



Forest fire, thinning, and flood in wildland-urban interface: UAV and lidar-based estimate of natural disaster impacts

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Abstract

Context Wildland-urban interface (WUI) areas are facing increased forest fire risks and extreme precipitation events due to climate change, which can lead to post-fire flood events. The city of Flagstaff in northern Arizona, USA experienced WUI forest thinning, fire, and record rainfall events, which collectively contributed to large floods and damages to the urban neighborhoods and city infrastructure.

Objectives We demonstrate multi-temporal, high resolution image applications from an unoccupied aerial vehicle (UAV) and terrestrial lidar in estimating landscape disturbance impacts within the WUI. Changes in forest vegetation and bare ground cover in WUIs are particularly challenging to estimate with coarse-resolution satellite images due to fine-scale landscape processes and changes that often result in mixed pixels.

Methods Using Sentinel-2 satellite images, we document forest fire impacts and burn severity. Using 2016 and 2021 UAV multispectral images and Structure-from-Motion data, we estimate post-thinning

changes in forest canopy cover, patch sizes, canopy height distribution, and bare ground cover. Using repeat lidar data within a smaller area of the watershed, we quantify geomorphic effects in the WUI associated with the fire and subsequent flooding.

Results We document that thinning significantly reduced forest canopy cover, patch size, tree density, and mean canopy height resulting in substantially reduced active crown fire risks in the future. However, the thinning equipment ignited a forest fire, which burned the WUI at varying severity at the top of the watershed that drains into the city. Moderate-high severity burns occurred within 3 km of downtown Flagstaff threatening the WUI neighborhoods and the city. The upstream burned area then experienced 100-year and 200–500-year rainfall events, which resulted in large runoff-driven floods and sedimentation in the city.

Conclusion We demonstrate that UAV high resolution images and photogrammetry combined with terrestrial lidar data provide detailed and accurate estimates of forest thinning and post-fire flood impacts, which could not be estimated from coarser-resolution satellite images. Communities around the world may need to prepare their WUIs for catastrophic fires and increase capacity to manage sediment-laden stormwater since both fires and extreme weather events are projected to increase.

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Introduction and study setting

Global forests cover 28% of the terrestrial area on Earth and play key roles in the functioning of ecological, hydrologic, and socioeconomic systems (FAO 2015). In particular, forests in wildland-urban interface (WUI) areas provide many ecosystem services for populations around the world (Miura et al. 2015). Forests, however, are undergoing large-scale changes (Hansen et al. 2013; Keenan et al. 2015) due to fire, drought, insect outbreaks, disease, deforestation, and climate change (Lierop et al. 2015). These changes acutely impact populations in WUI areas, which are rapidly increasing (Radeloff et al. 2018). The resulting population density increases and increasing number of houses are associated with landscape fragmentation, declines in wildlife habitat, native biodiversity, and increases in invasive species (Carlson et al. 2023).

In the western USA, millions of hectares (ha) of ponderosa pine (*Pinus ponderosa*) forests were historically characterized with naturally open conditions (Covington and Moore 2006), but throughout the twentieth century they were managed with policies that emphasized fire exclusion, livestock grazing, and timber harvest (Cooper 1960; Fule 2008). As a result, ~ 70% of the ponderosa pine forests across the western USA now have abnormally high tree densities and are particularly vulnerable to catastrophic wildfires (Covington et al. 1997; Allen et al. 2002). Forest fire management and landscape-scale restoration across the western USA, however, are complicated by increasing numbers of houses and structures in natural forests as towns and cities grow into the adjacent forests. Fire managers are averse to the risks of moderate and high-severity fire in such areas, which then prevents altering forest structure via prescribed fires at a landscape scale. Southwestern ponderosa pine forests, therefore, lack a mixed landscape pattern with a mosaic of structure and burn severity that would have historically been found (Donager et al. 2021a).

To reduce the risk of catastrophic fires, forest managers across the western USA are considering large-scale forest restoration projects (Grant et al. 2013;

Goeking and Tarboton 2020). The U.S. Forest Service is implementing the first and largest forest restoration project through mechanical thinning and controlled burning over a million ha of forests across four National Forests in the state of Arizona, USA (Four Forest Restoration Initiative 2013; “4FRI”). The treatments are hoped to create landscape patterns that mimic the natural range of variability in forest patches and structure. Thinning and controlled burning treatments are expected to create landscape patches with a mosaic of patch sizes, canopy openings, and ages (Four Forest Restoration Initiative 2013). The resulting treatment benefits have been well documented at regional scales (Dickinson et al. 2016; Fitch et al. 2018; Sankey et al. 2021a, 2021b, 2021c).

As part of the state-wide effort, the city of Flagstaff in northern Arizona implemented a forest fuels reduction project, known as the Flagstaff Watershed Protection Project (U.S. Forest Service 2014). Due to its proximity to residential structures, the WUI of the city of Flagstaff and the surrounding Coconino National Forest managed by the U.S. Forest Service was identified as a high priority area for fuels reduction via mechanical thinning (U.S. Forest Service 2014). The mechanical thinning treatment occurred in 2019–2020 (Fig. 1) and successfully treated approximately 300 ha. However, the thinning equipment ignited a fire in the WUI. Known as the Museum fire, the fire burned uphill of the thinned area and at the top of the Spruce Avenue watershed that drains into the city of Flagstaff (Fig. 1).

Immediately downstream of the burned area, we examine the thinning impacts on landscape heterogeneity, patch sizes, and forest structure using finer resolution UAV images over a smaller area, while we examine the larger burned portion of the landscape using Sentinel-2A satellite images (Fig. 1). In this nested approach (Rudge et al. 2022), the coarser-resolution satellite data allowed a landscape-scale analysis of the burned area, while the finer-resolution UAV image analysis over a smaller area enabled post-thinning forest stand- and patch-level analysis. There are often trade-offs in terms of spatial and temporal resolution of satellite and UAV remote sensing data (Solazzo et al. 2018; Zhu et al. 2018; Elkind et al. 2019; Alvarez-Vanhard et al. 2021). Satellite remote sensing is an important tool for fire science and management and can be used to estimate pre-fire fuel conditions and post-fire impacts across landscapes

