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# Being there: effectiveness of a 360-degree virtual tour for increasing understanding of forest treatments for fire hazard reduction in California, USA

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## Abstract

**Background** The increasing extent and severity of wildfires in the western USA poses a significant challenge to managers and to society. Forest thinning and prescribed fire treatments reduce fire hazard and improve resilience to climatic stressors. However, expanding the pace and scale of forest management is hampered, in part, by limited understanding and exposure of interested parties and the public to fuel reduction treatments. Virtual tour applications provide an opportunity to extend tours of treatment demonstration areas to anyone with a computer and internet connection. Yet there is little research on the effectiveness of virtual tours for enhancing understanding of forest treatments and if managers would deploy virtual tours to increase public awareness. Here we describe the development and evaluation of a virtual tour (https://chorophronesis.geog.psu.edu/virtualexperiences/StanislausWebsite/indexSummer2022.html) using surveys for three occupational groups: forest managers, university students, and non-student non-managers.

**Results** The virtual tour improved self-reported understanding of how fires historically shaped forests, how fuels changed in the absence of fire, how thinning affects wildfire hazard, how prescribed fire affects wildfire hazard, and how thinning can be modified to enhance biodiversity. The virtual tour was also effective at conveying differences between treatment and non-treatment and among thinning and prescribed fire treatments, for all three occupational groups. There was strong agreement by all groups that if a field tour of forest treatments was not an option, the virtual tour would be a good substitute. The manager and non-manager occupation groups expressed significantly greater agreement with questions on the utility of virtual technology for aiding land management planning discussions and stimulating dialog among their own networks compared to students.

**Conclusions** There was an overwhelmingly positive response to the virtual tour by all groups indicating significant potential to use virtual tours to improve understanding of fuel treatments. This could reduce social barriers impeding the scaling up of fuel reduction treatments that are needed to reduce fire hazard in California and elsewhere.

**Keywords** Wildfire hazard, Forest treatments, Virtual tours, Surveys, Managers, Perception, Place-based learning, 360° imagery, Virtual reality

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**Resumen**

**Antecedentes** El incremento en la extensión y severidad de los incendios de vegetación en el oeste de los EEUU significan un gran desafío tanto para los manejadores de recursos como para toda la sociedad. Los tratamientos de raleos y las quemas prescriptas reducen el riesgo de incendios y mejoran la resiliencia a los estresantes climáticos. Sin embargo, la expansión y velocidad de estos manejos es limitada, en parte, por el escaso entendimiento y la exposición de partes interesadas y del público en general sobre los tratamientos de reducción del combustible. La aplicación de visitas virtuales (virtual tours) proveen la oportunidad de extender estas visitas virtuales a áreas de demostración donde se realizan los tratamientos a cualquier persona que tenga una computadora y conexión a internet. Aun así, son muy pocas las investigaciones sobre la efectividad de aumentar el conocimiento de tratamientos forestales, y si los manejadores de recursos podrían desarrollar estas visitas virtuales para incrementar el conocimiento y la atención del público. En este trabajo, describimos el desarrollo y la evaluación de una visita virtual ((https://chorophronesis.geog.psu.edu/virtualexperiences/StanislausWebsite/indexSummer2022.html), usando un relevamiento sobre tres grupos ocupacionales: manejadores forestales, estudiantes de la universidad, y no estudiantes ni manejadores de recursos.

**Resultados** La visita virtual mejoró el autoconocimiento y el entendimiento sobre cómo los incendios han históricamente modelado los bosques, cómo los combustibles forestales cambian en ausencia del fuego, cómo los raleos afectan el peligro de incendio, como las quemas prescriptas afectan el riesgo de incendios, y cómo los raleos pueden ser modificados para aumentar la biodiversidad. La visita virtual fue también efectiva para hacer comprender las diferencias entre tratamientos y no tratamientos, y entre raleos y quemas prescriptas en los tres grupos analizados. Hubo un muy fuerte acuerdo por parte de todos los grupos en que, si una visita guiada al campo no pudiera concretarse, la visita virtual puede ser un muy buen sustituto. El grupo de manejadores de recurso y grupos de no manejadores expresaron un mayor acuerdo con preguntas sobre la utilidad de la tecnología virtual para ayudar a las discusiones en el planeamiento y la estimulación del diálogo entre sus propias redes comparado con los estudiantes.

