Advancing LiDAR and machine-learning applications for managing wildfires and cultural resources on public lands

Case studies in collaborative research with federal and academic partners

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Cultural Resource Sciences Program
New Mexico Consortium
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New Mexico Consortium

- Connects the Los Alamos National Laboratory (LANL) and other federal research with the three research universities in New Mexico (UNM, NMSU, NMTech)
- Non-profit educational institute to foster collaboration and cross-disciplinary science.

Cultural Resource Sciences Program

- Initiated in 2022 as one pillar of the **Center for Applied Fire and Ecosystem Science (CAFES)**
- Mission of the CRS program is to advance technology and data science to support archaeological research on public lands.

The CRS team

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CRS projects

- Advancing methods and technologies for managing fire risk to cultural resources
- LiDAR (terrestrial/aerial) data collection and modeling in archaeology
- Fire effects on archaeological sites
- Paleofire/cultural burning in restoration ecology

Our Motivation

- Ecological, geographical, and other physical sciences well represented in federal research initiatives and investments.
- Archaeology less represented, despite legislative obligation to manage and non-renewable resource…not to mention tangible and intangible cultural importance.

The Challenge

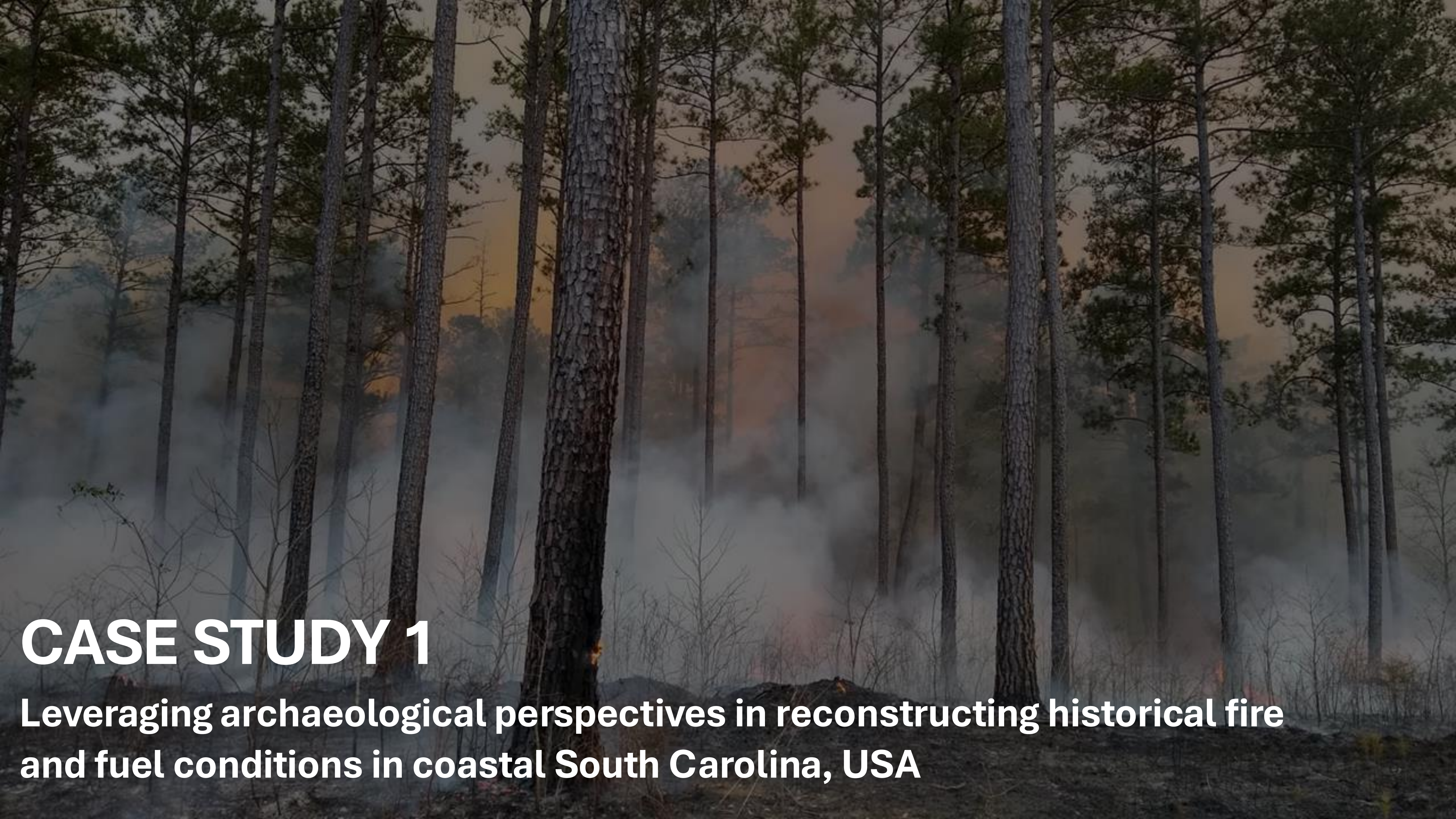
- Develop archaeological science and technology to support cultural resource management and research on public lands.
- How do we design actionable science, interdisciplinary approaches, and direct management implications?

Case study 1:

Leveraging archaeological perspectives in reconstructing historical fire and fuel conditions in coastal South Carolina, USA

Case study 2:

Deep learning approaches to archaeological object detection for enhancing site inventorying and wildfire protection measures

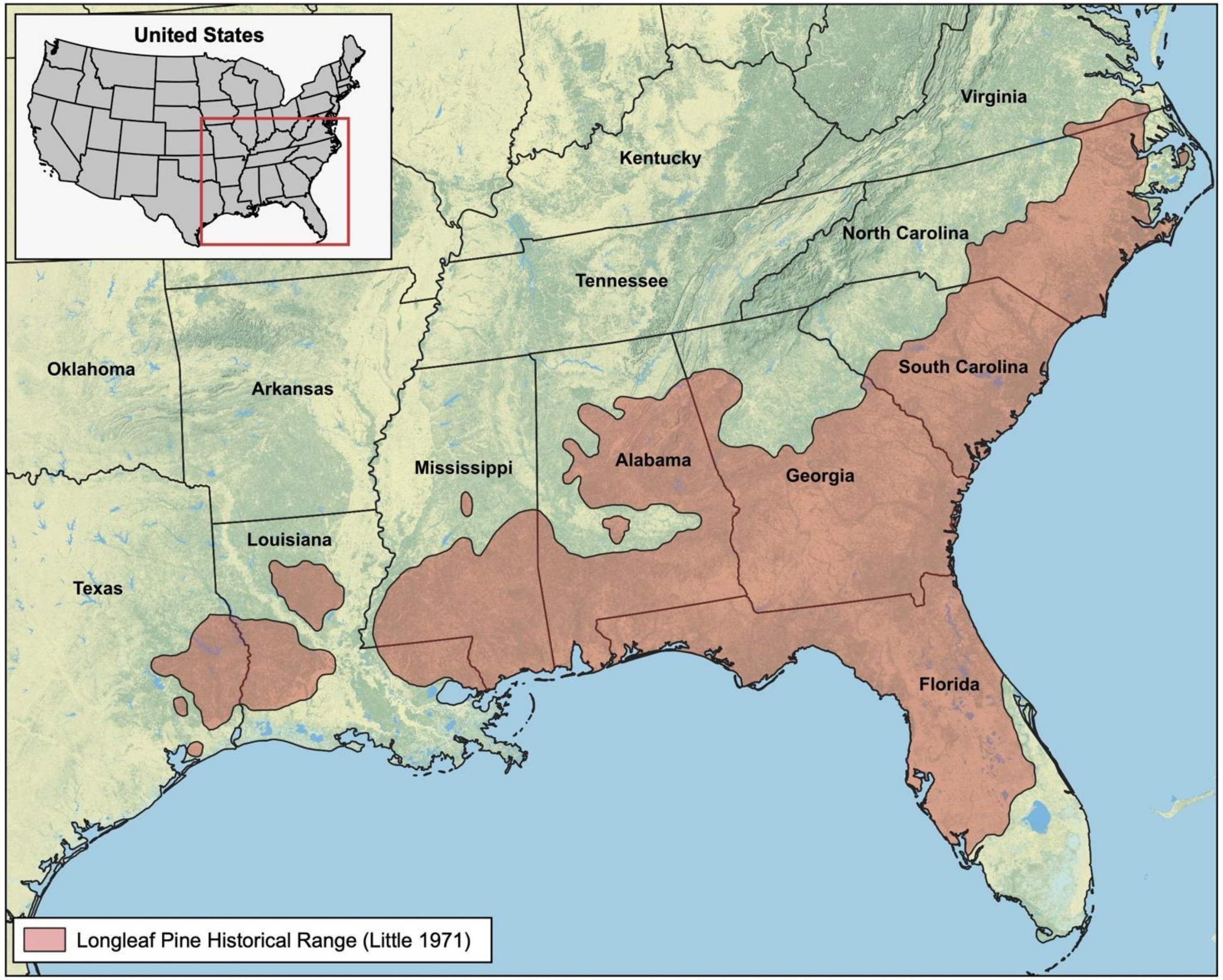


CASE STUDY 1

Leveraging archaeological perspectives in reconstructing historical fire and fuel conditions in coastal South Carolina, USA


Restoring Longleaf pine Ecosystems

Longleaf pine (*Pinus palustris)* ecosystems cover about 2 million acres of the US Southeast — which some suggest is **4%** of their original range.



Multitude of federal, state, private, and academic institutions involved in initiatives to restore and manage these ecosystems.

Fire is a **fundamental** component of Longleaf pine life history

Restoration includes regular **Rx burning**

US Forest Service – SRS: https://www.srs.fs.usda.gov/longleaf/research/silviculture

In the pine woods, Florida, 1906. Library of Congress: https://lccn.loc.gov/2016803946

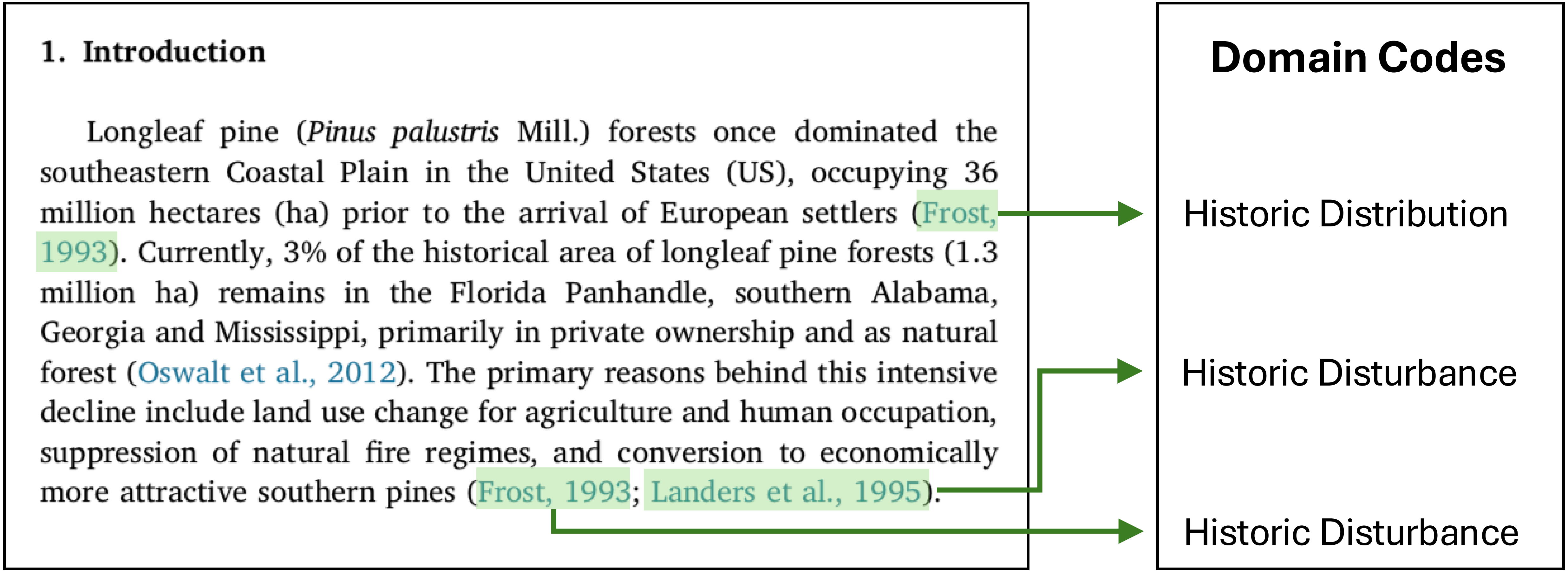
Restoration ecology points to **historical baselines** to justify fire frequency, fire intensity, and stand structure…

Which landscapes?

When?

Why?

Bibliometric analysis to determine how the current Longleaf pine restoration literature use historical baselines

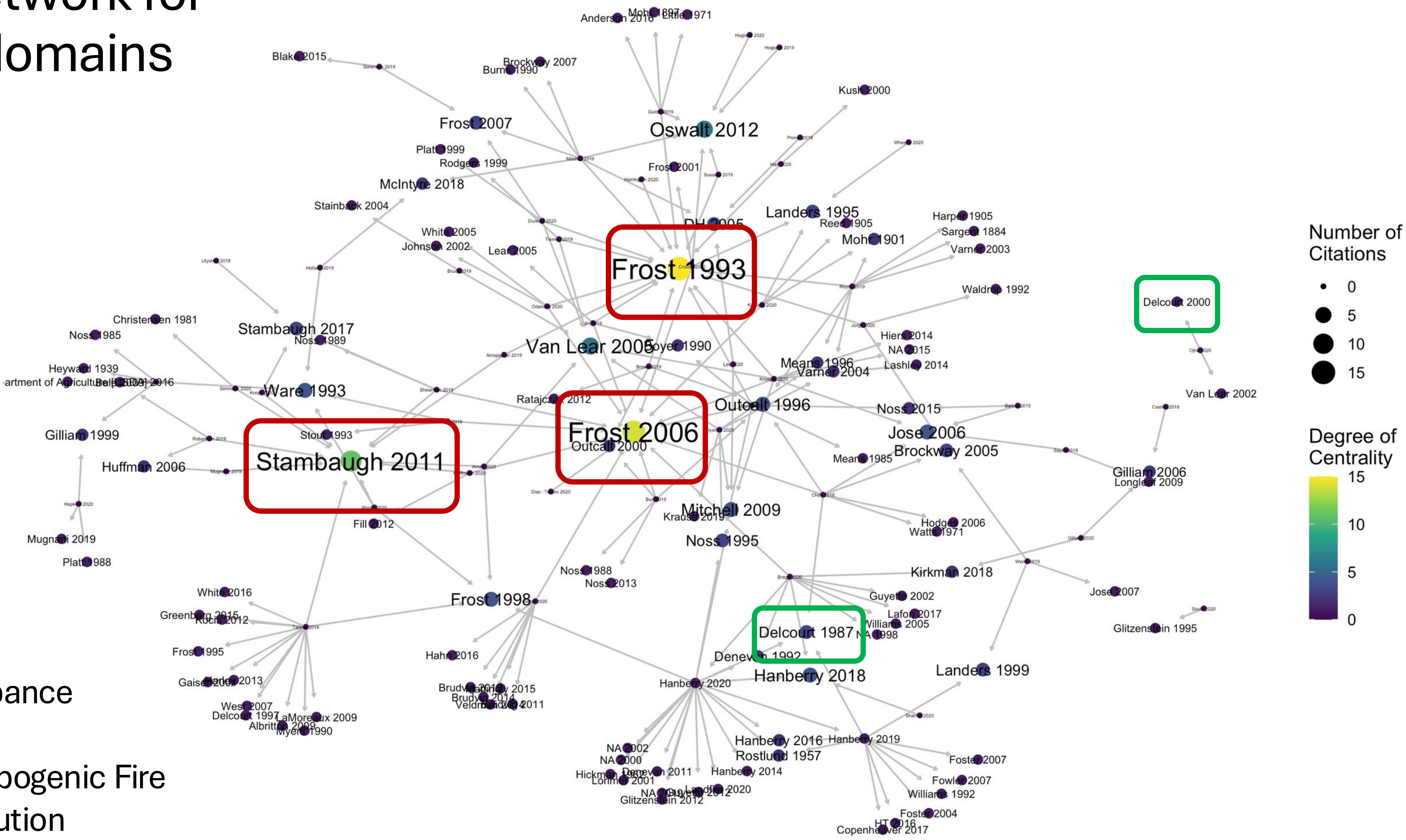


1. Introduction

Longleaf pine (*Pinus palustris* Mill.) forests once dominated the southeastern Coastal Plain in the United States (US), occupying 36 million hectares (ha) prior to the arrival of European settlers (Frost, 1993). Currently, 3% of the historical area of longleaf pine forests (1.3 million ha) remains in the Florida Panhandle, southern Alabama, Georgia and Mississippi, primarily in private ownership and as natural forest (Oswalt et al., 2012). The primary reasons behind this intensive decline include land use change for agriculture and human occupation, suppression of natural fire regimes, and conversion to economically more attractive southern pines (Frost, 1993; Landers et al., 1995).

