the Cass AOI), $\widehat{\mathrm{B}}$ is the vector of regression coefficients and μ_{x} vector of auxiliary variable means. $\mathrm{SE}_{\widehat{\mathrm{T}}_{\mathrm{y.reg}}}$ is the standard error of the regression model residuals, s^2_{reg} is the variance of regression model residuals. Estimates from the SRS to make comparisons of the total population were also conducted. From Lohr 1999, equation 3 represent the total SRS population estimate, and equation 4 represents the SRS variance.

(3) $$\hat{T}_{\boldsymbol{y}} = N\hat{Y}$$

(4) $$SE[\hat{T}_y] = \sqrt{N^2 \frac{s^2{}_y}{n}}$$

Where $\hat{T}_y$ is the SRS total estimate and $\hat{Y}$ is the mean of the observed sample. Finally the variance of the MA and SRS were compared to assess the impact of the two different estimates. Referred to here as the design effect (DE), equation 5.

(5) $$DE = \frac{SE_{\hat{T}y.reg}}{SE[\hat{T}_y]}$$

Sample Size Considerations

After comparison between the MA and SRS metric estimates and estimating the design effect, the impact of different sample sizes on the regression estimator was conducted. Plots were reduced via random sampling with replacement to desired plot numbers, and the population parameters (i.e inventory attributes) reassessed. The relative precision (RP, similar in calculation to DE) was evaluated against the SRS. This analysis followed the methodology outlined in Strunk *et al.* (2012) which utilized a resampling methodology at different sample sizes. Sample sizes were chosen based on reducing plots, as well as matching sampling intensities found in other studies for comparison. Though those studies are not discussed here.

UAS Imagery acquisition performed by NCTC:

Number of Site Covered in FY19:

38 Sites have drone imagery this year

74 Sites have drone imagery collection total

70 Sites were inaccessible or visited but could not be flown

144 Total Sites have been investigated (Flown/Visited/Inaccessible-some twice) during the project

Services provided:

-Northland owned UAS and camera sensors

-Imagery Processed using AgVault and Pix4D Software

-Operations compliant with FAA Part 107 Regulations

-Compliant with State policies and MN DNR UAS policy.

-Report out and presentation at Society of American Foresters Conference

Database Management:

All data has been uploaded to Northland's OneDrive

Access provided to DNR

Admin Folder contains a spread sheet capturing each flight activity and data collection

Dataset Folder contains plot specific folders containing the 3 types of collection profiles used at each site described in more detail below.

Collection profile of drone imagery data includes (most sites):

-Plot Center photos at various altitudes

-Low overlap, wide areas imagery coverage around site (10-30 Acres)

-High overlap, wide area imagery coverage around site (5-15 Acres)

Product outputs include products that can be integrated into existing GIS and other software:
-All raw imagery
-Point Cloud (.las)
-Ortho-Mosaics (.tiff)
-Digital Surface Model (.tiff)
-Digital Terrain Model (.tiff)

Concept of Operations
In 2016 Minnesota Department of Natural Resources Forestry Division was awarded a grant project through the Legislative-Citizen Commission on Minnesota Resources, Titled "Enhancing Forest Inventory Using Multiple Remote Sensing Technologies". The initial concept for the DNR Forestry LCCMR project was to develop a robust cost-saving methodology for an enhanced stand-based forest inventory, including attributes that relate to forest structure and habitat suitability, using LiDAR, high resolution imagery, and plot data. UAS was one platform to be used to collect the high-resolution imagery. The research area, 500K acres in northern Cass County, contained hundreds of small research plot areas (1/10 acre), that would be inventoried by ground assessment.

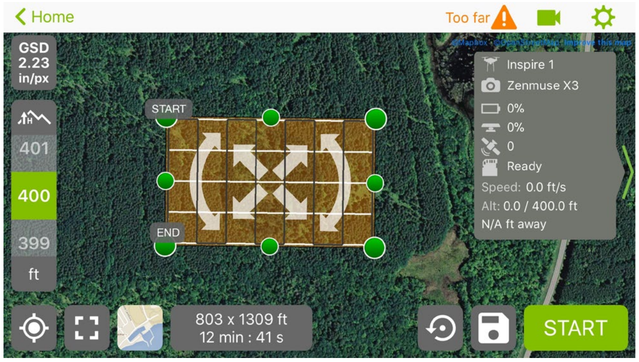
In addition to the ground assessment UAS would collect high resolution imagery over these 1/10 acre research plots. As the project began, ideas were discussed about some of the other recent projects and additional data collection that might be useful. This included expanding the flight profile and collecting imagery of a wider area surrounding the plot. This additional collection would allow for the generation of other products that could provide added value to the project.