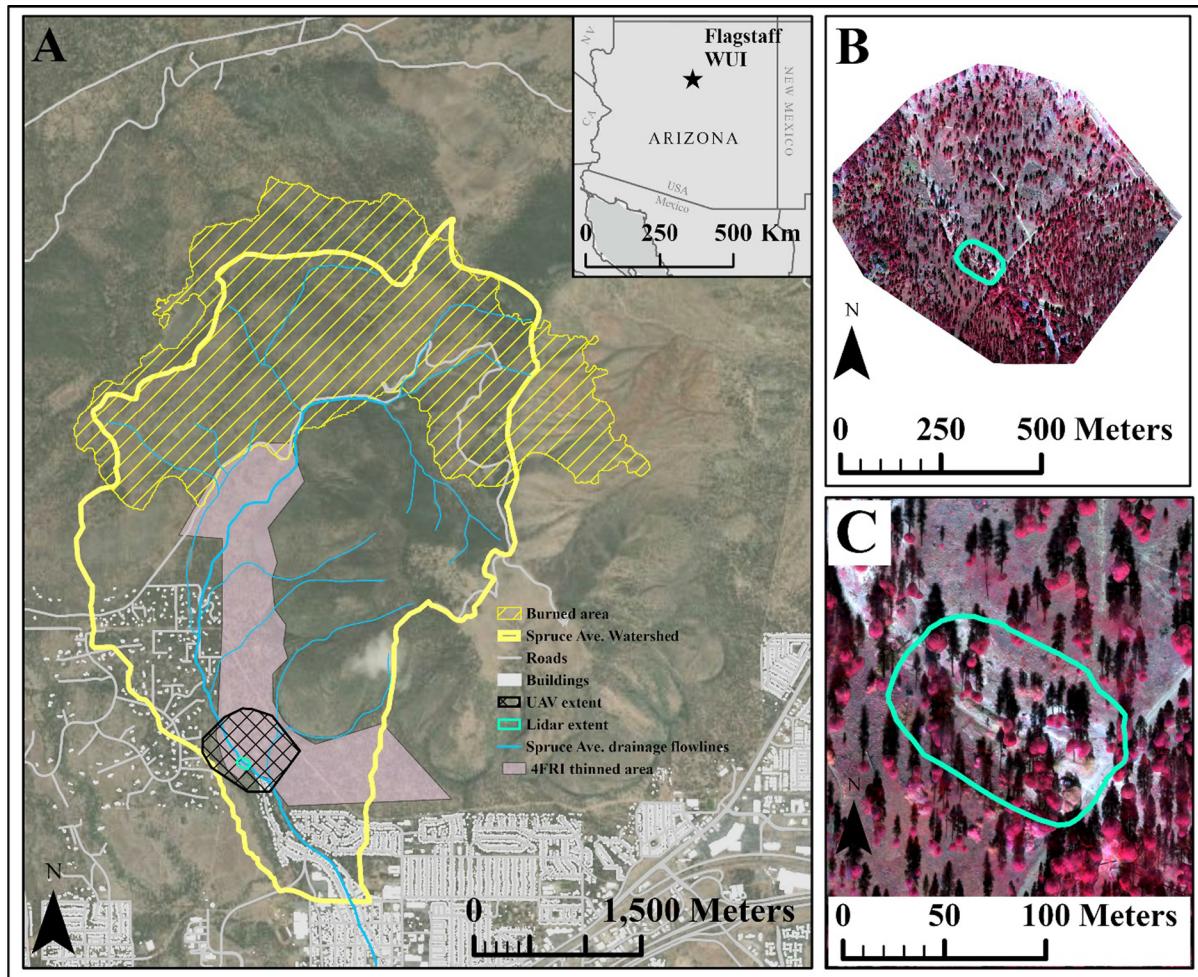


Fig. 1 Flagstaff WUI study area map. Panel **A** shows the entire extent of the Spruce Avenue Watershed and its tributaries (blue lines) immediately upstream of the Flagstaff urban areas in northern Arizona, USA (inset map). The high elevation portion of the Spruce Avenue Watershed was burned by the Museum Fire in 2019, while the middle elevation portion

of the watershed, downstream of the fire, was thinned (Panel **A**). Panels **B** and **C** show the unoccupied aerial vehicle (UAV) image extent (displayed as a false color composite) and terrestrial lidar data extent (cyan line), respectively, in the lower portion of the Spruce Avenue Watershed, where it drains into the city of Flagstaff, Arizona

(Chuvieco et al. 2020). However, satellite images are often too coarse in spatial resolution to capture important local-scale impacts and processes, although satellite data provide excellent coverage, temporal and spectral resolution. In contrast, UAV images can be used to characterize local-scale changes and processes in a very fine resolution, but over smaller spatial extents (Von Nonn et al. *in press*). Therefore, UAV data are increasingly linked to satellite image-based estimates across larger landscapes (Zhu et al. 2018; Alvarez-Vanhard et al. 2021). Such multi-scale remote sensing analyses can provide new insights

into landscape changes due to fires and post-fire disturbances.

In our study, immediately downstream of the burned area, the thinning treatment across ~300 ha aimed to reduce tree density and canopy cover and alter canopy height distribution. Such detailed changes, however, are challenging to detect with coarse-resolution, 2-dimensional satellite images including Sentinel-2A, especially within spatially-heterogenous WUIs, where houses and structures are intermixed with the adjacent forest landscape. Finer-resolution and 3-dimensional estimates of forest

structure are needed before and after thinning treatments. We demonstrate pre- and post-thinning UAV multispectral images and Structure-from-Motion (SfM) data in estimating changes in patch-level forest structure within the WUI. While UAV sensors are increasingly used in various environmental science applications, repeated and multi-year UAV multispectral and SfM data application in landscape change detection remains rare.

The thinned WUI forest as well as the city of Flagstaff immediately downstream of the burned area faced further challenges because burned landscapes are often associated with subsequent excess rainfall-driven erosion and flood events (Shakesby and Doerr 2006), which can be particularly devastating in WUIs (Kean et al. 2019). Burned soils can become water-repellent, which causes large run-off and soil erosion events (Neary et al. 2003; Cannon et al. 2008). Following the 2019 fire, the Flagstaff WUI experienced “exceptional” drought for two consecutive years and thus soils did not erode much. However, the North American Monsoon season in 2021 began with a 100-year rainfall event followed by a 200–500-year event on July 14 and August 17, respectively (Coconino County 2021). The 2021 record rainfall events were centered on and around the fire scar at the top of the Spruce Avenue watershed. The record rainfall resulted in much of the burned debris and sediment transported downstream through the thinned forest patches and then into the city of Flagstaff, which experienced damages of several million dollars to city infrastructure including roads and stormwater systems as well as houses despite substantial preparation by the city (Coconino County 2021). While the fire, thinning, and flood impacted different portions of the landscape at varying elevations, they sequentially impacted the Spruce Avenue watershed as a chain of events at various scales, ultimately impacting the city of Flagstaff and neighborhoods (Porter et al. 2023). Within our nested approach, we quantify the impact of the post-fire flood events using pre- and post-flood terrestrial lidar data.

