**Quantifying Firmageddon: Plots, planes, pixels, and vulnerability modelling**

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**Project Summary**

In 2022, the USDA Forest Service Forest Health Protection Aerial Detection Survey (ADS) documented extensive mortality of true firs (*Abies* spp.) in Oregon. Referred to as “Firmageddon”, concerns about its potential economic and ecological impacts highlight the need to develop unbiased and verifiable information on forest mortality events, and improve our understanding of forest vulnerability in the future. Using field data from the USDA Forest Service Forest Inventory and Analysis Program (FIA), ADS, and satellite time series imagery; this project will compare and integrate these different data sources to improve estimates of fir mortality. Additionally, this project will use the fir mortality event to develop and assess forest vulnerability models, and apply those models to map fir potential vulnerability to future mortality.

**Keywords**

Fir, forest decline; mortality; fir-engraver; forest inventory; aerial detection survey; satellite imagery.

**Background**

Recent observations of extensive true fir (*Abies* spp.) tree mortality in Oregon have been documented by the USDA Forest Service Forest Health Protection Aerial Detection Survey (ADS), with over 1.0 million acres of fir mortality in 2022, mostly attributed to fir-engraver (USDA Forest Service 2022a). As a major component of many forest types throughout Oregon, extensive mortality of true firs will potentially impact a wide range of ecosystem services. Recent large-scale mortality events in California driven by drought and bark beetle outbreaks provide an example of how events like Firmageddon have the potential to dramatically reduce carbon sequestration (California Air Resources Board 2019), negatively impact sensitive protected wildlife species and their habitat (Kordosky et al. 2021; Steel et al. 2023), and create fuel conditions conducive to more extreme fire behavior (Goodwin et al. 2021; Stephens et al. 2022). To understand the potential impacts of Firmageddon, there is a need for timely, spatially complete, unbiased, and verifiable information on fir mortality.

Quantifying tree mortality across large landscapes can be accomplished using field-based, airborne, and spaceborne data sources; however, each approach has specific advantages and limitations. The US Forest Service Forest Inventory and Analysis (FIA) program provides a gold standard for field-based forest measurement and change estimation, but (1) plot measurements lag behind mortality events (10-year measurement cycle), (2) the sampling intensity (approximately one plot per 760 ha on NFS non-wilderness lands, and 2500 ha on wilderness and non-NFS lands) limits addressing questions at landscape-levels, and (3) mortality agent attribution occurs in generalized groups (harvest, fire, insects, disease, etc.). In contrast, airborne observation by the ADS program occurs annually, collecting detailed information about specific agents of tree damage and mortality. However, ADS mapped mortality occurs as relatively coarse spatial polygons, lacks tree-level information, and may be difficult to use as the basis for unbiased estimates of tree mortality and ecosystem consequences. Lastly, spaceborne satellite remote sensing programs such as Landsat and Sentinel-2 provide spatially exhaustive moderate resolution (10m-30m) data for all forest lands multiple times per year. Spectral change from satellite imagery time series can provide information about disturbance extent, distribution, and severity over vast areas, providing an important monitoring tool for rapid disturbance detection (Kennedy et al., 2015; Senf et al., 2017). However, because large-scale remotely sensed data are limited in their ability to provide tree-level information, attributing tree mortality to precise biological agents is difficult, often requiring integration with forest inventory or other plot-level data (Meigs et al., 2011, 2015). These field, airborne, and spaceborne data sources individually have distinct limitations for quantification of forest mortality, which in turn lends each to different inferences about ecological change and its potential consequences.

There has been extensive use of field and remotely sensed monitoring data to retrospectively quantify forest disturbance and mortality. Far less developed are methods to quantify potential future trajectories and vulnerability under different scenarios and levels of uncertainty. Building on monitoring data and the retrospective drivers of mortality, development of mechanistic, statistical, and process-based models to quantify potential future trajectories and vulnerability is needed to inform management and policy directions (resist, accept, direct framework) to maintain functional ecosystems and their services.

**Objectives**

We propose using the Firmageddon event in Oregon as a case study to (1) compare and integrate the different primary data sources of tree mortality (FIA, ADS, and satellite imagery), and (2) use these mortality data sources to develop, validate, and map potential landscape drivers of true fir vulnerability. Specifically, our objectives are to:

1. [*Data Source Intercomparison*] Review and quantify the strengths, weakness, and complementary aspects of FIA, ADS, and Landsat and/or Sentinel-2 data in detecting and quantifying fir tree mortality during the current mortality event (2021-2023).
2. [*Data Source Integration and Firmageddon Mapping*] Develop a workflow for integrating FIA plots, ADS, and multispectral satellite image time-series to provide a spatially-explicit (mapped) estimation of true fir tree mortality.
3. [*Landscape Vulnerability*] Use mortality data and products in 1-2 above to model potential landscape drivers of fir vulnerability, and map future potential fir vulnerability in Oregon.

**Approach**

*Data Source Intercomparison*.

We will review literature on field, ADS, and spaceborne approaches to forest mortality estimation and mapping. We will quantitatively compare fir mortality estimates across data sources in a variety of ways. Spatially explicit (*i.e.,* mapped) extent comparisons will be made between ADS and Landsat based disturbance from the Landscape Change Monitoring System (USDA Forest Service, 2022b). Area estimates of fir mortality will be made between ADS and FIA data, following FIA estimation procedures for field data (Bechtold and Patterson, 2005)-based mortality. Total and per hectare mortality estimates will be estimated and compared between ADS and FIA data.

*Data Source Integration and Firmageddon Mapping*

We will build from and expand on prior research in the Pacific Northwest (Meigs et al., 2011, 2015), integrating field plots, ADS, and Landsat disturbance mapping into a workflow for combined mapping and mortality estimation. Conceptually, this workflow has three major components: (1) Merging ADS polygons with Landsat-based disturbance mapping to generate maps of attributed fir decline with Landsat pixel spatial resolution, (2) Develop statistical models relating Landsat-spectral change to fir mortality severity (cover, basal area per hectare, trees per hectare) observed on remeasured FIA plots, and (3) apply 1-2 to pre-Firmageddon gradient nearest neighbor (GNN, https://lemma.forestry.oregonstate.edu/) maps of forest attributes to spatially estimate fir mortality severity.

*Landscape Vulnerability*

We will examine how tree mortality varies with tree size, stand density, climate, and topographic position (e.g., Bell et al. 2015, Shriver et al. 2021). Differences in how stand density, climate, and topography alter mortality for trees contributing to biomass (large trees) and future resilience (small trees) could guide management prescriptions for resilient forests (Bradford & Bell 2017). We will apply size-dependent mortality models to GNN maps of forest attributes and climate projections to map mortality probabilities and identify areas with high potential for large patches of true fir mortality under current and projected future climatic conditions. Modelled vulnerability maps will be assessed against Firmageddon and historical mortality patterns from ADS and satellite imagery disturbance products.

**Deliverables**

* R and GEE scripts for plots-planes-pixels data integration approach, to be delivered to FIA and FHP
* Two manuscripts: a review/intercomparison/integration paper and a vulnerability assessment
* Map products to be map available on the lemma website (, <https://lemma.forestry.oregonstate.edu/>), which hosts GNN maps.
* Presentations to regional and national conferences
* A webinar, focused on federal and state agency forest health and protection audience

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