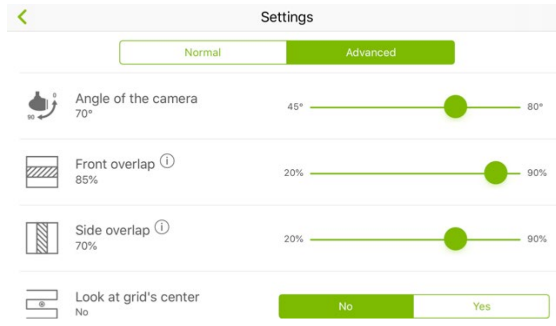
The collection profiles of drone imagery data included (most sites):
-Plot Center Imagery at various altitudes
-Low overlap, wide area imagery coverage around site (10-30 Acres)
-High overlap, wide area imagery coverage around site (5-15 Acres)

Plot Center Imagery was captured at multiple altitudes including: 100ft, 200ft, 300ft, 400ft. Not all areas allowed for capturing imagery at the lower altitudes due to line of sight requirements and the environment surrounding the research plot areas. The entire research plot was captured at an altitude of roughly 200ft. The additional altitudes allowed for viewing of higher resolution imagery, as well as expanded coverage around the research plot location.

Low Overlap profiles provided wide area coverage with a NADIR camera position. Imagery was collected with minimal amounts of overlap. The low overlap imagery allowed for a quick turn around on being able to view the imagery at the field end. Although the product generated in post processing software was not a stitched orthomosaic or point cloud, specific post processing software allows the imagery to be placed in roughly the correct location for quick viewing of the general area. Imagery maintained resolution so the user could zoom in on key areas of interest on the field edge and from the office.

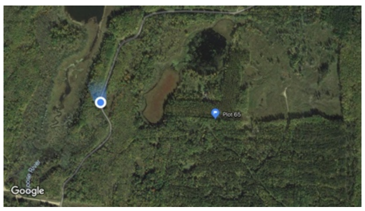
High Overlap profiles provided a smaller area of coverage around the plot area. Imagery was collected at shorter intervals and with a low oblique camera position. This collection profile allowed for post processing imagery into an orthmosiac and point cloud. The point cloud has a similar function as the LIDAR data and can be used with the same tools during post processing analysis.





Challenges

Line of Sight: Per current regulatory requirements the operator of the system must ensure a visual line of sight



with the unmanned aircraft at all times. In the forestry environment this created challenges to the areas that could be flown, the setup for operations, and how much area could be flown.

Corrective Action: Many times, this resulted in evaluating multiple approaches to be able to find a takeoff and landing location within a visual line of sight to the research plot.

Degraded GPS Signal: Different locations with rolling hills and tall trees caused degradation of GPS signals and performance of the aircraft. GPS is not required for the operation of the UAS. However inconsistent GPS caused variation in flight performance, including significant drifting. This must be considered when flying in areas with small clearances due to things such as vegetative cover. Although GPS is not required for flight, it is required for contingency or return home modes if anomalies are experienced causing loss of communication between the ground control station and aircraft.

Corrective Action: Extreme caution should be used and in many cases, flight is not recommended.

Lack of Data Services: Many locations in the project area did not have data service or had very inconsistent data service. The use of maps as a reference background is very common with most UAS control software. Without the data service, maps could not be readily updated in the field.

Corrective Actions: Each application or software program must be evaluated individually. Most applications will allow for caching or storing of maps before going to the field.

Power Management: Power Management is a key element for the success of remote field operations. It begins with pre-field operations and for the UAS, control devices, computers, etc. Power management must also be exercised during all operations.

Corrective Action: A sine wave power inverter and/or small generator are recommended for field operations.

Software Anomalies: Some UAS allow third party developers to engineer 3rd party solutions to controller UAS for specific functions. However, due to the rapid advance in software developments for the UAS and the control software it is fairly common to have mismatches in the software creating anomalies while operating the UAS.

Corrective Action: Take manual control and when properly maintaining line of sight and situational awareness the UAS can be flown back to the return home location and safely landed.

Roads and Access: There are many unpredictable factors that obstruct access to areas throughout the national forest.

Temperature and Precipitation: Most UAS today are referred to as fair weather aircraft. This means they have limitations for many environmental conditions. Most systems are not rated for any amount of precipitation. Temperatures during the Minnesota winters limit their operations as well.

Corrective Action: In some cases, there are no corrective actions for the limitations induced by weather conditions. However, there are accessories like battery warmers that can help alleviate some of the temperature related limitations.

Intrusive Pests:
Mosquitos, gnats, flies
Corrective Action: Insect repellent, body netting, general awareness training of hazards.