Post-fire runoff events cause rapid geomorphic changes within and downstream of burned landscapes (Brogan et al. 2019). In the western US, post-fire sedimentation is projected to significantly increase over the next two decades for a large majority of the forested watersheds, which could increase sedimentation by more than 100% in many surface water bodies that

are important for drinking water supply (Sankey et al. 2017a). However, climate change-driven geomorphic impacts such as increased post-fire soil erosion can be challenging to quantify owing to data limitations and the confounding effects of humans, land use, weather, and natural processes (East and Sankey 2020) and require high spatial and temporal resolution 3-dimensional survey data (Rengers et al. 2021; Brogan et al. 2019). Terrestrial lidar can provide geomorphic change estimates with 6–7% errors relative to the total volume of sediment erosion or deposition (Bremer and Sass 2012). Terrestrial lidar is a highly effective approach for detecting and quantifying landscape-scale geomorphic change (Wheaton et al. 2010), but can contain uncertainties from filtering methods, terrain curvature (Bremer and Sass 2012), data resolution (Kasprak et al. 2019), spatial variability uncertainty (Wheaton et al. 2010), scan -to-scan registration, and georeferencing (Lane et al. 2003). Using pre- and post-flood lidar data, we estimate geomorphic changes in the Flagstaff WUI caused by the post-fire record rainfall events. In addition, using the pre- and post-flood UAV multispectral images, we estimate changes in bareground not covered by tree canopy.

Our specific objectives were to demonstrate multi-temporal, fine-resolution UAV and TLS data applications in addressing the following specific questions:

- (1) How did forest pattern, patch size, and vertical structure change resulting from forest thinning?
- (2) Over a smaller portion of the watershed imaged with TLS, what was the geomorphic effect of post-fire flood within the WUI?

Methods

Study area description

Our study focuses on the WUI of Flagstaff, Arizona, USA and the surrounding Coconino National Forest. Specifically, we focus on the Spruce Avenue watershed that experienced a chain of events: (1) the Museum Fire burned at high elevations at the top of the watershed during July 21–August 12, 2019, (2) at middle elevations, immediately downstream of the fire, a smaller portion of the watershed was

mechanically thinned, and (3) the burned area at the top of the watershed experienced extreme rainfall events in 2021, which carried debris flow and sediment through the downstream thinned area and the city, where the watershed drains (Fig. 1).

The entire spatial extent includes 1,506 ha within the WUI, of which the U.S. Forest Service initially estimated approximately 900 ha was burned (BAER team 2019). The elevation of the entire study area ranges between 2158 and 2835 m with gentle to steep southerly- and southwesterly-facing slopes. The dominant overstory vegetation type is ponderosa pine (*Pinus ponderosa*) with occasional Gambel oak (*Quercus gambelii*). Understory vegetation includes native species of Arizona fescue (*Festuca arizonica*), bottlebrush squirreltail (*Elymus elymoides*), mountain muhly (*Muhlenbergia montana*), and Fendler's ceanothus (*Ceanothus fendleri*).

Since the Museum fire occurred at the top of the watershed covering the largest spatial extent, we used Sentinel-2A satellite data to detect the fire scar and calculate burn severity. Specifically, Sentinel-2A images from two dates were used: June 27, 2019 (pre-fire) and June 21, 2021 (2-years post-fire). The images were atmospherically corrected with the European Space Agency SNAP Sen2Cor processor (version 2.9) and co-registered to each other. An image differencing method, known as the differenced Normalized Burn Ratio (dNBR) index, provides an accurate estimate of fire damage in the forest canopy as well as the understory and ground surface (van Wagtendonk et al. 2004; Parsons et al. 2010; Meng and Zhao 2017; Gholinejad and Khesali 2021). The dNBR is also commonly used by land managers due to its efficiency, computational accessibility, and flexibility. Using the red edge band centered on 865 nm and shortwave-infrared band centered at 2,190 nm, we calculated the differenced normalized burn ratio (dNBR) (van Wagtendonk et al. 2004) in 20 m spatial resolution with the Eqs. 1 and 2:

$$NBR = (NIR - SWIR) / (NIR + SWIR) \quad (1)$$

$$dNBR = NBR_{prefire} - NBR_{postfire} \quad (2)$$

Using the dNBR image, we first delineated the fire perimeter and validated it using a pixel-by-pixel comparison to the preliminary BAER assessment (BAER 2019) map created by the U.S. Forest Service for the

fire control efforts. Next, using the thresholds determined by Key and Benson (2005) with a decision tree classifier, the dNBR image was classified into burn severity categories: unburned, low severity burn, moderate severity burn, and high severity burn. Since the burned area and thinned forest had little overlap, we did not compare non-thinned and thinned area burn severity.

At middle elevations of the Spruce Avenue watershed, the thinning treatment was implemented in summer 2019 with a specific prescription that aimed to reduce tree density and total canopy cover and create uneven-aged structure with a mosaic of openings and tree groups of varying sizes (FWPP 2013). To reduce active crown fire risks (continuous canopy that carries fire), the thinning prescription was also aimed at disaggregating the large contiguous forest patches into small patches to increase landscape heterogeneity. Specifically, the prescription sought to create openings that would occupy approximately 20% of the thinned area and tree patches that would vary in sizes ranging 200–2830 m² with 2–40 trees per group (FWPP 2013). Within the treated area, our study focuses on the Phase 1 area directly adjacent to residential neighborhoods, where the Spruce Avenue watershed main channel drains into Flagstaff. We imaged a portion of the Phase 1 area with a UAV multispectral sensor pre-thinning in 2016 and post-thinning in 2021.

Following the Museum Fire (July 21–August 12, 2019) at high elevations and the thinning at middle elevations, the study area received substantially lower precipitation than the mean annual precipitation over two consecutive years (Sankey and Tatum 2022). Mean annual precipitation is of 560 mm distributed in a bi-modal annual pattern with winter snowfall and North American Monsoon rainstorms in the summer with a mean annual temperature of 7.9 °C (NOAA). However, a 100-year rainfall event on July 14, 2021 produced 64–89 mm precipitation over the Museum Fire scar. This event was soon followed by a 200–500-year event on August 17, 2021 that brought 76–101 mm of rain (Coconino County 2021). The Spruce Avenue watershed experienced significant flooding during these events, which drained the burned area debris and sediment from the top of the watershed into the city. For example, the first culvert that drains the watershed into the city has an estimated carrying capacity of 8.5 cubic meter of

water per second (m^3/s), whereas the 200–500-year rainfall event resulted in flow rates approaching 85 m^3/s (Coconino County 2021). We imaged a segment of the main channel upstream of the first culvert with a TLS before and after the flood events (Fig. 1 Panels B and C). The Spruce Avenue channel that conveyed a majority of the sediment-laden flood waters from the burned area to the downstream urban neighborhoods of Flagstaff (Fig. 1 Panel C). Our UAV images included a larger spatial extent covering the hillslope areas surrounding the channel segment imaged by the TLS (Fig. 1 Panel B). The fine spatial resolution UAV images, photogrammetric data, and terrestrial lidar data represent the thinned portion of the forest immediately downstream of the burned area, but was heavily impacted by the post-fire flood (Fig. 1 Panels B and C), whereas the uphill burned area was examined with the Sentinel-2 A satellite data. The post-fire and post-thinning UAV images and terrestrial lidar data were collected immediately after the flood events, but prior to post-flood channel restoration work that was completed in this watershed.