Susaeta, A., Gong, P., 2019. Economic viability of longleaf pine management in the Southeastern United States. Forest Policy and Economics 100, 14–23. https://doi.org/10.1016/j.forpol.2018.11.004

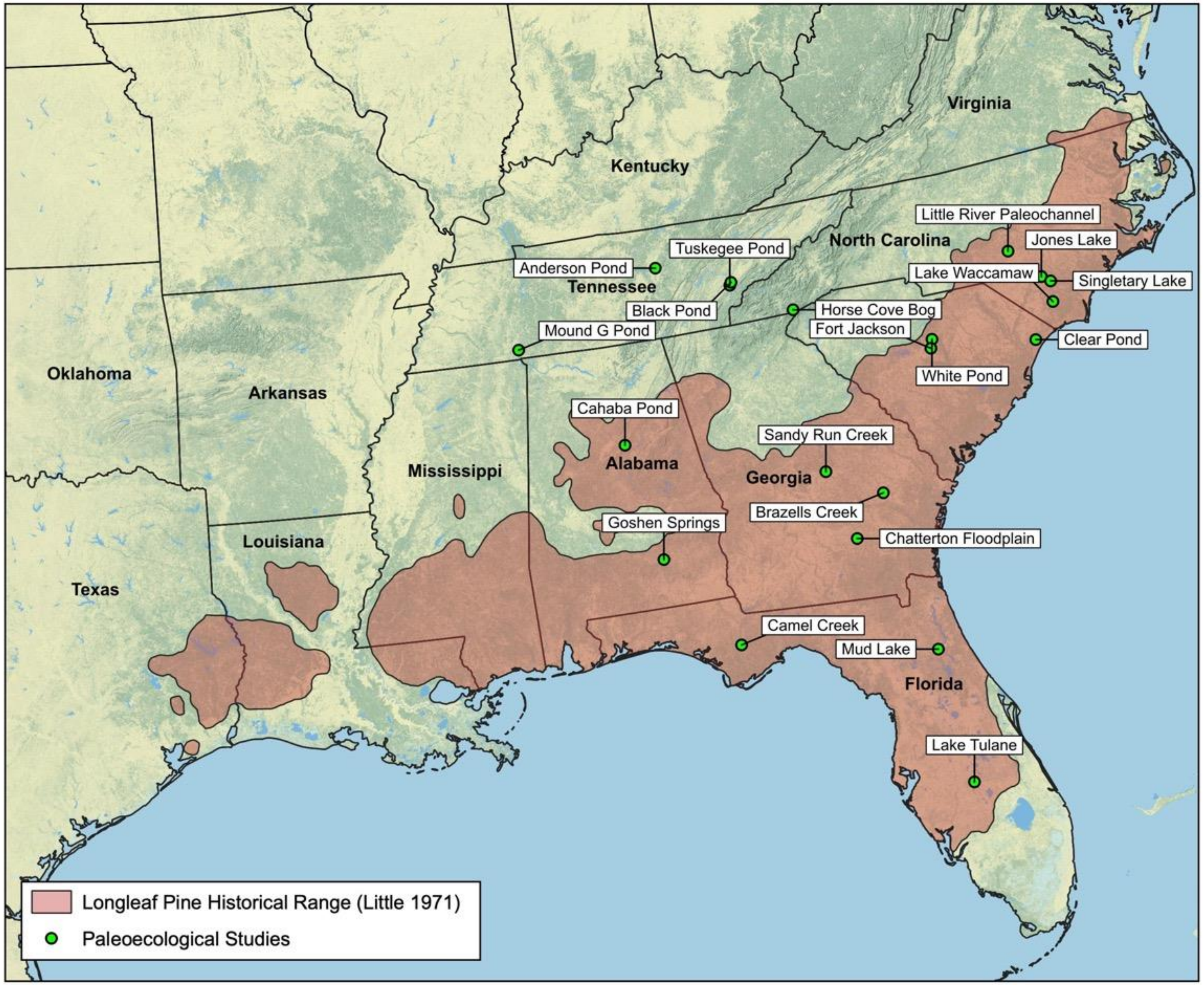
Citation network for all coded domains

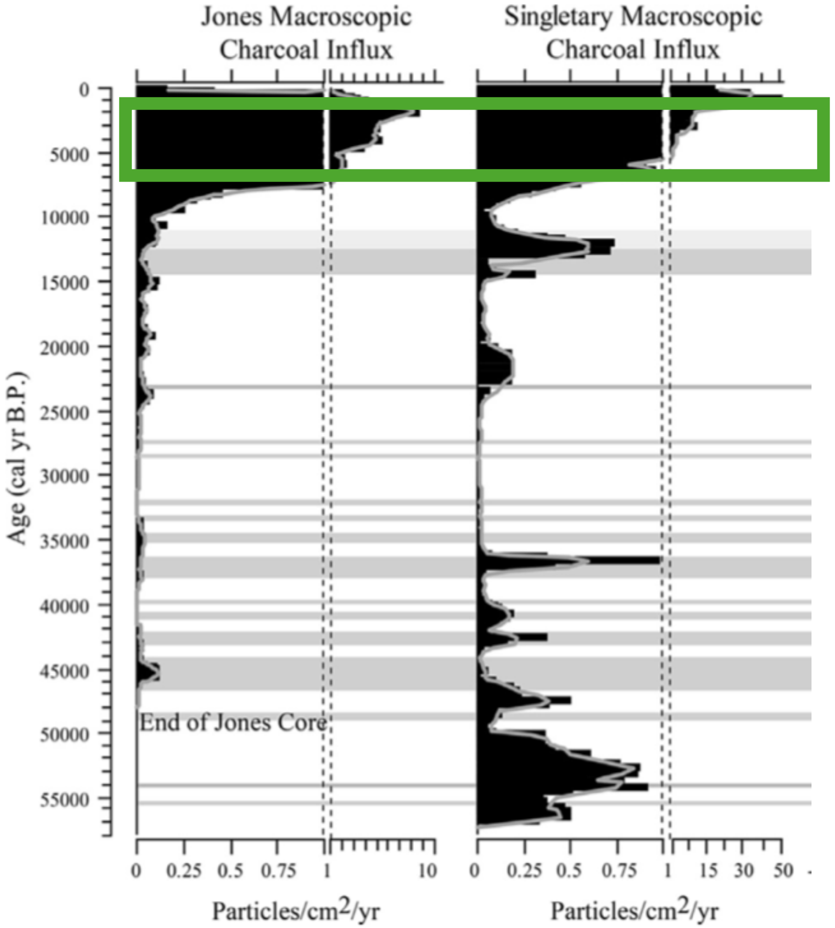


Domains

- Historic Disturbance
- Historic FRI
- Historic Anthropogenic Fire
- Historic Distribution
- Historic Longleaf Ecosystem Condition

What about **palynology** and **charcoal** studies?

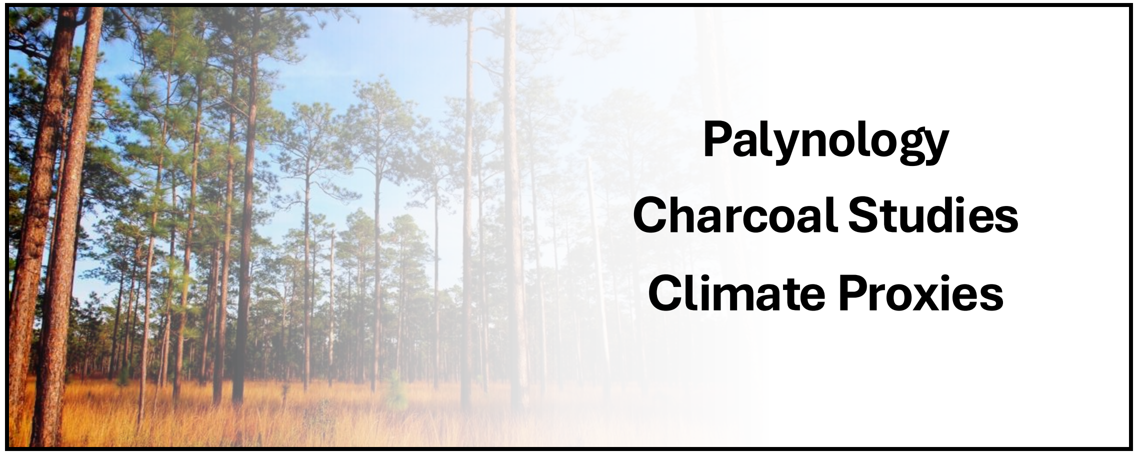




Challenges of **resolution** and **scale**.

Spencer, J., Jones, K.B., Gamble, D.W., Benedetti, M.M., Taylor, A.K., Lane, C.S., 2017. Late-Quaternary records of vegetation and fire in southeastern North Carolina from Jones Lake and Singletary Lake. Quaternary Science Reviews 174, 33–53. https://doi.org/10.1016/j.quascirev.2017.09.001

Historical baseline extends back to the Pleistocene, but lacks fine temporal resolution in recent centuries



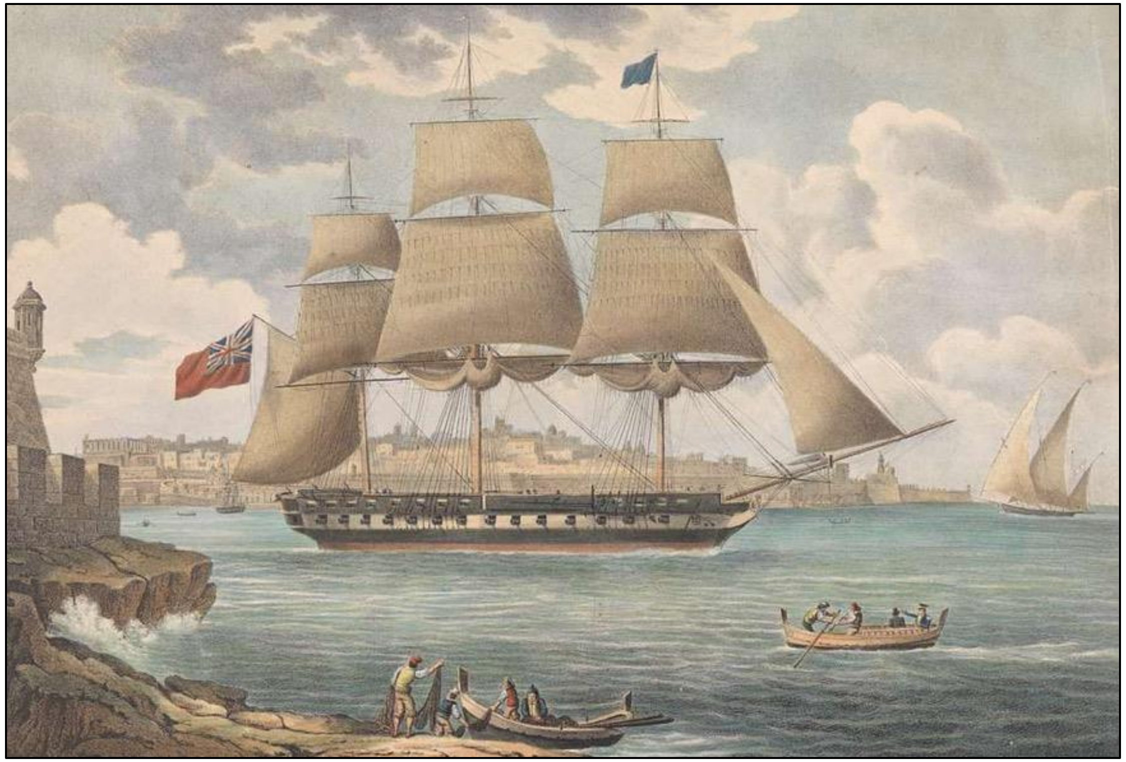
Fundamental Gap in Knowledge

Historical baseline extends back 100-250 years, but well after European colonization

Time

Identifying the **challenge** and **recognizing** opportunities for archaeological approaches


Leveraging Archaeology:
The Naval Stores Industry and Longleaf Pines



Naval stores and the myth of ***'pristine forests'***

Tar / pitch production in kilns

Turpentine (box cutting / cat faces)

Wood/stump distilling

Photos courtesy of South Carolina Forestry Commission

A Brief History of the Naval Stores Industry in the Southeast US

AD 1600s
Sporadic references to naval stores in North America

AD 1705
British Naval Stores Act creates economic incentives for colonies to export tar, pitch, turpentine

AD 1730s
Removal of British bounty reduces naval store production

AD 1775 – 1783
Increased demand for domestically produced Naval stores during the American Revolutionary War

AD 1780s – 1830s
Continued high production of tar and pitch, but turpentine gradually becoming the dominate industry

AD 1830s – 1900
Continued decline in tar and pitch production, but increased turpentine production, particularly after the American Civil War

AD 1900s
Tar and pitch production are very minor industries and turpentine production continues to grow until the 1930s and 1940s

What is a **tar kiln** in the Southeast US?

Tar Kiln Schematic

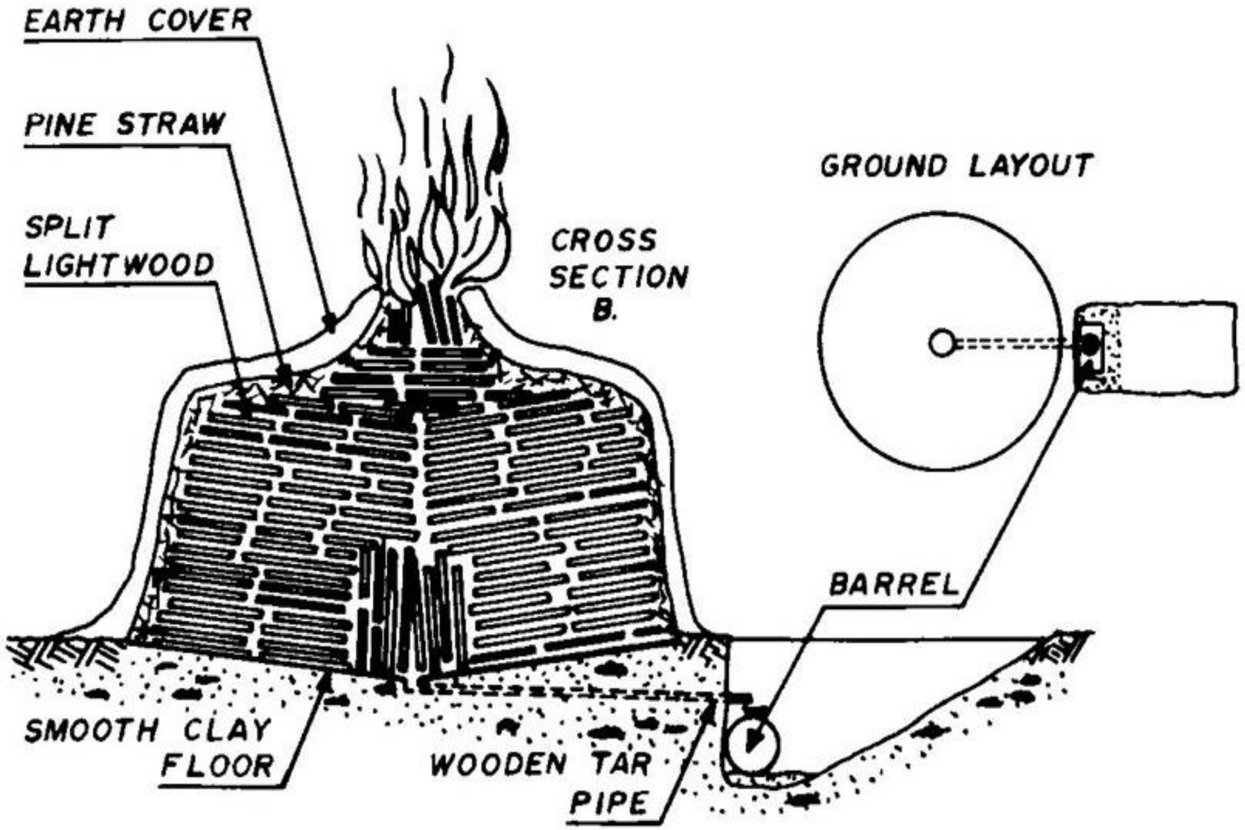
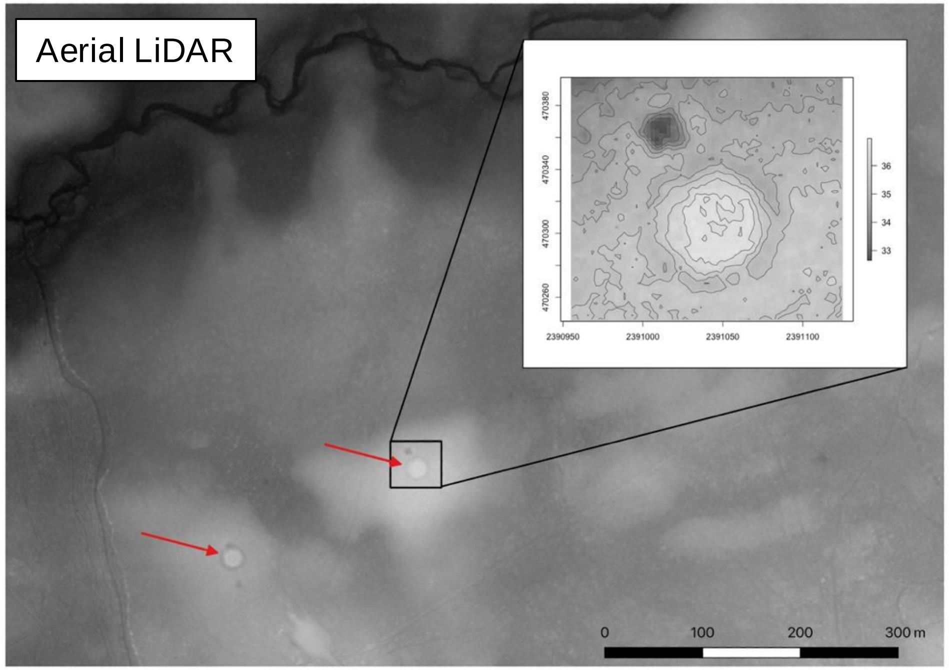


Figure is reproduced from Combes 1974

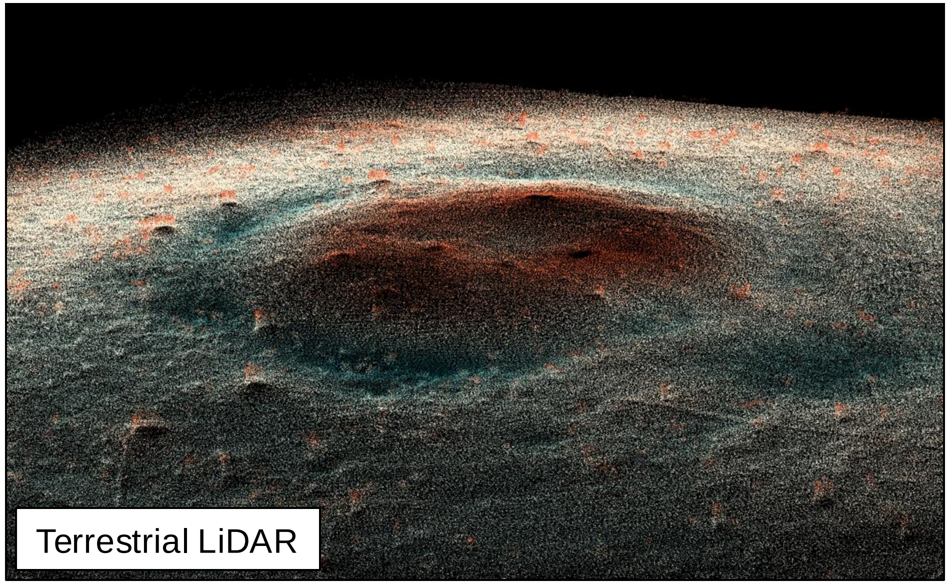
Tar Kiln Examples

What do tar kilns look like in the **field**?