Lessons Learned
Homogenous Environments: When processing imagery with a common homogenous surface (i.e. snow, water, vegetation) it was noted that automated stitching software frequently had difficulty in matching the similar georeferenced images to create a mosaic. This commonly resulted in a blank spot or black spot in the mosaic.

Time of day considerations: Since stitching software utilizes similarities of image and georeferencing to create the mosaic, the differing times of day can affect the shadowing of vegetation and terrain. This in turn can negatively affect the stitching of the images.

Corrective Action: It is ideal to collect imagery when the sun is closest to apogee. Try to get all of the imagery for a given subject on the same date and time. Recommend not mixing imagery from different dates and times.

Reliable Repeatable Processes – During the imaging and processing of the DNR Forestry Plots, a couple of reliable repeatable processes were developed.

Actions Taken: Flight planning and imagery capture processes were developed to preplan plots to be flown, define efficient routing to each plot, and team tasks on site; Image capture and processing was also developed to optimize efficiency by immediately downloading data from asset to computer/thumb drive, saving data in established naming convention/data management format while in route to next site, and uploading to server at earliest convenience; Data Flow Process was established to pass completed mosaics to customer via OneDrive, allowing them to pull down finished imagery from that site.

External use/share of data/applications – The imagery obtained thru the DNR has been added to our continuing working relationship with SCSU. Work has begun to incorporate SCSU's SARC to assist in the processing and database management of the imagery. Also, potential use of the Visualization lab at SCSU is currently being discussed.

Actions Taken: Establish Labs/Lesson Plans/Practical Exercises - Utilizing DNR Imagery (RGB, LiDAR), Labs, Lesson Plans, and Practical Exercises are being developed to be integrated into curriculum as real-world examples of applications of geospatial technology; Plot/image sizes optimum – Imagery taken of the forestry plots has assisted in ascertaining optimal sizes for different species of tree plots for evaluation; Use in class – All imagery can be of use in class, but some more than others. One plot provided an excellent educational opportunity when it presented challenge due to a spike in the point cloud causing a severe skew to the image. This presented an opportunity to utilize this example in class to identify the issue with the image, analyze the possible causes, and determine a working solution to the issue bringing the image into a more reasonable, representative state; Imagery types available – The DNR has SPL, Linear, RGB, and LiDAR imagery available for use and processing in conjunction with their LCCMR project. This data has been made available to us to compare and analyze. This creates a wealth of imagery and data that can be utilized and integrated into curriculums.

Extended external reach to other areas/agencies – The lessons learned while working with the DNR have been applied and utilized in other grant projects.

Action Takens: Our work with the BWSR project has been enhanced from workflow processes and data management developed in the DNR project. Also, lessons learned from both projects have been incorporated into the Imagery Analysis and Geospatial Intelligence Analysis curriculum.

ACTIVITY 3: Analyses of the methodology: comparing accuracies, cost, and value
Description: To determine cost savings and identify overall efficiencies and information gains achieved using the above approaches, a simple cost-benefit analysis and a simple accuracy assessment will be conducted to compare traditional inventory methods to our use of high density LiDAR and high resolution imagery using fewer ground reference plots. Additionally, a brief report will be written to discuss our results.

Summary Budget Information for Activity 3: **ENRTF Budget: $ 11,057**
Amount Spent: $ 11,057
Balance: $ 0

Outcome	Completion Date
1. Develop a cost-benefit analysis comparison to forest inventory methods from 2010-2015	June 2018
2. Develop a manual with protocols for practical application	May 2019
3. Submit final reports, including methods of outreach and technology transfer	June 2019

Activity Status as of January 31, 2017:
- No work completed on this activity to date.

Activity Status as of July 31, 2017:
- No work completed on this activity to date.
- **Amendment request (10/12/17):**
  - I request to move funding as follows:
    - $586 from Other: DNR's direct and necessary costs in Activity 3, line item 30 to the contract for segmentation in Activity 1, line item 21.
- **Amendment Approved by LCCMR 10-16/2017**

Activity Status as of January 31, 2018:
- No work completed on this activity to date.

Activity Status as of July 31, 2018:
- Project Manager, Biometrician, Remote Sensing Analysts, and the Forester have begun to develop a cost benefit analysis in several areas:
  - Difference between field collection costs of this fixed radius plot method and the CSA variable radius stand method – no final outcomes yet.
  - The development of our methods has begun to be written but not yet finalized.
  - Presentations of our methods and of the data has occurred as listed below in part V dissemination.

Activity Status as of December 10, 2018 for the January 31, 2019 update:
- No real work was completed on this portion of the project after the July update. This will be completed by the next and final update.