UAV multispectral and photogrammetry data for post-thinning forest change detection

In fall 2016, we operated a Sensefly eBee fixed-wing UAV platform equipped with a multispectral sensor (Sensefly, Lausanne, Switzerland) to image 45 ha of the Phase 1 focus area (Shin et al. 2018). We then revisited the same area with the same UAV platform and multispectral sensor in October, 2021 after all disturbances: (a) forest thinning treatment in 2019, (b) the Museum Fire in 2019, and (c) post-fire flooding in summer 2021. UAV flights on both dates were conducted at 120 m altitude with 85–90% latitudinal and longitudinal overlap, which resulted in image pixel resolution of 15 cm in four spectral bands: green, red, red edge, near-infrared (Fig. 2). The flight planning and mission control were performed in Sensefly eMotion software (Sensefly, Lausanne, Switzerland). This software also integrates the flight log and image GPS data to geotag and georeference the images, which were then processed in Sensefly Pix4D software (Sensefly, Lausanne, Switzerland) to create a final orthomosaic image for each date as well as a photogrammetrically generated point cloud data (point density of 14 points/ m^3) via the Structure-from-Motion (SfM) algorithm (Fig. 2). The root mean square error

(RMSE) reported by the Pix4D software were 0.4, 0.5, and 0.7 m in the X, Y, and Z dimensions, which are similar to previously estimated UAV data accuracies (Sankey et al. 2017b, 2018, 2019, 2021b, 2021c; Elkind et al. 2019; Solazzo et al. 2018; Belmonte et al. 2019, 2021; Donager et al. 2021a, 2021b).

By comparing the 2016 and 2021 UAV images (Fig. 2), we estimated changes in tree density and total tree canopy cover due to the thinning. In both images, individual tree canopies were delineated using a minimum threshold of 0.2 in normalized difference vegetation index (NDVI) derived from the multispectral image and 1.37 m in canopy height value derived from the UAV SfM data. Canopy cover and tree density were then summarized in 10 m cells. We also used 2016 and 2021 UAV SfM data to estimate changes in the mean forest canopy height due to the thinning. We previously demonstrated that our UAV SfM-derived canopy height estimates are strongly correlated with field-measured canopy heights ($R^2=0.71$; RMSE=1.8 m; Shin et al. 2018). However, canopy base height cannot be reliably estimated with UAV SfM data ($R^2=0.34$; RMSE=2.5 m), although the UAV SfM-based estimates are more accurate than LANDFIRE satellite image-based estimates (Shin et al. 2018). We, therefore, estimate mean canopy base height from our field-based measurements only ($N=192$ trees) for this study. The mean field-based canopy base height across the study area was 7.7 m.

UAV multispectral images and terrestrial lidar data for geomorphic change detection

First, the 2016 and 2021 UAV multispectral images were classified in ENVI software using the Machine Learning module and random forest classifier (Harris Geospatial, Denver, CO) to detect changes in percent of bareground that was not covered by tree canopies or other lower height vegetation strata due to the post-fire flood events and possibly thinning (overall classification accuracy of 95%). Specifically, the classification focused on areas that were not classified or delineated as trees (described above in “[UAV multispectral and photogrammetry data for post-thinning forest change detection](#)” section). The classification included only two different classes: other lower height vegetation versus no vegetation cover (i.e., bareground).

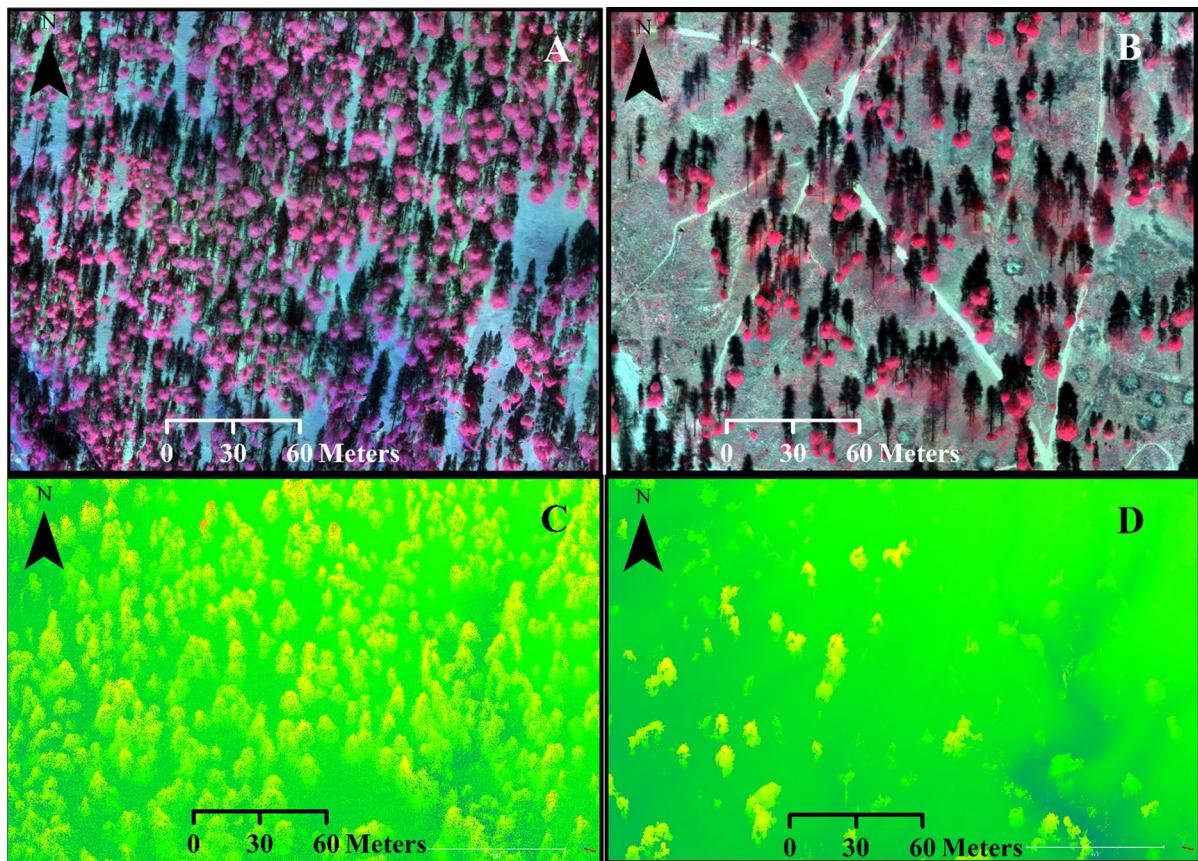


Fig. 2 UAV multispectral images from 2016 (Panel **A**) and 2021 (Panel **B**) of the same area before and after thinning, respectively. A sharp bend in the road can be seen in the upper left corner of both images. The same road and other trails are much more visible in the post-thinning image (Panel **B**) along with small circular scars from pile burning of the cut material. Panels **C** and **D** show photogrammetrically generated 3D data from 2016 pre-disturbance (Panel **C**) and 2021 post-