Photograph of archaeological tar kiln (April 2021)



Aerial LiDAR



Terrestrial LiDAR

Connecting tar kilns to **fire and fuels**

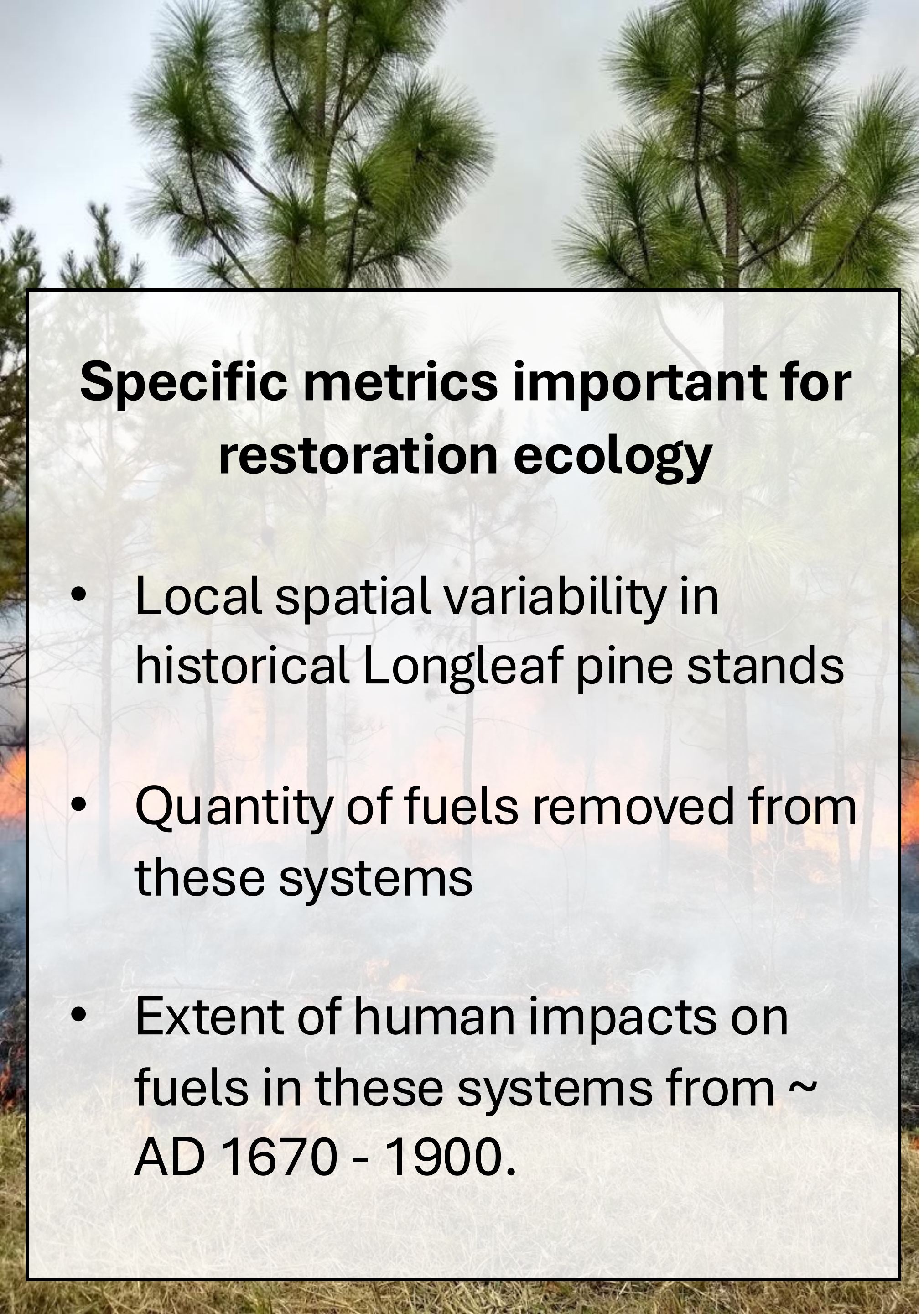
- Kiln-produced tar required large quantities of Longleaf pine "light wood"

- Primary accounts suggest ~400 cubic meters of lightwood needed per kiln…**about 10 standard shipping containers**

- Implications for Longleaf pine stand density, course woody debris, and fuel connectivity — all factors that shape our historical baselines

Project Objectives

1. Utilize remote sensing datasets to identify tar kiln production sites
2. Quantify tar kiln sites / attributes within 170,000-hectare study area in collaboration with USFS
3. Validate dataset with archaeological survey and previously known sites
4. Connect tar kilns to the emergence of largescale exploitation of Longleaf pine ecosystems and influence on fire and fuel conditions to support management objectives



Specific metrics important for restoration ecology

- Local spatial variability in historical Longleaf pine stands
- Quantity of fuels removed from these systems
- Extent of human impacts on fuels in these systems from ~ AD 1670 - 1900.

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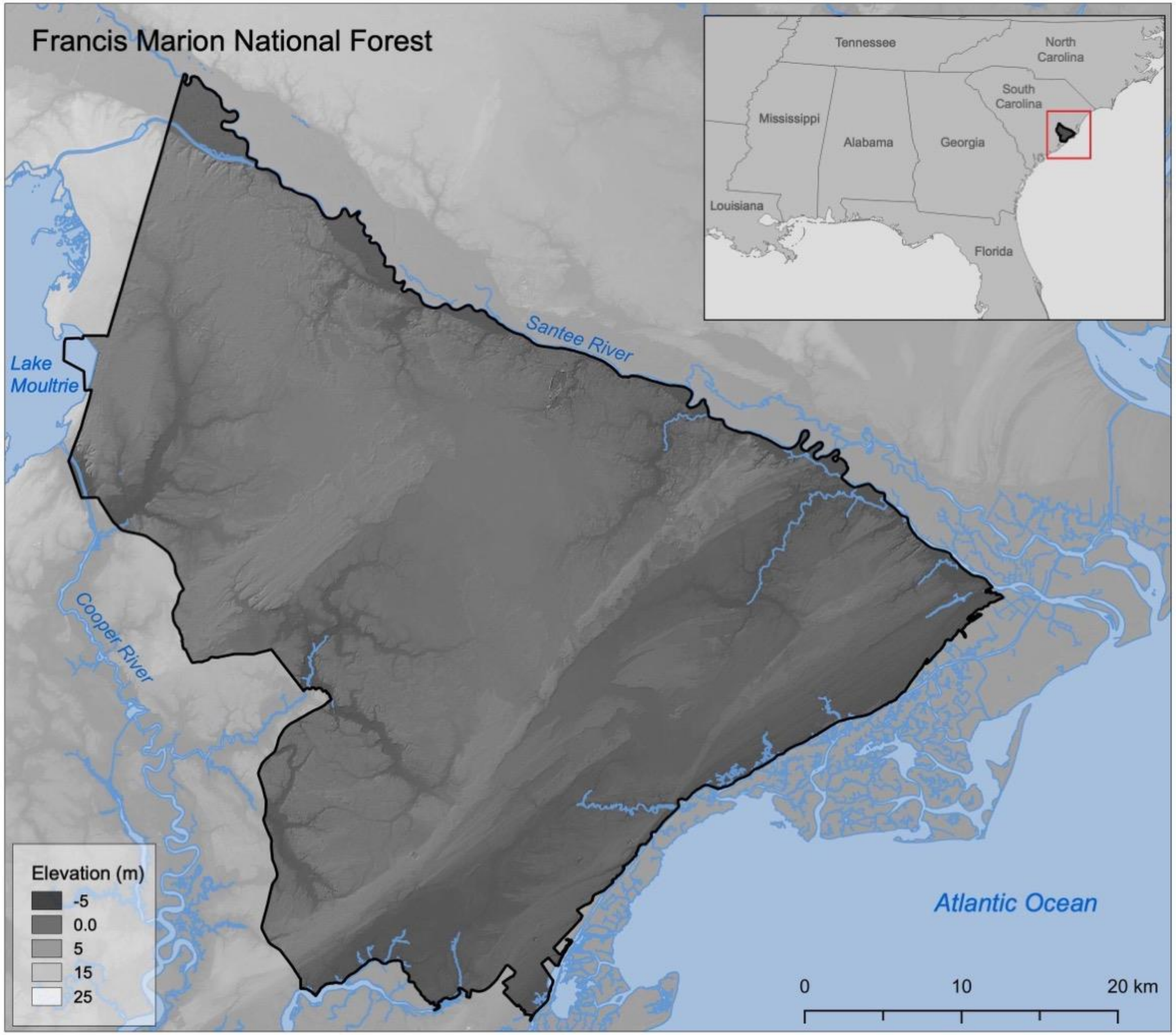
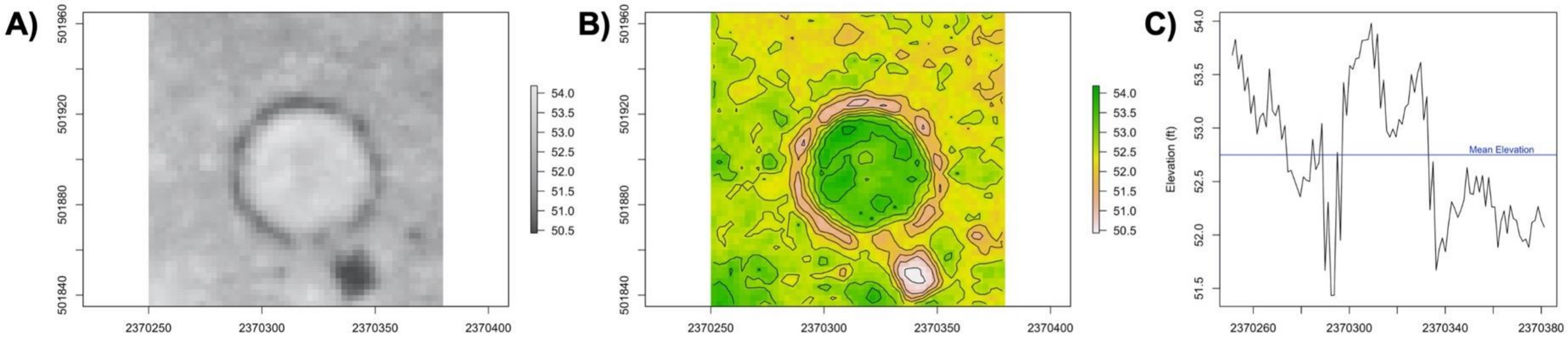
The **Francis Marion National Forest** serves as the study area for this project

- Managed by the US Forest Service (170,000-hectares)
- 50 km northeast of Charleston, SC
- Euro-American land-use since the founding of Charles Town in AD 1670.



The Tar Kiln Feature Detection (**TKFD**) workflow

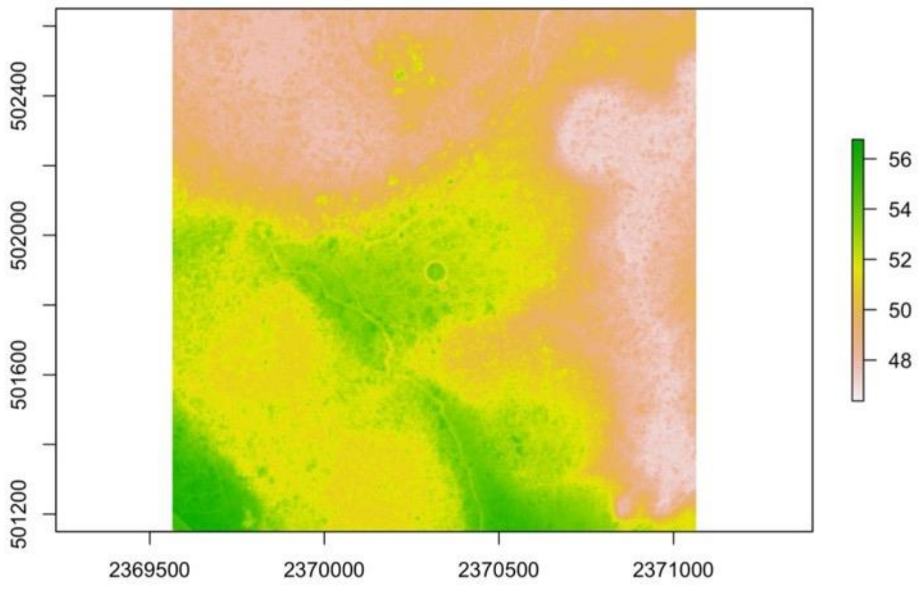


- Scripted, open-source workflow linking R and FIJI
- Computer vision technique to extract archaeological features that might not be highly visible in the field
- Relies on tar kiln morphology for detection: [**A**] circular, [**B**] slightly mounded, and [**C**] surrounding trench

The Tar Kiln Feature Detection (**TKFD**) workflow

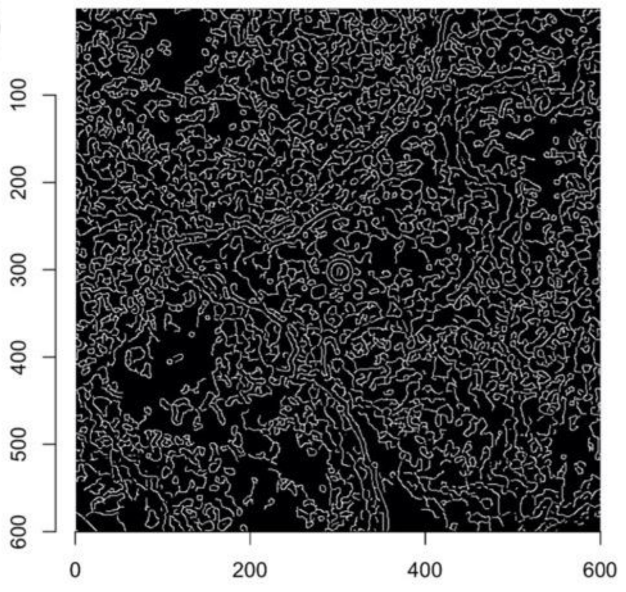
Brief overview

A)



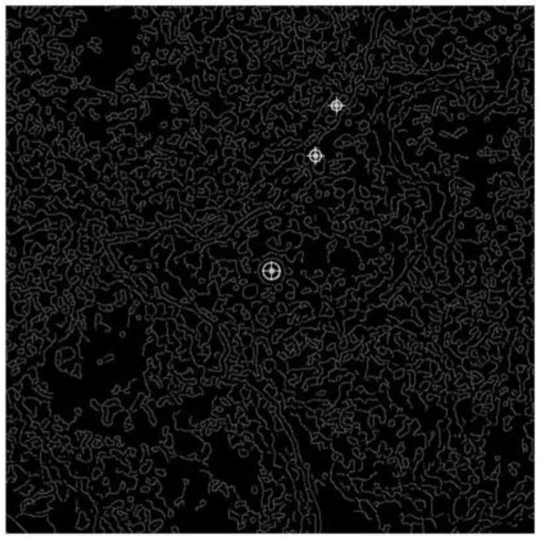
1-meter DEM from aerial Lidar

B)