Final Report Summary:

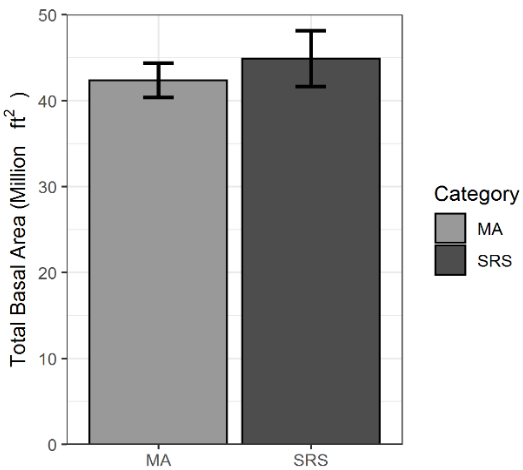
A cost comparison was also conducted, the model assisted (MA), and the business as usual (BAU) approach was evaluated. The BAU was based on the DNR's current cooperative stand assessment protocols. To draw formal comparisons, a number of assumptions were used.

(1) If a stand is less than 10 acres it receives 8 variable radius plots, more than 10 acres it receives 12 variable radius plots.
(2) The cost to survey an acre of forest under the BAU is approximately $6.80
(3) The cost of high density LiDAR acquisition is $0.50 cents an acre.
(4) We estimated the total cost of acquiring one fixed radius plot to be 0.50 cents per acre (this includes the cost of placing the plot, as well as travel times).
(5) An analyst costs $2.00 per acre for the MA approach.

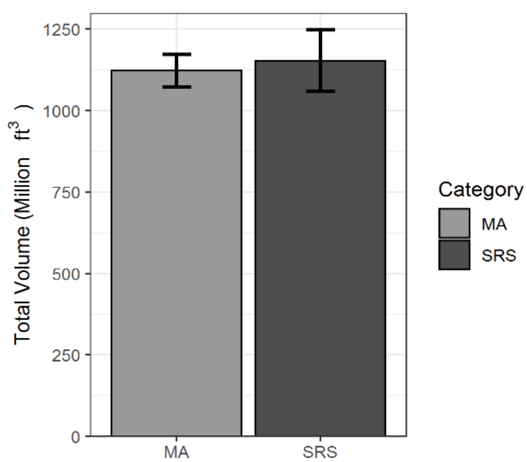
Model Assisted vs. Simple Random Sample

In general we found that the MA approach improved precision over the simple random sample alone.

(a)



(b)



Figures (a; basal area (ft^2)) and (b; volume (ft^3)) demonstrate the increase in precision achieved by the MA compared to the SRS. The MA approach improved the overall precision for all forest inventory metrics from both a yield (basal area, volume, trees per acre, and biomass), as well as non-yield metrics (max height, quadratic mean diameter (QMD), and basal area weighted height (BAWHt)), see table 1 below:

Table 1. LiDAR metrics and associated statistics

Metric	Method	SRS Estimate	CI Half Width	SE (%)	DE (%)	Plots to Match MA
Volume (ft^3)†	SRS	1,152,976,164	94,402,383	4.2	---	1214
Volume (ft^3)†	MA	1,122,885,280	50,028,656	2.3	27	---
AGB (tons)†	SRS	45,761,544,289	3,747,140,631	4.1	---	1246
AGB (tons)†	MA	46,750,439,614	1,960,233,170	2.2	26	---
Stems†	SRS	86,995,482	6,197,488	3.4	---	488
Stems†	MA	93,656,646	5,180,779	3.0	68	---
Basal Area (ft^2)†	SRS	42,367,243	3,265,009	3.7	---	890
Basal Area (ft^2)†	MA	44,896,340	2,020,827	2.4	37	---
QMD (in.)	SRS	9.3	0.3	1.6	---	644
QMD (in.)	MA	9.4	0.2	1.1	51	---

Max Height (ft.)	SRS	68.8	2.0	1.5	---	1114
Max Height (ft.)	MA	68.6	1.1	0.8	29	---
BAWHt (ft.)	SRS	54.2	1.7	1.6	---	990
BAWHt (ft.)	MA	53.7	1.0	1.0	33	---

DE is design effect, CI is confidence interval, SE is standard error
AGB is above ground biomass, QMD is quadratic mean diameter, and BAWHT is basal area weighted height.
† Indicates an area total. All DE estimates are essentially divisions, so only reported under MA.

In all cases it would require additional plots to apply an SRS estimate alone that matched the precision gained under the MA approach (see last column in table 1). The largest gain in precision was in biomass estimation, where it would require 1248 plots to match the MA estimate. As a baseline for comparison estimations were based on using 333 forested plots. Stems showed the least gain from including LiDAR, though still gained precision over plots alone.

Sample Size Considerations

The number of sample plots could be reduced in most cases, and still achieve benefit over the SRS. It was found that in most cases the number of plots could be reduced to approximately 1 plot per 2730 acres, before the MA estimate no longer showed gain over the SRS estimate in terms of precision (See table 2).