**Conclusiones** Hubo una notable respuesta positiva de todos los grupos sobre la visita virtual, indicando el potencial significativo de éstas para mejorar el entendimiento de los tratamientos de combustible. Esto podría reducir las barreras sociales que impiden el escalamiento de los tratamientos de reducción de combustible que son necesarios para reducir el riesgo de incendios en California y en cualquier otro lugar del mundo.

## Background

Both the area burned and area burned at high severity have been increasing in public forests in the American West since the mid-1980s. Consequences are acute, with heightened risks to lives and property (Calkin et al. 2014), carbon sequestration (Harris et al. 2019; Hurteau et al. 2019; Hemes et al. 2023), endangered species and biodiversity (Spies et al. 2006; Jones et al. 2021), water quality (Chow et al. 2021), and other ecosystem services. The increasing wildfire trend has steepened over the last decade (Abatzoglou and Williams 2016), and 2020 witnessed a modern record of 1.74 million hectares burned in California (Safford et al. 2022). Key factors contributing to the fire problem in California include abundant fuels from a century of fire suppression (Scholl and Taylor 2010; Airey-Lauvaux et al. 2022), expansion of housing into the wildland-urban interface (Radeloff et al. 2018), a warming climate that increases fuel aridity (Williams et al. 2019; Higuera and Abatzoglou 2021), and the reduced ability of firefighters to suppress fires under extreme weather conditions (Kreider et al. 2024). This mix of factors has contributed to the enormous socio-ecological and economic costs of wildfires. For example, estimated economic impacts for just the 2018 California wildfires, including property values, health costs from air pollution, and indirect economic disruption exceeded $148 billion (Wang et al. 2018). The magnitude of these impacts has put reducing fire hazard and potential for large and uncharacteristically severe wildfires at the core of public forest land management (Hessburg et al. 2021; USDA Forest Service 2022).

Demonstrated effectiveness of thinning and/or prescribed fire treatments for reducing wildfire severity (Brodie et al. 2024; Davis et al. 2024) and the need to bend the curve on costs has led to state fire prevention, vegetation management, and public education grants; defensible space and fire hazard severity zones, and federal legislation to support the pace and scale of treatments (Wildfire protection package, S.B. 901, Chapter 626, 2018; S.B. 63, Chapter 382, 2021); Infrastructure investment and jobs act, H.R. 3684, 2021). This is no small task. Current treatment rates on western US forests lands are five to tenfold lower than historical fuel reduction from frequent fires before cessation of indigenous burning and fire suppression (North et al. 2012, Taylor et al. 2016, Valliant and Reinhardt 2017, Donato et al. 2023). Successfully increasing treatment rates will likely require an integration of fire and forest management that uses mechanical thinning, prescribed burning, and managed fire (wildfire burning under moderate weather conditions) to reduce fire hazard (Hiers et al. 2020; North et al. 2021). Due to limited public understanding of forest management practices and the importance of public trust in forest management agencies in advancing fuel reduction programs, building support for treatment expansion will be essential (Toman et al. 2011; McCaffrey et al. 2015).

Research on perception of fire risk and trust of agencies to reduce fire hazard with forest treatments show that the direct experience of stakeholders with areas of treated forest improves public understanding and helps build trust for forest treatment programs (McCaffrey et al. 2008; McCaffrey and Olsen 2012; Wilson et al. 2017). Trust and risk perception can vary with other factors including race/ethnicity, education, income level, or gender. For example, women rated perception of wildfire threats higher than men (Marsi et al. 2023), which is consistent with results for risk of all types on natural hazards (Cuesta et al. 2022). Furthermore, men express more fire knowledge and less trust in agencies than women (Winter and Cvetkovich 2010).