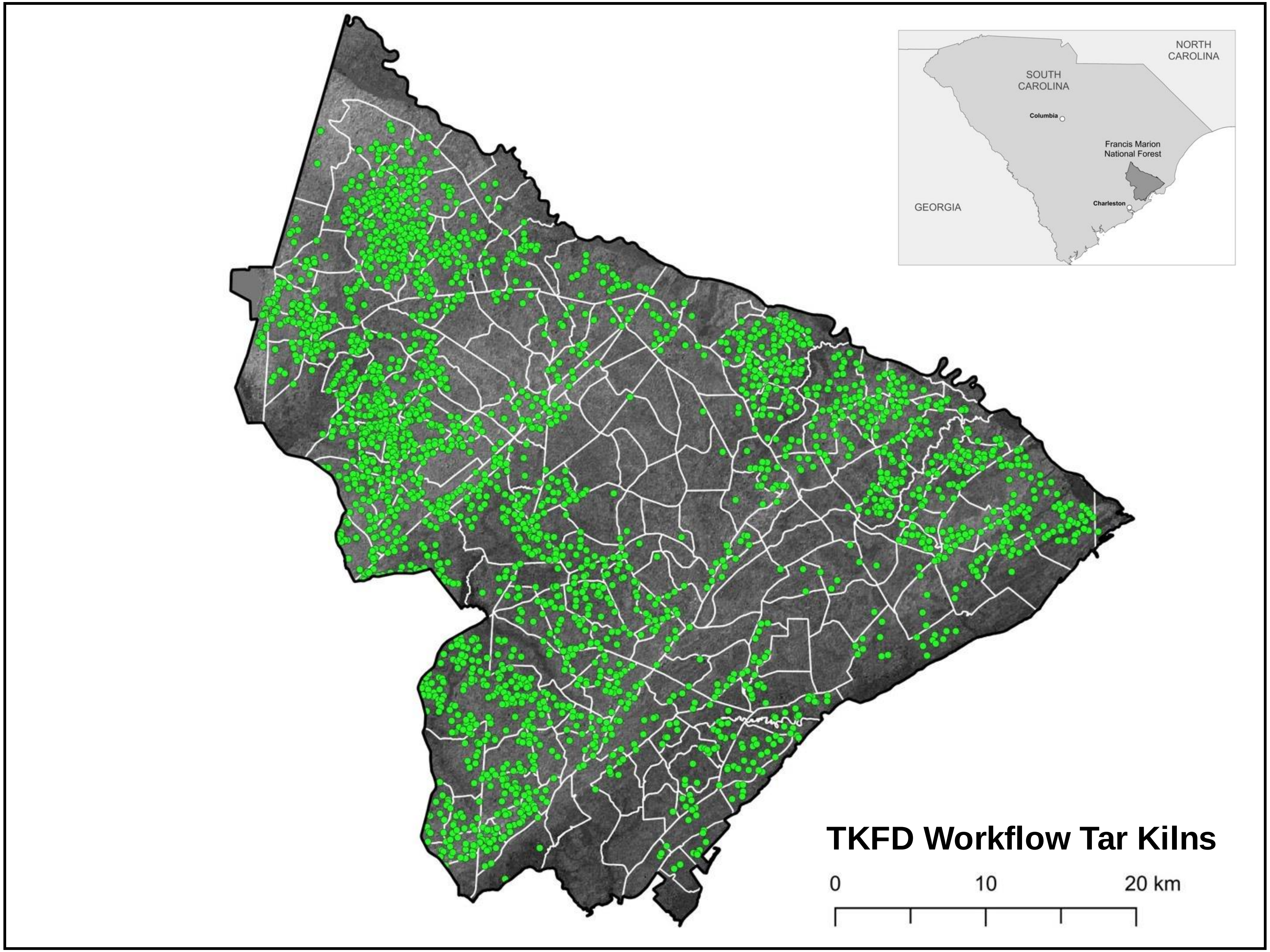


Canny edge detector to extract image structure

C)



Circle Hough Transform to detect circular objects



Distribution of tar kilns according to the **TKFD workflow**, but how do we verify these results?

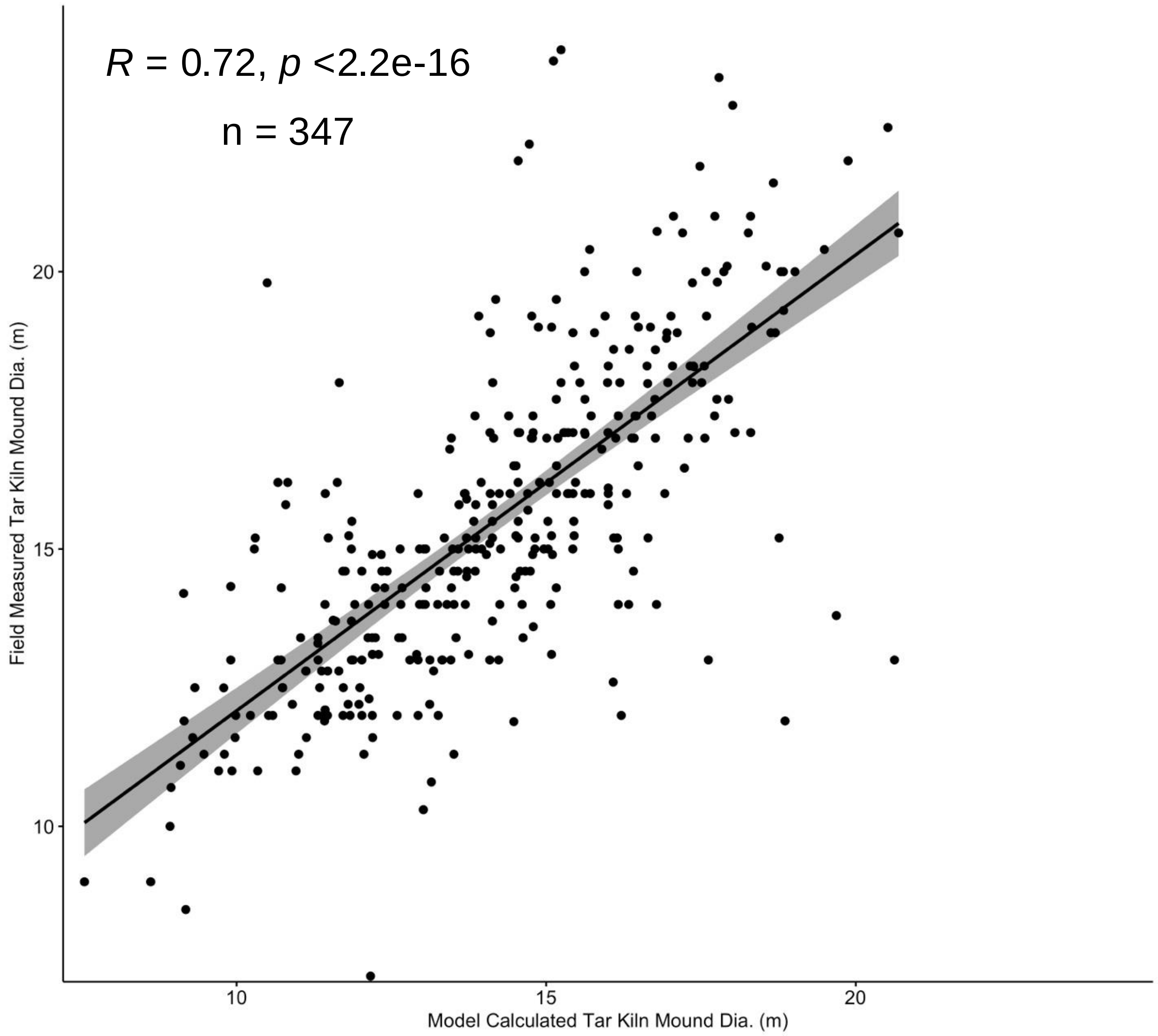
Validation of **Tar Kilns** detection

Previously known tar kilns, fieldwork, and random points

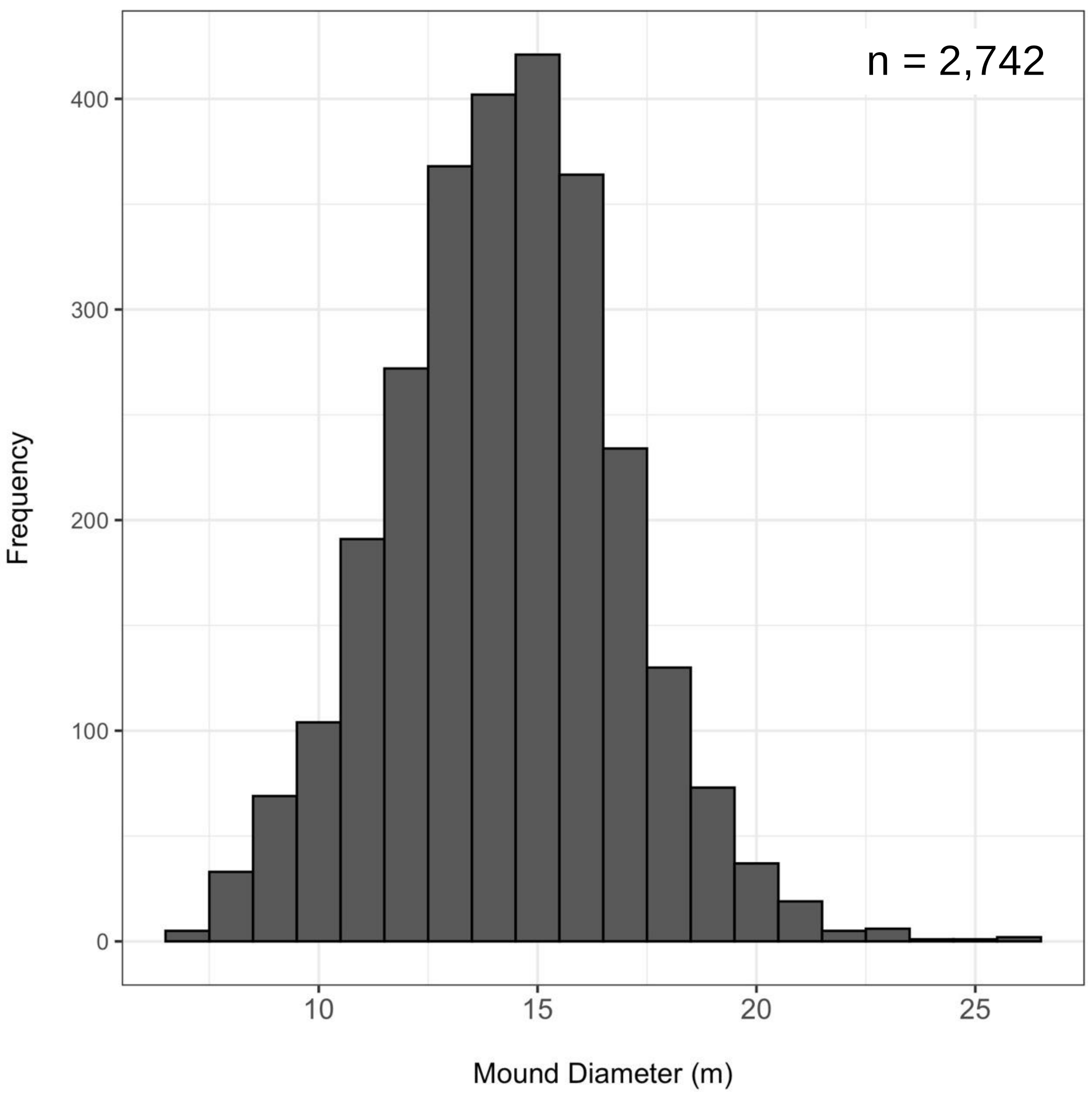
Balanced Accuracy: 90.6%

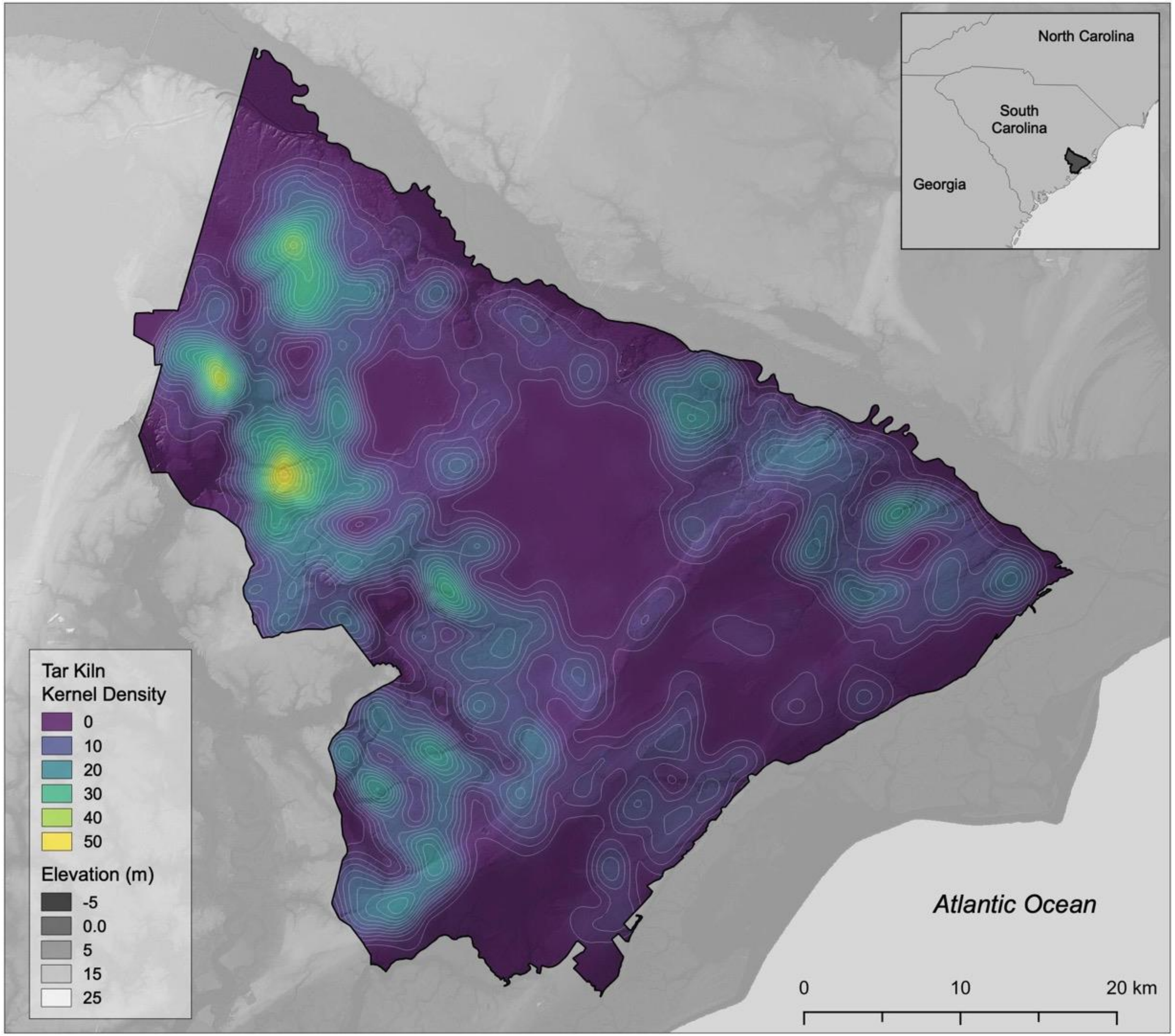
Measuring and validating of tar kiln diameter