Table 2. Relative precision (RP) of MA to SRS estimates at different sample sizes

Plot N	Acres Per Plot	Volume(ft^3)	AGB (tons)	BA (ft^3)	Stems	BAWHT
333	1459	0.27	0.26	0.37	0.68	0.33
296	1641.8	0.58	0.55	0.64	0.69	0.36
237	2050.5	0.66	0.64	0.73	0.79	0.42
178	2730.0	0.8	0.79	0.89	***1***	0.5
119	4083.7	***1.13***	***1.12***	***1.25***	***1.32***	0.69
59	8236.7	***2.21***	***2.33***	***2.45***	***2.79***	***1.21***
30	16198.8	***5.78***	***6.8***	***5.8***	***7.22***	***2.39***

Bold and italic numbers indicate an RP value >1, 1 indicates similar precision from SRS and MA

For Volume, AGB and BA, a sample size of 178 plots was adequate to achieve some gain in precision over the simple random sample. Stems showed parody with the SRS at 237 plots, while BAWHT showed that 119 plots exhibited gain over the SRS.

(c)

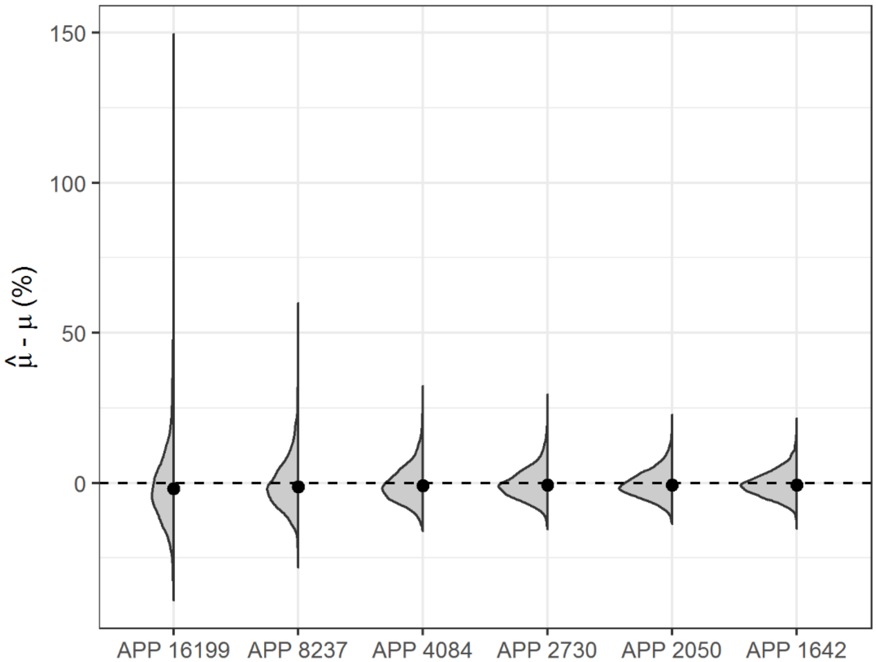


Figure (c) shows the simulated residual distributions at different acres per plot (APP). The distribution of residuals expands as the sample size decreases. Distributions for other metrics showed similar responses.

Final Cost Benefit Analysis

Cost benefit analysis indicates savings from the MA to the BAU approach (see table 3). In most cases under these assumptions the gain from LiDAR could be as much as 55.6% savings in direct costs, with an increase in efficiency of 2.25 times over the BAU approach to forest inventory.

Table 3. Model assisted (MA) vs. business as usual (BAU) approach to forest inventory

	Model Assisted (MA)	**Business as Usual (BAU)***	**MA vs. BAU***
Cost of 126K Acres of Forest Inventory	$380,520	$856,800	55.6 % savings
2.7 Million Acres of State Commercial Forest	$8,154,000	$18,360,000	55.6 % savings
3.7 Million Acres of State Administered Forest	$11,174,000	$25,160,000	55.6 % savings
Acres done per year for $1.4 Million	463,576 ac	205,882 ac	2.25 times more
Years to update complete inventory	8 years	18 years	2.25 times faster

*BAU plot estimates are based on a 10 Basal Area Factor (BAF) methodology for CSA

Comparisons to lower sample sizes was not conducted, however these results indicate the above estimated savings as conservative compared to even further reductions in costs on a per acre basis.

Conclusion:

Using a model assisted approach to forest inventory showed direct gains in precision over a simple random sample alone. In some cases the gain was an almost 100% decrease in the standard error of the estimate. This increase in precision is important for confidence in the inventory within an area. In determining allowable harvest, or other management activities of interest, understanding the availability of a resource is critical to managers across the natural resources spectrum. In this case LiDAR assisted estimation provided gains in confidence through a reduction in the CI half width and reducing the standard error of the estimates of all forest inventory metrics.

