THE ARIZONA TREE STRESS EXPLORER AND ALERT SYSTEM

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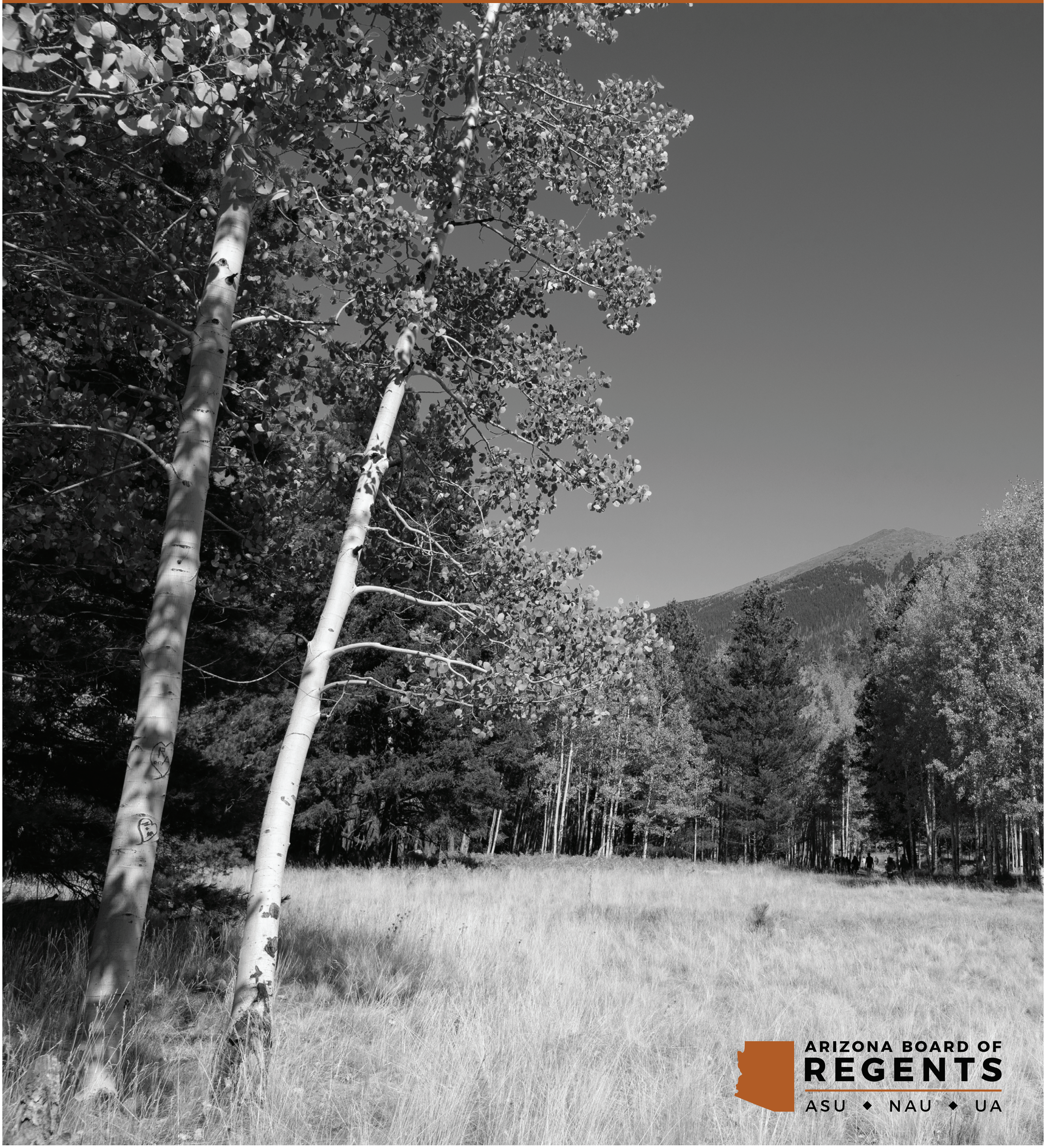