Forest treatment demonstration areas in the American West for educating interested parties are typically remote from population centers (Rogers 2022). The limited access to demonstration areas hinders societal understanding of forest treatments and potentially constrains the development of the support needed to increase the pace and scale of fuel treatments. Moreover, manager and public perceptions of benefits and barriers to implementing forest treatments can be mismatched (Toman et al. 2011; Rasch and McCaffrey 2019; Wu et al. 2022), and research is needed to help managers understand public perceptions in developing more effective outreach for fuel management planning.

New technologies, specifically immersive technologies such as 360° cameras, provide a means of developing virtual field trips to allow anyone with a computer and an internet connection, smartphone, or Virtual Reality headset to visit remote locations. Evidence from educational research on place-based virtual tours indicates that virtual experiences can provide learning outcomes comparable to actual field trips (Klippel et al. 2019; Wallgrün et al. 2021). Immersive media allow the viewer a unique way to see and experience a field site. Instead of simply looking at a computer or tablet, the user can experience data at a more visceral level with the same agency as in the physical world (Lee et al. 2020; Guy et al. 2023). This feeling of 'being there' created through immersive media, whether experienced on a desktop or through a head-mounted display, adds to engagement (Wagler and Hanus 2018; Klippel et al. 2020b), which potentially improves retention of the learned material (Schöne et al. 2019). 'Being there' is intimately linked to the concept of *place*, which is also at the center of dominant learning theories including place-based and transformative learning. Place-based learning (e.g., Semken et al. 2017) builds on the scaffolding and contextualizing power of place to facilitate constructivist, experiential learning. Transformative learning (TL), which focuses on profound changes in someone's perspectives, beliefs, and understanding, also stresses place-based experiences as a core element (e.g., Pisters et al. 2019). Place creates an opportunity for grounding embodied experiences and interactions vital to meaningful, deep, and lasting education and learning.

Methods of delivering virtual field trips vary in their degree of immersion, with desktop-based virtual environments providing less immersion than head-mounted displays (VR headsets) (Zhao et al. 2020). The use of VR headsets for virtual field trips is increasing (Klippel et al. 2020b; Lampropoulos and Kinshuk 2024; Vandelli et al. 2024) but the added value over desktop-based virtual environments is not universally established. More immersive VR can be beneficial for certain aspects of learning but simply putting on a VR headset by itself seldom improves learning outcomes more so than desktop virtual environments (Makransky et al. 2019; Zhao et al. 2020). Additionally, less immersive, desktop-based virtual environments still have the advantages of easier access and greater scalability (Mead et al. 2019; Wallgrün et al. 2021). Desktop-based virtual tours are available on-demand to audiences who would not otherwise be able to visit a field demonstration site due to travel and time constraints, geographic distance, hazards, or seasonal inaccessibility, many of whom also do not have access to VR headsets.

While the potential of virtual experiences for place-based education holds tremendous promise (Freina and Ott 2015; Makransky et al. 2019; Klippel et al. 2020a; Brambilla et al. 2024), empirical research on the effectiveness of virtual tours for increasing knowledge in forest/natural resources management among interested parties is limited. The perceived value of virtual field trips increased substantially with the widespread restrictions of on-site visits and face-to-face interactions during the SARS-CoV-2 pandemic, but acceptance and use, especially among environmental scientists and professionals, is only slowly growing (Klippel et al. 2020a; Vandelli et al. 2024). Moreover, little is known about forest managers' familiarity of virtual tools and whether decision-makers would deploy virtual tours in the process of planning and implementing fire hazard reduction projects at local or even regional scales.