disturbance (Panel **D**). The 2021 UAV multispectral image shows the decreased tree cover from thinning, and the eroded Spruce Avenue Watershed runoff channel and hiking trails that served as small runoff channels during the post-fire flooding. The 2021 UAV multispectral image also shows impacts of the burning of cut tree piles, which are visible as small, circular burn scars

Secondly, using a Leica BLK360 terrestrial lidar scanner (single laser return centered at 830 nm), we imaged a section of the Spruce Avenue watershed main channel that drains into downstream urban neighborhoods in the city of Flagstaff (Fig. 1). The vendor-reported scanner positional accuracy of the laser is 8 mm at 20 m range with a beam diameter of 2 mm. We collected two sets of lidar images from the channel: one on July 14th, 2021 prior to the record rainfall events but post-fire and thinning, and one on October 29th, 2021 after both record rainfall events. Individual scans were georeferenced and mosaicked together using six ground control points (RMSE of 1 cm), which were mapped with a Trimble GeoXH

GPS receiver (accuracy of 5 cm). The resulting lidar image from each date included 6–8 million laser points covering a total overlapping area of 7935 m² with a ~70 m channel width and ~100 m long segment of the channel (average channel width = 20 m). The images from the two dates were co-registered (RMSE = 2.6 cm) and then rasterized in CloudCompare software to create bare earth digital elevation models (DEMs) in 10 cm cell resolution. We used the iterative filtering method to determine the lowest point in each cell as bare earth.

The DEMs were then compared in the Geomorphic Change Detection software of Wheaton et al. (2010) to estimate the topographic changes owing to

sediment erosion and deposition in the channel segment caused by the post-fire flooding events. The Wheaton et al. (2010) software incorporates spatially variable estimation of DEM uncertainties and propagates those uncertainties through the DEM change detection on a cell-by-cell basis at a user-defined confidence level; we specifically used slope and terrain roughness error surfaces as two key sources of DEM uncertainty at 95% confidence. Given the co-registration errors (RMSE of 2 cm) and our error propagation estimates (Lane et al. 2003), we then used a 2 cm change detection threshold to exclude all elevation changes < 2 cm from our final estimates of significant topographic changes. We determined topographic changes per pixel area to estimate volumetric changes, in which sediment erosion and deposition are represented by negative and positive topographic changes, respectively. We calculated the sediment imbalance (SI) (Kasprak et al. 2019):

$$SI = \left[\frac{V_{dep} - V_{eros}}{2 \times (V_{dep} + V_{eros})} \right] \times 100 \quad (3)$$

which is a commonly used geomorphic metric to characterize sediment dynamics, in which V_{dep} and V_{eros} are the volume of deposition and erosion, respectively, determined from topographic change detection per pixel area. SI of -50% or 50% indicates that topographic change was entirely erosional or depositional, respectively. SI of 0% indicates that the volumes of erosion and deposition were equal.

Results

Thinning and forest structure changes

Upstream of the thinned area at the top of the watershed, we estimate from Sentinel-2A images that the Museum Fire burned a total area of 728 ha, which had a 90% spatial overlap agreement with the initial, rapid assessments made by the U.S. Forest Service BAER team for firefighting and imminent flood response planning (Fig. 3; Table 1). In the Sentinel-2A image, a majority of the burned area was classified as low severity burn with the most severe burn impacts occurring in the central and southwest portions of the burned area (Table 1) closer to the city of Flagstaff.

Downstream of the burned area and at middle elevations in the Spruce Avenue watershed, UAV multispectral image analysis indicated that the thinning significantly reduced tree canopy cover ($p < 0.001$) from a mean cover of 36% ($SD = 20.8\%$) to 8% ($SD = 12\%$; $N = 2753$ cells), whereas the mean tree density was significantly reduced ($p < 0.001$) from 4 to 2 trees per 10 m cell ($SD = 1$; $N = 2753$ cells) (Fig. 2), indicating that the prescription goals were successfully met within the specific extent of forest area imaged by UAV. The mean tree canopy height changed from 17.3 m ($SD = 4.1$ m) to 9.7 m ($SD = 7.5$ m), which indicates that the prescription goal to create uneven-aged structure was likely met as well. The thinning also disaggregated the large contiguous forest patches into many small patches. As a result, the mean patch area decreased from 90 m^2 ($SD = 469 \text{ m}^2$) to 24 m^2 ($SD = 74 \text{ m}^2$). The large standard deviation relative to the mean suggests that patch sizes are highly variable and the prescription goal to create varying sizes and shapes was successfully met within the imaged extent of forest area. Taken together, these results also suggest the thinning prescription goal to reduce active crown fire risk was successfully met.

Flooding and geomorphic changes

UAV multispectral image analysis indicated that bare ground covered only 0.9% of the forested area in 2016, whereas post-flood and post-thinning bare ground cover was 3.7% in 2021. This indicates that bare ground cover more than tripled over the 4-year period, although it continues to be a very small portion of the forested area overall. Areas of bare ground are those portions of soil not covered by vegetation canopy, stems, or stumps at any level of the vegetation strata from understory to overstory. Thus, there may be additional areas of soil that are covered by the canopy of the ponderosa pine trees but are bare when evaluated at the ground surface. Bare soil is more prone to erosion by runoff caused excess rainfall.

