MICHIGAN STATE UNIVERSITY

Remote Sensing Technology for Improved Forest Carbon Inventorying

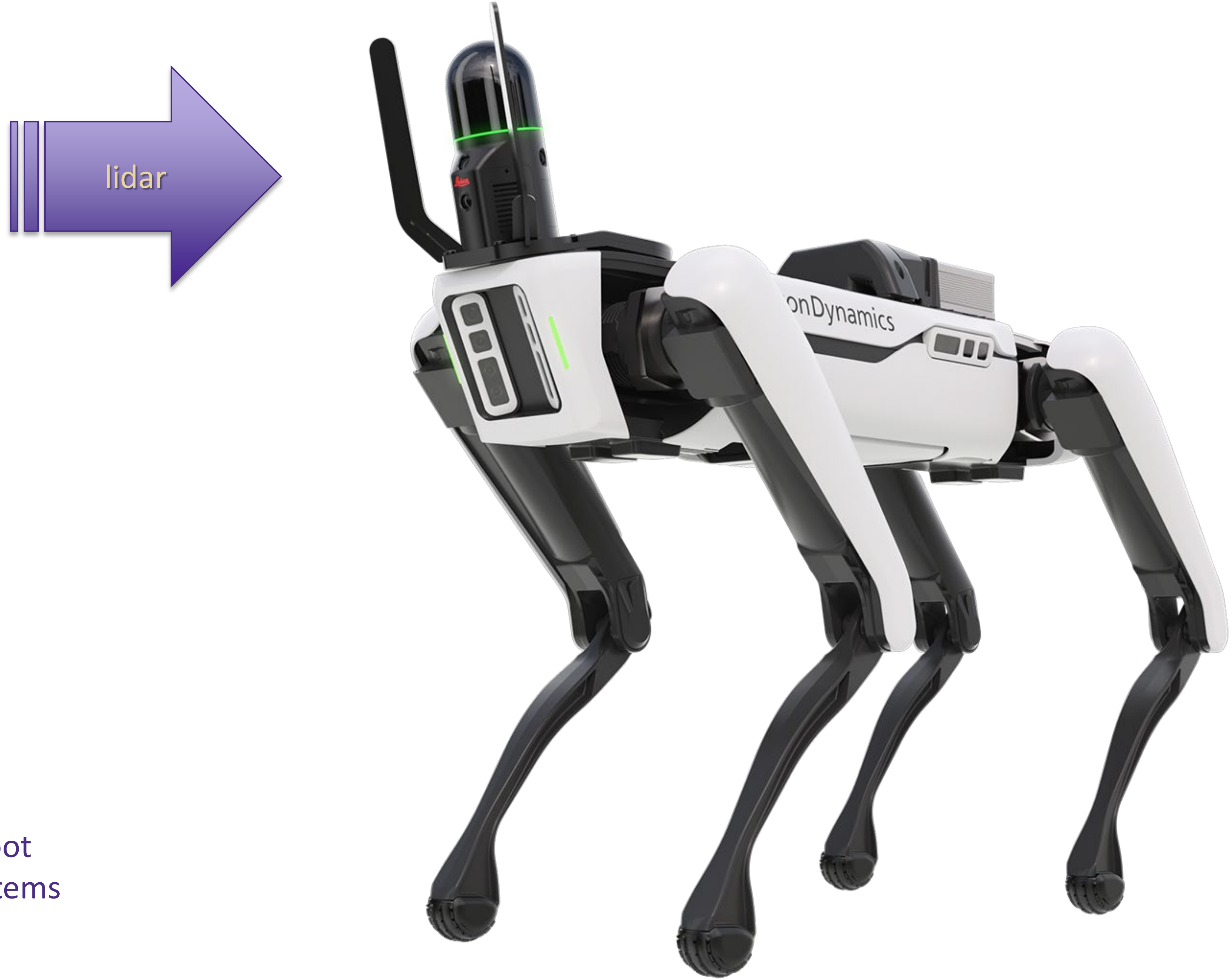
L. Monika Moskal

Professor of Remote Sensing
Director of Precision Forestry Cooperative
Associate Director of Research Programs in the School of Environmental and Forest Sciences

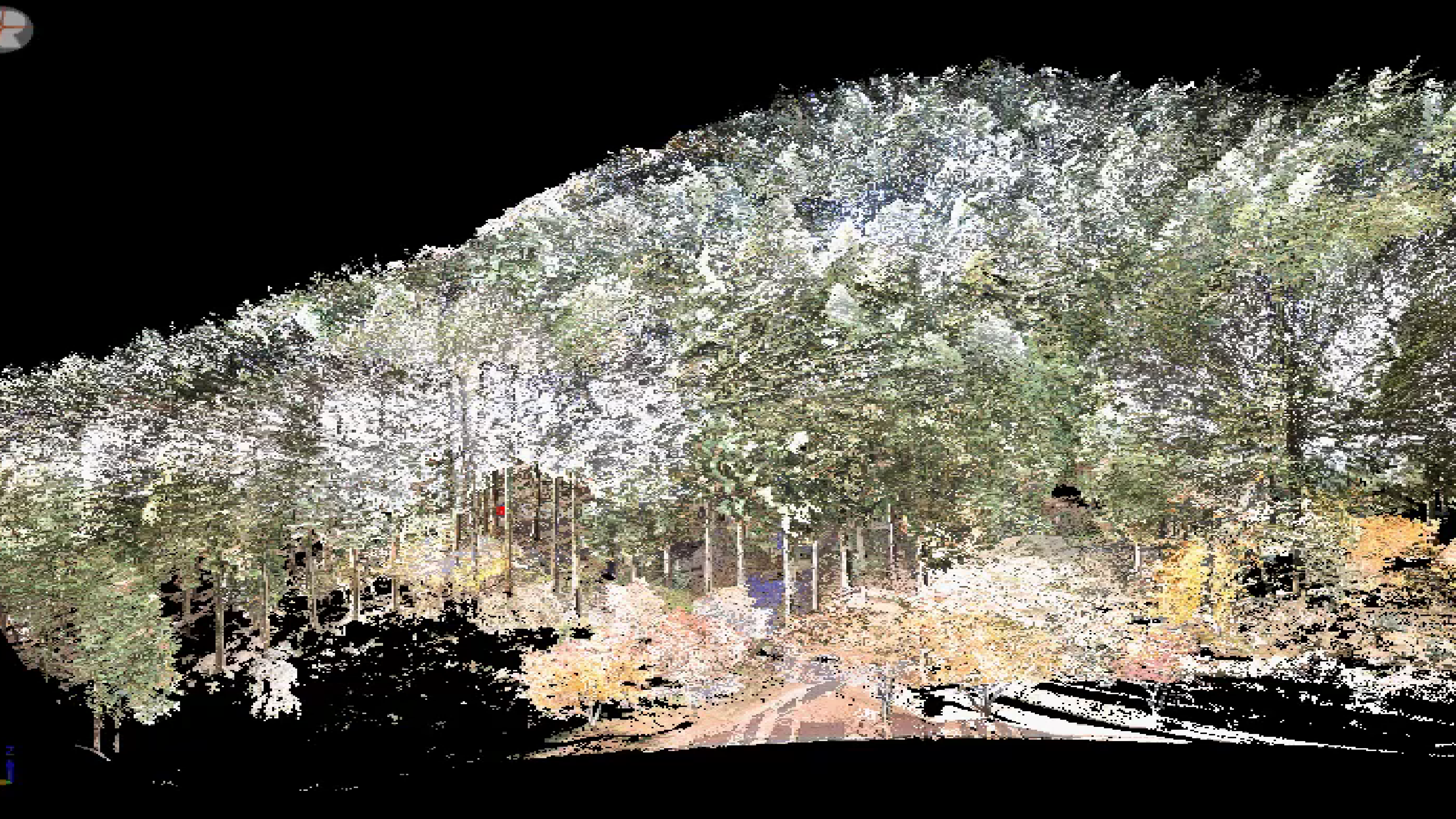
SCHOOL OF ENVIRONMENTAL AND FOREST SCIENCES
UNIVERSITY of WASHINGTON
College of the Environment

RSGAL Remote Sensing & Geospatial Analysis Laboratory
PFC PRECISION Forestry Cooperative

Credits: Intuitive Robots shows off Boston Dynamics Spot the robot dog scans a forest with a Leica Geosystems payload
YouTube: https://www.youtube.com/watch?v=s3zWXRLaAFw&list=PPSV



Boston Dynamics Spot
with a Leica Geosystems
BLK ARC payload

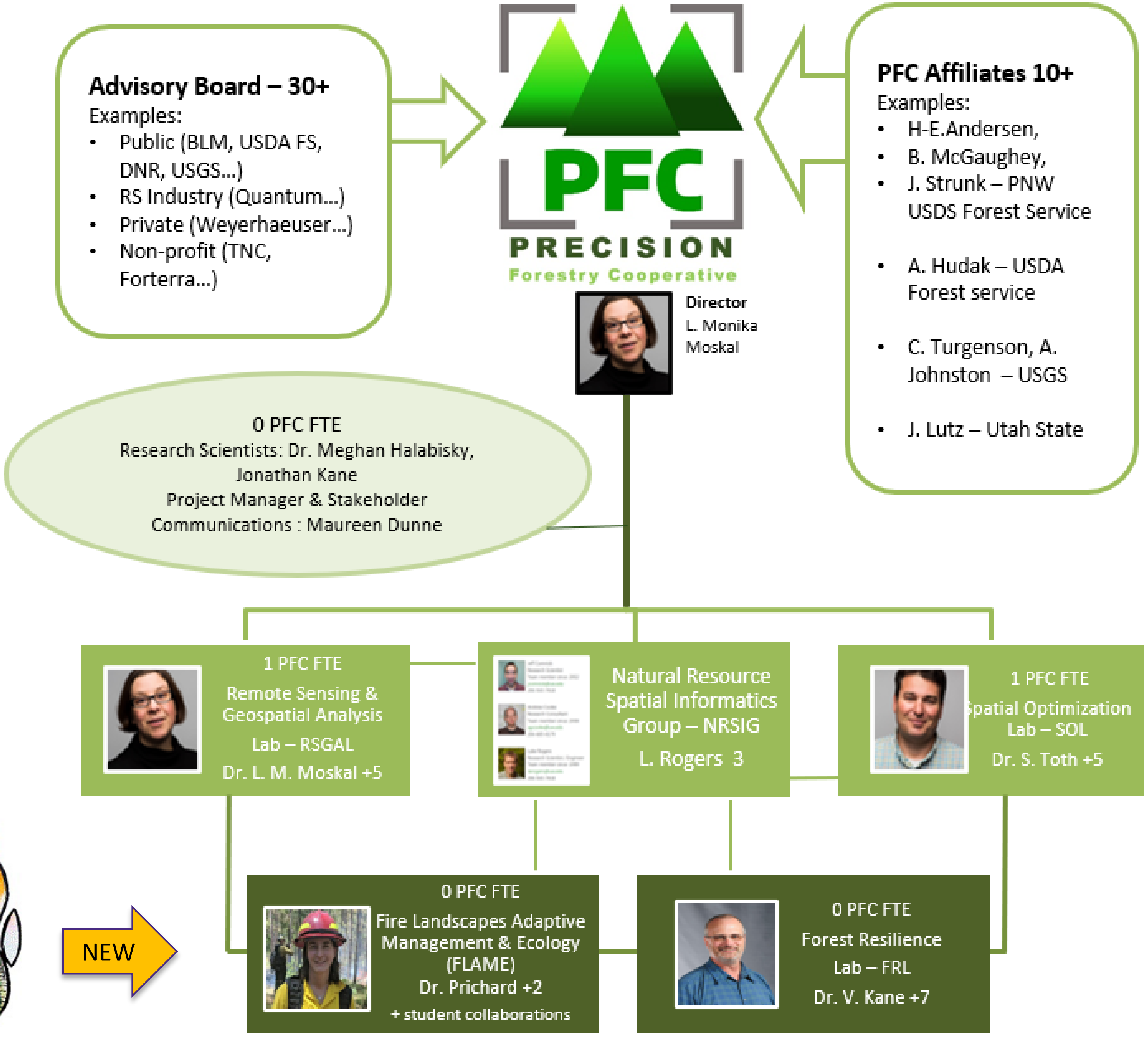


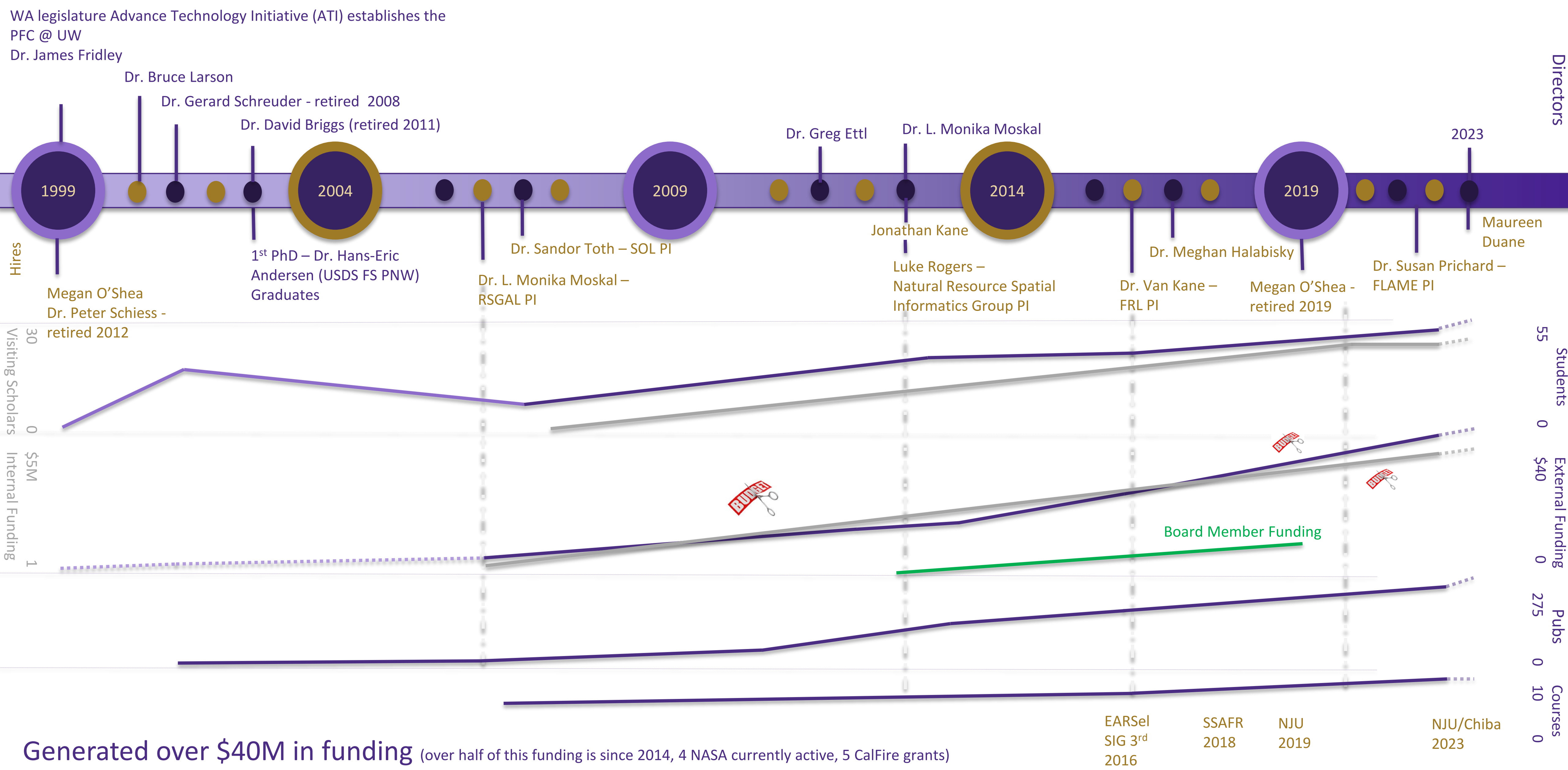
PFC
PRECISION
Forestry Cooperative

UW/SEFS/Precision Forestry Cooperative

Mission: *development of advanced technology solutions to improve the quality & reliability of information needed for planning, implementation, monitoring and conservation of ecological resources, to ensure sustainable landscape outcomes on forests, wetlands, meadows and wildlife habitats.*