ARIZONA BOARD OF REGENTS
ASU ◆ NAU ◆ UA

OPPORTUNITY STATEMENT

Proposal submitted to the Arizona Board of Regents & Arizona Department of Forestry and Fire Management (ADFFM), Opportunity #2, Mobile Tree Health Monitoring System

PROPOSAL SUMMARY

The School of Informatics, Computing, and Cyber Systems (SICCS) at Northern Arizona University (NAU) proposes to build a **Tree Stress Explorer System** that will monitor tree water stress at the individual-tree scale in near-real time across all of Arizona. The system would be the first of its kind. Also, the system will be easily available and understandable to ADFFM, Arizonans, and other stakeholders by a phone/tablet app and a website. The project will also comprise an **Alert System** that will warn stakeholders of significant changes in tree stress in their areas of interest.

The proposed system relies on the changing optical properties of leaves when a tree is stressed. A tree responds to water stress in numerous ways, but the first early signs of that stress are expressed as reduced water content of needles and leaves. When leaves start to dry out, their optical properties change, which is observable via satellites, based on sunlight reflecting off those leaves. Tree stress responses to bark beetle infestations are also visible via remote sensing through the green (early), red (mid), and grey (late) phases of infection.[1,2] Hence, this system will be able to detect both drought and bark beetle stress in trees. T**o provide an early warning system for tree health, the optical properties of all adult-statured trees across Arizona will be monitored.** *Every 9 square meter patch of land in Arizona* that contains a tree will be monitored **daily** via satellite and International Space Station (ISS) borne platforms for signs of stress, including drought and bark-beetle infestations, with automated alerts made available to ADFFM and the general public by an easy-to-use web and mobile app interface.

The data to conduct this ambitious monitoring effort will be comprised of near real-time multispectral satellite imagery acquired on a daily basis across Arizona. The imagery will be passed to a high-throughput analysis pipeline conducted on NAU's high-performance computing cluster to transform the imagery into stress metrics. The resulting data will be presented via an app and website in an intuitive and accessible manner. Stakeholder meetings will be regularly held, during development, to ensure usability for both ADFFM and the public.

If funded, this system would enable ADFFM to respond proactively to forest stress events, be they drought- or bark-beetle induced. The technology would enable Arizonans to monitor the trees around them, and would connect them to nature and ecological processes. Also, the system would serve as an example for other states to follow, and **would place Arizona as a leader in ecological monitoring of vegetation.**

PROPOSAL ADVANTAGES

No system of significant scale exists to monitor tree stress in near real-time, and on spatial scales that correspond to the size of individual trees, neither in the country nor in Arizona. For example, the prominent web interface DroughtView,[3] developed in or before 2008, displays vegetation greenness on a coarse scale of approximately 1500 ft In comparison, this project would:

1. deliver data at much finer spatial and temporal resolution,
2. use state-of-the-art methods for extracting data from satellite multispectral indices,
3. increase reliability for characterizing unique drought profiles calibrated across the types of Arizona ecosystems,
4. provide data on drought stress and bark-beetle infestation to the general public by a mobile app,
5. focus on usability and adaptive improvements for both ADFFM and laypersons.

More than just a modernization of current systems, this project would fundamentally change the way tree stress is monitored, assessed, and shared with the general public in Arizona.

This project would help ADFFM assist the public in ways that do not currently exist. With this tool's spatial acuity, Arizonans will be able to evaluate the health of their trees in their backyards, communities, and across all of Arizona, just by launching an app on their phone. If ADFFM conducts thinning to improve drought resilience, or treatments to control beetle spread, the public could observe the effects with this tool.

SCOPE OF WORK

Imagery Analysis
The availability of relatively new thermal and hyperspectral Earth observing platforms opens new opportunities for the measurement and prediction of plant water stress. Nonetheless, expert processing capability is required to render the data interpretable.