In this article, we describe the development of a virtual tour of experimental forest treatments designed to reduce fire hazard in California and to evaluate tour effectiveness in three populations representing different occupational groups: (1) forest management professionals, (2) university students, and (3) non-student non-managers (others). Forest managers are more likely to have direct experience with the topic, but potentially less knowledge or experience with immersive technology, whereas non-manager audiences represented by groups 2 and 3 are likely to have less knowledge of the topic, and varying familiarity with immersive technology. Our specific research questions were (1) did the virtual tour increase self-reported understanding of different forest treatments designed to reduce fire hazard and did this understanding differ among occupational groups; (2) did the three occupational groups vary in their perception of treatment differences; and (3) did manager and non-manager audiences differ in their assessment of potential benefits of the virtual tour approach for increasing engagement among interested parties and developing trust for implementing fire hazard reduction treatments?

## Methods

### Study area and fire hazard reduction treatments

The "Variable Density Thinning" (VDT) study in the Stanislaus-Tuolumne Experimental Forest, near Pinecrest, California, which formed the basis for the virtual tour application, was established to test the ecological outcomes of two mechanical thinning treatments for reducing fire hazard, with and without application of prescribed fire, compared to an untreated control. Treatments were implemented in second growth mixed conifer forests which were first selectively cut in the 1920s. Prior to thinning, a policy of fire exclusion beginning in the early twentieth century led to substantial ingrowth, filling of natural gaps, and dense relatively homogenous structure compared to historical forests with an intact fire regime (Scholl and Taylor 2010; Knapp et al. 2012; Lydersen et al. 2013). The site had not burned since 1889. Prescribed fire was used, following thinning, in half of the study units to reduce the litter, duff, and downed wood that had accumulated since the last fire.

The standard fire hazard reduction thinning treatment results in trees that are relatively evenly-spaced (e.g., "Low Variability"), which reduces the probability of crown fire spread, but lacks the tree group and gap structure that is characteristic of historically mixed conifer old-growth forests. The "High Variability" treatment varied the thinning prescription at the tree group scale, retaining groups with higher tree density and creating small gaps (Knapp et al. 2012; Churchill et al. 2013, Pawlikowsli et al. 2019). The replicated ($n = 4$) treatment units were all *ca*. 4 ha in size. Mechanical thinning was completed in 2011, and prescribed fire units were burned in the fall of 2013.

### Treatment visualizations

The virtual tour experience we created and evaluated is predominantly based on 360° imagery taken at different heights above ground within the VDT study site. High-resolution 360° photographs of stand conditions in each treatment were captured in August 2018 at points on a 30-m grid using a Panono 360° 108MP camera mounted on a telescoping tripod. Photographs were taken at heights of 1.8 m and 8.2 m above ground (the latter providing a within-canopy perspective) and then stitched together automatically by Panono in the cloud. To capture an over canopy perspective, we took 36 high-resolution images at each of three heights—45, 75, and 137 m above the ground—using a DJI-Mavic drone outfitted with a Hasselblad L1D-20c camera. These were stitched together using PTgui.

### Desktop Virtual Reality tour application

We are calling our application a Virtual Reality (VR) tour as it is based on 360° imagery (as an immersive technology) but accessed through a web browser on a normal computer screen rather than a VR headset. While the term VR is sometimes restricted to 3D digital worlds experienced through VR headsets, we use this term to distinguish the application from traditional 2D media. The VR virtual tour experience developed for this study was built in the Unity3D™ game engine with the help of our own set of tour creation tools (Wallgrün et al. 2017). These tools were designed to make the process of tour development as efficient as possible and limit the technical expertise required. They provide a template for a tour project that simplifies the process of incorporating media such as 360° images, complementary photos or video (non-360°), and audio tracks, and define the order of scenes in the tour. With the availability of relatively inexpensive and easy-to-use 360° cameras, 360° image-based tours have the advantage that, in contrast to VR experiences based on full 3D models, they can be produced rather quickly and at a low cost, allowing domain experts to produce the media materials themselves without a background in immersive technologies.