Vision*: engagement with technology, environmental, public & non-profit sectors in fulfillment of our mission.*





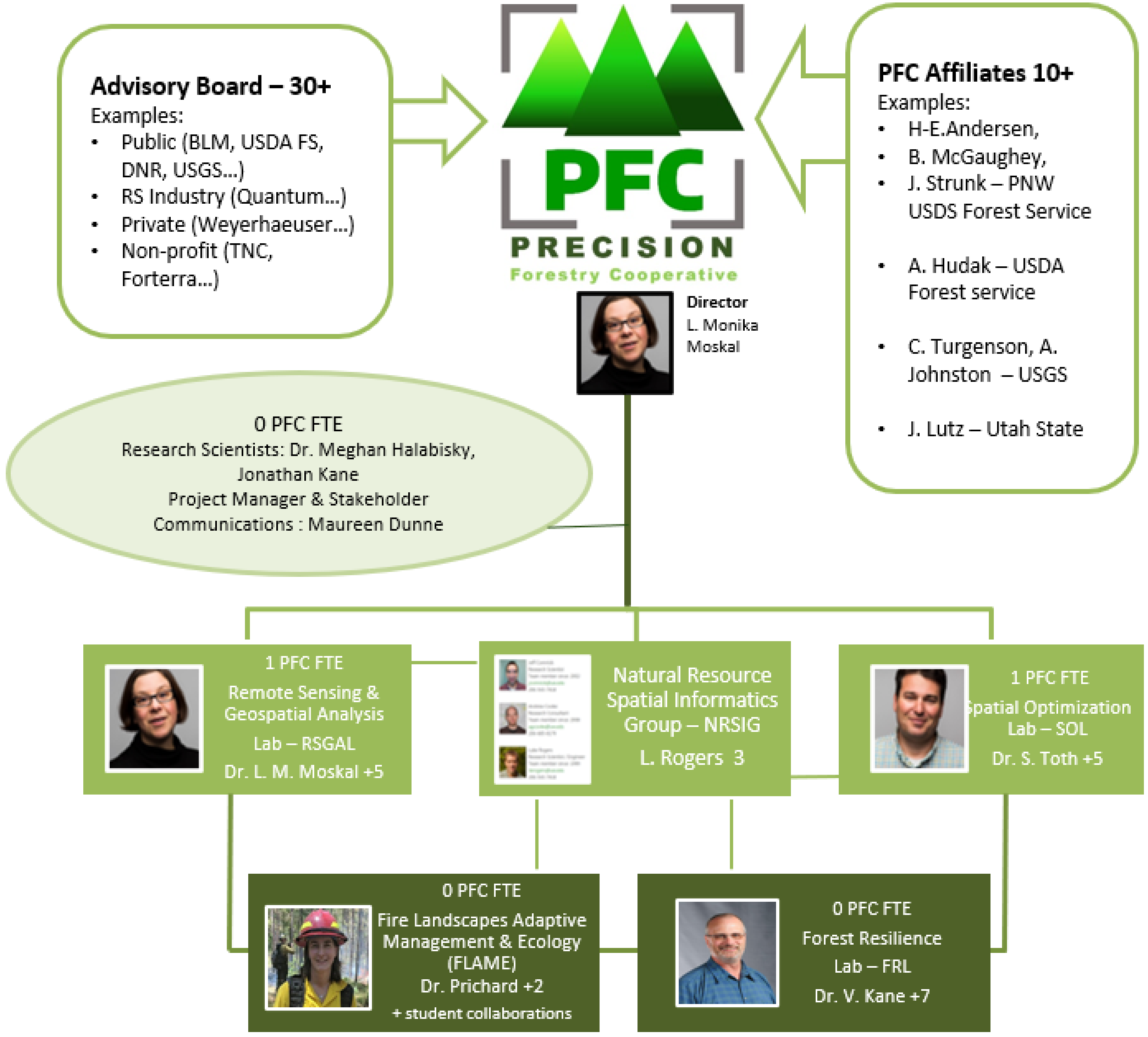
Generated over $40M in funding (over half of this funding is since 2014, 4 NASA currently active, 5 CalFire grants)

Published 250 papers (+many reports)

Teaching extending beyond classroom

Over 55 students with ~90% job placement (95% placement for 2021-2023); we aim for having every student funded

PFC Labs



Advisory Board – 30+
Examples:
• Public (BLM, USDA FS, DNR, USGS...)
• RS Industry (Quantum...)
• Private (Weyerhaeuser...)
• Non-profit (TNC, Forterra...)
PFC
PRECISION
Forestry Cooperative
Director
L. Monika Moskal
PFC Affiliates 10+
Examples:
• H-E.Andersen,
• B. McGaughey,
• J. Strunk – PNW USDS Forest Service
• A. Hudak – USDA Forest service
• C. Turgenson, A. Johnston – USGS
• J. Lutz – Utah State
0 PFC FTE
Research Scientists: Dr. Meghan Halabisky, Jonathan Kane
Project Manager & Stakeholder Communications : Maureen Dunne
1 PFC FTE
Remote Sensing & Geospatial Analysis Lab – RSGAL
Dr. L. M. Moskal +5
Natural Resource Spatial Informatics Group – NRSIG
L. Rogers 3
1 PFC FTE
Spatial Optimization Lab – SOL
Dr. S. Toth +5
0 PFC FTE
Fire Landscapes Adaptive Management & Ecology (FLAME)
Dr. Prichard +2
+ student collaborations
0 PFC FTE
Forest Resilience Lab – FRL
Dr. V. Kane +7

PFC: Natural Resource Spatial Informatics Group (NRSIG)

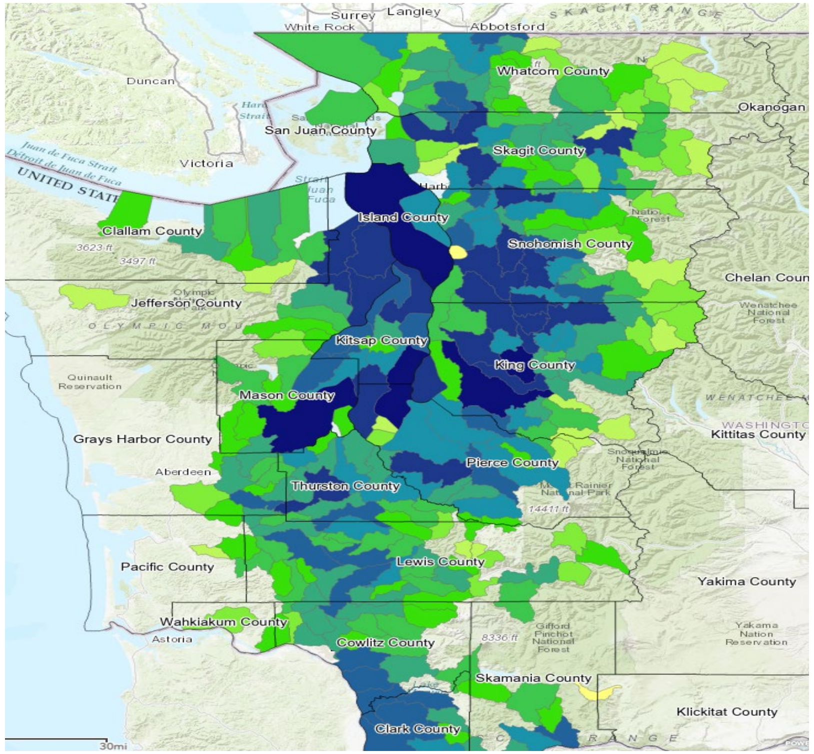
Table 16: Accuracies of Mashel models in the Pilot Study

	Mashel Pilot Study Results	
	r^2	RMSE
Basal Area	0.72	63.12
Density	0.46	68.96
Diameter	0.70	2.77

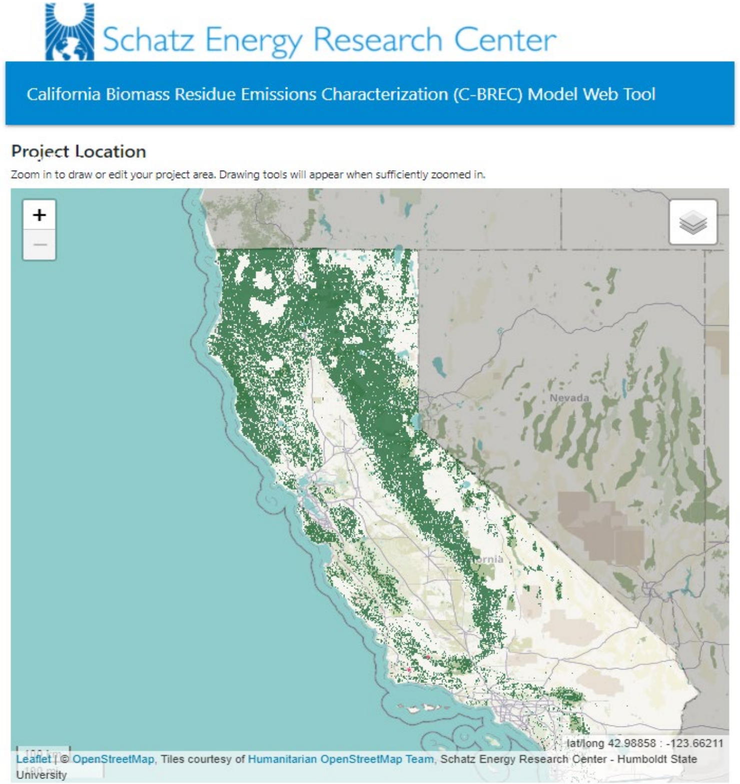
Table 17: Accuracies of the Mashel Models, and new OESF models, predicting full OESF plots

	Existing Mashel Models		Refit Mashel Models		Adapted Mashel Models		New OESF Models	
	r^2	RMSE	r^2	RMSE	r^2	RMSE	r^2	RMSE
Basal Area	0.32	59.50	0.36	57.90	0.44	54.16	0.61	44.87
Density	0.44	57.40	0.53	52.58	0.53	52.67	0.71	41.51
Diameter	0.70	2.28	0.77	2.02	0.76	2.05	0.86	1.55

Riparian assessments and modeling/transferability



Where to 'grow' maple syrup in WA



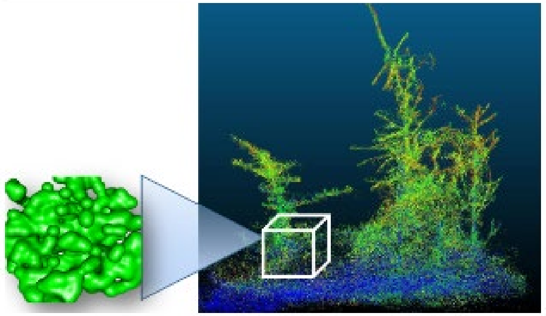
Biomass Web collaboration with Humbolt State

NRSIG has been working with LiDAR since 2000; operationalization of PFC (and other) research, generated close to $1million in external funding in this biennium, participated in several workshops, published numerous reports, ask them about collaboration with Humboldt State

Latest LiDAR related publication:

Cooke, Andrew G, and Warren Devine. 2020. Extensive Riparian Vegetation Monitoring, Model Transferability Testing. Seattle, WA: University of Washington. [Agreement No. 93-098916 (1)]

PFC: Fire • Landscapes • Adaptive Management • Ecology (FLAME)



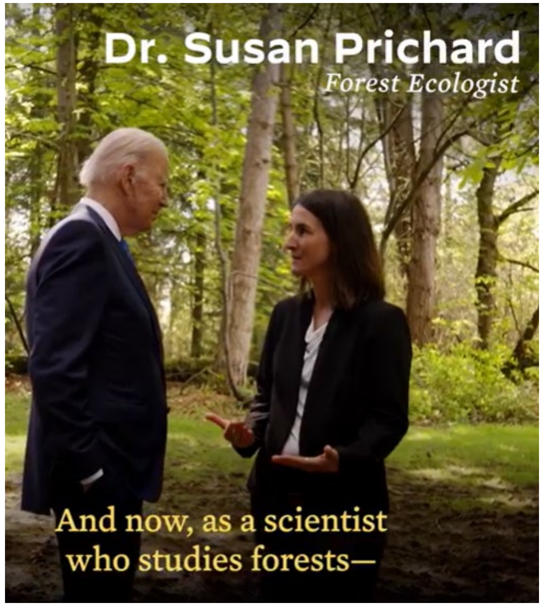
3D fuel characterization for evaluating physics-based fire behavior, fire effects, and smoke models on US Department of Defense military lands (SERDP Project RC19-C1-1064)

3D fuels project

ADAPTING WESTERN FORESTS TO CLIMATE CHANGE

In an Invited Feature, Susan Prichard, Paul Hessburg and Keala Hagmann recently led a large synthesis of the existing science on the need for adaptive forest management across fire-prone forest ecosystems of the western United States. The synthesis was created to address ongoing uncertainty about the extent of fire exclusion, forest departures, and science-based adaptation strategies. The project received broad support, including funding from the California Department of Forestry and Fire Protection (CALFIRE), Ecological Restoration Institute, Washington State Department of Natural Resources, US Forest Service Pacific Northwest and Pacific Southwest Research Stations, The Nature Conservancy, The Wilderness Society, and the US Fish and Wildlife Service.