Sources
Planet. Planet Labs' satellites image the entire globe, on average, once per day. First launched in 2014, the PlanetScope satellites produce optical reflectance imagery at 3 meter ground resolution with 4-8 bands, including red, two greens, red edge and near infrared. These bands are designed to measure plant stress, and particularly water stress, as a leaf's red edge and near infrared reflectance changes significantly with the amount of water held in the leaf.[4]

Landsat. Provides long time series (data available 1982 - present) of well calibrated moderate resolution (30m) satellite imagery every 16 days with proven utility for forest management applications. Landsat time series provide critical trend data, from which deviations (e.g., acute stress) can be detected using finer resolution imagery.

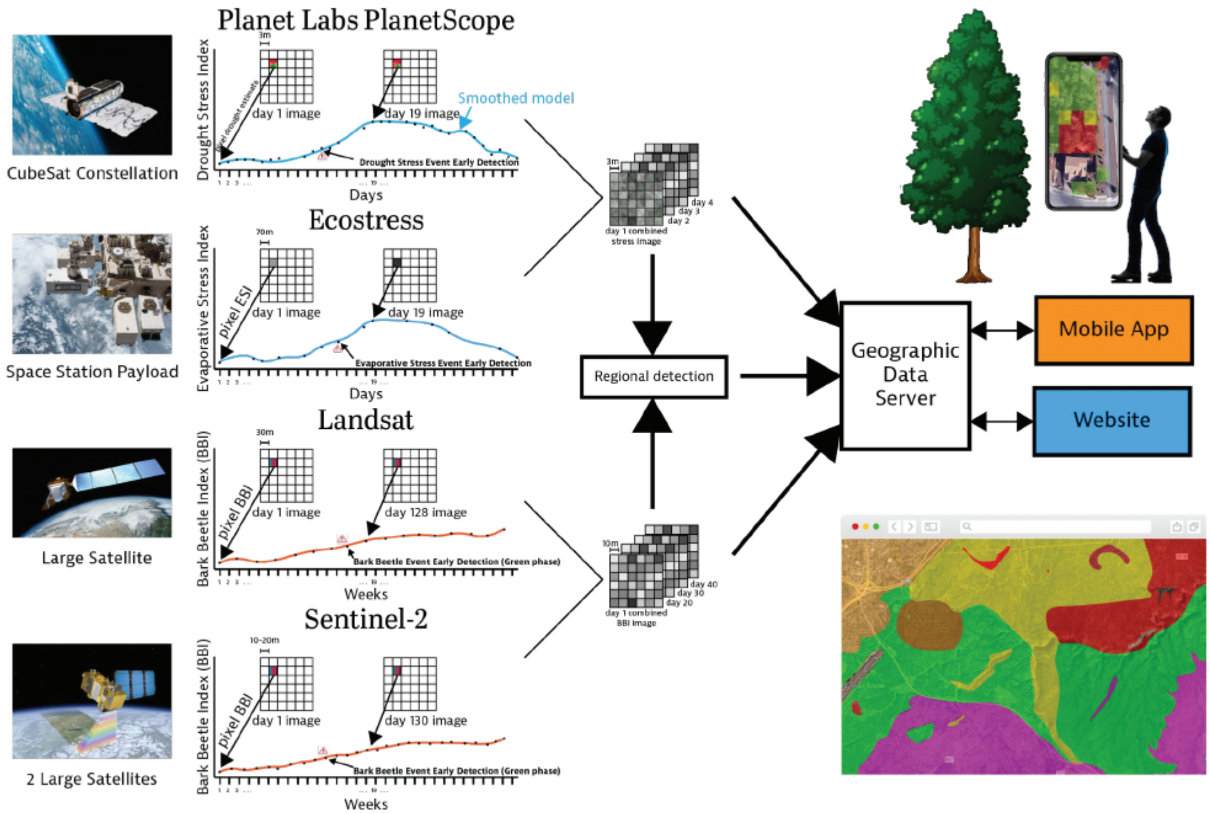

Figure 1. Pipeline of image processing to create stress maps for mobile apps and website, and to detect events for the alert system.