After creating the tour in Unity3D it was exported as a WebGL application and hosted on a web server so the tour could run in a standard web browser and be controlled with a mouse (https://chorophronesis.geog.psu.edu/virtualexperiences/StanislausWebsite/indexSummer2022.html). Based on feedback from initial work on an earlier version of the tour (Wallgrün et al. 2021), we reduced the tour length, added embedded content, and increased interactivity. The revised tour application starts with an overview map and provides instructions on putting the app into full screen mode and operating it with the mouse (Fig. 1a). The interface consists of blue buttons overlain on the scene that allow the user to move between stops on the tour and to access additional content. The camera can be freely rotated via the mouse and the mouse wheel provides a zoom in and out capability. The zoom range was constrained to reduce distortion when the camera is moved too far off the center of the 360° image. Audio narration describing the scene and explaining different aspects of the VDT study was provided for each of the 11 tour stops. Audio tracks can be paused or moved forward or back at each tour stop. After an embedded video introduction (Fig. 1b), content focuses on scenes of each treatment type, which include still photographs (Fig. 1c), illustrations (Fig. 1d), and text labels (Fig. 1e) overlaid on 360° images that highlight content presented in the audio narration. Scenes at ground level (Fig. 1c), within the canopy (Fig. 1d, e), and above canopy (Fig. 1f) are all used to illustrate differences among treatments. Optional content in the form of data tables and additional audio explanations can be accessed via buttons (see Fig. 1e). The tour is 21 min long, not including optional content.

## Questionnaire and study populations

Our main target audiences for evaluating the VR tour application were initially forest management