Comparison to field measured kilns



Tar Kiln Diameter (m) Distribution

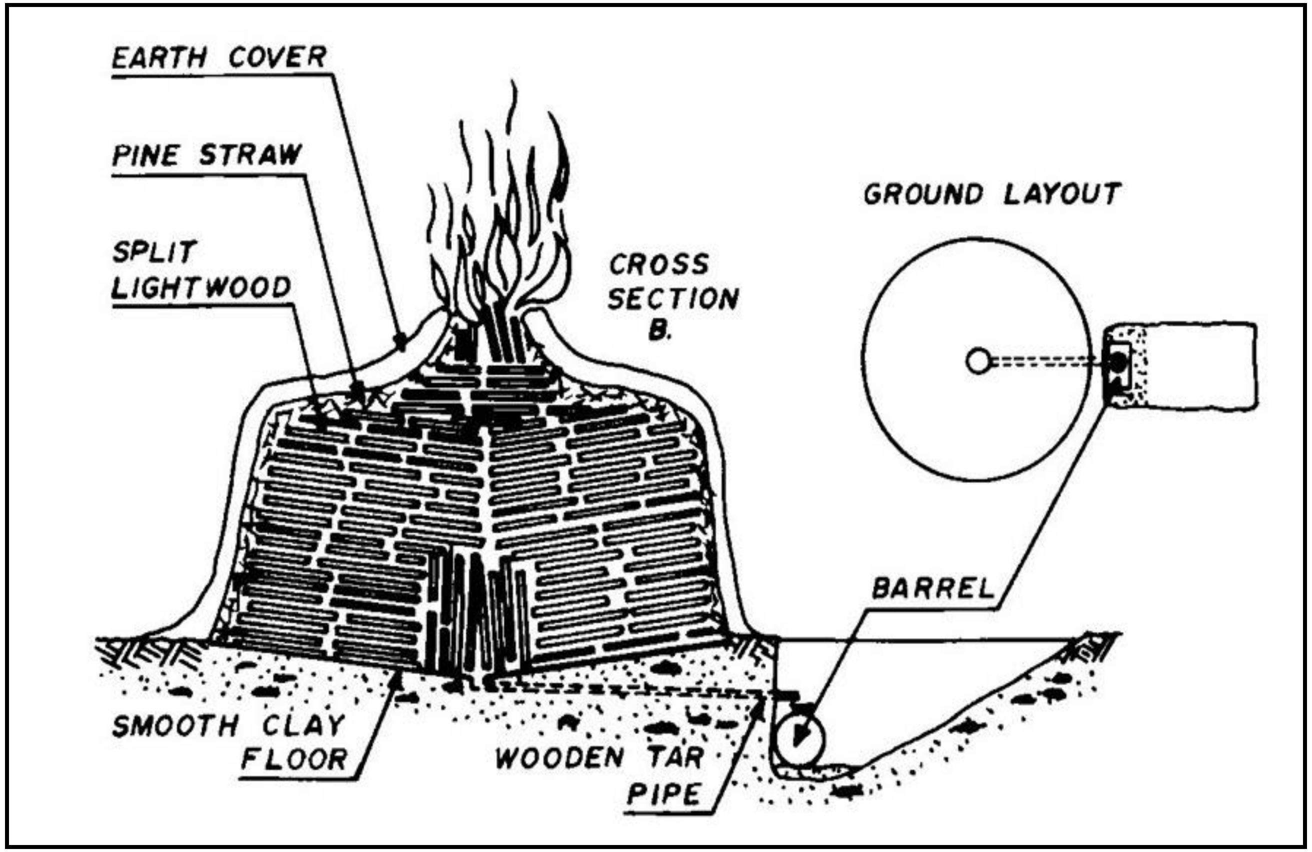




Tar kilns as a proxy for the local distribution of Longleaf Pine stands

Heterogeneous and patchy, rather than uniform

Estimating the **quantity** of Longleaf pine removed from the Francis Marion National Forest



Lightwood calculations based on: Gonzalez-Benecke, C.A., Gezan, S.A., Martin, T.A., Cropper, W.P., Samuelson, L.J., Leduc, D.J., 2014. Individual Tree Diameter, Height, and Volume Functions for Longleaf Pine. Forest Science 60, 43–56. https://doi.org/10.5849/forsci.12-074

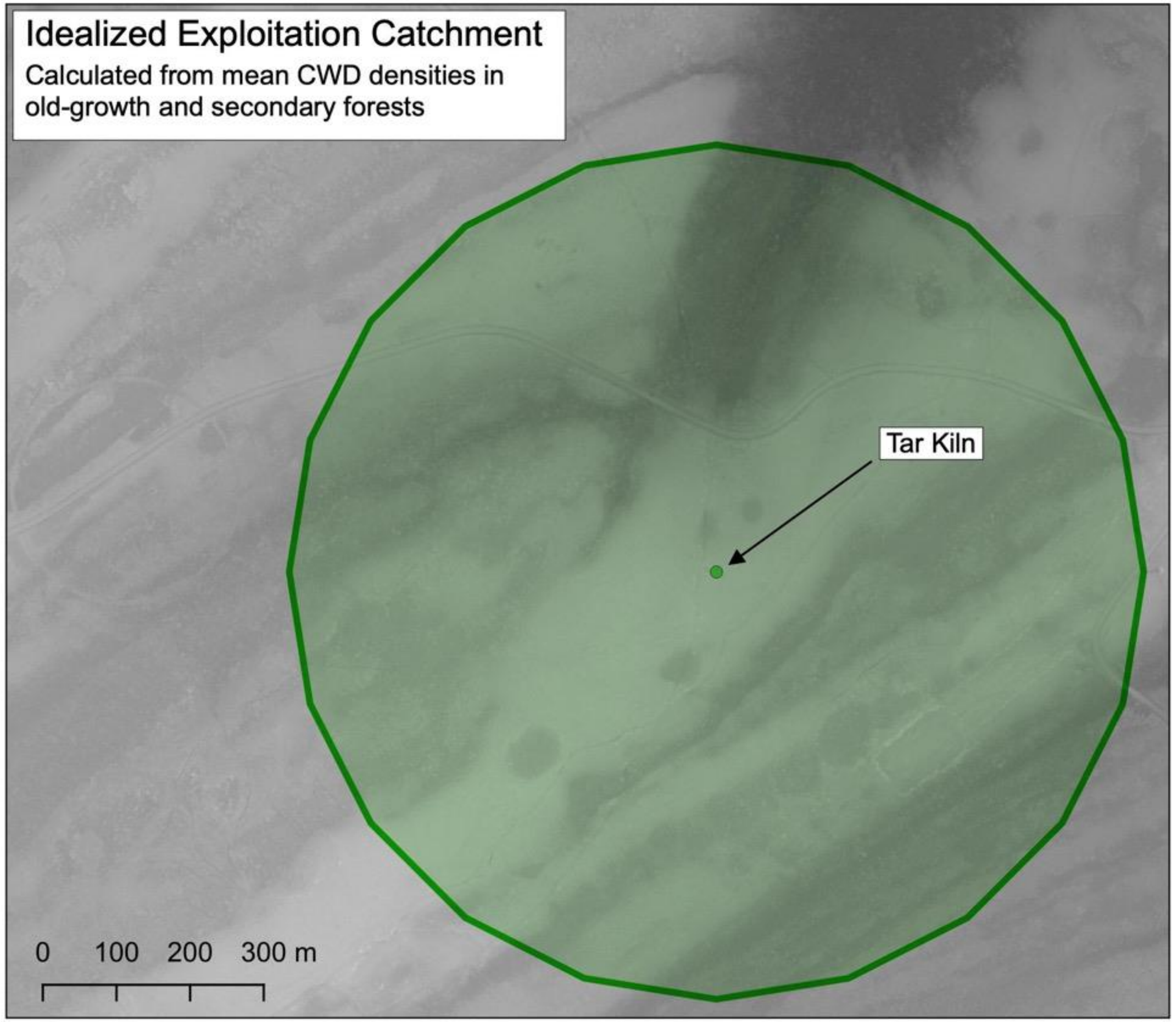
- Kiln volume calculated from diameter

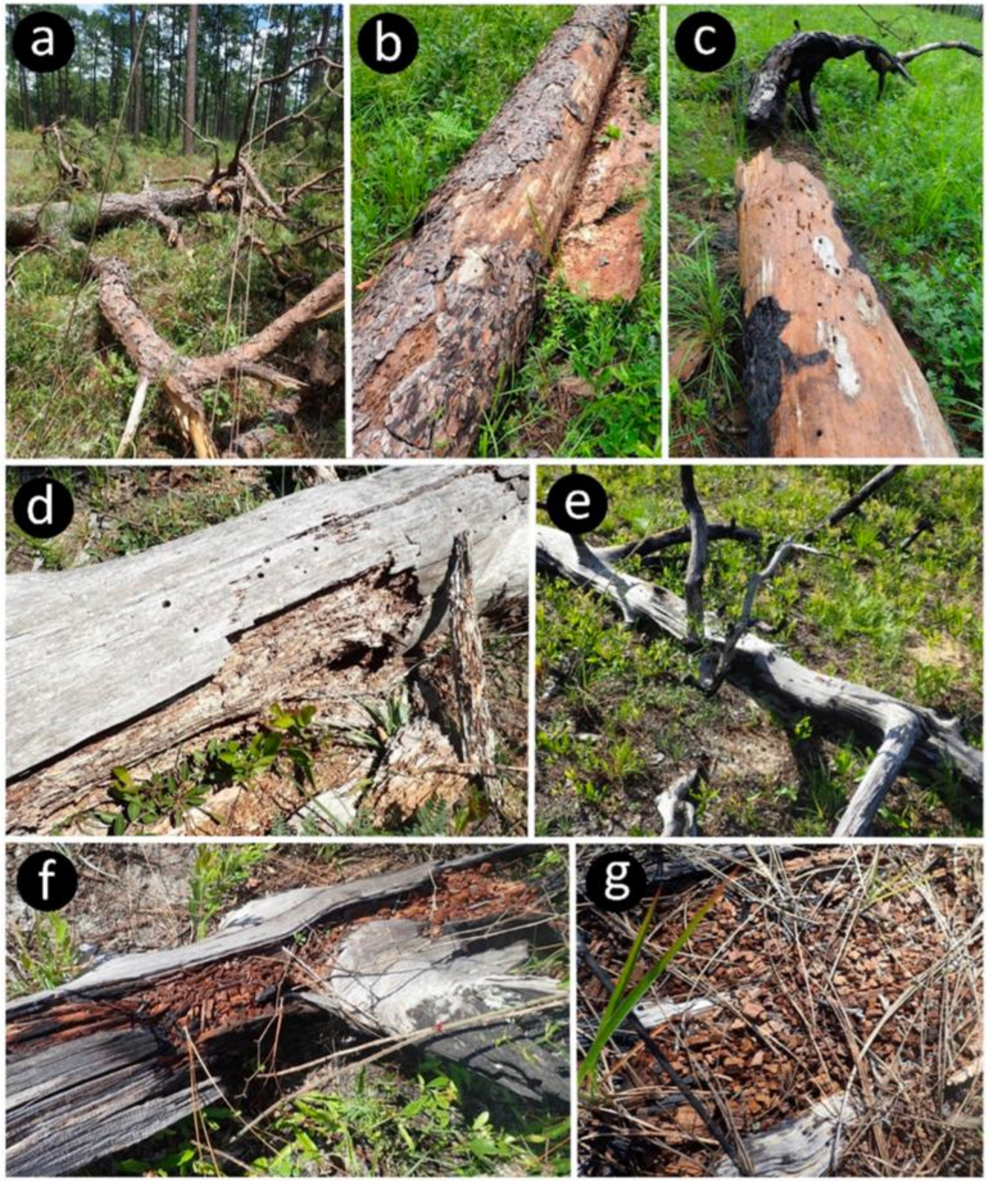
$$V = \pi r^2 \frac{h}{3}$$

If each kiln were used only once…

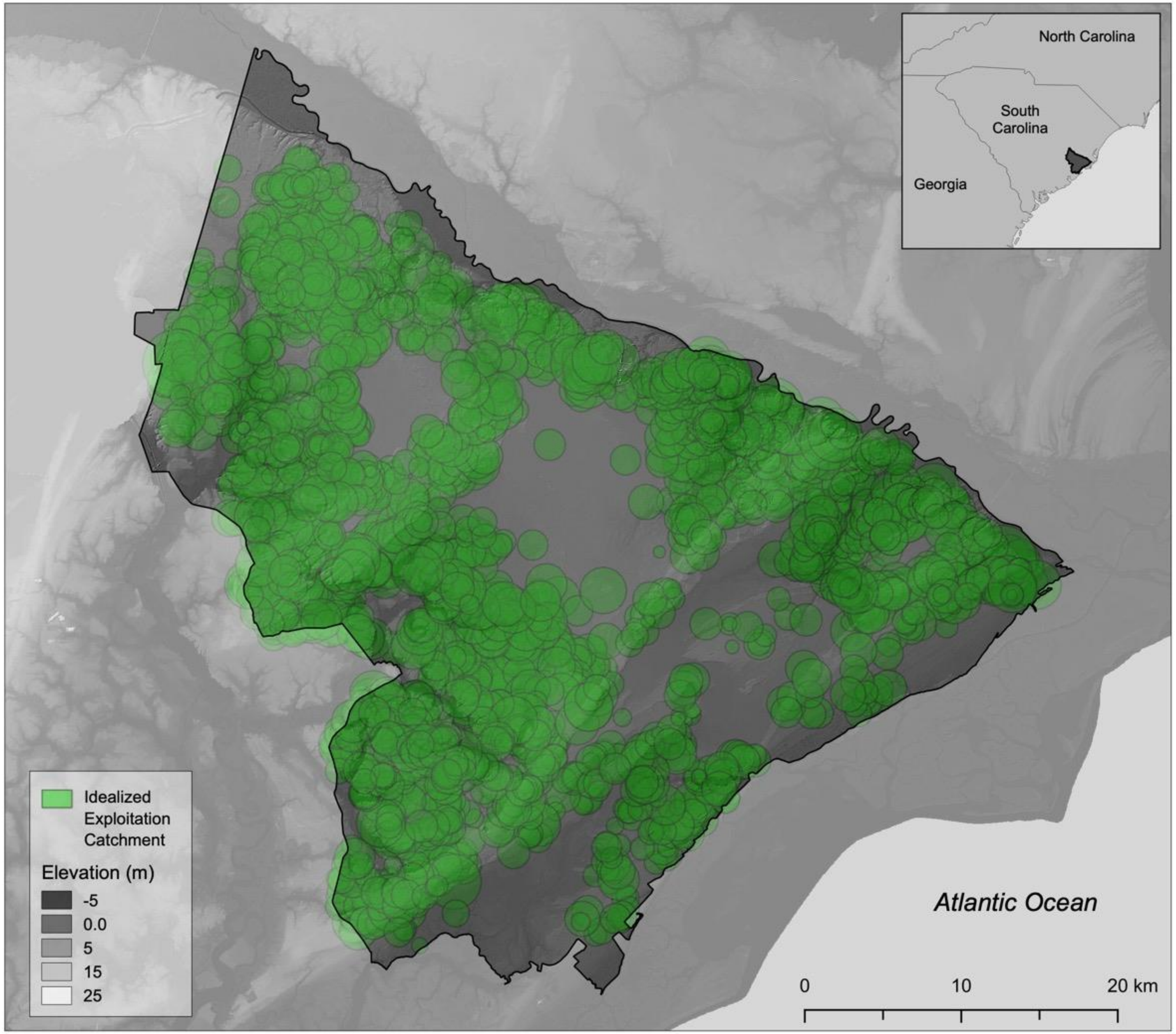
- Almost **1.2 million cubic meters** of lightwood needed
- Equivalent of over **750,000** mature, old-growth Longleaf pines removed

Quantifying the extent of **human impacts** on fuels in these systems from ~ AD 1670 - 1900





Ulyshen, M.D., Horn, S., Pokswinski, S., McHugh, J.V., Hiers, J.K., 2018. A comparison of coarse woody debris volume and variety between old-growth and secondary longleaf pine forests in the southeastern United States. Forest Ecology and Management 429, 124–132. https://doi.org/10.1016/j.foreco.2018.07.017



Estimated that **76%** of the Francis Marion National Forest was impacted by coarse woody debris collection for tar production between ~ **AD 1670 - 1900**


The Archaeology of Fire and Fuels

What does this all mean for the restoration of **Longleaf pine ecosystems**?

- Acknowledging that these are, and have been, intensively modified landscapes

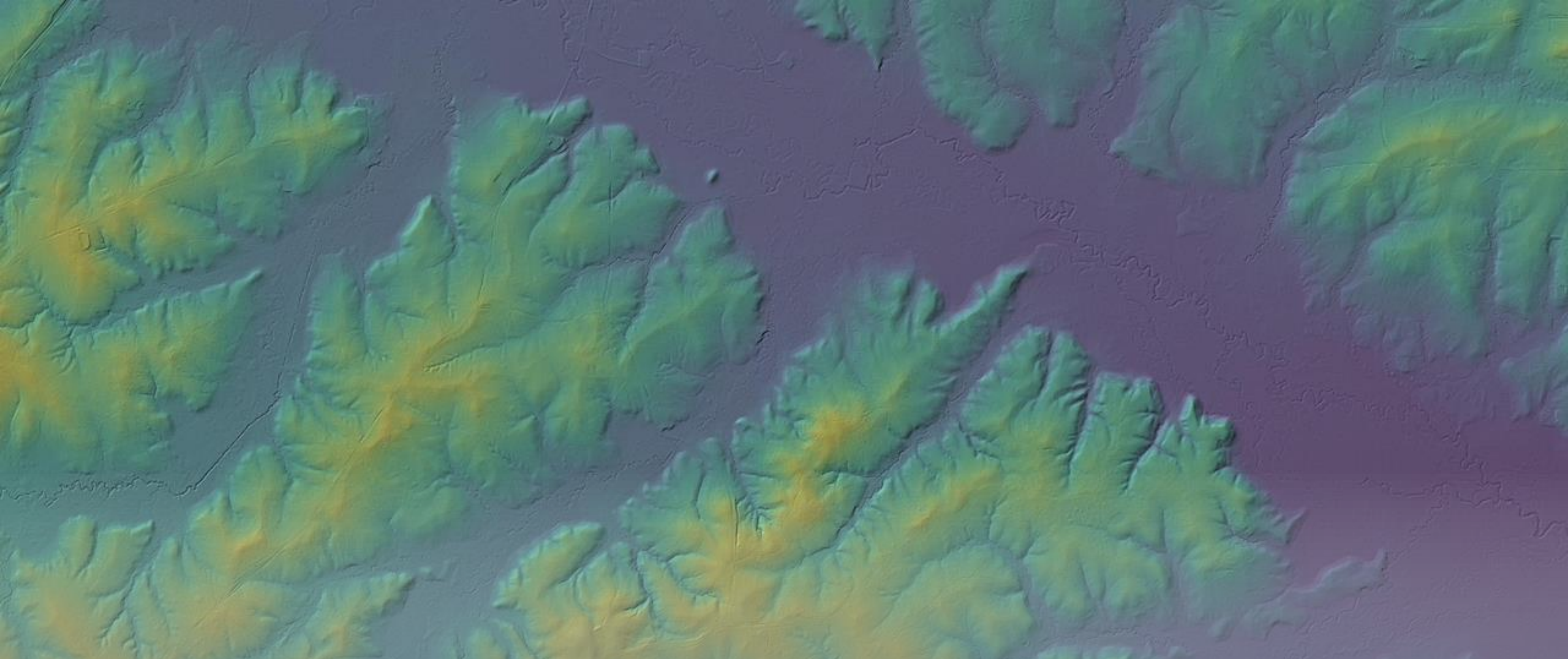
- Bias in historical reference conditions

- Situating historical fire regimes into a context of historical fuels

A Social Ecology of Fuels

Where do we go from here?