Sentinel-2. This satellite provides multispectral data at higher spatial resolution than Landsat (10-20m) and higher revisit frequency (every 5-10 days), whose bands, like those of Landsat, have been shown to be able to detect bark beetle infestation.[5] Data is available from 2017. This project will use level 2A data - surface reflectance.

Ecostress. A thermal camera on the ISS that derives evapotranspiration (ET) and evaporative stress (ESI) of vegetation at a spatial resolution of 70m every 1-7 days. This project will employ the level 4 ESI product (ECO4ESIPTJPL.001) to monitor water stress.[6]

High-resolution land cover

The system will leverage the unique optical reflectance profiles of tree canopies versus ground vegetation to discriminate (mask out) areas without trees[7] (where tree cover <20% per pixel) using fine resolution optical imagery from the National Agriculture Imagery Program (NAIP) 2019, PlanetScope, and Sentinel-2.

Computing Architecture and Algorithms

The system will enable fine spatial and temporal resolution maps of tree stress that can be used by various stakeholders. The estimated upper bound storage requirements are roughly 100 TiB over three years. In addition, the downloaded imagery data products will not be stored, as those products can be retrieved, retroactively, on demand if required. All computations will be conducted on NAU's compute cluster, Monsoon.

The system will carry out several core computational tasks, on the schedule described, as follows:

Task 0 – Daily processing: **Automatically download** new scenes from the four imagery sources above, using scripts and APIs. Data quality flags will be used to exclude cloudy, aerosol-affected, or otherwise poor-quality data, to ensure that only usable images will be downloaded.

Task 1 – Daily processing: **The stress index score will be computed** (Figure 1) for each tree-hosting pixel. All pixels are independent of each other, and the computational requirements are minimal. The time needed to carry out this task will be related to data movement (downloading the data to NAU and reading it from the parallel filesystem).

Task 2 – Daily processing: **Each time a new pixel is ingested, the model will be updated.** The model will reject noise and detrend seasonal variations based on its own history. Data noise and false positives will be mitigated by relying on error flags and spatio-temporal filtering algorithms that reduce anomalous readings. Algorithms account for variance in solar illumination across dates and times of day through radiometric normalization prior to the derivation of optical-based stress metrics. Detrending is a critical noise-reduction technique that determines baseline reflectance profiles for any one pixel, from which deviations due to acute stress can be detected. In other words, this detrending process will employ inter-annual reflectance profiles from the imagery, isolating acute stress events from discrete land cover change, medium-term trends like phenology, or long-term trends, such as those observed from compositional turnover or climate change. Roughly, 3 billion daily models can be computed with Monsoon, using approximately two compute nodes for 24 hours. This computing architecture will enable near-real time stress maps and near real-time alerts to be sent to users.

Task 3 – Weekly processing. Using the output of Tasks 1 and 2, pixels will be combined into **contiguous regions** that are used to indicate whether a geographical area has a high stress index. To do this, these maps will be dynamically updated with computer vision/machine learning algorithms. This task will require storing the historical stress index of each pixel for several geographical areas derived by fusion of imagery at fine (e.g., PlanetScope) and medium (e.g., Landsat) resolution. The meamory requirements for this task are roughly 2 TiB. Using the Message Passing Interface, a distributed-memory approach will be used to run the regionalization algorithms. This computation can be accomplished using roughly 10 nodes on Monsoon.

Task 4 – Weekly processing: **Compute the new pyramid** (precomputing the maps at different spatial resolutions) and make it available to the geographic data server that sits at the back end of the web interface.

Task 5 – Daily processing: **Compute and send alerts** to users based on the output of task 2.