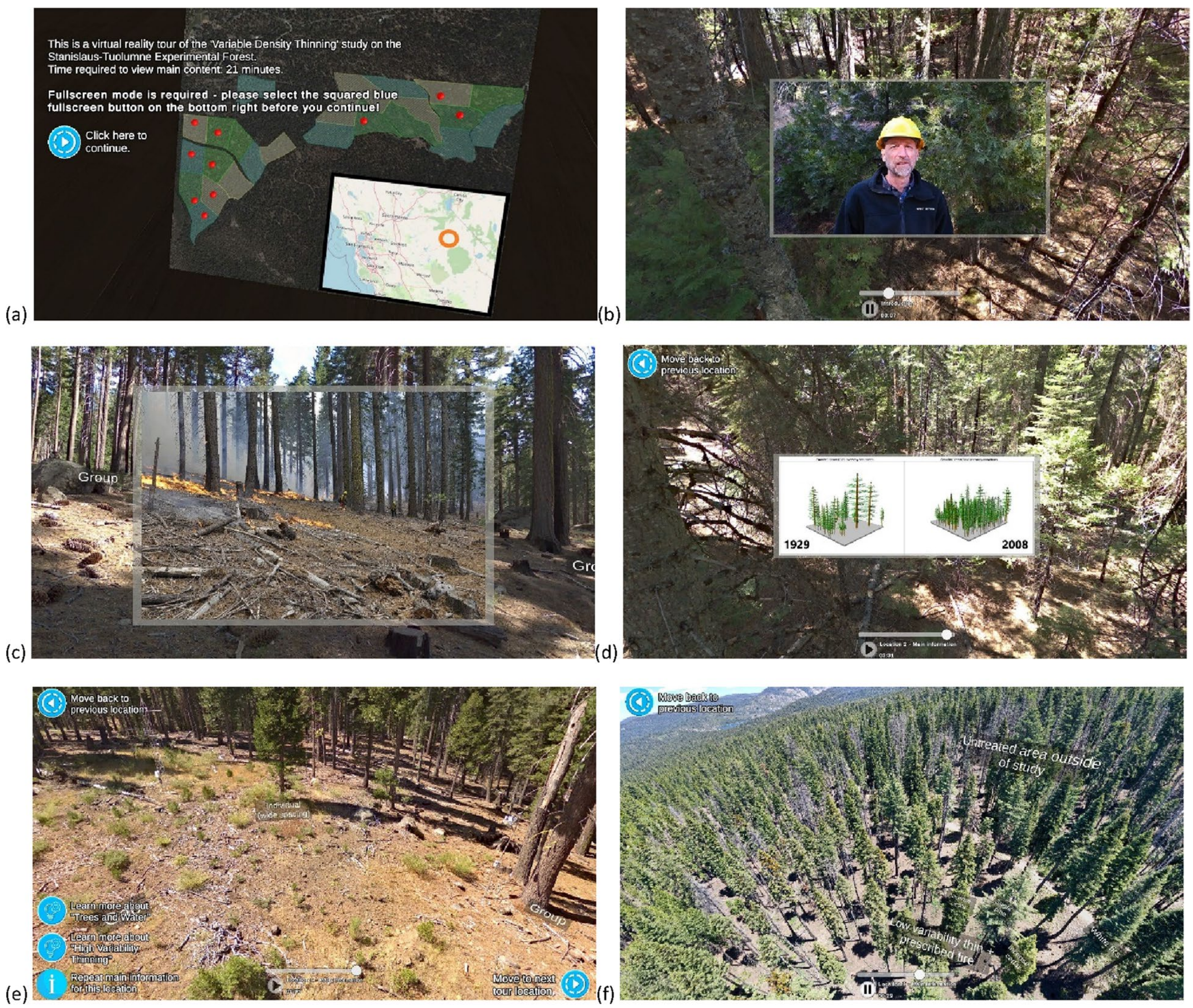


**Fig. 1** Images from the VR tour used in this study: **a** overview map and instructions; **b** VR scene with video overlay; **c** ground level VR scene with overlay photo showing prescribed burns being applied; **d** elevated VR scene with overlay illustration showing the change in forest density and structure over time; **e** elevated view with labels and user interface for controlling tour and providing access the optional content; **f** drone-image scene with labels

professionals and university students. University students represented a non-manager population generally without direct experience in forest and fire management, a similarity shared with a broad cross-section of the public. To recruit forest management professionals, links to the tour and questionnaire were provided to (1) forestry and fire management personnel working in western USA public forests; (2) California Cooperative Extension forestry professionals; (3) forest land management collaboratives and non-governmental organizations (NGO) focused on forest management and forest policy in California; and (4) participants in a wildland fire training course. Notices were also included in newsletters and on social media by the Joint Fire Science Program Fire Science Exchange networks (https://www.firescience.gov/JFSP_exchanges.cfm).

Student participants were recruited from four undergraduate classes at Penn State University (PSU) and California State University, Fullerton (CSUF): (1) BISC 3 Environmental Sciences (PSU), (2) BIOL 110 Basic Concepts and Biodiversity (PSU), (3) Information System and Decision Sciences (CSFU), and (4) Information System and Decision Sciences 2 (CSFU). The methods we used to recruit manager participants also often reached individuals who were interested in forest management or involved in some way in forest management practices and decision-making, but were not land managers. We therefore split this non-student group into (1) Managers, and (2) Others, based on their answer to a pre-tour question about profession. The Manager group ($n=77$) consisted mainly of employees of federal or state agencies (79%), non-governmental organizations (11%), and foresters working for private companies (5%) (Fig. 2, left). The Others group ($N=58$) was comprised of non-manager government employees or individuals involved in forest policy (33%), researcher/scientists (21%), educators (8%), or other/retired (38%) (Fig. 2, middle). A total of 964 students from PSU participated in the study (303 male, 647 female, 14 other) and 119 students from CSUF (52 male, 66 female, 1 other). Student participants were rewarded course credit. We anticipated that the Others (non-manager, non-student) group would have less direct experience with thinning, prescribed fire, and other land management activities than the Managers group, but more so than the Students group.