- Recognize these as social-ecological systems—restoration to a “pristine” condition is not possible or helpful
- How do humans, fire, and fuels interact in these forests in the context of climate change
- Leverage archaeological perspectives and remote sensing techniques (Aerial LiDAR) to understand the social ecology of fire and fuels elsewhere



CASE STUDY 2

Deep learning approaches to archaeological object detection for enhancing site inventorying and wildfire protection measures

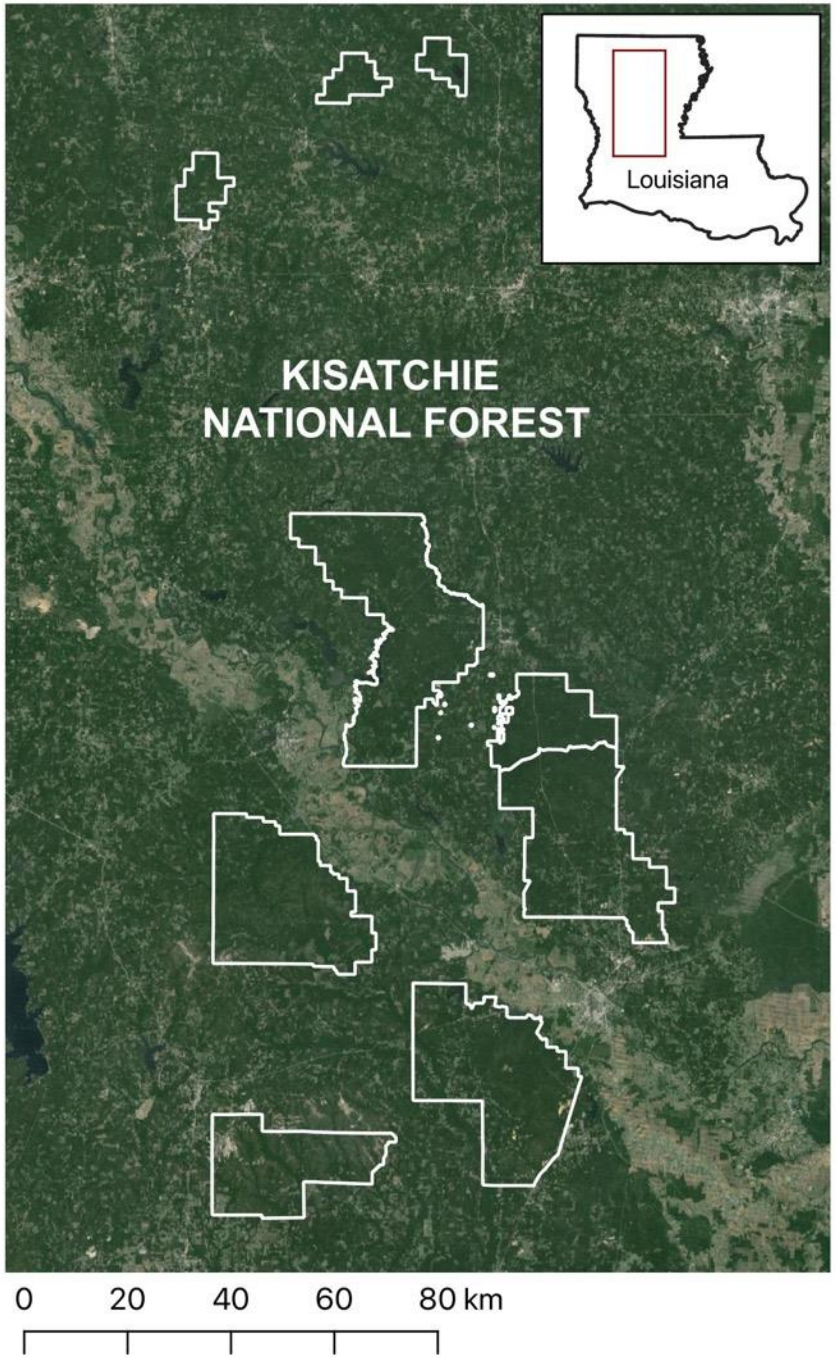

Meeting the challenges of CRM on public lands

The Kisatchie National Forest Heritage LiDAR Project

- Three-year project to collect and process **LiDAR data** on the Kisatchie National Forest and to develop heritage feature detection tools to improve predictive models, site identification, and cultural resource management.

- Develop analytical products for the Heritage Program to aid in monitoring the effects of disturbance (e.g. wildfire) for use throughout the Southern Region.

- Partners include both **USFS and USFWS**



- **Kisatchie National Forest** is the only national forest in Louisiana

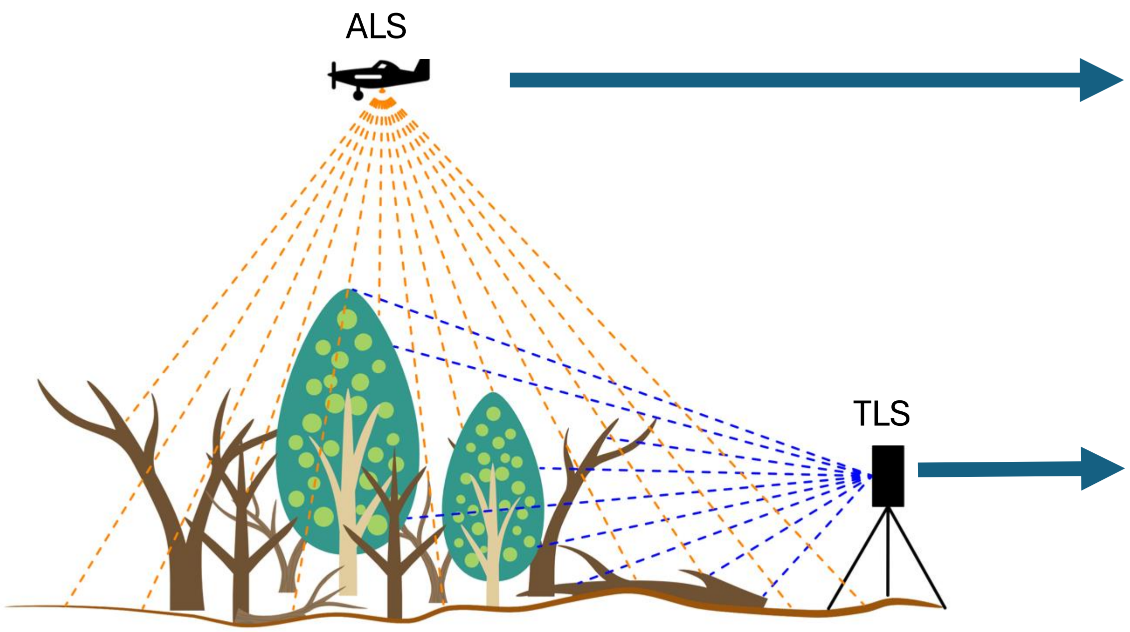
- Over **600,000 acres** of public land, intermixed with private inholdings and DoD property

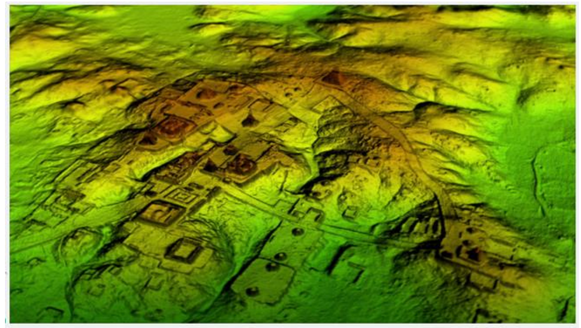
- Diverse landscapes (dry upland conifers, wet lowland swamps) and diverse archaeology spanning the late Pleistocene to the 20th century

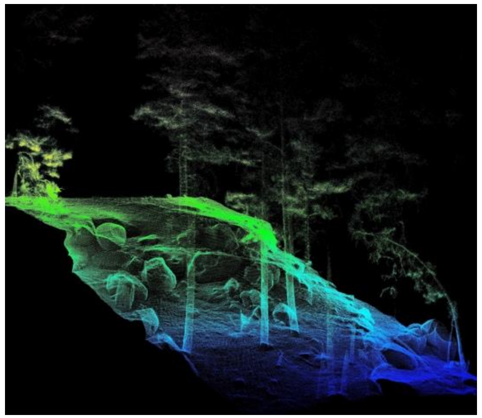

LiDAR and deep learning for archaeological
inventorying and risk mitigation

Aerial and Terrestrial LiDAR for CRM

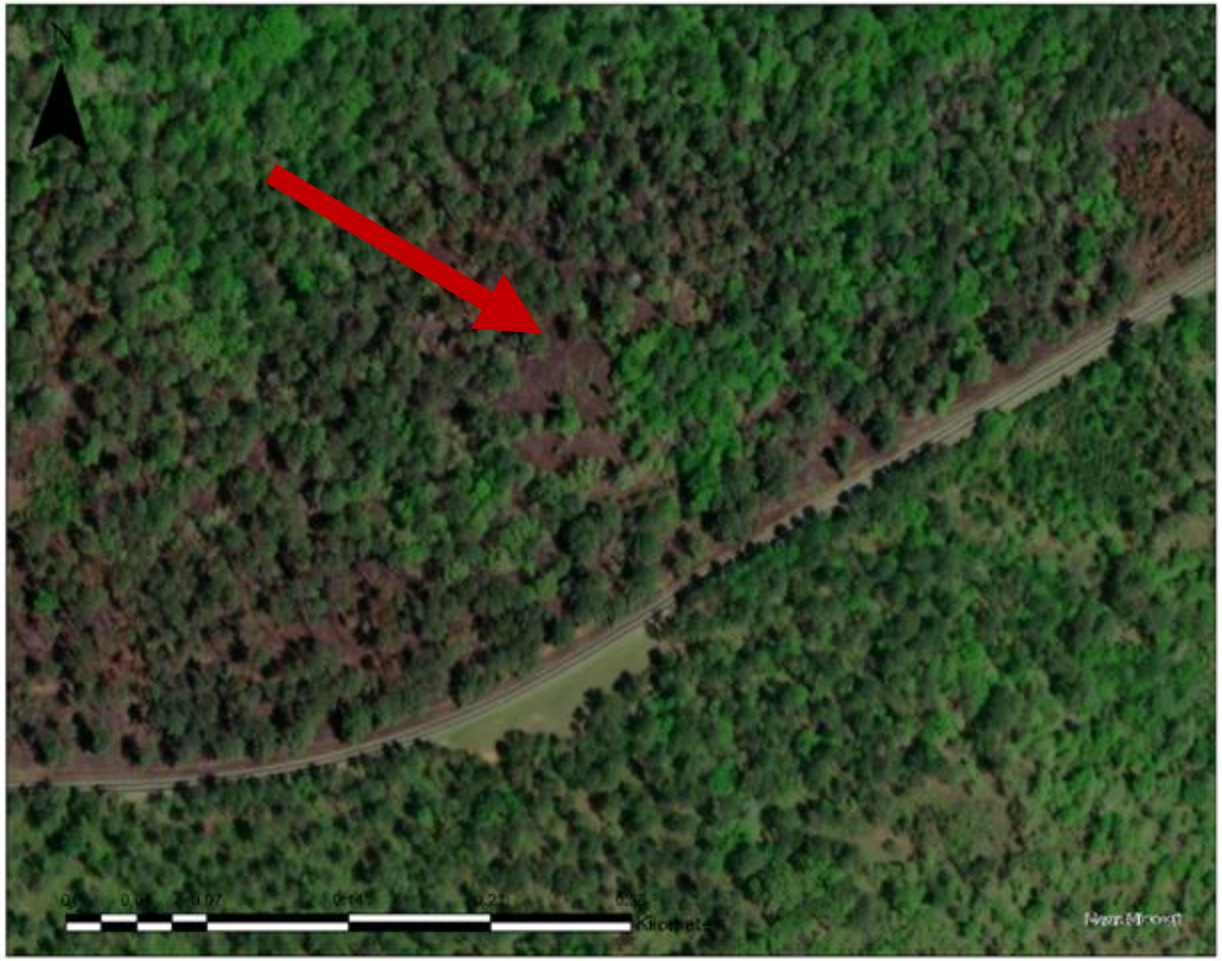
- ALS (aerial LiDAR) and TLS are remote sensing techniques that use calibrated laser returns to create 3D representations of topography, vegetation, structures, etc.
- Opportunities for cultural resource monitoring, wildland fire risk, fuel monitoring, etc.