Forest adaptation to climate change project



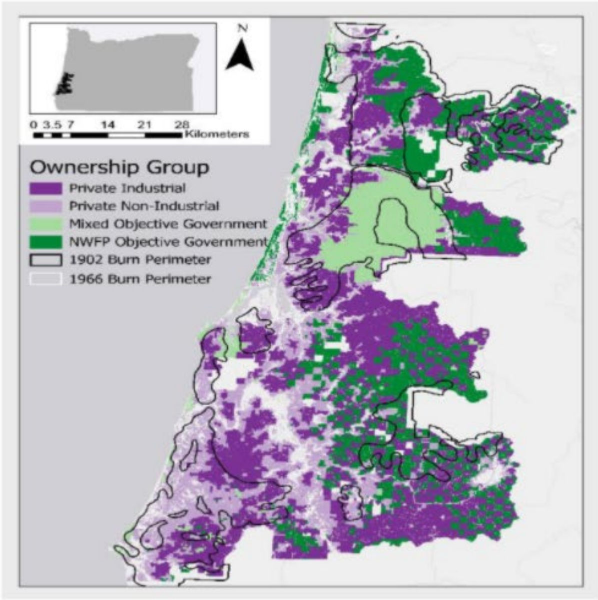
Dr. Prichard talks with President Joe Biden, 2022

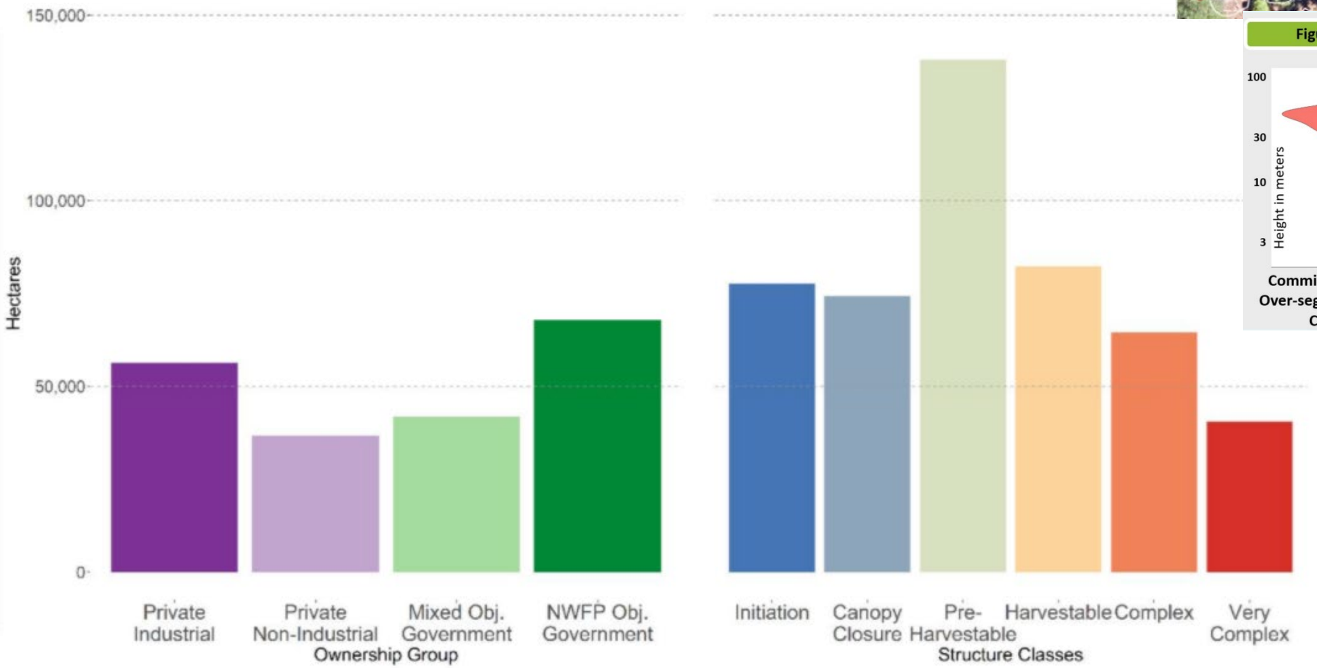
S. Prichard is a research scientist with over 25 years experience in forest and fire ecology. Her research is centered around landscape fire ecology with an emphasis on wildland fire and fuels management.

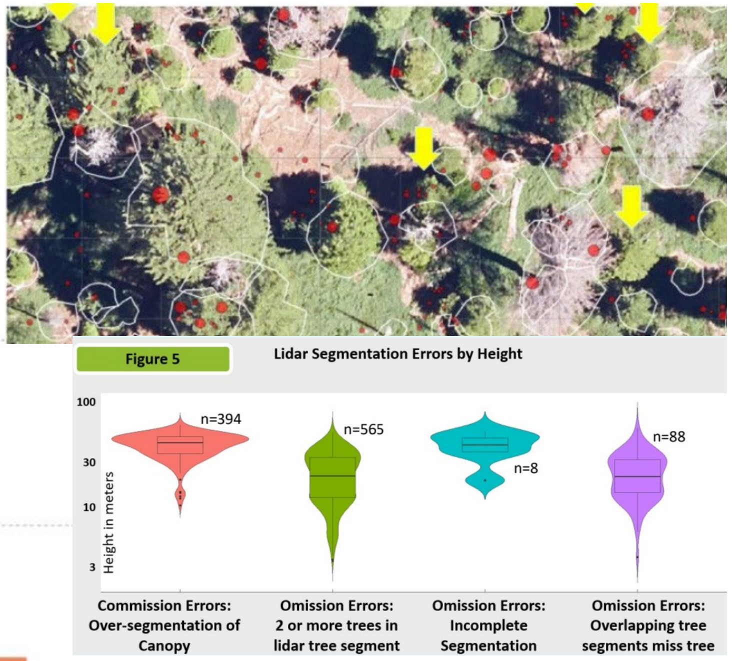
Latest LiDAR related publication:

Batchelor, J. L, RowellE, Prichard, S., Nemans, D., Cronan J., and **L. M. Moskal**, 2023. Quantifying Forest Litter Fuel Moisture Content with Terrestrial Laser Scanning, Remote Sensing. 15(6), 10.3390/rs15061482.

PFC: Forest Resilience Laboratory (FRL)







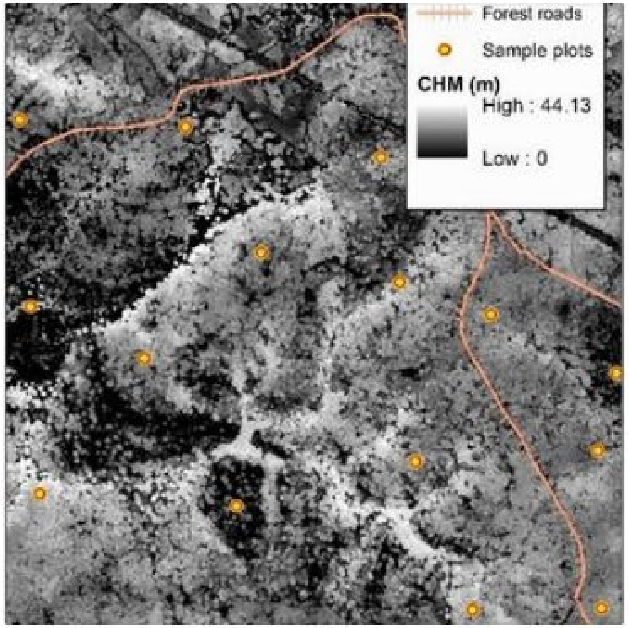
June 2, 2023
PhD Defense
Seeing forest processes from the overstory trees: strengths and weaknesses of forest remote sensing
Liz V, M. North, S. Jeronimo, V. R. Kane

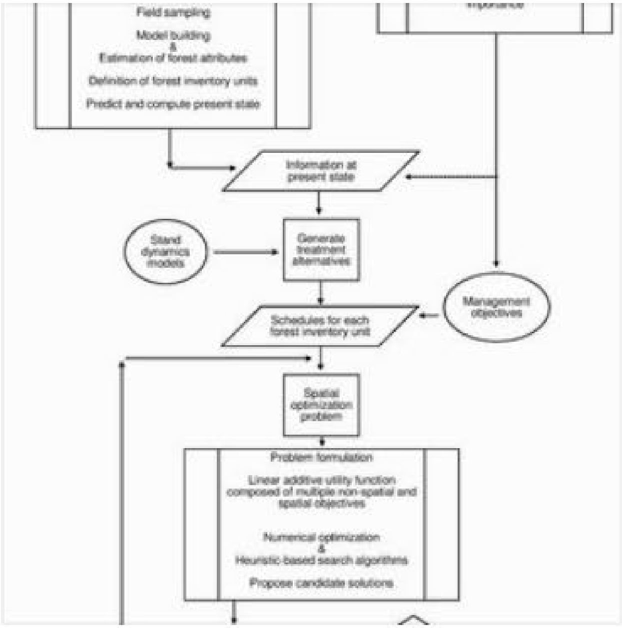
V. Kane has been working with LiDAR since 2007; advises and mentors large student lab, has generated over $2million in funding in this biennium including grants from NASA and CarFire

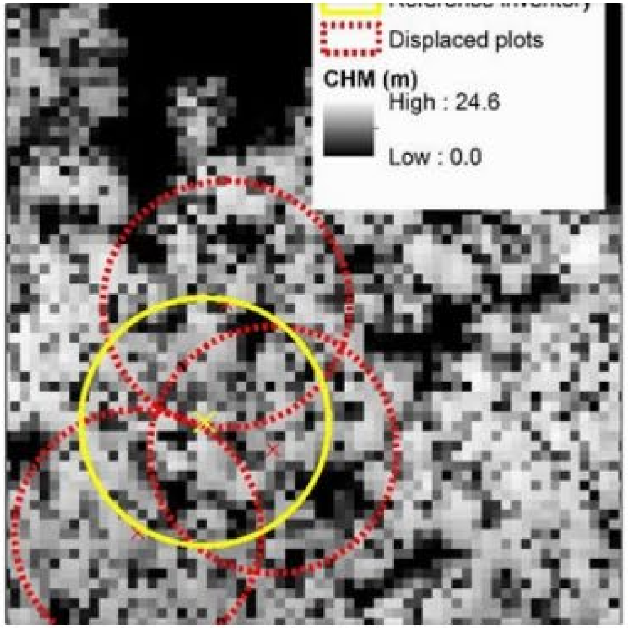
Latest LiDAR related publication:

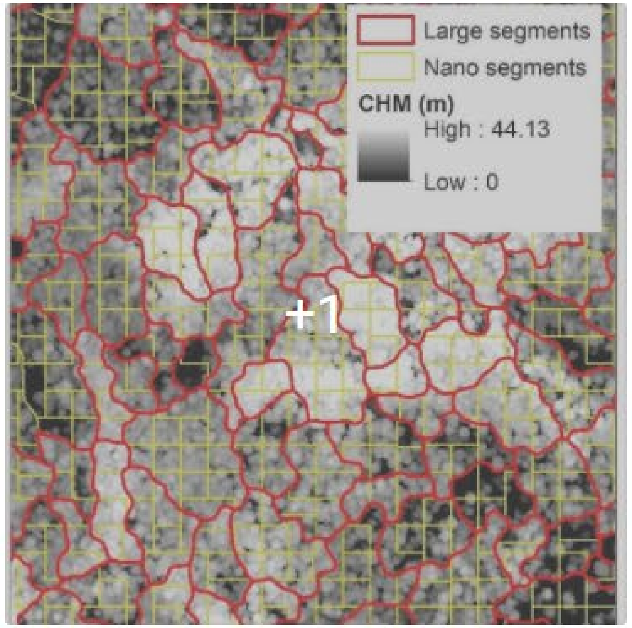
Griffey, V.S., Kellogg, B.S., Haugo, R.D., **Kane**, V.R. 2021. Ownership patterns drive multi-scale forest structure patterns across a forested region in southern coastal Oregon, USA. Forests. 12, 47. 10.3390/f12010047

PFC: Spatial Optimization Laboratory (SOL)









S. Toth has been working with LiDAR since 2015, teaches optimization and consulting courses, generated close to $200K in external funding in this biennium, graduates numerous students including PhD, ask him about ECOSEL

Latest LiDAR related publication:

Pascual, A. & S.F. **Tóth**. 2021. Using mixed integer programming and airborne laser scanning to generate forest management units. Journal of Forest Research. 33, 217-226. [10.1007/s11676-021-01348-2]

RSGAL

Remote Sensing &
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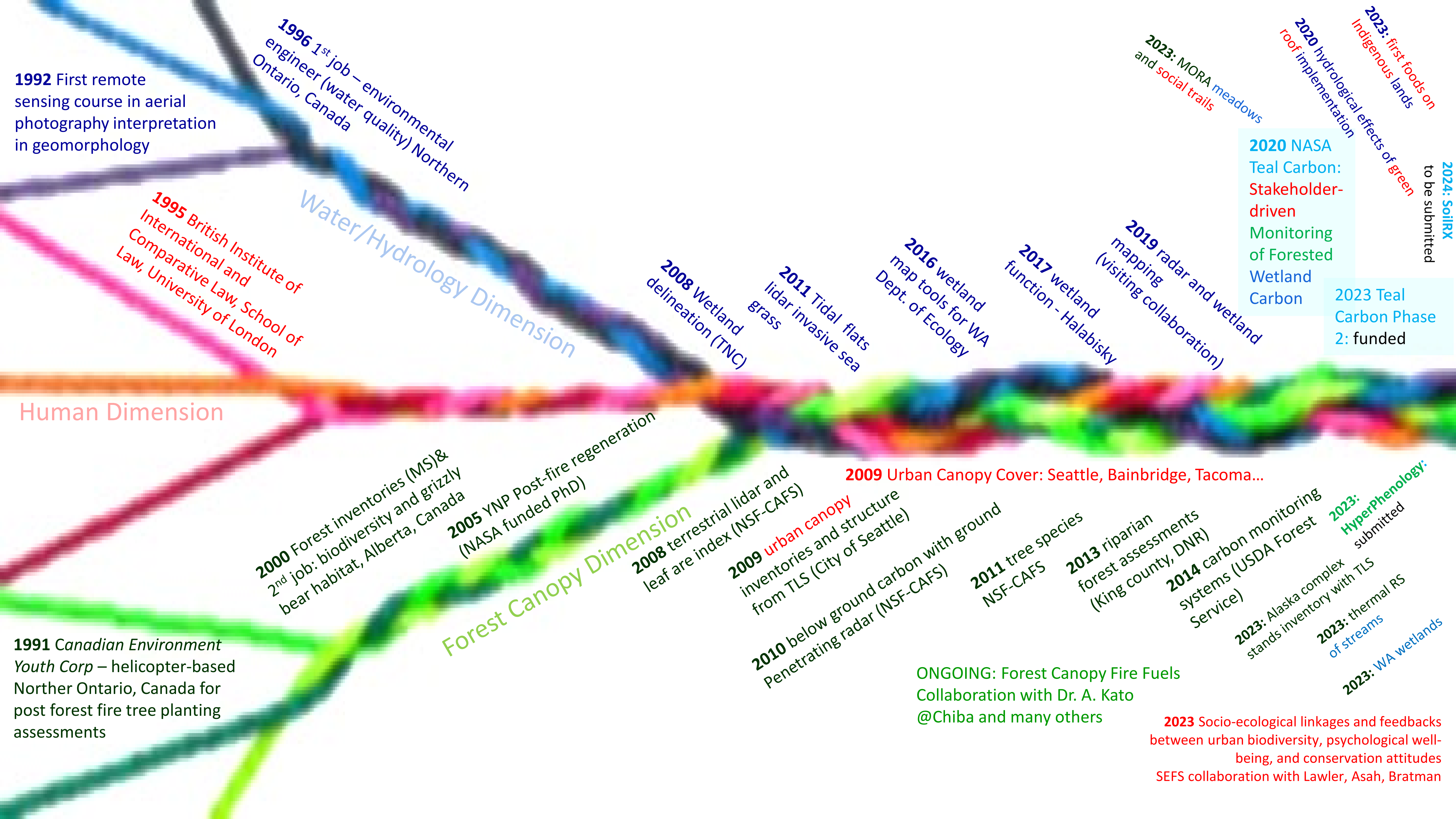
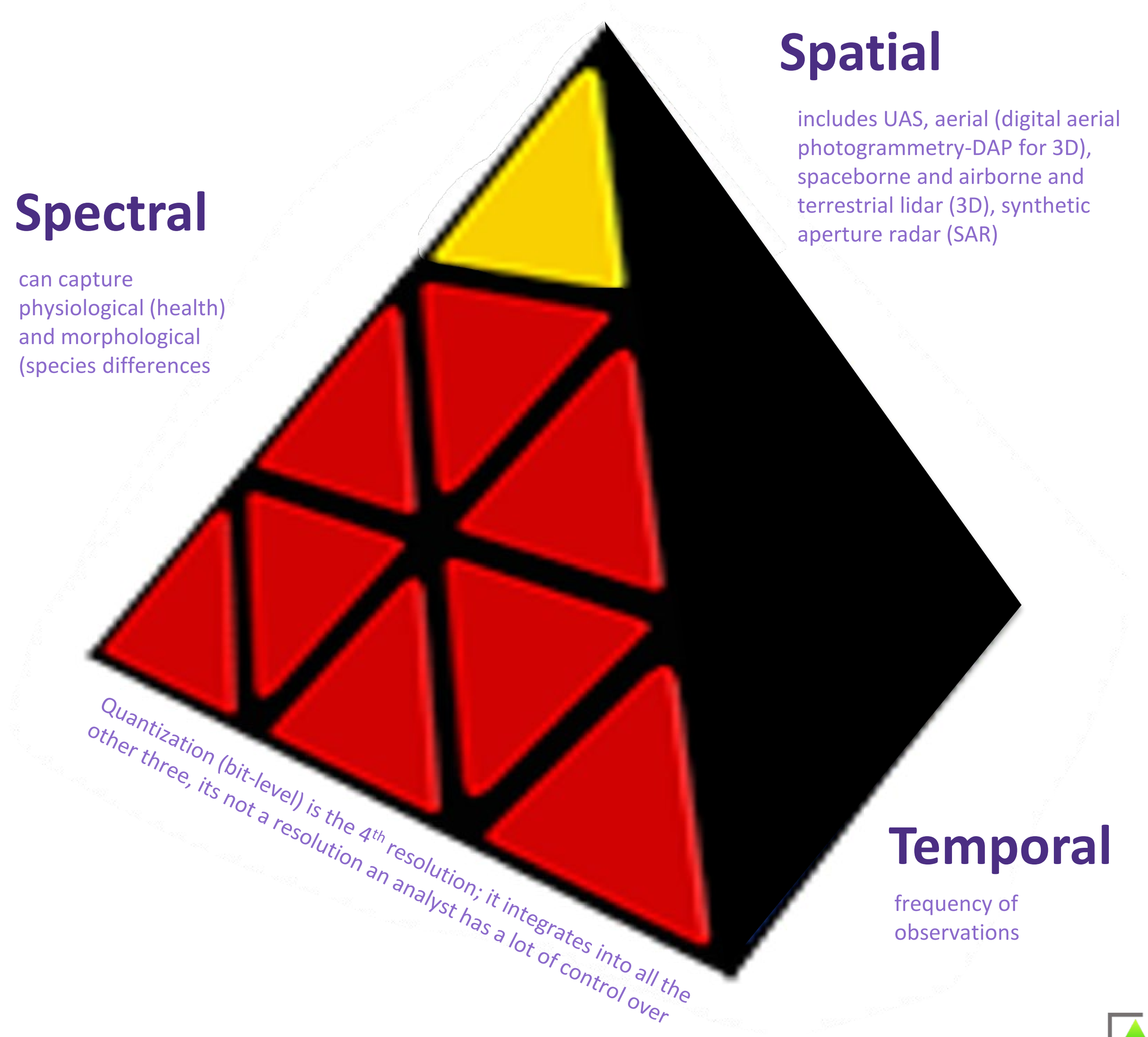