Advanced Computing Technologies: Many components of the tasks above will employ advanced computing technologies. In particular, the power of general purpose computing will be harnessed on graphics processing units (GPGPU),[8] which refers to using GPUs for general purpose computation, and not rendering graphics. GPUs have thousands of cores (compared to ~64 on a CPU) and very high on-card memory bandwidth. For this reason, 7 of the top 10 supercomputers worldwide use GPGPU.[9] Utilizing this technology is critical for ensuring that we are able to carry out many of the tasks in near real-time fashion such that end users are able to obtain the most up-to-date information regarding tree stress.

While the tasks are interrelated, they address different shareholder concerns. The product of Tasks 1 and 2 will be useful for the general public, as they will be able to use the information to assess whether trees are stressed on small spatial scales (e.g., a tree in their backyard). In contrast, the product of Task 3 will be useful for various mitigation efforts, such as those carried out by ADFFM.

Field Work

The ecology Post-doc, Graduate Research Assistant (GRA), and fieldwork assistant will travel to representative plots in distinct tree-bearing ecoregions of Arizona,[10] measuring the relationship between drought- and bark-beetle induced stress and leaf optical reflectance. In each plot, they will cut branches, measure leaf water potential (LWP) with a Scholander pressure chamber (existing NAU equipment) and take full range spectral reflectance measurements with a field spectrometer (existing NAU equipment). Bark-beetle infested areas will be sought out, and spectral measurements of leaves will be taken in green- and red-phase infection areas. The goal is to be able to predict LWP and bark-beetle infection with handheld spectral measurements. These measurements will then be used to calibrate the satellite imagery analysis.

Outreach and Education

There will be three ADFFM/NAU workshops in the first two years to review product goals, including fieldwork plans, analysis framework, and UI. The GRA will conduct surveys with interested laypersons to determine usability requirements for the public, which will then inform platform improvements and updates. Then, a training workshop will be held for stakeholders in Year 3, when the tool is largely functional.

Enabling Future Projects

The analytic products this project produces are based on the latest space-borne Earth observation data and technology, including those on the ISS, and are processed using state-of-the-art computational and analytical tools. These advanced products will enable other potentially high impact projects. The high-resolution, near-real time stress maps produced in this project are what would be needed to build an early warning system for fires, pest outbreaks, and large-scale tree die offs. The thermal data (present in Landsat, Ecostress, and Sentinel-2 products) outputs from this project, combined with the tree cover maps generated here, comprise the key analytic inputs for analysis of the effects of vegetation on urban temperature environments.

Future enhancements could include capabilities for users to upload their own photos, observations, and measurements that would improve the predictive performance of the system. Numerous citizen science initiatives could be conducted in this manner.

Deliverables (year-by-year)

Table 1. List of annual deliverables.

Task ↓ Year →	1	2	3
Fieldwork			
Field-based model			
Tree mask			
Task 0: imagery ingestion			
Task 1: per-pixel stress index calc			
Task 2: per-pixel smoothed model			
Task 3: regional models			
Task 4: pyramid construction			
Task 5: user alert system			
Website/App data architecture			
Website			
iPhone + Android mobile app			
Stakeholder meetings (3 total)	x1	x2	
Training			
Public release			

Team Members

Alexander Shenkin is an assistant research professor in SICCS at NAU. He is an expert in modeling how tree and forest structure affects functions such as evapotranspiration and carbon cycling.

Michael Gowanlock is an assistant professor in SICCS at NAU. He is an expert in parallel and high performance computing.

Chris Doughty is an associate professor in SICCS at NAU with a long track record of creatively coupling remote sensing with forest health.

Christopher Hakkenberg is an assistant research professor in SICCS at NAU. He has a focus on remotely sensed optical imagery, using satellite and airborne data, hyperspectral, and time series processing.

Scott Goetz is a full professor in SICCS at NAU. He is an acknowledged senior leader in the field of using remote sensing to understand ecosystem processes.

Budget: 3-year budget $1,259,942

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