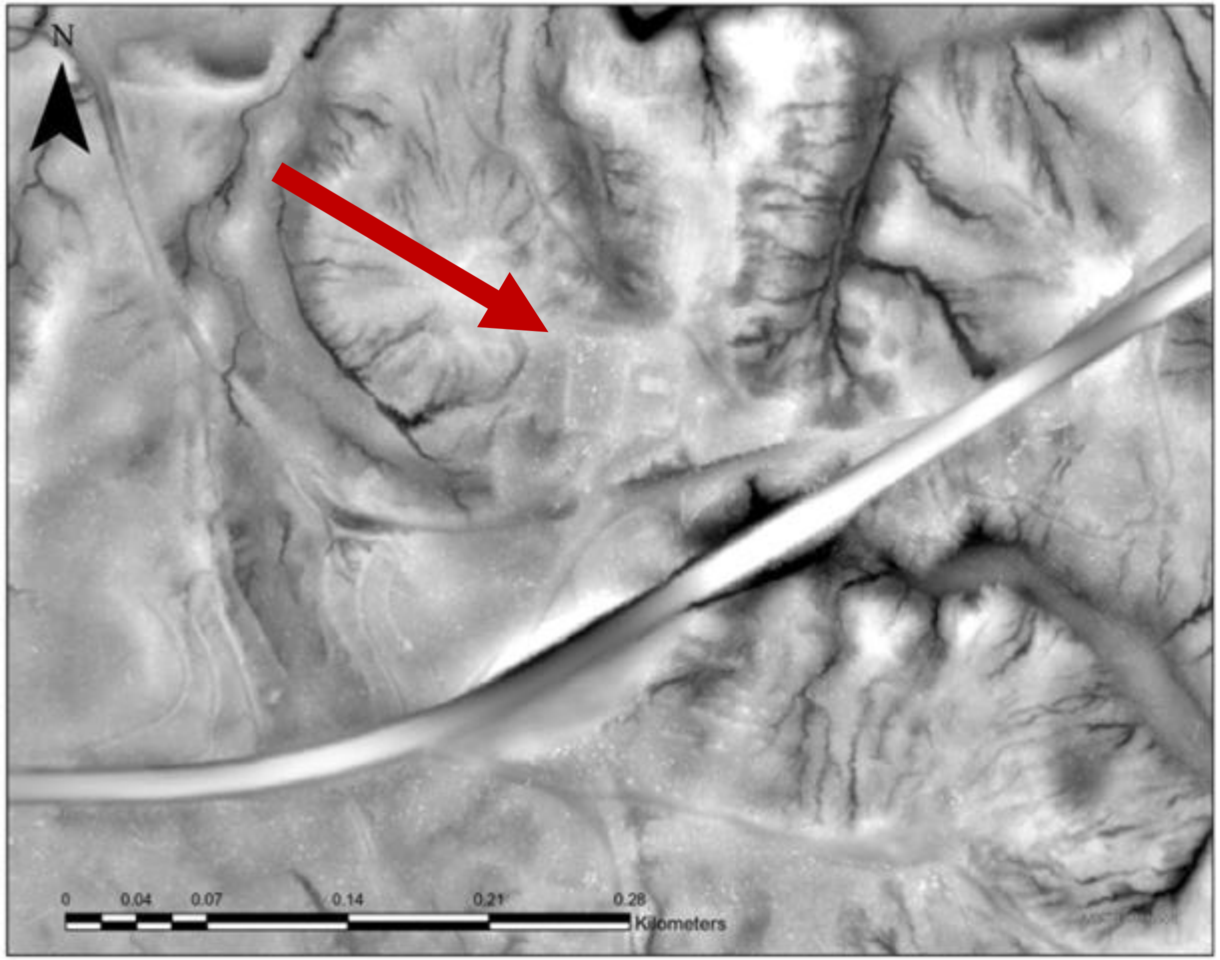




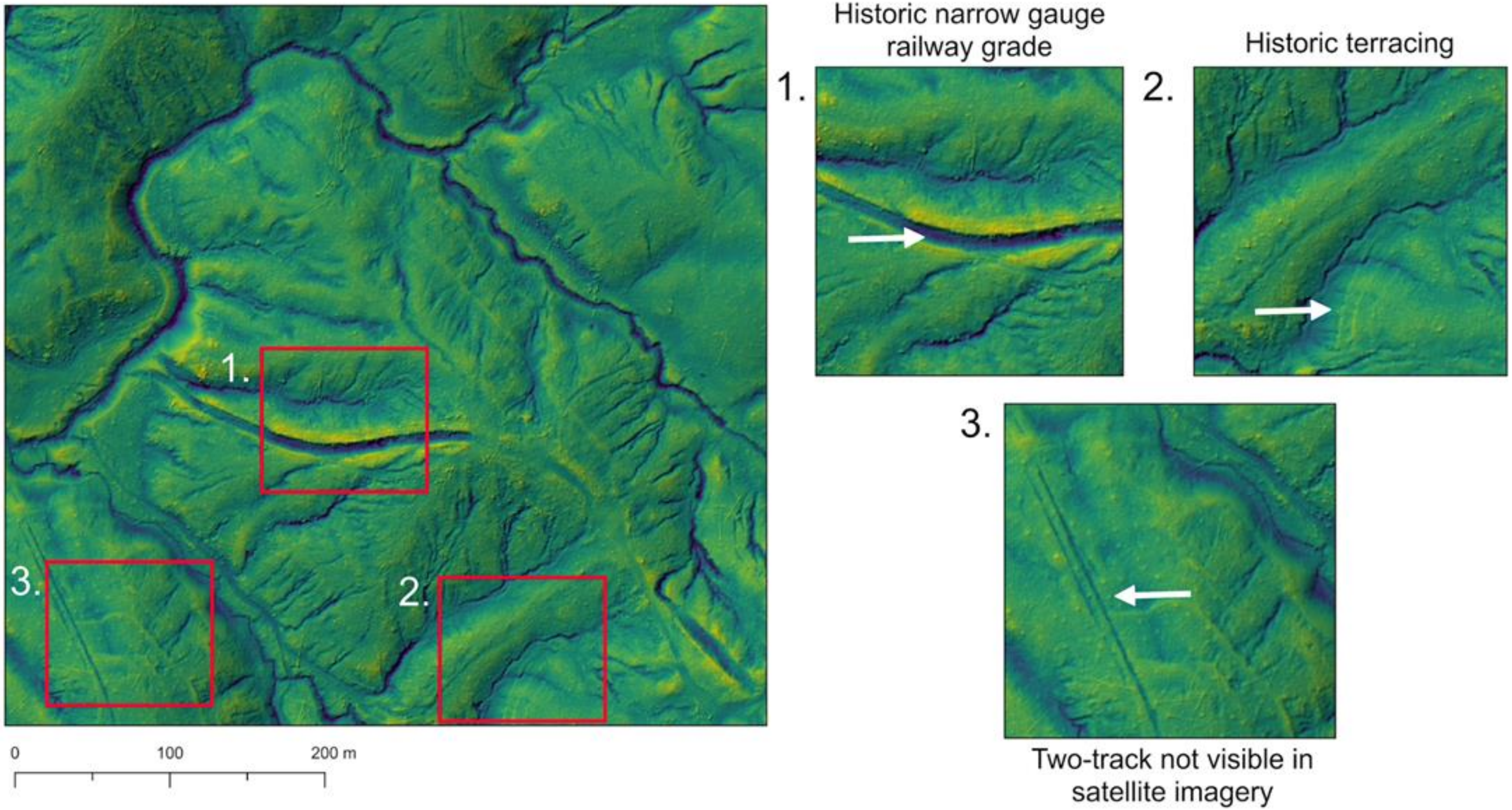


Identifying archaeological features





Deep learning to inventory archaeological features



Brief overview of Deep Learning

How can Apple/Google create ‘magic’ folders of just images of your dog/cat?

Object detection

Algorithm creates a box around the object detected in an image.

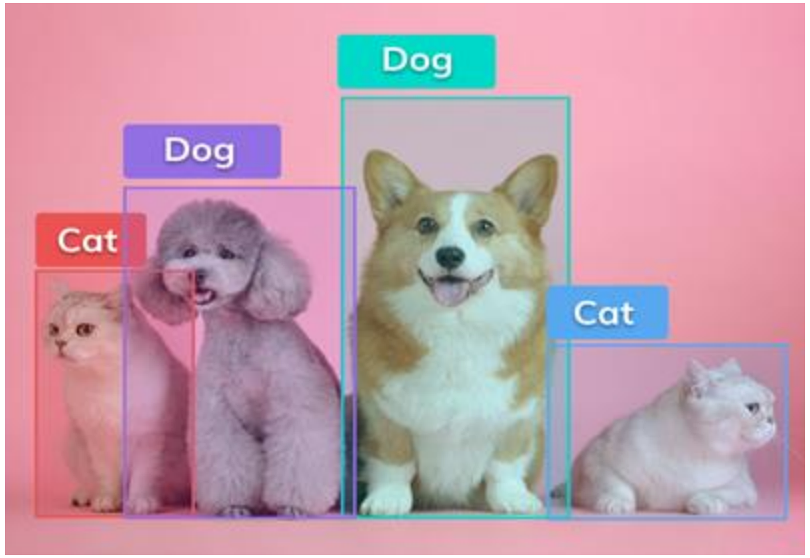
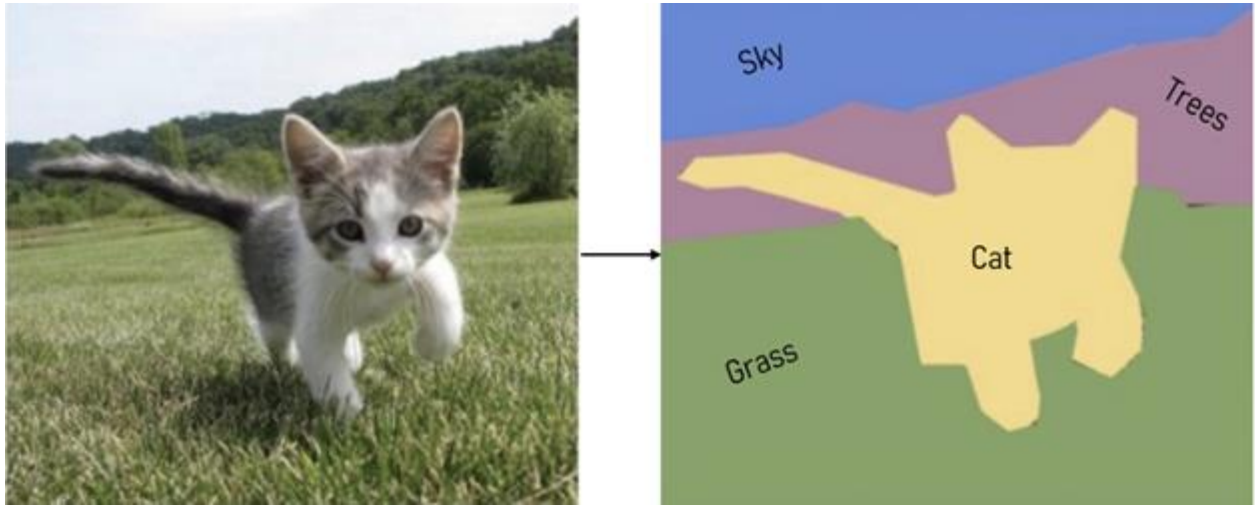


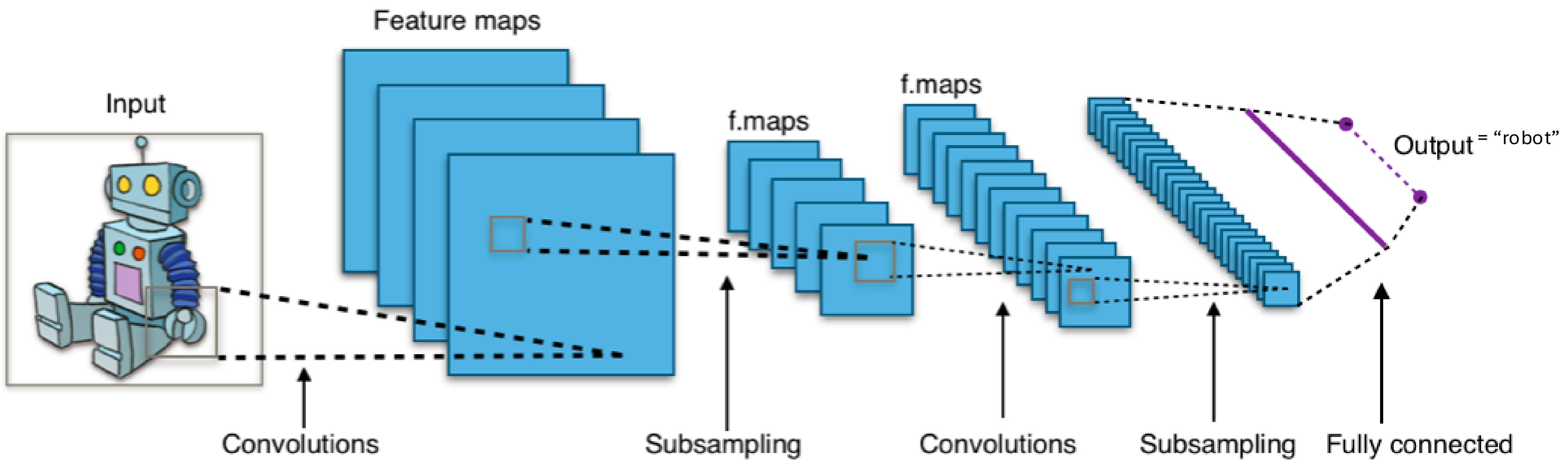
Image segmentation

Algorithm classifies all pixels of an image.

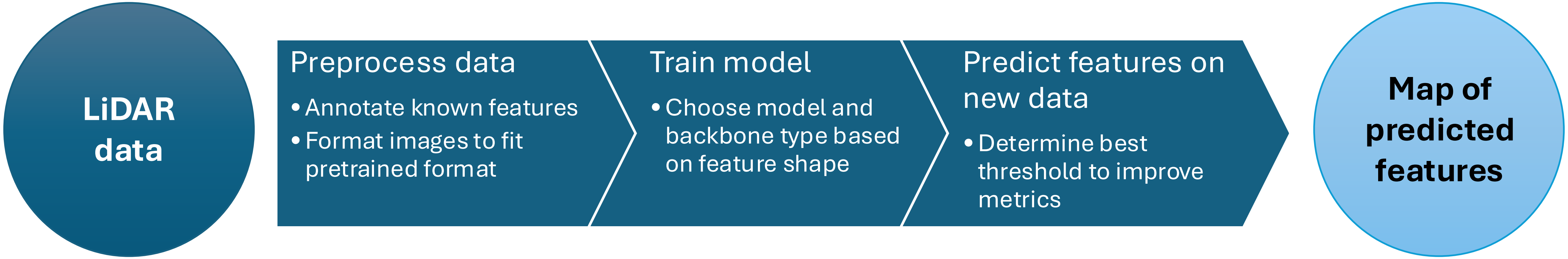


Convoluted Neural Networks (CNN)

- Deep Learning machine learning algorithms that specialize in detecting features in visual contexts (images).
- CNNs are relatively recent but have taken over the world. They are everywhere (self-driving cars, facial recognition, medical image analysis, etc.)



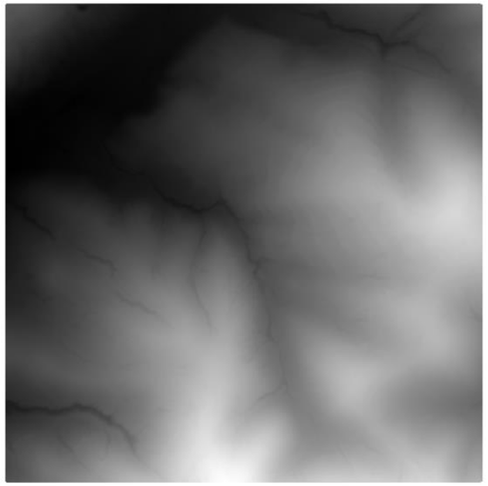
Developing a Deep Learning Model Library for Public Lands



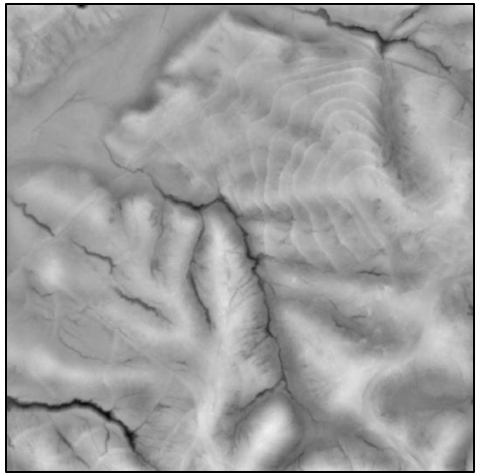
- Develop, train, and deploy CNN models to inventory and monitor diverse types of archaeological sites and features across the Kisatchie NF.
- Multiple architectures (U-Net, Mask R-CNN, YOLO, etc.) and backbones to meet needs of multiple site types.
- Currently advancing models to detect historical structures, historical trails, pre-contact earthworks, pre-contact village sites, terraces, legacy roads, and others.