1992 First remote sensing course in aerial photography interpretation in geomorphology
1996 1st job – environmental engineer (water quality) Northern Ontario, Canada
Water/Hydrology Dimension
1995 British Institute of International and Comparative Law, School of Law, University of London
Human Dimension
2008 Wetland delineation (TNC)
2011 Tidal flats lidar invasive sea grass
2016 wetland map tools for WA Dept. of Ecology
2017 wetland function - Halabisky
2019 radar and wetland mapping (visiting collaboration)
2023: MORA meadows and social trails
2020 hydrological effects of green roof implementation
2023: first foods on Indigenous lands
2020 NASA Teal Carbon: Stakeholder-driven Monitoring of Forested Wetland Carbon
2023 Teal Carbon Phase 2: funded
2024: SoilRX to be submitted
2009 Urban Canopy Cover: Seattle, Bainbridge, Tacoma…
2000 Forest inventories (MS)& 2nd job: biodiversity and grizzly bear habitat, Alberta, Canada
2005 YNP Post-fire regeneration (NASA funded PhD)
Forest Canopy Dimension
2008 terrestrial lidar and leaf are index (NSF-CAFS)
2009 urban canopy inventories and structure from TLS (City of Seattle)
2010 below ground carbon with ground Penetrating radar (NSF-CAFS)
2011 tree species NSF-CAFS
2013 riparian forest assessments (King county, DNR)
2014 carbon monitoring systems (USDA Forest Service)
2023: HyperPhenology: submitted
2023: Alaska complex stands inventory with TLS
2023: thermal RS of streams
2023: WA wetlands
1991 Canadian Environment Youth Corp – helicopter-based Northern Ontario, Canada for post forest fire tree planting assessments
ONGOING: Forest Canopy Fire Fuels Collaboration with Dr. A. Kato @Chiba and many others
2023 Socio-ecological linkages and feedbacks between urban biodiversity, psychological well-being, and conservation attitudes
SEFS collaboration with Lawler, Asah, Bratman

Understanding remote sensing through the domains of resolution

– remote sensing is entering a ‘hyper-resolution’ era
– for each of the remote sensing resolution domains, there are tradeoffs to getting the best results
  > data costs
  > analysis time
  > accuracy
– there are synergies when fusing multiple domains
– access, equity and inclusion have a ways to go



….finally let us look at some research form RSGAL

RSGAL

Remote Sensing &
Geospatial Analysis Laboratory

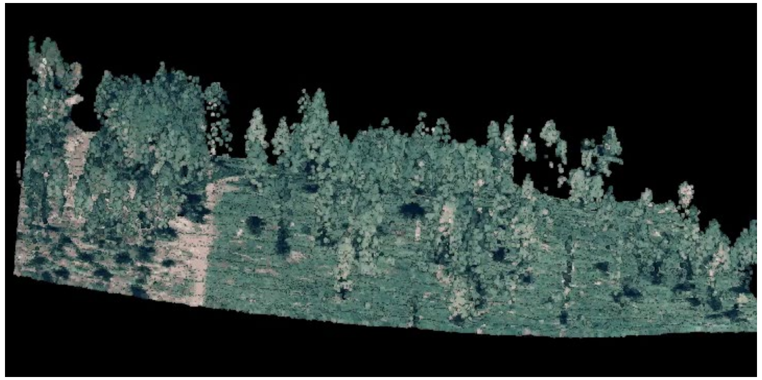
Inventories and structure in heterogenous forests – ecosystem view

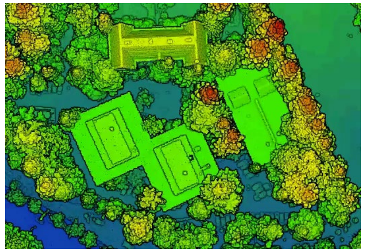
Collaborators: *A. Kato (PhD, now Associate Prof. in Japan, G. Zheng (PhD, Now Associate Prof. in China, J. Richardson (MS & PhD, now Prof. in Vermont), N. Vaughn (PhD & Postdoc, now Asner Lab), D. Styers (Postdoc, now Associate Prof. in NC), T. Axe (MS, now Weyerhaeuser), A. Cooke (PFC NRSIG Lab)*

Support: *NSF CAFS, USDA Forest Service, BLM, UW Royalties Fund*

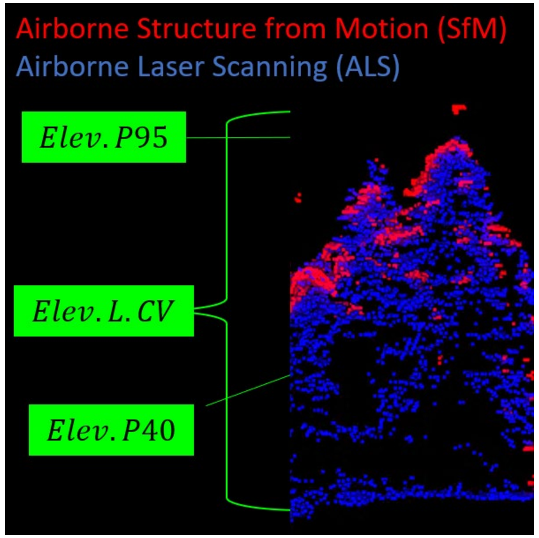
Publications: *+30*

- Heterogenous forests such as urban and riparian forests are hard to model
- Uncertainty is high
- Leaf Area Index!
- Need to fuse RS resolution domains – capturing structure is key (lidar, digital photogrammetry, even radar)

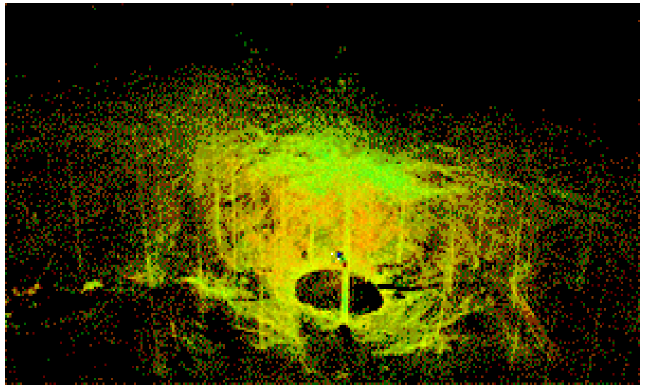




aerial lidar in forest inventories is now operational and easily combined with optical imagery



many ways to get at forest structure; tradeoffs

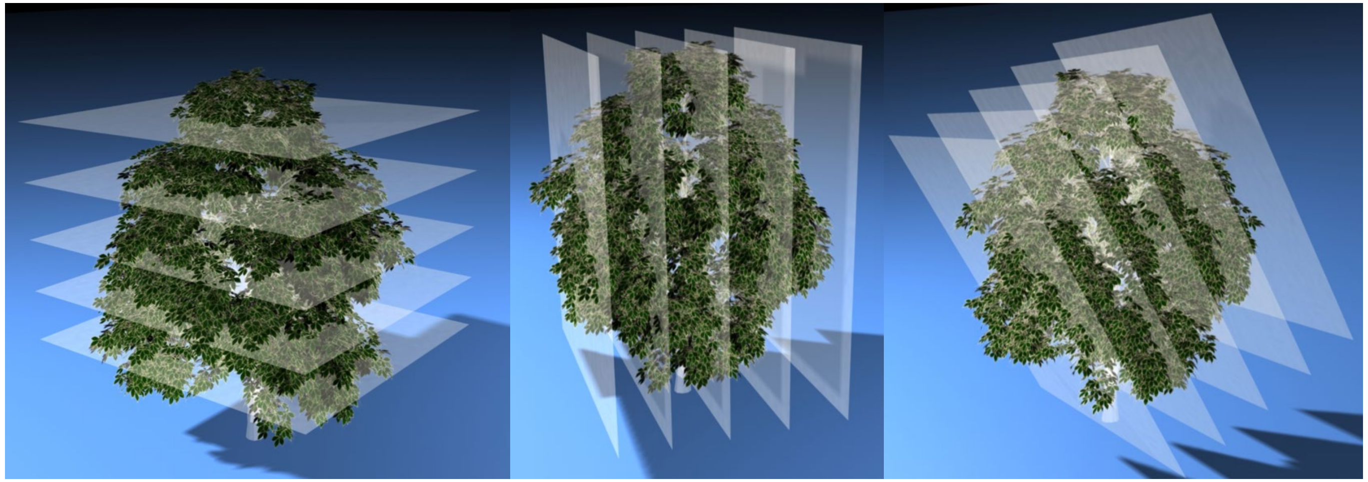


1st terrestrial lidar scan form 2009, Wind River

PFC: Remote Sensing and Geospatial Analysis Laboratory (RSGAL)

To get at above ground carbon get at above ground biomass: Leaf Area Index (LAI) w/LiDAR

RSGAL went after fine spatial resolution LAI, best part, we can scale up with the coarse scale models



(1) Zheng, G. Ma, L.X., He, W., Eitel, J.U.H., **Moskal, L.M**. and Zhang, Z.Y, 2016. Assessing the contribution of woody materials to forest angular gap fraction and effective leaf area index using terrestrial laser scanning (TLS) data. IEEE Transactions on Geoscience and Remote Sensing, 54(3), 1474-1484. (2) Zheng, G., **Moskal, L.M.** and S-H. Kim, 2012. Retrieval of effective leaf area index in heterogeneous forests with terrestrial laser scanning, IEEE Transactions on Geoscience and Remote Sensing, 51(2);777-786. (3) Zheng, G. and **L.M. Moskal**, 2012. Computational Geometry-Based Retrieval of Effective Leaf Area Index Using Terrestrial Laser Scanning, IEEE Transactions on Geosciences and Remote Sensing, 50(10); 3958 - 3969. (4) Zheng, G. and **L.M. Moskal**, 2012. Leaf Orientation Retrieval from Terrestrial Laser Scanning Data, IEEE Transactions on Geoscience and Remote Sensing, 50(10); 3970 – 3979. (5) Zheng, G. and **L.M. Moskal**, 2012. Spatial variability of terrestrial laser scanning based leaf area index, International Journal of Applied Earth Observation and Geoinformation, 19, 226–237. (6) Zheng G. and **L.M. Moskal**, 2009. Retrieving Leaf Area Index (LAI) Using Remote Sensing: Theories, Methods and Sensors. Sensors, 9(4):2719-2745. (7) Ma, L., Zheng, G., Eitel, J., **Moskal, L.M.**, He, W. and H. Huang. 2016. Improved Salient Feature-Based Approach for Automatically Separating Photosynthetic and Nonphotosynthetic Components Within Terrestrial Lidar Point Cloud Data of Forest Canopies. IEEE Transactions on Geoscience and Remote Sensing, 54(2), 679-696. (8) Ma, L., Zheng, G., Eitel, J., Magney, T. and **L. M. Moskal**. 2016. Determining woody-to-total area ratio using terrestrial laser scanning (TLS), Agricultural and Forest Meteorology, 228-229, 217-228