Lidar data analysis indicated that the post-fire flooding eroded 132 m^3 of sediment and deposited 265 m^3 sediment over the $7,935 \text{ m}^2$ area of the Spruce Avenue channel segment that was scanned (Fig. 4). Based on the incorporation of slope and terrain roughness error surfaces, and at a 95% confidence interval, error volumes reported by the GCD software were approximately 23%. The depth (thickness)

Fig. 3 Museum Fire boundary (Panel A), detected in the Sentinel-2A satellite images and validated by the initial BAER map developed by the U.S. Forest Service for firefighters, and Sentinel-2A image-derived burn severity classes (Panel B)

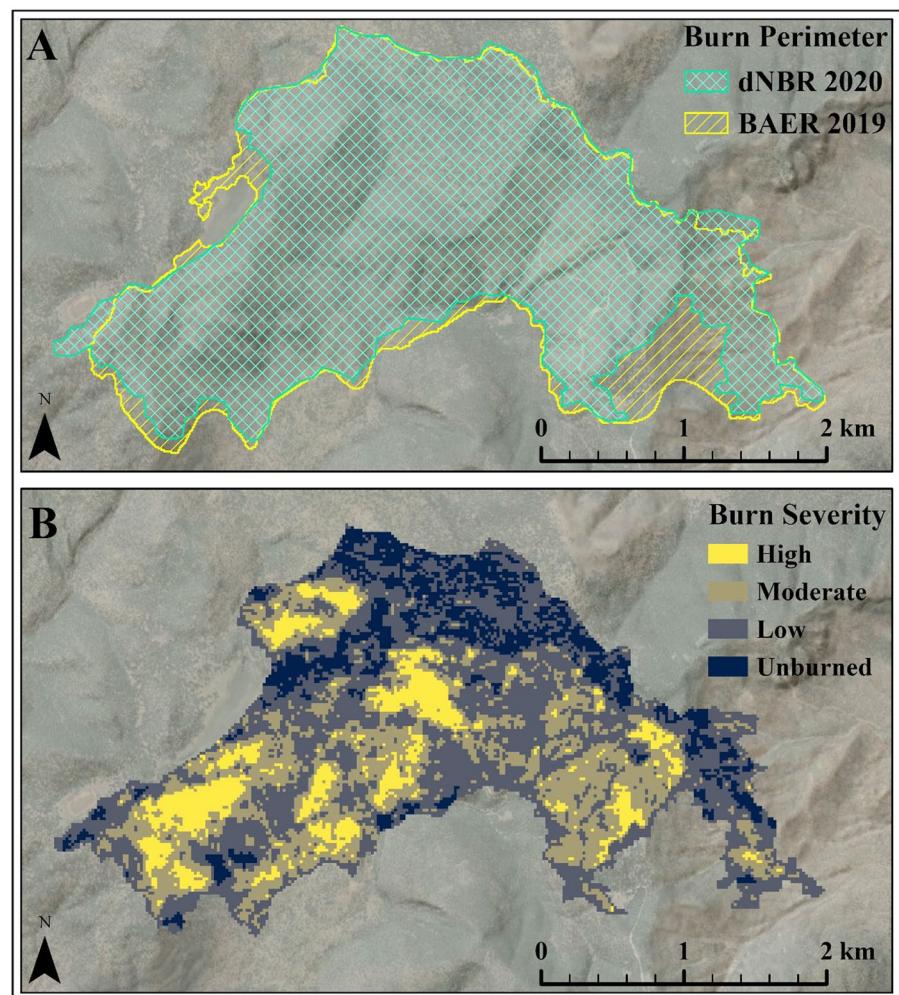


Table 1 Sentinel-2A image-derived and BEAR team's burn severity classes of the Museum fire

Burn class	Sentinel-2A clas-		BAER classifi-		
	classification	Area (ha)	classification	Area (ha)	%
Unburned		114.1		95.6	12
Low severity		317.7		380.3	48.1
Moderate-high severity		213.16		220.9	27.9
High severity		83		93.8	11.8
Total		713.2		790.4	100

of topographic change per pixel area ranges from the minimum significance threshold of 2 cm to 0.94 m of sediment deposition or 0.75 m of sediment erosion, respectively (Fig. 4). The SI was 16% for the

channel segment area imaged with lidar. This indicates that though erosion and deposition occurred in the channel, the topographic changes were slightly net depositional.

Discussion

As global populations increase, WUIs are growing into the adjacent forested areas putting more people and forests at risk from fire (Radeloff et al. 2018). The presence of the buildings, infrastructure, and humans also alter the forested landscapes, their functioning, wildlife, and ecosystem services (Carlson et al. 2023). Cities may need to prepare their WUIs for fire, extreme weather, flood, and geomorphic events, which are projected to increase in many

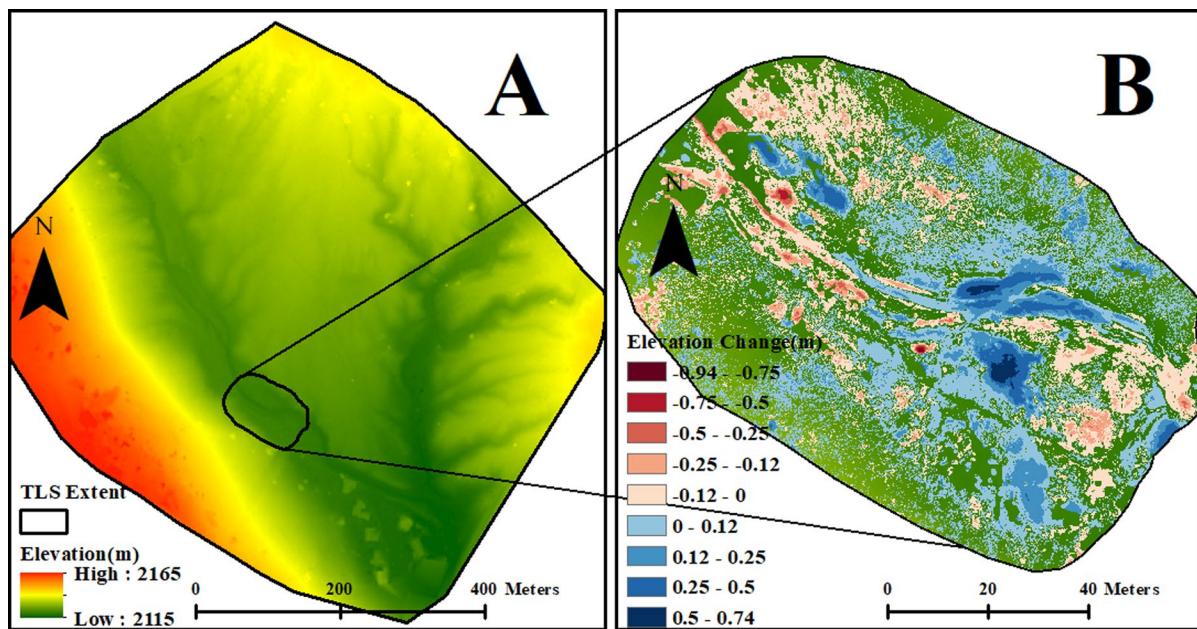


Fig. 4 Post-disturbance DEM derived in 10 cm spatial resolution from UAV image photogrammetry (Panel A) and geomorphic changes estimated from the pre- and post-flood terrestrial lidar data (Panel B)