Data formatting and visualizations

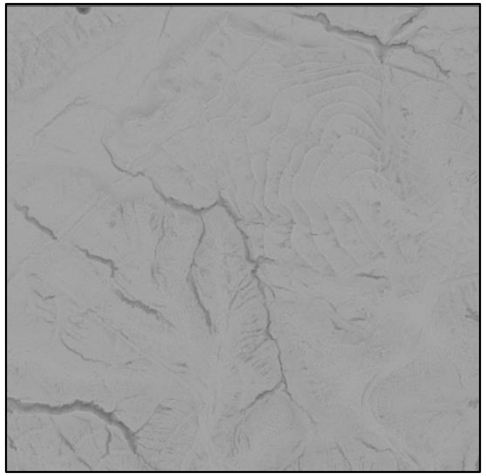
DSM



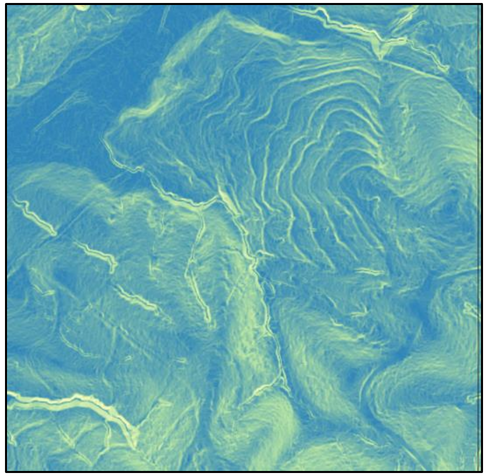
Simple Local Relief Model



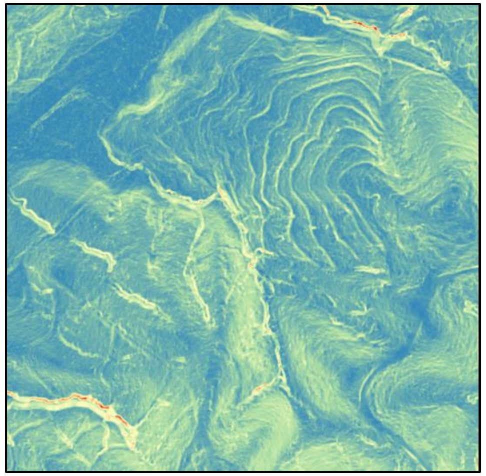
Positive openness



Slope



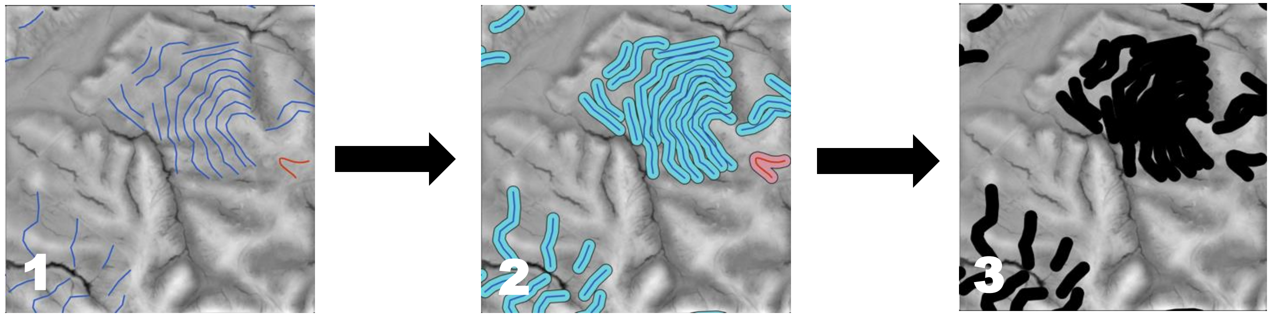
Terrain Ruggedness Index



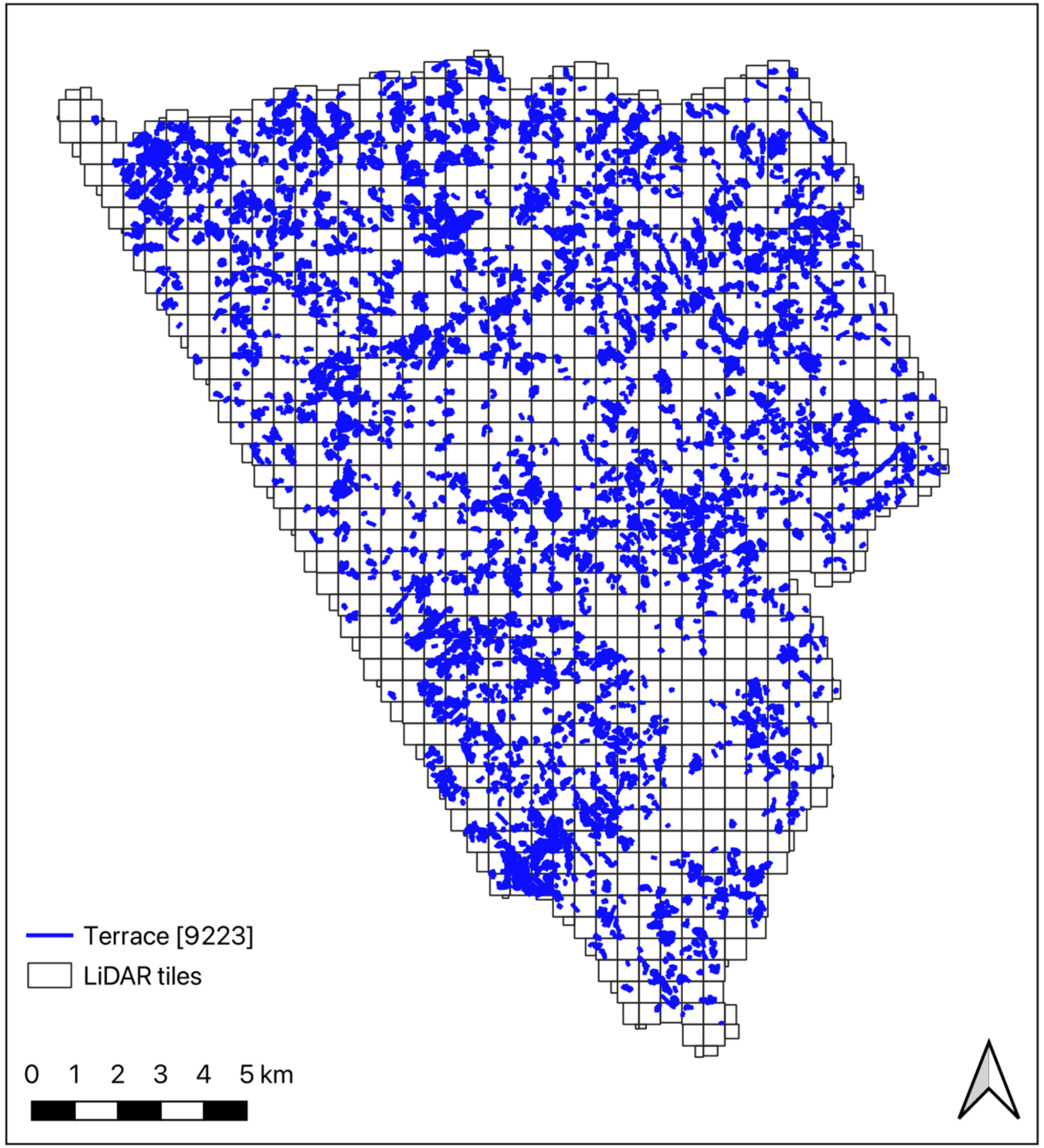
Multiple visualizations of the DSM to enhance the visibility of a wide diversity of archaeological features.

Annotating archaeological sites and features

- Manual digitizing of exiting features, synthesis of existing datasets from agencies, and SHPO records.
- Transform annotations into buffered vectors to capture geographic context (tried 5m, 10m, and 20m).

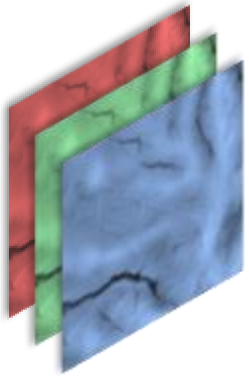


Examples from Piedmont National wildlife Refuge, GA.

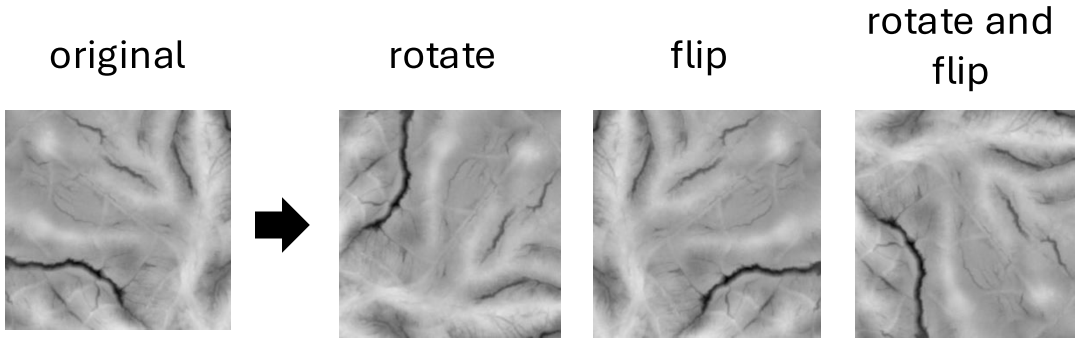


Augmenting inputs to enhance training

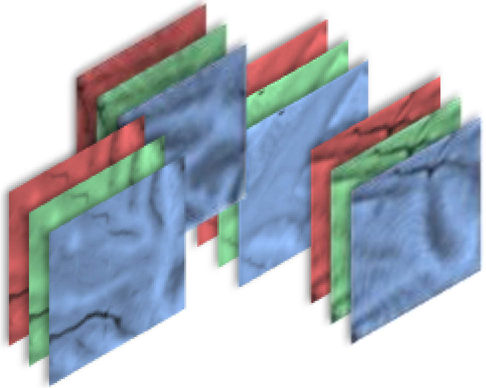
- 3-bandi input tiles by combining 3 visualizations to fit the model pretrained backbone requirements.



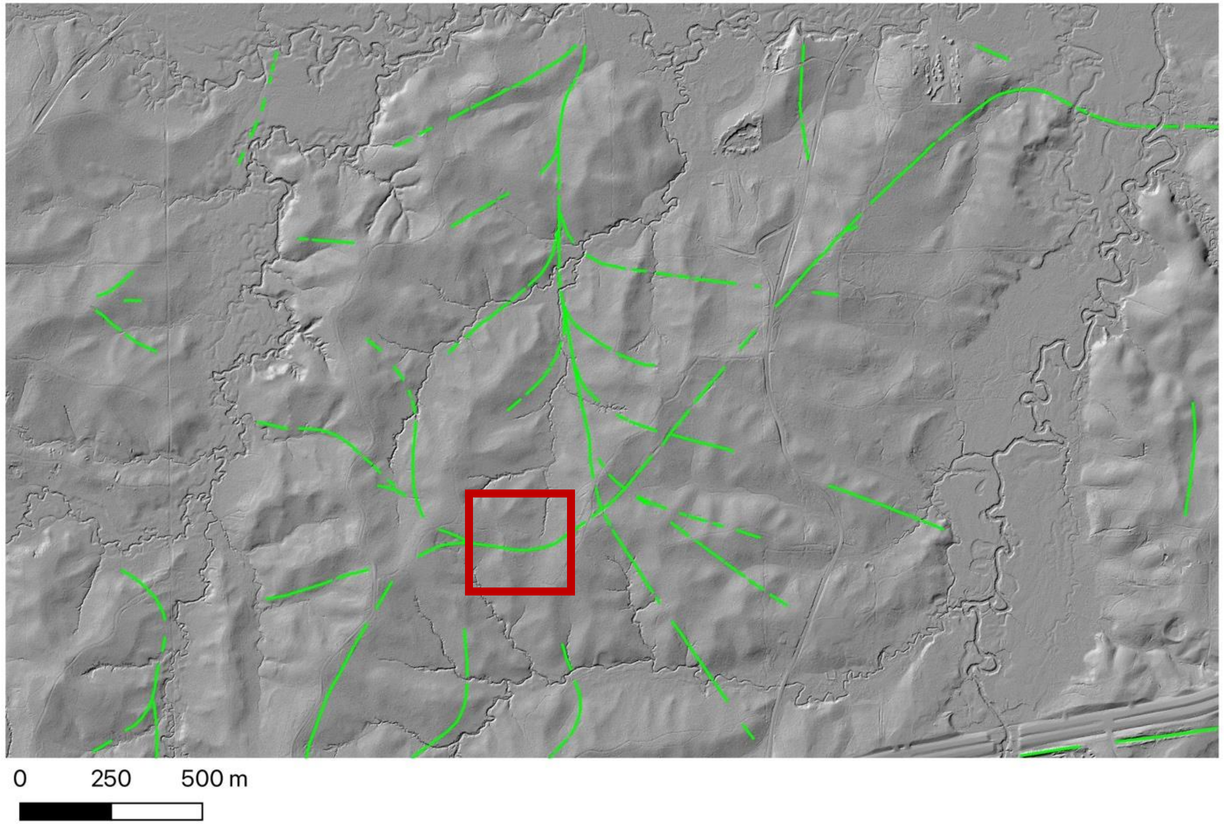
- Augmentations to increase the number of different images seen by the model.



- Fed the 3-band images in batches, adjusted to increase model performance.



Simulated features to extend training sets

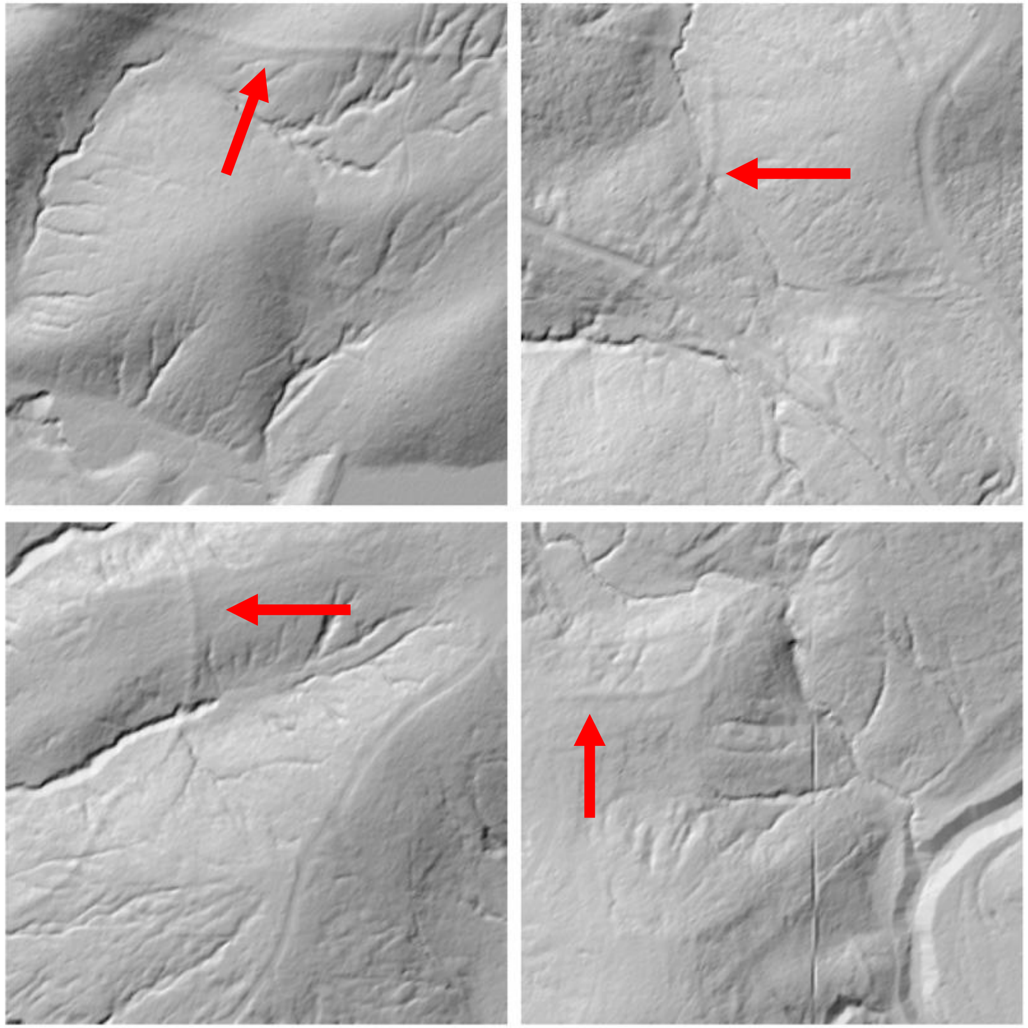


Examples of grade features on the Kisatchie NF

- Detecting features requires a large training dataset
- Some features are relatively rare
- **Potential solution:** Create simulated features for training

Simulated features to extend training sets

- To mimic this feature, generate a least-cost path from two random points on the tile edges
- Buffer, simplify, and smooth feature to match examples observed in DEMs and field.
- Add to landscape and annotate for training.
- **Amplify training sets for model development**



Above-grade simulated features across test tiles

What have we learned; how do we continue?

- Building research objectives and products that can scale to the mission area of the agency
  - Not working at the scale or a site or landscape, rather a region consisting of **100,000 acres or more**.

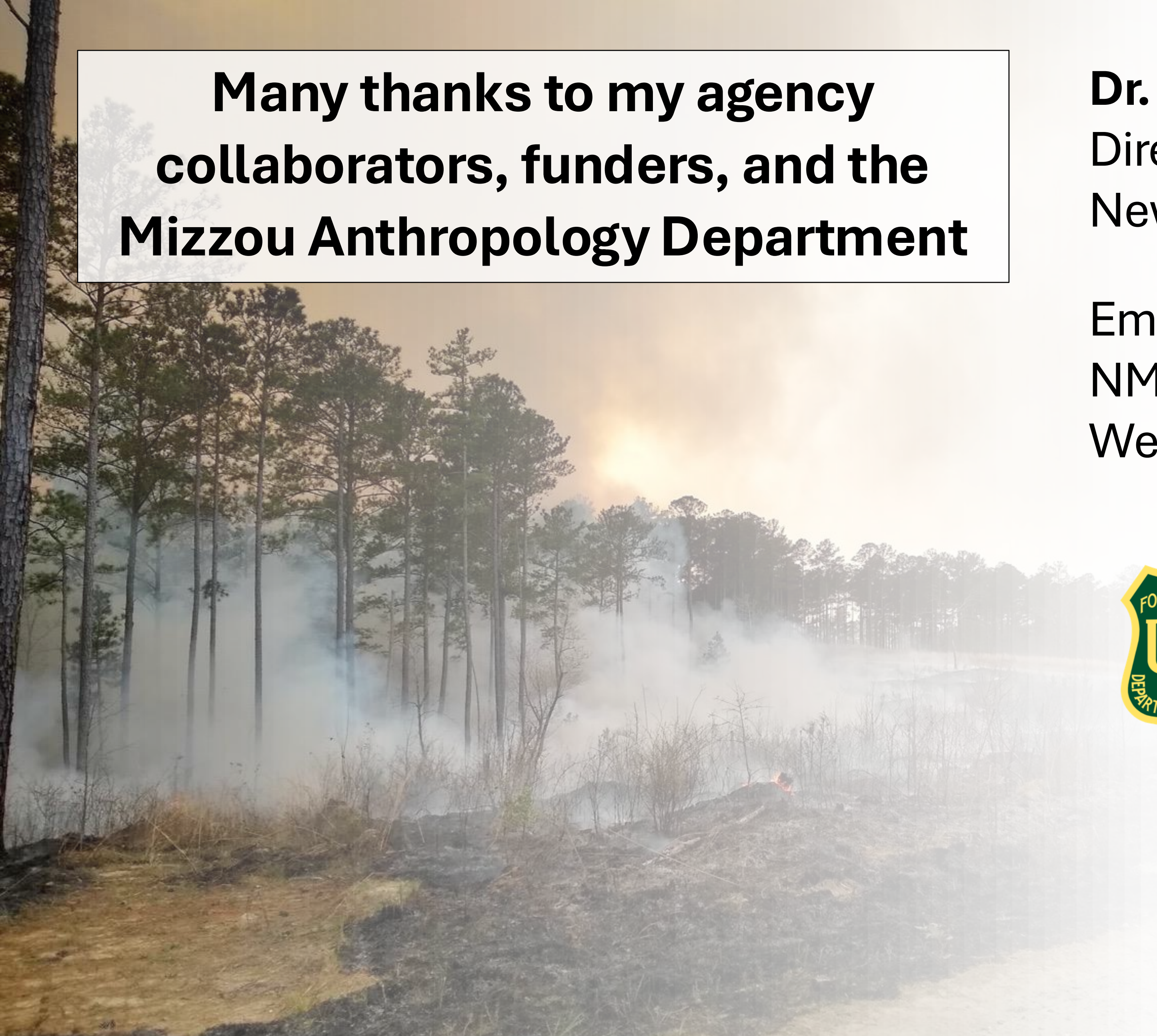
- Finding the intersection between research and management
  - Emphasis on **multiple resource benefits**

- Designing tools and products that prioritize the needs of Heritage programs and integrate into existing infrastructures
  - Agency partners have limitations on time, resources, and authorizations
  - Cannot easily adopt technologies or products like the academic community

Moving forward

- New experiments to understand compounding disturbances on archeological sites (hurricanes, wildfires, grazing, etc.)
- Expanding deep learning to new regions, archaeological site types, and management needs
- Develop training opportunities for the next generation of archeologists interested in academic-agency partnerships to support archeological science

Pile burning experiment on the Plumas NF, 2024



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