Participants were provided a link to the virtual tour website which explained the tour, the study, and how to operate the VR tour application. After giving consent, participants were directed to a pre-tour questionnaire to answer demographic-related questions (age, gender, ethnicity, occupation, affiliation, education) and then questions on previous familiarity with principles of fire and forest management, the western US fire problem, and VR technology (Table 1). Participants answered these questions using a continuous slider on a scale between 1 (low familiarity) and 5 (high familiarity) (Table 1). Participants then took the tour and were free to decide how much of the optional content to explore. After finishing the tour, participants were sent back to the survey to answer post-tour questions on their experience and opinion on a discrete scale of 1 (strongly disagree) to 6 (strongly agree) (Table 1). The survey concluded with two open-ended questions asking the participants what they liked most and least about the tour.

## Data analysis

Of the 1239 individuals who completed the surveys, 21 were removed from the analyses due to illegitimate responses or unreasonably short survey completion times (< 1 min for either the pre- or post-tour part), resulting in the final numbers reported above (77 managers, 58 others, and 1083 students) for analysis. Possibly because of differences in sample size, the three groups showed statistically significant differences in variance

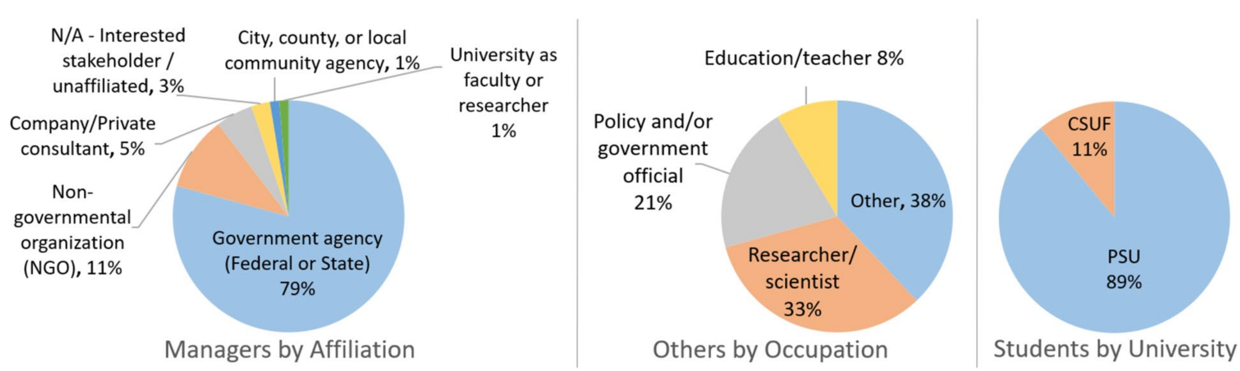


**Fig. 2** Overview on participant groups: "Managers" ($n=77$) grouped by affiliation, "Others" ($n=58$) grouped by occupation, and "Students" ($n=1083$) grouped by University (Pennsylvania State University (PSU) vs. California State University, Fullerton (CSUF))

**Table 1** Pre-tour and post-tour questions used for assessing the effectiveness of a virtual reality tour for understanding forest fire hazard reduction treatments