locations as a function of land use, climate change, and other factors (IPCC 2022). We examined the combined effects of a forest fire, thinning, extreme rainfall, and flood events in a WUI. Specifically, (1) the high elevation Museum fire burned at the top of the Spruce Avenue watershed, which drains into the city of Flagstaff, (2) the Museum fire was ignited by forest thinning that took place immediately downstream of the fire at mid-elevations but within the same watershed, (3) the Spruce Avenue watershed experienced extreme rainfall events, which carried burned forest debris and sediment downstream through the thinned forest and into the city of Flagstaff. Our results highlight that: (1) forest thinning helped reduce future catastrophic fire risks, but unfortunately also ignited a fire, (2) the fire burned at a spatially variable burn severity including high severity within <3 km of the city, (3) post-fire and post-thinning extreme rainfall and runoff flood events caused geomorphic changes downstream of the burned area. Collectively, these observations illustrate a cascade of events that culminated in severe damages caused by the sediment-laden flooding, which exceeded the carrying capacity of the city's stormwater infrastructure (Coconino County 2021).

Fire in wildland-urban interface areas

Both the size and frequency of wildfires are increasing globally due to climate change (Hawbaker and Zhu 2012). WUIs across the US, where 100 million people reside, are at increasing risk from wildfire (Radeloff et al. 2018). The Flagstaff WUI in northern Arizona experienced a forest fire that burned within 3 km of its downtown and threatened neighborhoods. Importantly, the Museum fire burned at high elevations at the top of the Spruce Avenue watershed that drains into the city with subsequent and long-lasting impacts downstream and especially on the city of Flagstaff and its water supplies. Our Sentinel-2A image analysis indicate that WUI burn severity can be spatially variable at a local scale in the semi-arid ponderosa pine forest. Some areas within the fire boundary burned at a moderate to high severity, which could have impacted the city to an even greater extent without the successful and rapid fire suppression. When combined with the thinned areas downstream of the burned area, the Spruce Avenue watershed now has much more heterogeneous landscape with varying vegetation cover types and a mosaic of forest patches. Over 70% of the 56 million ha ponderosa pine forests across the western USA have high density trees and

are vulnerable to catastrophic fires (Covington et al. 1997; Allen et al. 2002). Millions of these forest hectares border urban areas and can be prioritized in forest thinning efforts as more states across the western USA adopt regional forest restoration treatments such as the currently ongoing 4FRI effort across the state of Arizona.

At the high elevation portions of the Spruce Avenue watershed, the Sentinel-2A satellite image-derived fire detection allowed burn severity analysis in a coarse spatial resolution but across a larger spatial extent within our nested and hierarchical analysis (Rudge et al. 2022). Since the fire had limited spatial overlap with the thinned area downstream, we did not examine the thinned area at mid-elevations with Sentinel-2A image but used finer-resolution UAV images for patch-level vegetation structure change analysis. Such varying remote sensing images across spatial scales provide important tools to monitor the processes at different portions of the same watershed (Rudge et al. 2022). The Sentinel-derived burn severity classification had a strong agreement, both in terms of total burned area and burn severity (Table 1), with the preliminary BAER map created by the U.S. Forest Service for emergency fire control (BAER team 2019). The differences observed between the two maps were likely due to the varying satellite image sources as well as the methods and timing of the analysis. The BAER team's rapid assessment used a single WorldView-2 image from late July, 2019 with an NDVI-based classification approach, whereas we used two Sentinel-2A images from before and after the fire. The strong spatial agreement in the two maps indicate that the European Space Agency's Sentinel-2 satellite data can be successfully used to estimate forest fire impacts. The varying burn severity areas across the burned area could now be treated with different restoration approaches including seeding and invasive species treatments.

Thinning and forest structure changes

Immediately downstream of the Museum fire, we examined thinned forest patches and patch-level vegetation structure changes. Forest thinning is increasingly used as an important restoration tool and we demonstrate multi-temporal UAV image application in monitoring thinning impacts. Across the four national forests in Arizona, the 4FRI effort will thin

many forest hectares to reduce the risk of catastrophic fires (Four Forest Restoration Initiative 2013). Other western states are similarly implementing or considering large-scale forest restoration projects (Grant et al. 2013; Goeking and Tarboton 2020). Despite the forest fire occurrence in the Flagstaff WUI associated with the thinning equipment, public support for the thinning project continues to be strong in Flagstaff, Arizona (Edgeley and Colavito 2020).

Our finer-resolution UAV image analysis at the mid-elevation portion of the Spruce Avenue watershed indicate that the thinning treatment significantly altered the forest structure and landscape patterns in the WUI. First, UAV-based estimates show that the thinning significantly reduced forest canopy cover (from 36% to 8%) and tree density (reduced in half) and met the prescription goals in these criteria for the area imaged. Secondly, the thinning disaggregated the spatially contiguous, large patches and created many small patches of trees with large interspaces, which also met the prescription goals and increased landscape heterogeneity. Specifically, the prescription sought to create canopy openings that would occupy approximately 20% of the thinned area, which was accomplished. The treatment also aimed to create varying tree patches ranging 200–2830 m² in size, whereas our results indicate that the mean patch area was decreased to 24 m² with a large standard deviation of 74 m² and highly variable patch sizes (FWPP 2013). Such small patches can be accurately mapped with UAV images and SfM data, but are otherwise difficult to detect from satellite data alone (Sankey et al. 2017a, 2017b; Belmonte et al. 2019; Rudge et al. 2022). Thirdly, the thinning reduced the mean forest canopy height, which indicates that many of the dominant overstory trees were removed leaving sparsely distributed trees of varying heights and ages. Furthermore, using the 2016 UAV data, Shin et al. (2018) previously demonstrated that pre-thinning canopy base height within this WUI was much greater at 7.7 m compared to the LANDFIRE estimate of 1 m, which resulted in much greater predicted active crown fire risks. Given the 7.7 m mean canopy base height and significantly reduced canopy cover, tree density, and patch size, we document that the thinning treatment has substantially reduced future risks in the Flagstaff WUI from active crown fires that are initiated from surface fires and carried through areas of dense trees with contiguous forest canopy cover.