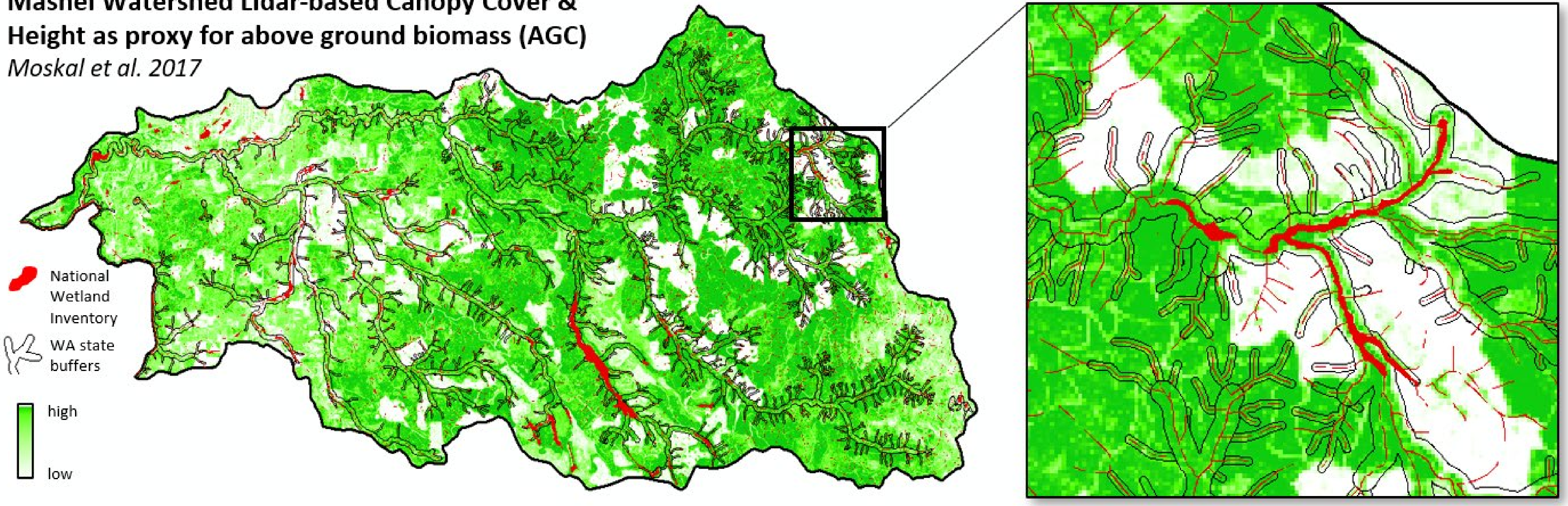
L. M. Moskal works with LiDAR (since 2002 IceSat), teaches 3 remote sensing courses, students in RSGAL involved in teaching GIS, generated close to $1million in external funding in this biennium, was selected as one of the Wilburforce Leaders in Conservation Science 2021 and is stepping down from SEFS Associate Director of Research in Fall 2021, 70 peer-reviewed publications

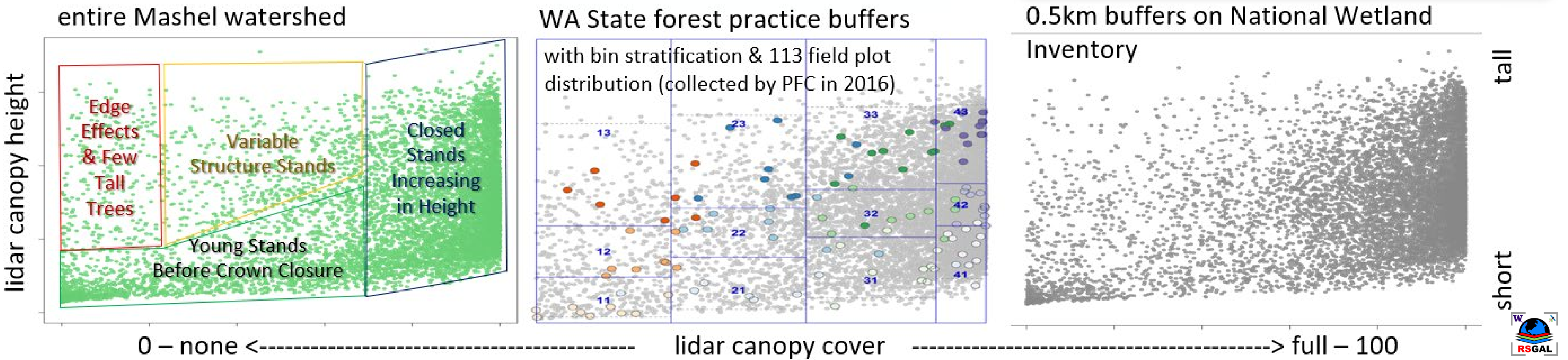
Latest LiDAR related publication:

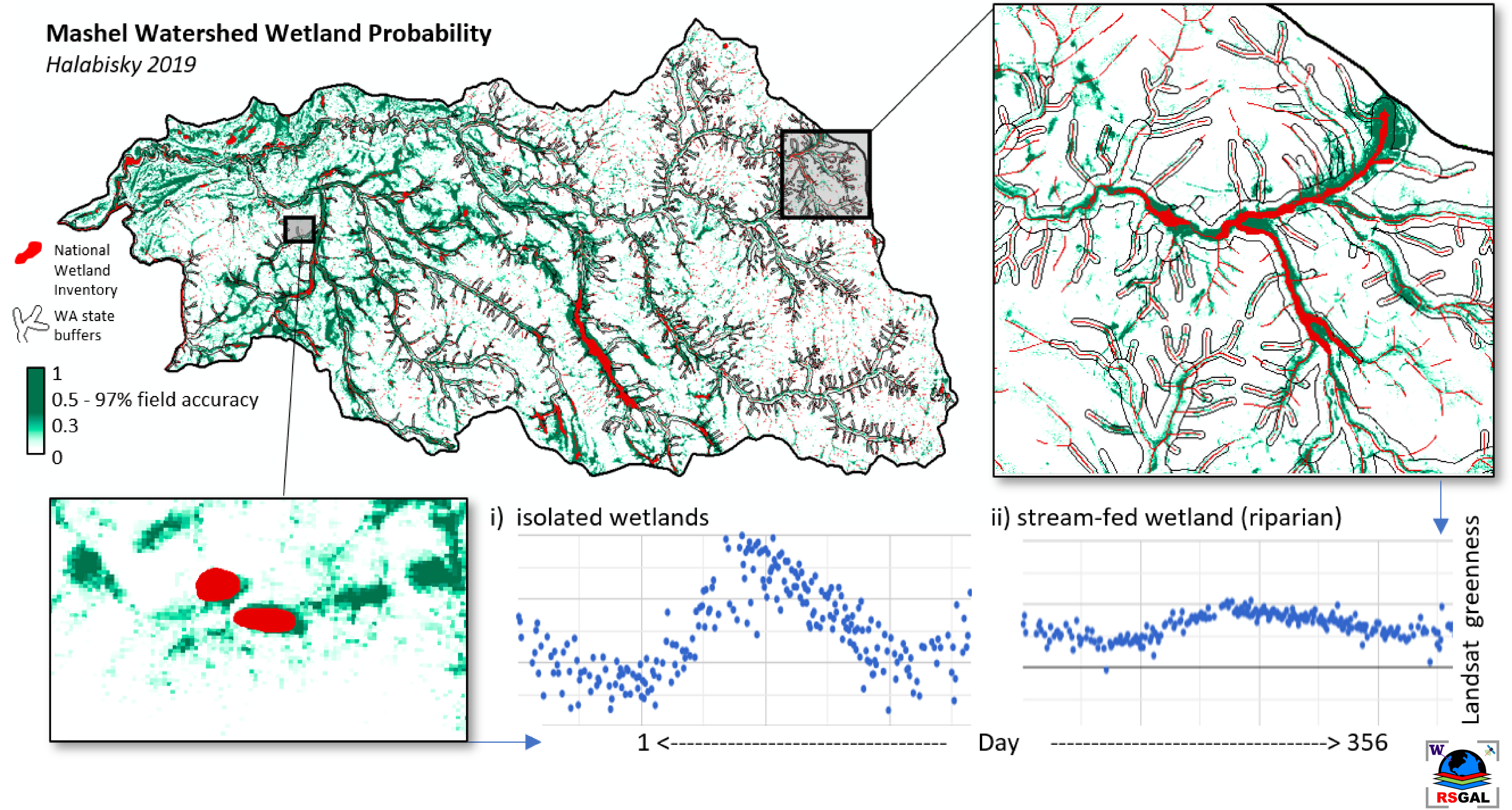
Batchelor, J. L, RowellE, Prichard, S., Nemans, D., Cronan J., and **L. M. Moskal**, 2023. Quantifying Forest Litter Fuel Moisture Content with Terrestrial Laser Scanning, Remote Sensing. 15(6), 10.3390/rs15061482

Mashel Watershed Lidar-based Canopy Cover & Height as proxy for above ground biomass (AGC)

Moskal et al. 2017







Mashel Watershed Wetland Probability
Halabisky 2019
National Wetland Inventory
WA state buffers
1
0.5 - 97% field accuracy
0.3
0
i) isolated wetlands
ii) stream-fed wetland (riparian)
Landsat greenness
1 <---------------------------------- Day ----------------------------------> 356
RSGAL

L Monika Moskal
March 15, 2019 ·

Good news!

EOS.ORG

New Budget Bill Rescues NASA's Carbon Monitoring System - Eos

"We're back!" says $10-million-per-year project's science team leader.

Meghan Halabisky, Laboratorium Geomatyki and 3 others 5 Comments

Like Comment Share

Dan Brown
Maybe we should be working on a proposal 1
Like · Reply · 1y

Kate Legner
That's ME in this photo! 1
Like · Reply · 1y

L Monika Moskal replied · 3 Replies

Write a comment...

2020-2023 Teal Carbon Phase 1: Stakeholder-driven Monitoring of Forested Wetland Carbon

PI: Prof, L. M. Moskal

Co-I's and Collaborators: M. Halabisky (MS, PhD, now UW), D. Butman (UW), B. Harvey (UW), C. Babcock (PhD, now Assistant Prof at U of Minnesota), A. Stewart (PhD Student), M. Duane (Project Manager UW)

Support: NASA CMS 2019; **$575K to UW**

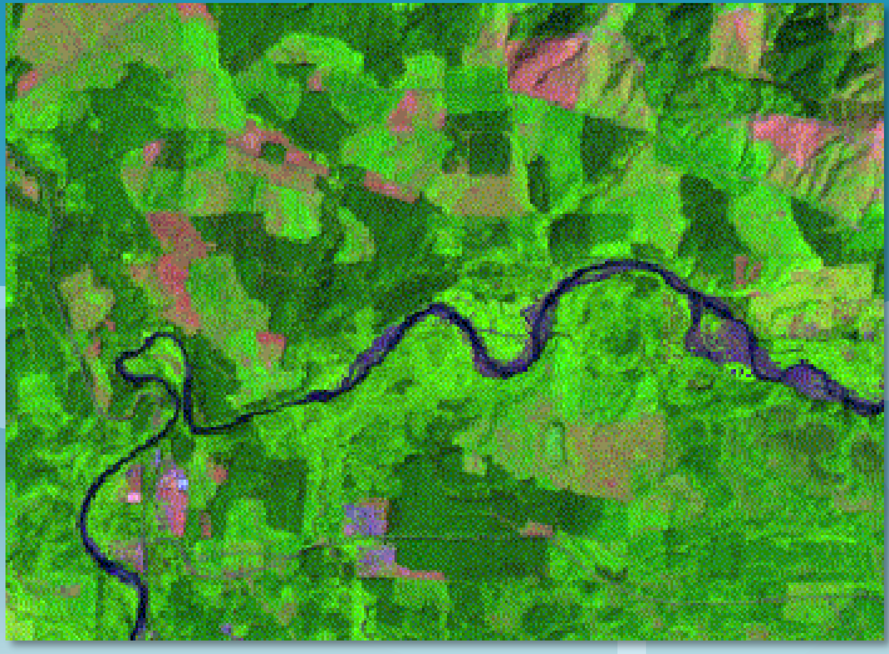
Deliverables: 2021 literature review w/ NASA wet carbon specialty group on the way; 2022 wetland intrinsic probability tool & paper; 2023 cryptic carbon paper (in review)

2023-2026 Teal Carbon Phase 2: Scaling Wetland Carbon Accounting and Uncertainty Estimation to Meet Stakeholder Policy and Decision-Making Needs

PI: Prof, L. M. Moskal

Co-I's and Collaborators: M. Halabisky (MS, PhD, now UW), D. Butman (UW), B. Johnson (UW), C. Babcock (PhD, now Assistant Prof at U of Minnesota), Stewart (PhD Student), M. Duane (Project Manager UW), A. Hudak (USDA FS), Lisamarie-Windham-Myers (USGS), David D'Amore (USDS FS), Amy Yahnke (WA ECY)

Support: NASA CMS 2023; **$950K to UW**



Time series of landscape change from 1984-2020 Land Trender analysis in part of the Hoh River watershed. The harvest impacts as well as river migration are both detectable.

PFC

(1) University of Washington
(2) University of Minnesota

Project synthesis

Background:

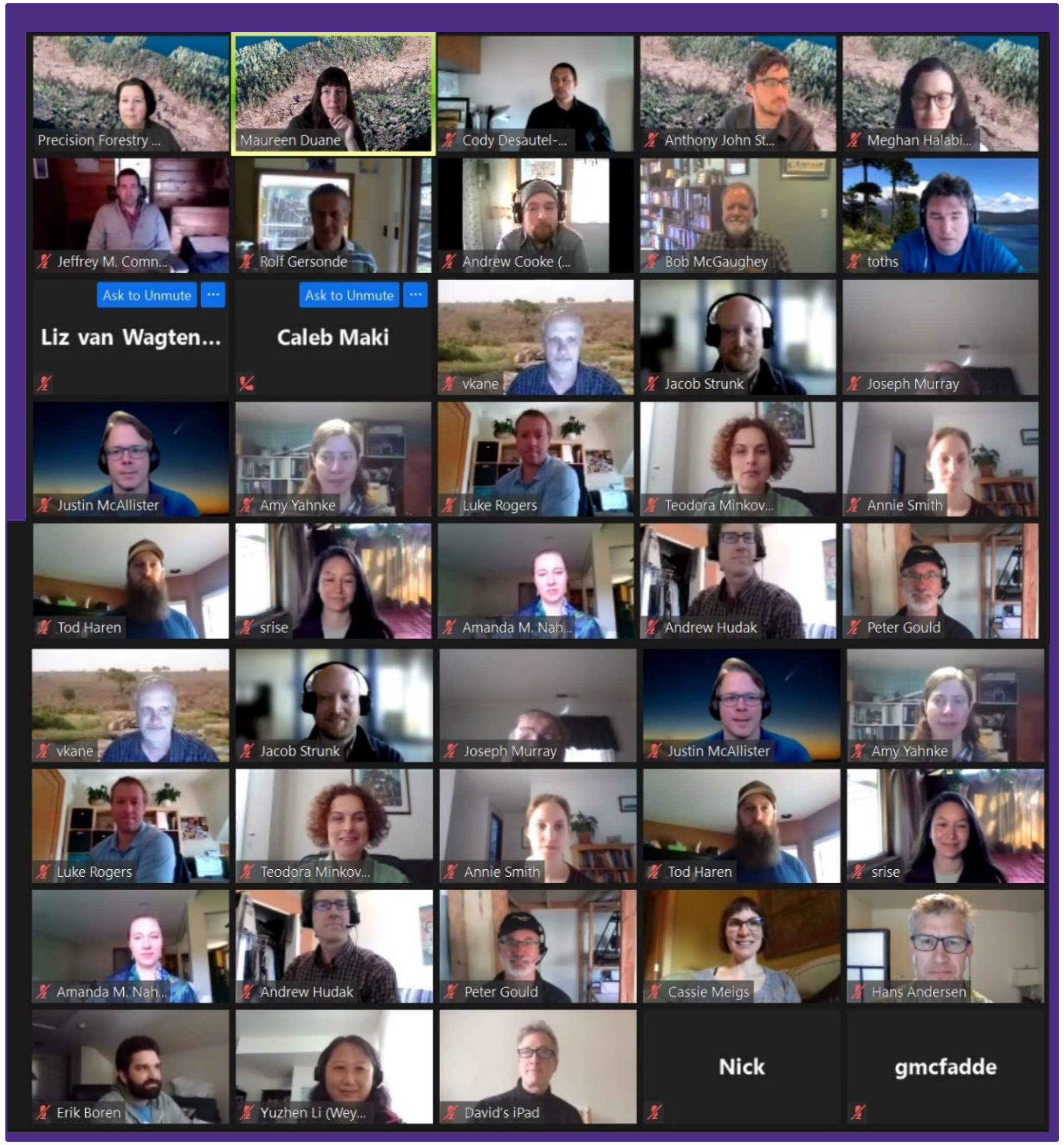
- Wetlands disproportionately contribute to carbon storage, storing 30% (202–754 PgC) of the global soil organic carbon stock (1500 PgC) while only occupying 8–11% of the land surface. Due to the magnitude of carbon storage in inland wetlands, Nahlik and Fennessy referred to this carbon as **'teal carbon'**.
- Inland freshwater wetlands have 10x soil carbon than blue carbon sites in the U.S., but we have limited knowledge about these these landscape features (Nahlik & Fennessy, 2016), their fluxes or +/- impacts on emissions.