While gains in precision are desirable, gains in precision may increase operating costs. In this case a field sample plot was approximately US. $40. When looked at in the context of a statewide acquisition, it may be desirable to reduce sample sizes, or reduce samples over time to minimize cost increases. However a desired sample size must be vetted to insure that gains in precision are still realized. Ultimately, managers must decide an acceptable precision level factoring time and cost considerations.

Within this study it was found that sampling size could be reduced from the 333 plots used for modeling, to a lower sampling intensity and still achieve some gains in precision as measured through the relative precision metric. Models with higher coefficients of variation and low residual standard error were more robust to reductions in the number of plots, versus weaker models. Basal area weighted height (BAWHt) was robust to sample size reductions, maintaining a relative precision gain over the SRS down to approximately 119 plots, or 4083.7 acres per plot. Whereas trees per acre, had a relative precision < 1 down to 237 plots or 2050 acres per plot. Other metrics were able to achieve some gain in relative precision down to 178 plots or 2730 acres per plot. This compares with other studies using lower density LiDAR (Strunk *et al.* 2012) that achieved gains down to 35 plots, but similar acres per plot at 2303.8 acres per plot. Stems in that study showed a similar pattern of being the metric least robust again reduced sample size, having a relative precision >1 at 65 plots or 886 acres per plot. The high density LiDAR allowed for large reductions in plot density relative to other studies, as measured by acres per plot, however more studies are needed in this area.

While it is clear that a reduction in the number of plots is possible and still achieve some gain over the SRS, caution should be exercised. While some gain is achieved errors tend to increase as could be seen by the distribution of residuals (see Figure (c)) as the acres per plot is increased (i.e plot count is reduced). The optimal number of plots may differ for various forest metrics, and determining metrics most germane to forest managers will be critical in determining an optimal sample based on minimizing plot count. Further sampling design may be a critical factor, as different sampling designs may not allow for reductions. This study points to a reduction of approximately 95 plots is possible given our study area, and still achieve gain from an MA approach vs the SRS. In real dollars that equates to approximately $3800 dollars. This savings may not be worth the reduction in precision.

Overall, the MA approach could reduce the overall costs of conducting inventory by approximately 55%, given cost assumptions. The MA approach benefits from taking advantage of economies of scale around technology. This dictates that over time, and with large enough LiDAR acquisitions the cost of acquiring LiDAR data will remain similar or possibly decrease. While boots on the ground, inevitably will increase in costs, as price of labor increases. Analysts are the estimated largest portion of the expense at approximately $2.00 per acre for the MA approach. This cost however can also be kept in check by automation. Overall the MA approach points to the possibility of major immediate cost and time reductions to the DNR to complete a statewide inventory of the forest lands it administers in eight years. Long term the MA approach can benefit from advances in technology that will likely control costs, and possibly improve methodology and estimation precision.

V. DISSEMINATION:
Description: we will conduct an analysis of the newly acquired high density LiDAR and any high resolution aerial photography with the 300 newly acquired field plots and whatever existing plot data is easily accessed and statistically/spatially accurate. If possible, all of the newly acquired data will be provided free to the public and will be hosted through the most effective acceptable internet website (e.g., http://www.mngeo.state.mn.us/, https://gisdata.mn.gov/). A brief report will be prepared to summarize the project research and development, including a condensed version of an accuracy assessment.

Activity Status as of January 31, 2017:
- No work completed on this activity to date.

Activity Status as of July 31, 2017:
- No work completed on this activity to date.

Activity Status as of January 31, 2018:
- No work completed on this activity to date.

Activity Status as of July 31, 2018:
- Several presentation have been given to the following groups:
  - DNR Forestry Supervisors and Management team.
  - Minnesota Forest Industry (MFI)
  - Minnesota Forest Resources Council (MFRC)
  - Society of American Foresters (SAF)
  - ASPRS Remote Sensing community

Project Status as of January 31, 2019:
- Several presentation have been given to the following groups:
  - Presented to more than 10 different stakeholder groups, regional and national conferences, and internal DNR meetings on the preliminary results from the UMN, field data, and the goals for the near future
  - DNR Forestry Area Staff.
  - Minnesota Forest Resources Council (MFRC)