The Flagstaff WUI can also anticipate three additional important benefits that have been observed from thinning treatments regarding drought resiliency in the semi-arid ponderosa pine forests: (1) forest thinning increases summer-time canopy moisture content for the remaining trees (Sankey et al. 2015; 2021a), (2) forest thinning increases winter snow accumulation on the ground (Belmonte et al. 2021; Donager et al. 2021b), and (3) thinned forests have greater soil moisture than non-thinned forests (Simonin et al. 2007; Kerhoulas et al. 2013; O'Donnell et al. 2021; Belmonte et al. 2022; Sankey and Tatum 2022). The Flagstaff WUI and surrounding region has experienced record drought conditions in recent years (Belmonte et al. 2022) as have many other WUIs in regions across the western USA during the currently ongoing North American megadrought (Williams et al. 2020). The improved drought resiliency is especially important because hotter and drier regional droughts are projected to increase and will likely trigger further impacts from insects and diseases in forested ecosystems (D'Amato et al. 2013; Sankey and Tatum 2022).

Flooding and sediment

The burned area at high elevations and downstream thinned forest within the Spruce Avenue watershed all drain into the city of Flagstaff. Following the 2019 forest fire, the Flagstaff WUI area experienced an extreme swing in precipitation from exceptional drought to record rainfall, which concentrated on the fire scar and resulted in large floods in the city of Flagstaff. Such large swings between extreme events are projected to increase with changing climate in the region (Sanderson et al. 2019) and could impact other WUIs around the world that are experiencing increased wildfires (Touma et al. 2022). As an example of such WUIs, events in Flagstaff indicate that the impacts of such floods can overwhelm the current infrastructure in cities that are designed for the normal range of precipitation. Our UAV remote sensing helps illustrate how the sediment, debris, and water flow exceeded Flagstaff's current stormwater infrastructure. The UAV image analysis indicated that the area of bare soil not covered by tree canopy more than tripled in the forested WUI possibly as a result of the rainfall driven run-off events or the thinning. Our UAV image analysis could not separately quantify the

impacts on bare soil from the run-off events versus the thinning operation, since both events took place between the pre- and post-disturbance UAV image collection dates. Furthermore, the Spruce Avenue watershed drains both the burned area and the thinned forest, which partially overlap (Fig. 1). Consequently, this study could not separately quantify the impact of the fire versus the thinning treatment. In addition, a portion of the hillslope below the burn scar, but upstream of the segment of the channel scanned with lidar, received post-fire mitigation work, which distributed rocks and boulders on the alluvial fans in order to redistribute post-fire flood water and capture some of the sediment. This mitigation work also occurred upstream of our UAV images in the unburned, but thinned areas. Our estimates of the impacts of the run-off events to geomorphic changes within the segment of the Spruce Avenue channel scanned with lidar, therefore, indicate the combined impacts of rainfall runoff following forest fire, thinning and potentially the mitigation work.

During the flood events, a total net (i.e., deposition–erosion) volume of 132 m^3 of sediment was deposited in the channel segment imaged by the lidar sensor near the bottom of the Spruce Avenue watershed. The first culvert (approximately 600 m downstream of the lidar scan) in the main channel that drains the Spruce Avenue watershed into the city has an estimated carrying capacity of 8.5 cubic meters of water per second (m^3/s), whereas the 200–500-year rainfall event resulted in flow rates approaching $85 \text{ m}^3/\text{s}$ (Coconino County 2021). The culvert is below the lidar scan area (approximately 600 m downstream) and outside of our image extent, so we did not estimate sediment deposition at the culvert. However, during the flood events, this culvert rapidly filled up with sediment and debris from the fire scar. Consequently, many residential homes and city infrastructure were damaged by water and sediment in the flood events.

Lidar-derived estimates indicate that geomorphic changes caused by the floods from the 100-year and 200–500-year rainfall events, combined with the WUI forest fire and thinning effects, resulted in sediment erosion and deposition in the runoff channel. Sediment imbalance calculations indicated that sediment deposition exceeded erosion in the channel, which nonetheless conveyed large quantities of water and sediment into the city. Local agencies are

currently trying to enhance the landform sediment imbalance by constructing water and sediment detention basins along the channel downstream of the segment scanned with lidar but upstream of the culvert, where future sediment-laden floods might deposit their sediment load and infiltrate into the soil as opposed to flowing immediately to the city. Our estimates do not separately quantify the impacts of the fire and thinning since the data was collected after all of these events had happened. Our estimates also do not evaluate the impact of the mitigation work. Future studies can quantify the effectiveness of the mitigation efforts and channel restoration work by comparing our estimates with additional data collection over longer segments of the channel and newly constructed basins. The city is continuing to invest millions of dollars to increase its stormwater capacity because post-fire flood events are expected to continue in this WUI over the next several years similar to many other WUIs across the western U.S. (Touma et al. 2022).

Our results demonstrate that both terrestrial lidar and UAV images can provide useful estimates of flood impacts. Since terrestrial lidar data cover a small spatial extent, future monitoring can benefit from multiple terrestrial lidar scan locations along the drainage that can be repeatedly and consistently imaged over time to better represent the entire landscape. Such spatially-distributed lidar datasets can also allow a successful scaling between the detailed terrestrial lidar data and the coarser-resolution, lower-accuracy UAV SfM data over a larger spatial extent. In this study, we experimented with such scaling efforts in geomorphic change detection, but the errors in the UAV SfM data could not be sufficiently estimated, and corrected for, across the entire UAV image extent, given the limited spatial coverage of the terrestrial lidar data at one specific section of the drainage. Similarly, multiple UAV and SfM data collections over the entire extent of disturbed and undisturbed landscapes (e.g., burned, thinned, and undisturbed) would allow successful scaling and statistical linking between the UAV and SfM data versus satellite images over even larger spatial extents. We found the difference in spatial resolution too big between the UAV image versus the Sentinel-2A image and terrestrial lidar versus other lidar data such as the spaceborne GEDI data in determining the thinning and burning impacts on fine-scale processes such as bare soil cover increase or sediment erosion and

deposition. Finer spatial resolution satellite data such as PlanetScope or WorldView-2 and -3, and airborne lidar data may be better suited for such direct linking and scaling. While pre- and post-disturbance satellite data can be easily acquired, appropriately-timed and spatially-distributed UAV images from multiple years are rare.

Conclusions

WUIs are globally expanding into the adjacent forests. Cities might need to better prepare their growing WUIs against catastrophic forest fires and extreme weather events. Forest canopy cover, tree density, patch sizes, and mean tree canopy height can be reduced via careful mechanical thinning to reduce active crown fire risks. Lessons can be learned from the Flagstaff WUI forest fire as mechanical thinning continues to be used as a common management tool with widespread public support. Cities might also need to bolster their WUI stormwater infrastructure to tolerate floods from extreme precipitation events.

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Author contributions TS conceptualized this study and coordinated all data collection efforts. TS also collected and analyzed the UAV images. LT collected and analyzed the TLS data. JT analyzed and summarized the Sentinel-2 images. JS conceptualized and interpreted the TLS change detection data.

Declarations

Competing interests The authors declare no competing interests.

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