Project Goal:

To improve wetland extent and baseline data on carbon stocks of forested wetlands.

Objectives:

1. Improved Wetland Mapping & Quantifying Total Carbon Stocks of Inland Wetlands
2. Modeling & Uncertainty of Total Carbon Stock Assessments
3. Disturbance Case Study & Stakeholder Engagement



Stakeholder engagement during the PFC board meeting, April 8th, 2021; we have also engaged with our stakeholders 2020 and 2022 and grown this network. Our stakeholder engagement is headed by ***Maureen Duane*** (yellow thumbnail outline) in the UW Precision Forestry Cooperative.

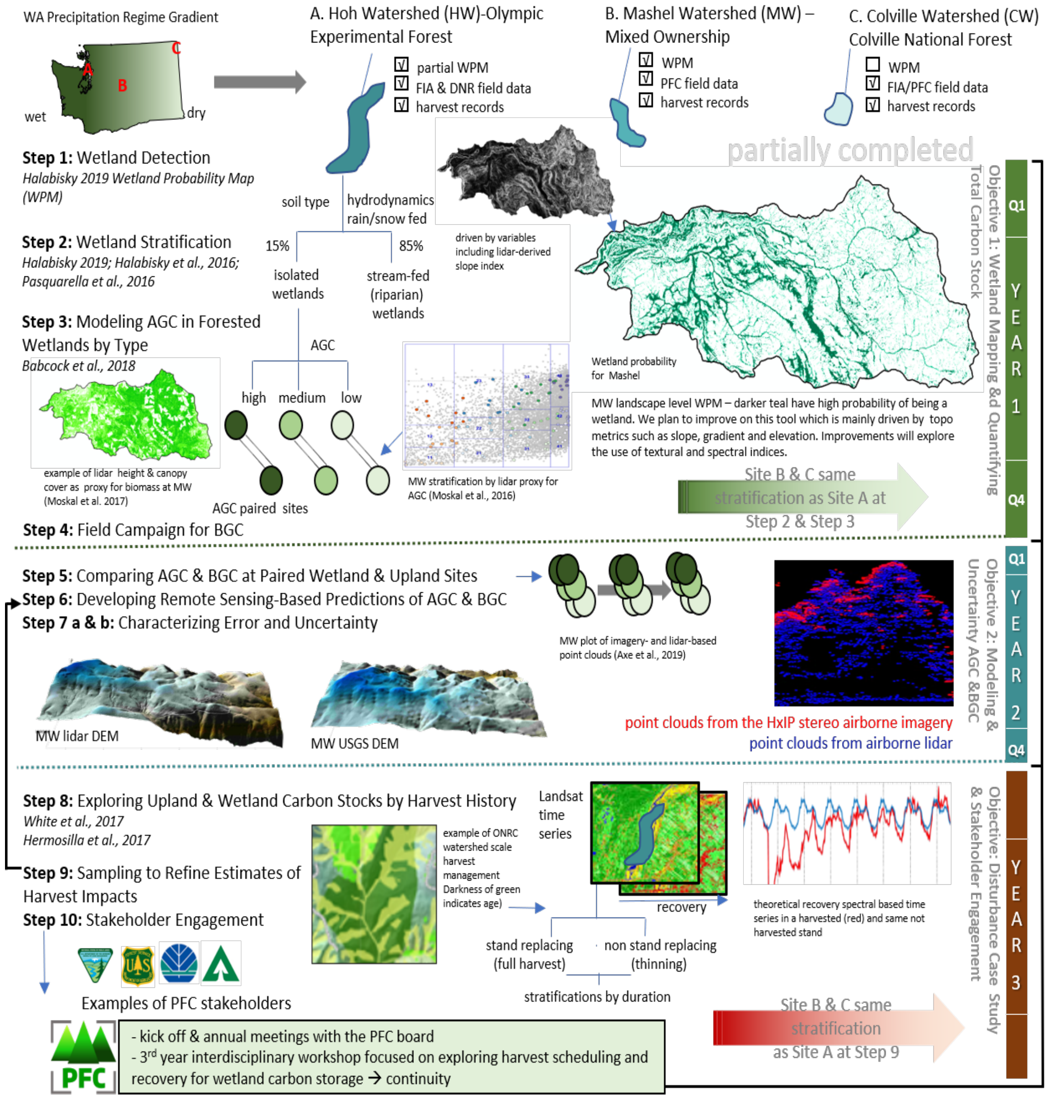
What are wetlands?

The challenge

- *Cryptic wetlands (Creed et al., 2003)*

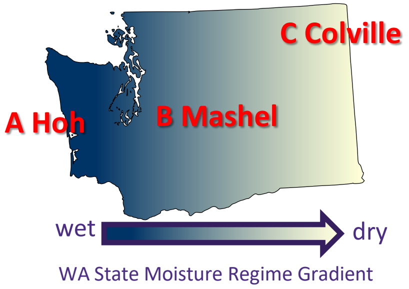
Teal Carbon – Our questions

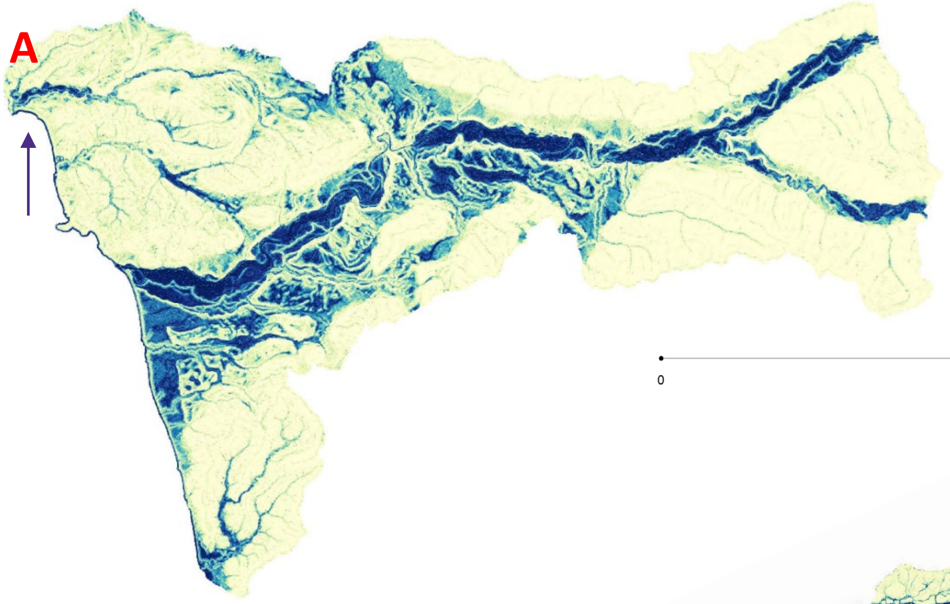
1. What are the current stocks of total carbon (AGC and BGC) in forested wetlands of the PNW and are these stocks significantly greater than upland ecosystems?
2. Are the variations in carbon stored in forested wetlands across precipitation gradients found in the PNW predictable or systematic?
3. How does hydrologic position of wetlands (i.e., connected or disconnected to surface flow) affect total carbon storage?
4. Do current and legacy forest harvest practices inside forested wetlands affect their carbon storage capacity across differing forest ecosystem types?

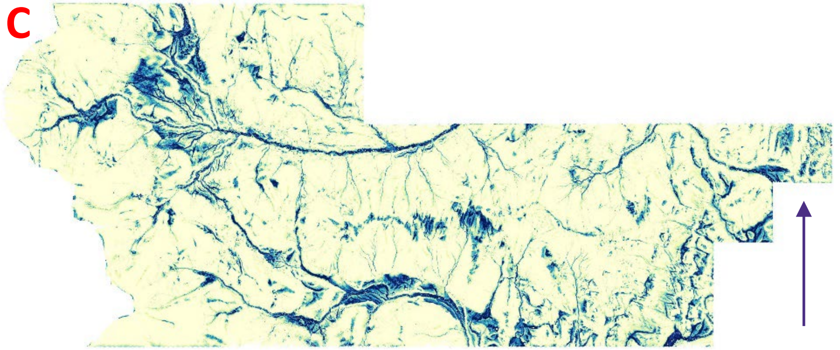


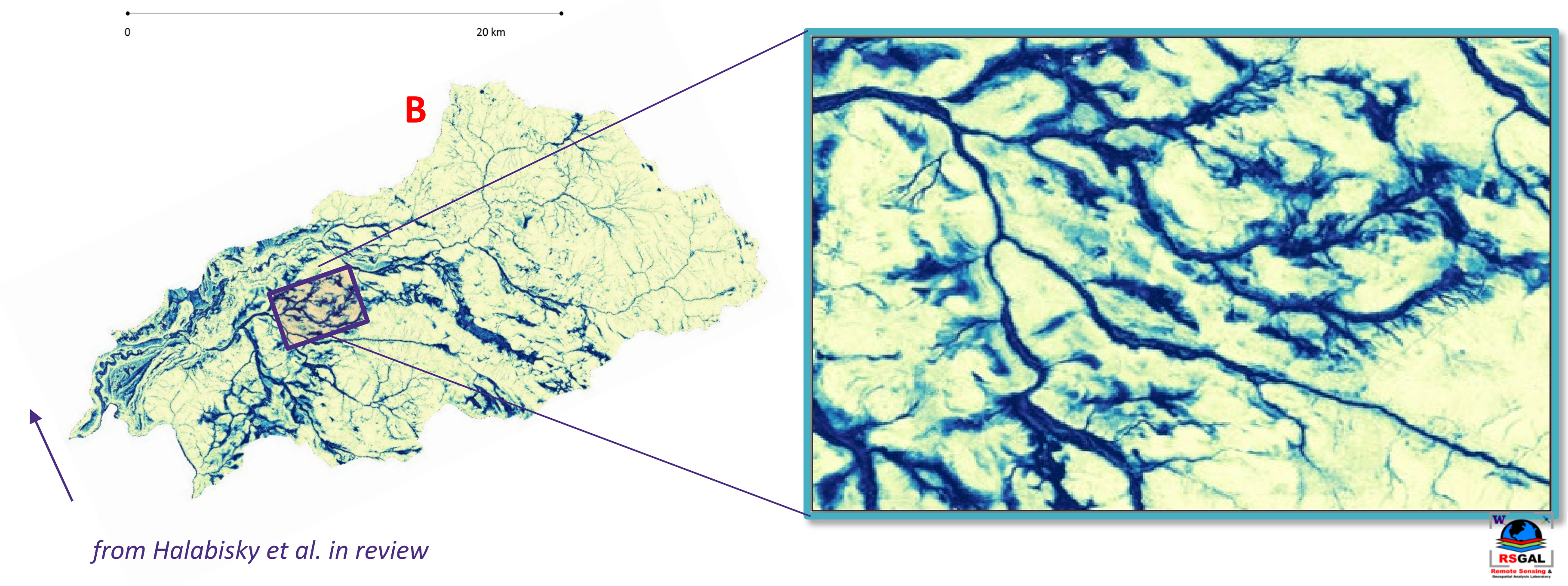
Top-level science results

- The **Wetland Intrinsic Potential - WIP**
- Halabisky et al. *in review.* The Wetland Intrinsic Potential tool: Mapping wetland intrinsic potential through machine learning of multi-scale remote sensing proxies of wetland indicators; Hydrology Earth and System Sciences.