Final Report Summary:
Analyses of the newly acquired high density LiDAR has resulted in several forest inventory metrics and cover type models created, utilizing more than 300 newly acquired field forest inventory plots with over 9,000 trees measured. All of the LiDAR and derived products will be provided free to the public and will be hosted as LiDAR point cloud files on an ftp server with other state LiDAR data holdings, as well as several web mapping services produced by the MNDNR and accessible via the Minnesota Geospatial Data Commons (https://gisdata.mn.gov/). The project team from DNR Resource Assessment has already and will continue to deliver the results of this project in a number of other ways, including presentations at regional and national conferences in the fields of forestry, geographic information systems, and remote sensing, meetings and conference calls to share information directly with stakeholder groups, as well as the eventual submission of peer-reviewed manuscripts to scientific journals. In addition, DNR Resource Assessment has created a webpage that will be a central repository for all of the methods, reports, and links to access data.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 260,170	DNR project manager: 12% FTE for 3-yrs. ($30,673), remote sensing analyst 1: 30% FTE for 3-yrs. ($77,060) remote sensing analyst 2: 20% for 3-yrs. ($52,400), biometrician: 4% FTE for 3-yrs. ($10,037), forester: 12% FTE for 3-yrs. ($30,000) and 6 interns: 2 FTE for 1-yr. ($60,000).
Professional/Technical/Service Contracts:	$ 459,988	Acquisition of remotely sensed data, high density LiDAR data & possibly aerial photography, over ~500,000 acres in northern Cass County ($371,409); technical contract with UofM to segment the remote sensing data into stands ($77,819); technical contract with Northland Technical College to collect high resolution imagery using Unmanned Aerial Systems ($10,760)
Equipment/Tools/Supplies:		
Capital Expenditures over $5,000:	$ 45,205	Purchase 3-survey grade GPS units to tie field plot data to LiDAR data ($30,884), purchase developer eCognition software for LiDAR classification ($14,321)
Travel Expenses in MN: *	$ 30,755	Activity1 ($0), meetings and outreach for project manager and remote sensing analysts; Activity2 ($28,136), forester and interns field work; Activity3 ($2,618), meetings and outreach for project manager and biometrician.
TOTAL ENRTF BUDGET:	**$ 796,117**	

Explanation of Use of Classified Staff: This funding will be used to pay project-associated costs for classified and unclassified staff paid with special project funds. Each year these positions are assigned work based on the particular combination of soft funding available to address DNR Program activities. These classified positions (Project Manager, Remote Sensing Analysts, Biometrician, and Forester) are all currently available within RA and paid through independently funded project assignments. The Biometrician position and one Remote Sensing Analyst position are currently vacant and soon to be filled. Resource Assessment (RA) is a government enterprise within the DNR Division of Forestry per statute 89.421. This LCCMR project and the LCCMR funding structure are both well suited to enhance RA's soft funded project based business model, staffing structure, professional expertise and future forest inventory service potential.

Explanation of Capital Expenditures Greater Than $5,000: For accurate results, survey grade GPS's are critical in connecting field plots to high density LiDAR. eCognition software is a major component to accurately and successfully segment and classify aerial imagery and LiDAR data.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: Professional staff: ~0.8 average FTE's per year over the 3-year grant period (~2.4 FTE's total), temporary forest interns: ~1.15 FTE for 1-year, total number of FTE's funded by this grant is ~3.5.

*Overall travel expenses changed significantly for both professional outreach and field work; the elimination of meetings and outreach for the Project Manager, Remote Sensing Analysts, and Biometrician resulted in a $7,000 reduction, and the reduction in field plots decreased overall field assessment work from $57,000 to $33,400. The total reduction in travel expenses is $30,600. Total travel expenses are all field work for the Forestry interns and the Forester training and assessing the data collection

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
Cass County	$30,000	$30,000	Contribution to LiDAR acquisition.
Cass County	$10,000	$10,000	In-kind inventory and QA field work.
Chippewa National Forest	$120,000	$119,878	In-kind inventory and QA field work.
Fish & Wildlife Service	$20,000	$20,000	In-kind sub-meter satellite imagery + contribution for LiDAR data.
State			
	$3,677	$3,599.24	Contribution to LiDAR acquisition.
TOTAL OTHER FUNDS:	**$183,677**	**$183,477.24**	

VII. PROJECT STRATEGY:

A. Project Partners: Collaborators include the University of Minnesota, providing expertise, resources, and staff time (professors Alan Ek, Joe Knight, and Michael Falkowski); U.S. Fish & Wildlife Service providing free sub-meter satellite imagery and feedback; Chippewa National Forest and Cass County Land Department will also be giving in-kind and financial support; Northland Community and Technical College will provide high resolution imagery via UAV; and the Minnesota Forest Resources Council will be providing a venue for information dissemination and feedback; Ronald McRoberts from the USFS Northern Research Station will also provide analytical and feedback support.

B. Project Impact and Long-term Strategy: The long-term strategy is to benefit Minnesota's natural resource stakeholders by developing a revolutionary, enhanced forest inventory method at a significantly reduced cost that can be used across all ownerships. This project will enable Minnesota to continue its leadership role of using emerging technologies to collect and maintain modern and valuable information for a plethora of natural resource management objectives. It also coincides well with other long-term initiatives, such as the permanent plots being established by DNR project partners in the 2016 ENRTF proposal; *A statewide Monitoring Network for Changing Habitats in Minnesota.*

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
General Fund (1000) and Forest Management Investment Account (2113): AC1:23402-FOR Forest Inventory Direct Activity Charge ($407,415), Areas CSA Inventory General Operations & Admin Allocation ($309,432), FOR Resource	July 1, 2014 – June 30, 2015	$ 1,026,848

Assessment CSA Inventory amount; AC1: FY15=23700 ($310,000)		
General Fund (1000) and Forest Management Investment Account (2113): AC1:23402-FOR Forest Inventory Direct Activity Charge ($382,290), Areas CSA Inventory General Operations & Admin Allocation ($297,039), FOR Resource Assessment CSA Inventory amount; AC1: FY14=23700 ($238,566)	July 1, 2013 – June 30, 2014	$ 917,896
General Fund (1000) and Forest Management Investment Account (2113): AC1:23402-FOR Forest Inventory Direct Activity Charge ($170,024), Areas CSA Inventory General Operations & Admin Allocation ($130,918), FOR Resource Assessment CSA Inventory amount; AC1: FY13=23654 ($233,058)	July 1, 2012 – June 30, 2013	$ 534,000

Environment and Natural Resources Trust Fund
M.L. 2016 Project Budget

Project Title: Development of Innovative Cost Saving Methodology for Forest Inventory
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 03o
Project Manager: Dennis Kepler
Organization: Department of Natural Resources, Division of Forestry, Resource Assessment
M.L. 2016 ENRTF Appropriation: $800,000
Project Length and Completion Date: 3 Years, June 30, 2019
Date of Report: June 30, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 01/08/2019	Amount Spent	Activity 1 Balance	Revised Activity 2 Budget 01/08/2019	Amount Spent	Activity 2 Balance	Revised Activity 3 Budget 10/12/2017	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE	
BUDGET ITEM	*Acquisition, processing, and utilization of*			*Relating field plot data to remotely sensed*			*Analyses of the methodology: comparing*					
Personnel (Wages and Benefits)	$154,960	$153,613	$1,347	$95,500	$95,499	$1	$11,057	$11,057	$0	$261,517	$1,347	**$260,170**
Project Manager: $32,012 (76% salary, 24% benefits); Ave. 8% FTE for three years.												
Remote Sensing Analyst - 1: $94,000 (70% salary, 30% benefits); Ave. 36% FTE for three years.												
Remote Sensing Analyst - 2: $79,400 (70% salary, 30% benefits); Ave. 22% FTE for three years.												
Biometrician: $10,000 (75% salary, 25% benefits) Ave. 3% FTE for three years												
Forester: $13,000 (70% salary, 30% benefits) Ave. 4% FTE for three years.												
6 Interns for ~3 months: $33,00 (93% salary, 7% benefits); 1.15 FTE for one year.												
Professional/Technical/Service Contracts												
Contract for high density LiDAR acquisition on ~ 500K acres in Northern Cass County - TBD through competitive bid contract.	$371,409	$371,409	$0							$371,409	$0	
Contract for Segmentation of LiDAR data using eCognitions software with the University of Minnesota's remote sensing lab.	$77,819	$77,819	$0							$77,819	$0	
Contract for high resolution imagery of a sample number of field plots using an Unmanned Aerial system with Northland Technical College.				$10,650	$10,760	-$110				$10,650	-$110	
Equipment/Tools/Supplies												
Capital Expenditures Over $5,000												
Purchase desktop eCognition software with one (1) license.	$14,321	$14,321	$0							$14,321	$0	
Purchase three (3) survey grade GPS units to be used by field crews to accurately tie the field data to the high density LiDAR data.				$30,884	$30,884	$0				$30,884	$0	
Travel expenses in Minnesota												
In-state travel expenses: fleet ($4,160), lodging ($17,000), and meals ($12,240) for interns & Forester field reconnaissance.				$30,540	$28,136	$2,404				$30,540	$2,404	
Travel expenses outside Minnesota (outstate)												
Out-state travel expenses: registration ($1,200) Shuttle/Taxi ($50), lodging ($750), and meals ($360) Airfare ($500) for attending conferences. The use of these funds is for out of state travel and conference attendance to present project findings.	$2,860	$2,618	$242	$0	$0	$0				$2,860	$242	
COLUMN TOTAL	**$621,369**	**$619,781**	**$1,588**	**$167,574**	**$165,280**	**$2,294**	**$11,057**	**$11,057**	**$0**	**$800,000**	**$3,883**	