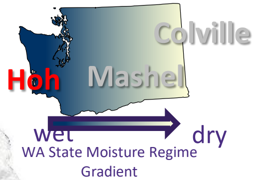


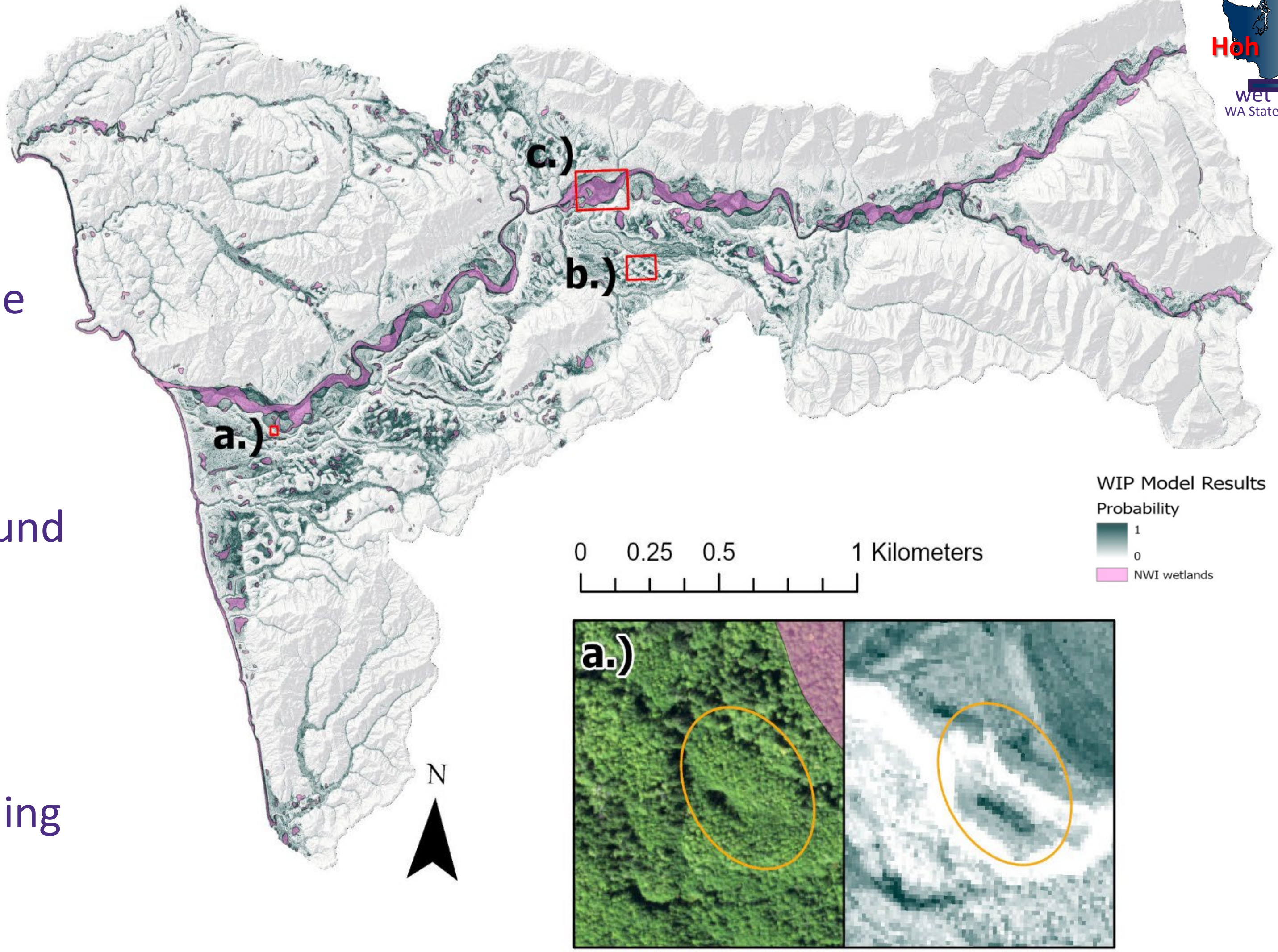


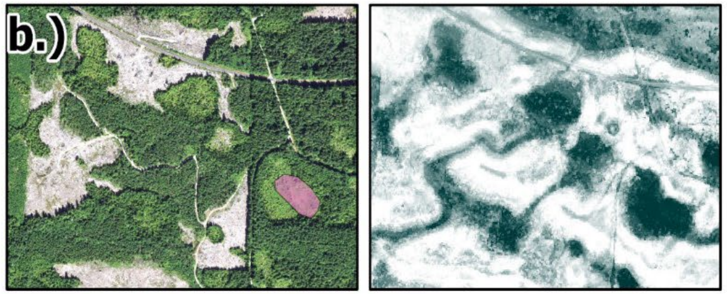
from Halabisky et al. in review

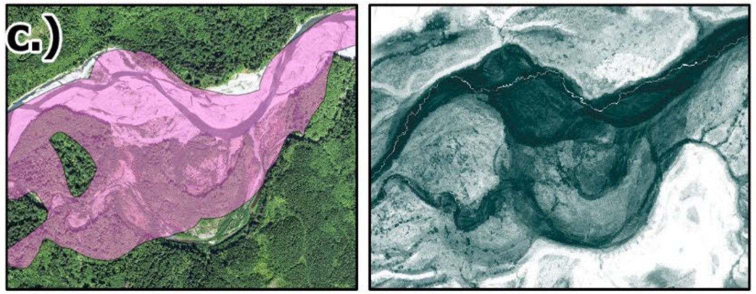
Top-level science results

- **WIP** modeling tool uses input datasets derived from high resolution aerial imagery, lidar, and soil surveys that represent the full suite of wetland indicators
- Within the Hoh watershed in Washington State, an area within the Olympic National Park, we found 140% increase in the wetland areas using the WIP tool, then previously detected in the National Wetland Inventory
- The WIP is an **<u>open source</u>** modeling tool that we developed into an ArcGIS toolbox for increased accessibility and is currently being used across the Pacific Northwest by our stakeholders



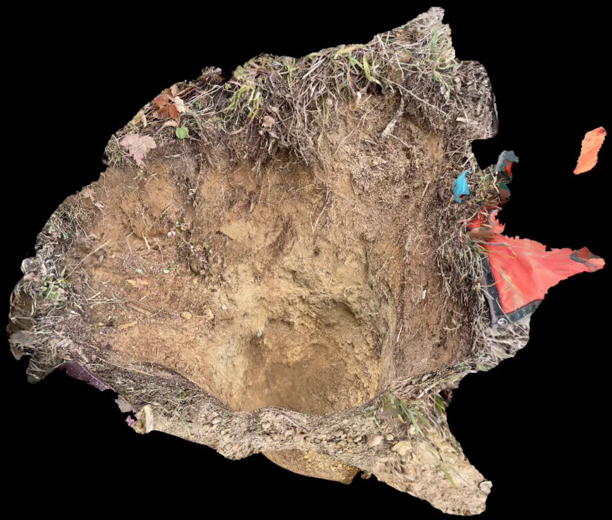






In situ sampling

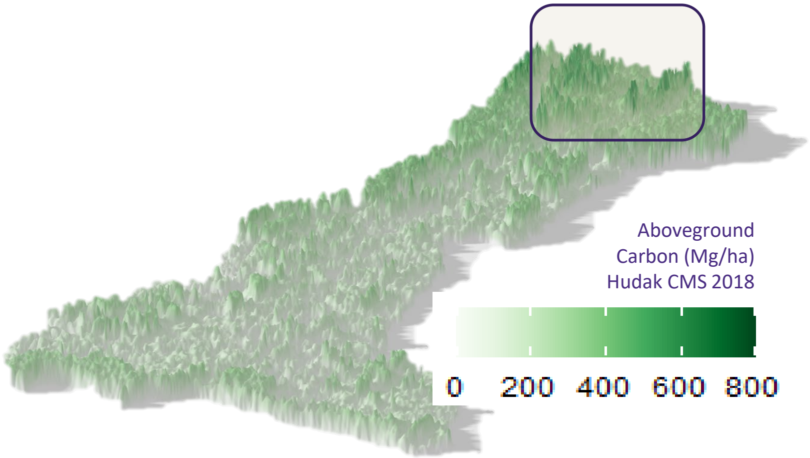
- 97 pits in WA; approximately 1m depth
- **Soil pit characterization**
  - Abbreviated soil survey characterization
  - Vegetation survey
  - Initial hydrogeomorphic and Cowardin wetland classification
  - Samples collected for Bulk Density and Total Carbon

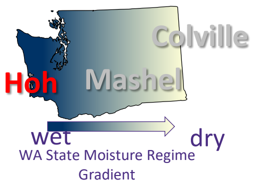


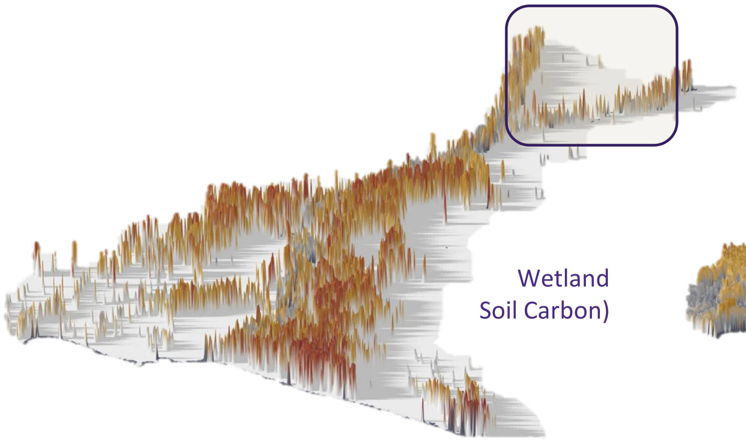
Thanks to our student field assistants: Claire Johnson, Hazel Sanders, Abby Nesper, Thomas Kakatsakis

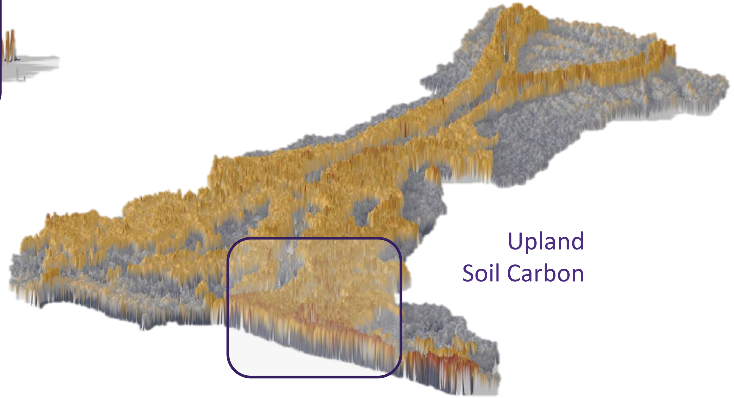
Top-level science results

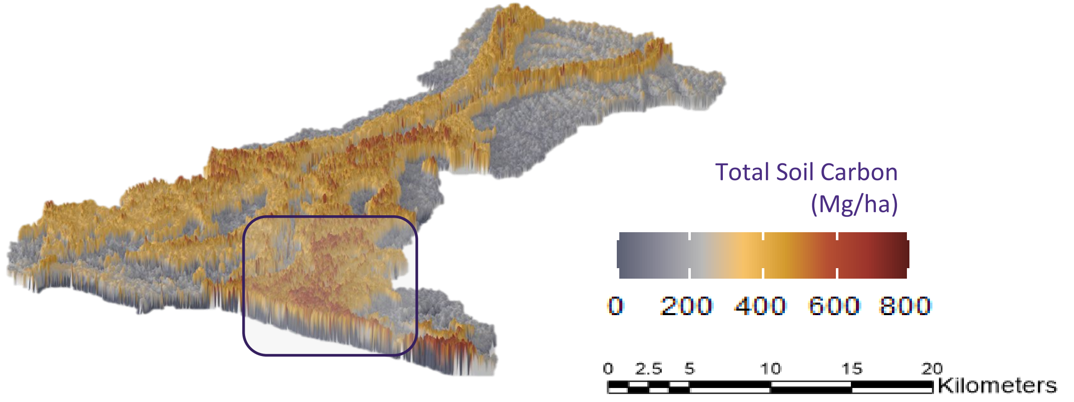
- Wetland probability index (wet-dry gradient) is the best predictor of soil carbon in all three watersheds across the precipitation gradient.
- Wetlands had almost twice the soil carbon than uplands. Although riverine wetlands had much lower soil carbon estimates.
- Through the whole watershed there is twice as much carbon in the soils then above ground carbon
- The WIP tool can identify both wetlands and moist forest. We are currently exploring this gradient and how it controls soil carbon stocks.

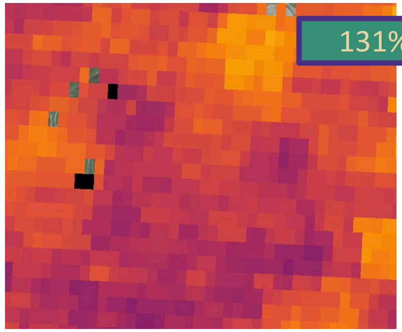




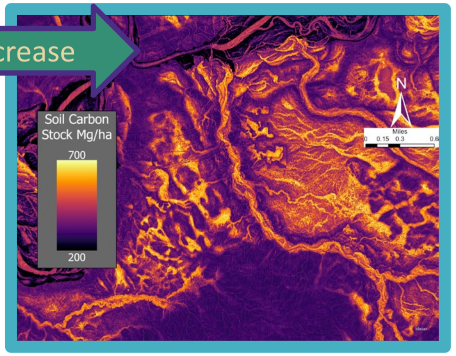








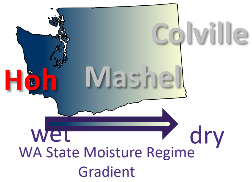
SoilGrids 250m*30cm depth Hengl et al., 2017



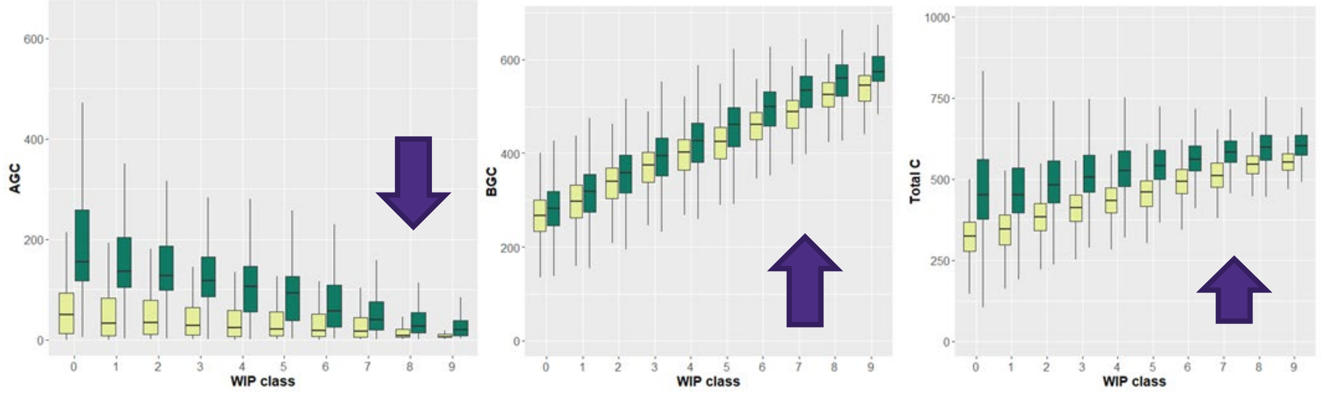
UW TealCarbon 2023

Top-level science results

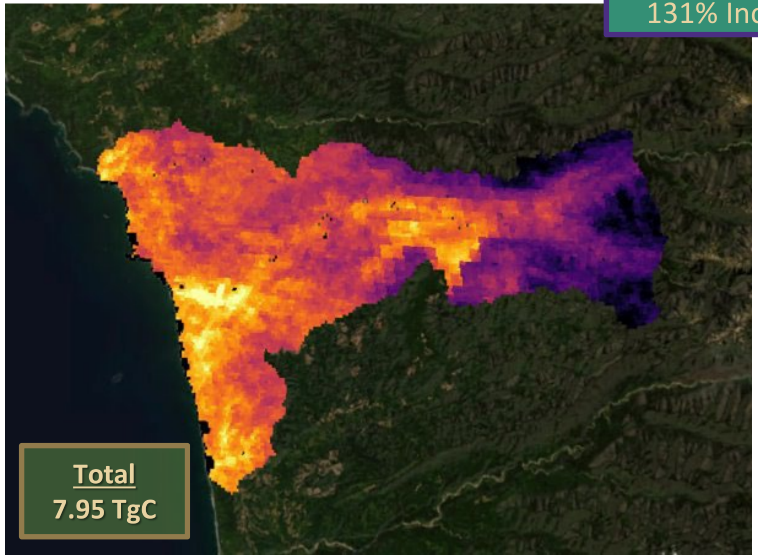
- Forested wetlands (not including riverine) have higher AGC; Wetter = Higher BGC, Lower AGC. Management plays a role.
- Stakeholders are asking for management level products. Where are the wetlands, high BGC and AGC?
- Methods and tools from this project can now provide them with that management level data.



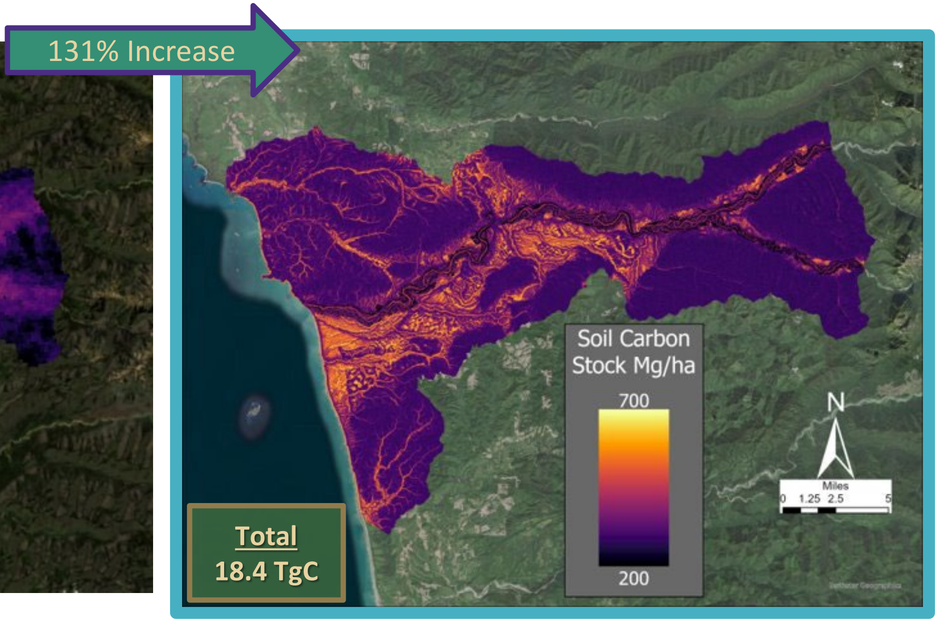
Example of AGC, BGC, and Total C stocks for the Hoh watershed along the wet to dry gradient. Protected forests (not disturbed in the last 50 years) are represented in dark green; managed forests are represented in light green

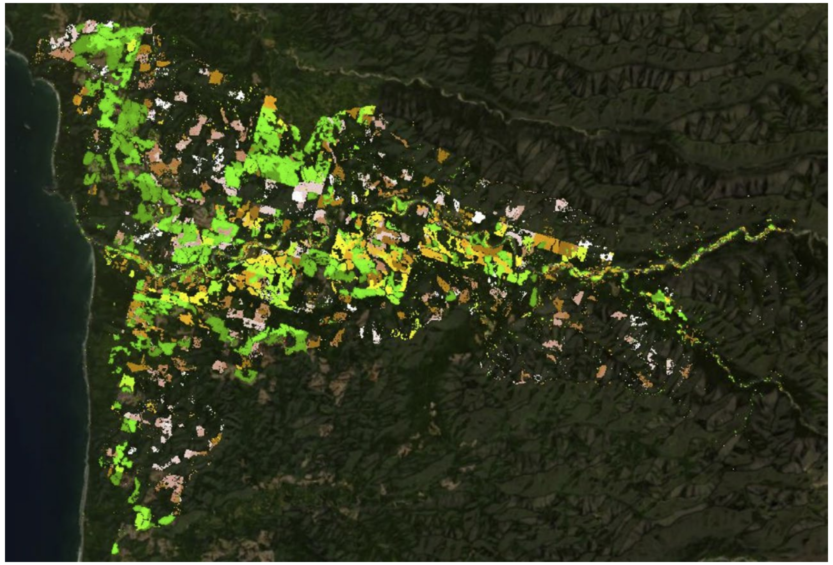


Wetter soils = Higher WIP class score (0-9)



SoilGrids 250m*30cm depth Hengl et al., 2017





Landscape Change Monitoring System - LCMS (USDA Forest Service) change in the Hoh study site in the last 50 years

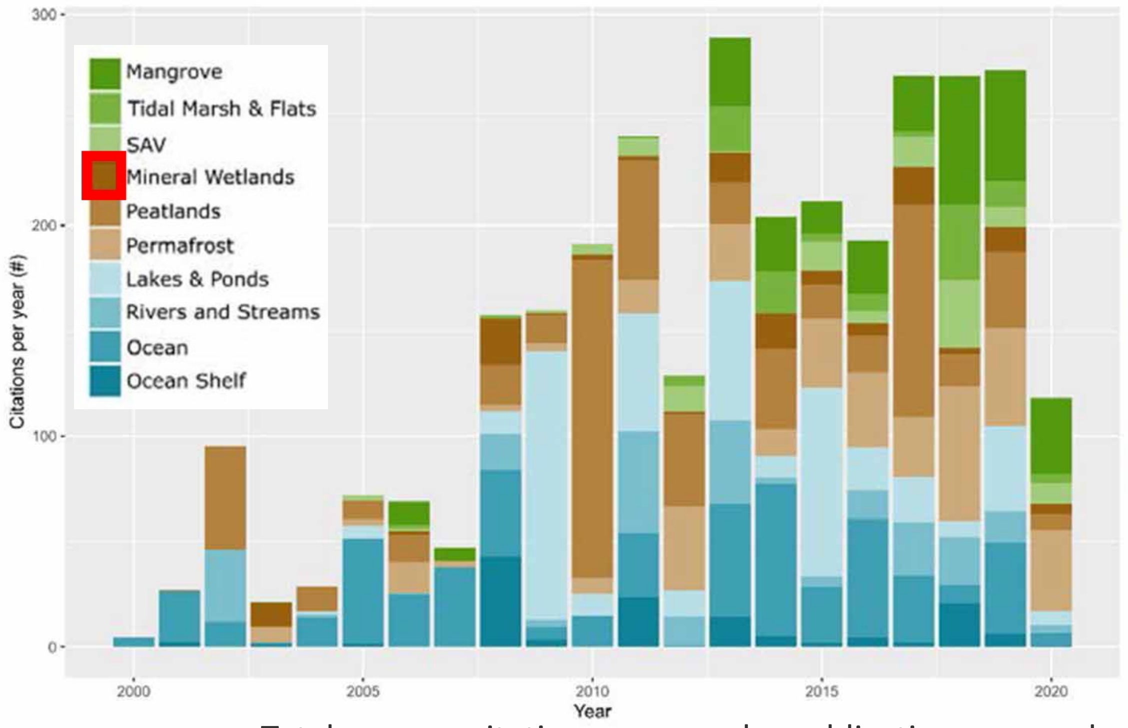
Connections to ongoing synthesis efforts

- Wet Carbon Working Group - M. Halabisky (co-I) and C. Mitchell co-chairing
  - Campbell, A.D. et al., 2022. A Review of Carbon Monitoring in Wet Carbon Systems. Environmental Research Letters. Focus on Carbon Monitoring Systems Research and Applications Special Issue. Jan 2022, [10.1088/1748-9326](10.1088/1748-9326).

*"The review highlighted that remote sensing is routinely albeit with considerable variability, used to globally map carbon in mangroves and oceans, whereas seagrass, **terrestrial wetlands**, tidal marshes, rivers, and permafrost would benefit from more accurate and comprehensive global maps of extent.*

*"…clear gaps exist. Several systems lack fundamental remote sensing baselines, such as, location, extent, and change. Complete global extent maps are a priority for seagrass, tidal marsh, and mineral wetlands…There are additional systems that were not a focus of this review due to limited remote sensing-based **carbon monitoring research that would benefit from global mapping forested wetlands, freshwater tidal marshes, and riparian wetlands**."*

– Campbell et al. 2022



Total average citations per year by publication year and WC system category

– Campbell et al. 2022

- Uncertainty Working Group – C. Babcock (co-I)
- Biomass Working Group – L. M. Moskal
- NASA ABoVE – Exploring cross collaborations through D. Butman (co-I); co-chair the Wetland Working Group
- Hudak's NASA CMS 2018 - using products in our work

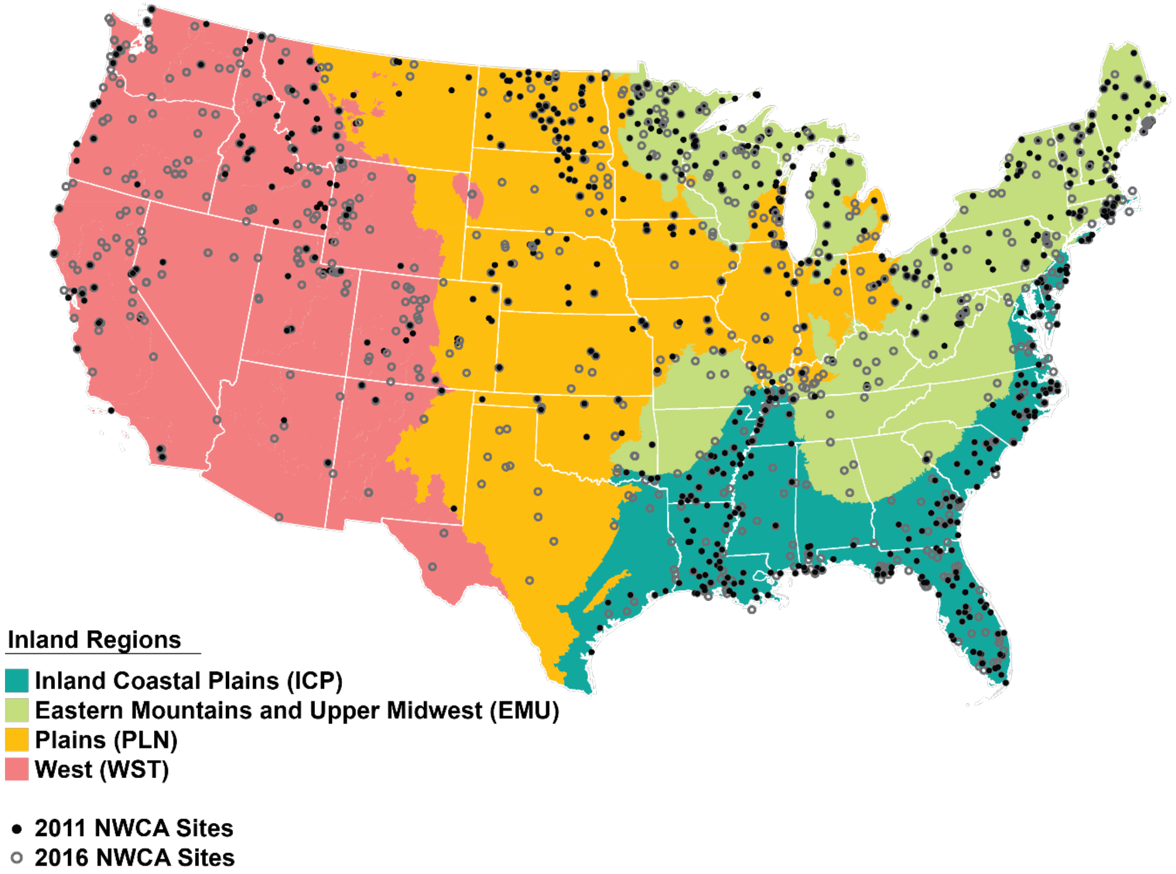
Future directions

In Phase 1, *we developed a remote sensing-based approach, called the Wetland Intrinsic Potential (WIP) tool that harnessed the topographic, temporal, and spectral characteristics of wetlands to improve wetland mapping, specifically focusing on solving the issue of forested wetlands missing from current wetland inventories (Halabisky et al, in review). We used the outputs from the WIP tool to develop spatially explicit estimates of belowground carbon (BGC) with associated uncertainty, for the entire wet to dry continuum in three forested watersheds across the precipitation gradient. The WIP tool is an open-source tool and is currently being used across the Pacific Northwest by our stakeholders.* ***Through our stakeholder engagement we have identified future needs and directions for this research***.

Teal Carbon – Phase 2: National wall-to-wall **Teal Carbon Phase 2: Scaling Wetland Carbon Accounting and Uncertainty Estimation to Meet Stakeholder Policy and Decision-Making Needs**

This will:

1. Provide improved wetland maps including mapping forested wetlands and wet soils that do not meet wetland definition.
2. Provide quantitative assessments of the carbon budget (AGC and BGC) for forested (previously omitted from maps) and all other terrestrial wetlands at a national scale.
3. Explore disturbance impacts on the carbon budget of terrestrial wetlands.



Through close collaboration with our stakeholders, we plan to leverage existing in-situ wetland data of AGC and BGC from the National Wetland Condition Assessment-NWCA (EPA 2011, 2016 and 2021 inventories), Washington State Dept. of Ecology, and the US Forest Service.

Lessons along the way?

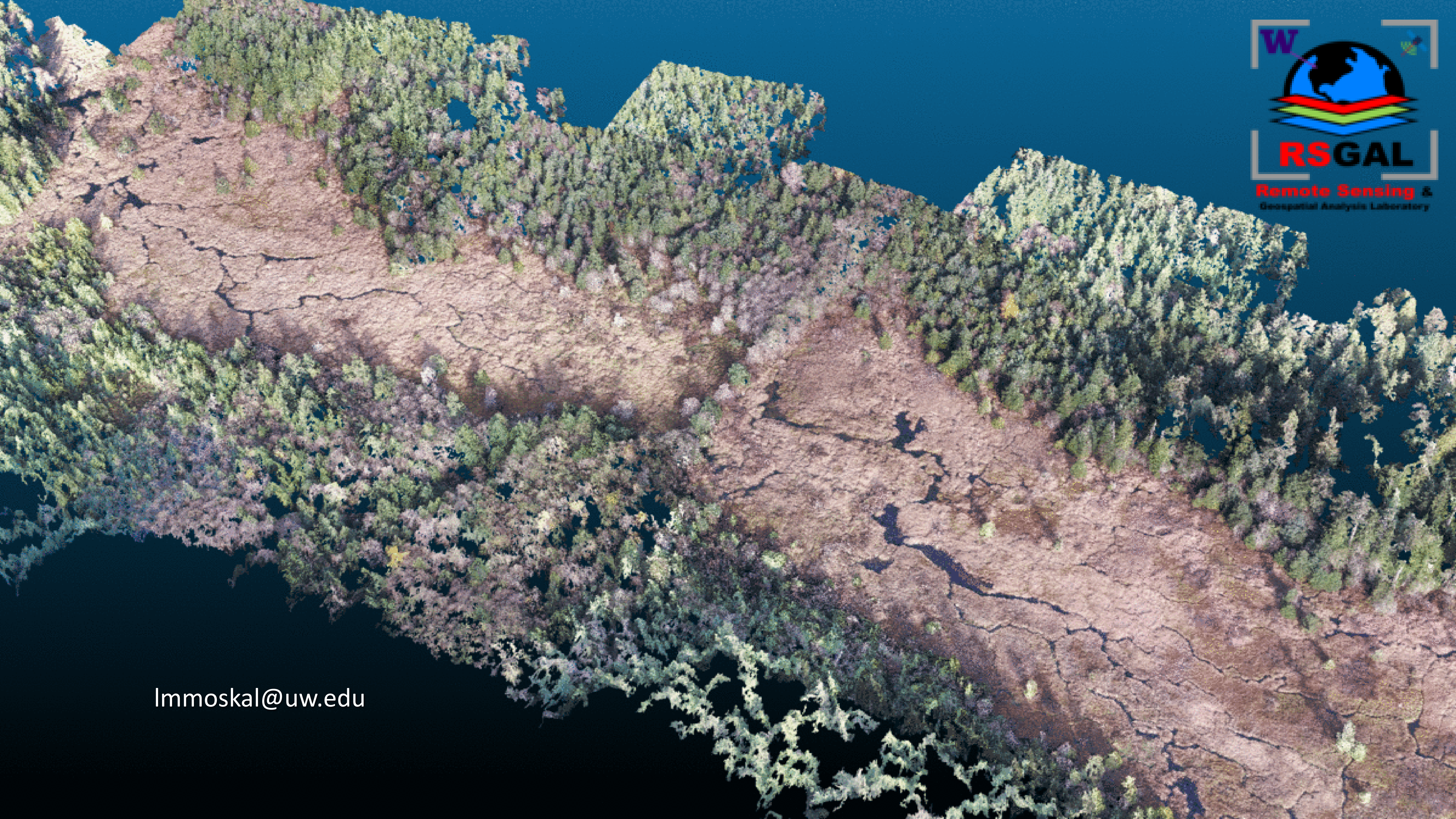
together we can go farther

- It takes a team
- Stakeholders are key
- Admit mistakes, these are opportunities

Your job is to:

'get messy and have fun'!

Anthony Stewart (PhD student) TealCarbon 2020 field campaign, Hoh river watershed



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