| |
|---|
| Pre-tour familiarity (continuous scale 1–5)<br>Questions:<br>- Western fire problem<br>- Principles of fire and forest management<br>- Digital technology<br>- VR technology and tools |
| Post-tour self-assessed outcomes (continuous scale 1–6)<br>Questions:<br>Did the tour improve…<br>- Understanding of how fire historically shaped forests and fuels and how forests and fuels change in the absence of fire?<br>- Understanding of how thinning affects wildfire hazard?<br>- Understanding of how prescribed fire affects wildfire hazard?<br>- Understanding of how thinning can be modified to enhance biodiversity?<br>- The difference between an untreated forest and one treated with mechanical thinning was obvious<br>- The difference between a forest with > 100 years of surface fuel accumulation and one treated with prescribed fire was obvious<br>- The difference between a forest thinned with high variability and low variability was obvious<br>- Forest thinned with high variability and prescribed fire looked more natural than other treatments or the untreated control<br>- If attendance of an onsite field tour was not an option, the VR tour would be a good substitute<br>- VR technology could be useful for enhancing public understanding of forest management options in fire-prone forests<br>- VR technology could be useful for land management planning discussions among stakeholders and the general public<br>- I could use a similar VR tour to stimulate dialog among my own networks |
| Open-ended questions<br>- What did you like most about the tour?<br>- What did you like least about the tour? |

($p < 0.05$) in their responses to all our survey questions based on Levene's tests. Consequently, we used one-way Welch's ANOVA tests to compare group mean scores for the different survey questions (see Table 1). When significant, we followed up with Games-Howell post-hoc tests for pairwise comparisons. We also performed the same kind of comparisons for subgroups, either by splitting the entire population based on some criterion (e.g., VR familiarity, gender (men or women; "other" was also an option, but the sample size too small to analyze), or geographic location) or by doing the same for the occupational groups individually (e.g., comparing responses from managers who identified as men or women).

When using a numeric criterion such as reported familiarity scores, we used a median split approach to create two groups with scores above and below the median. We only report the results of these additional comparisons in cases where we found significant differences relevant to the article. All analyses were conducted using R Statistical Software (v3.6.1; R Core Team 2021). *P*-values from Welch's ANOVAs are reported in the text, while the results of the pairwise comparisons are shown in Figs. 3, 4, 5, and 6. Group sizes ($n$) reported in these figures vary slightly because not all participants answered every question.

In addition to these quantitative analyses, we performed qualitative content analysis (Schreier 2012) of the manager responses to the open-ended questions with two of the authors coding the results. The resulting categories and frequencies are shown in the supplement (Tables S1, S2).

## Results

### Pre-VR tour familiarity

The three occupational groups differed in their self-assessed familiarity of the western US fire problem ($p < 0.001$) and principles of forest and fire management ($p < 0.001$). For both questions, all groups differed statistically from each other, with Managers reporting the highest familiarity for both, Students the least, and Others intermediate (Fig. 3a, b). All groups self-assessed equal familiarity with the latest digital technologies ($p = 0.498$) (Fig. 3c). However, differences were found among groups in self-assessed familiarity with VR technology ($p < 0.001$). Managers expressed significantly lower familiarity than Others or Students, with the latter two groups not differing significantly from each other (Fig. 3d).

### VR tour effects on understanding

Scores for self-assessed improved understanding of fire hazard reduction treatments from the VR tour were high for all occupational groups, with mean scores ranging from 4.08 to 4.77 out of 6 (Fig. 4a–d). Improved understanding scores for forest structure and fuel changes in the long-term absence of fire (Fig. 4a), as well as how thinning (Fig. 4b), and prescribed fire (Fig. 4c) help to reduce wildfire hazard differed significantly ($p < 0.001$) among groups. For all three questions, significantly lower changes in self-assessed understanding scores were noted for Managers than Others and Students (Fig. 4a–c). The change in understanding scores for the Others and Students groups did not differ significantly for these questions (Fig. 4a–c). In contrast, no difference among any of the groups was identified for the self-assessed understanding of how thinning can be modified to enhance biodiversity ($p = 0.517$) (Fig. 4d).

### Perceptions of treatment differences

The VR tour was effective at conveying differences between thinned and unthinnned forest, between forest treated with prescribed fire and without prescribed fire, and between thinning treatment type, based on the high scores across occupational groups, with means ranging from 4.25 to 5.59 out of 6 (Fig. 5a–c). However, significant

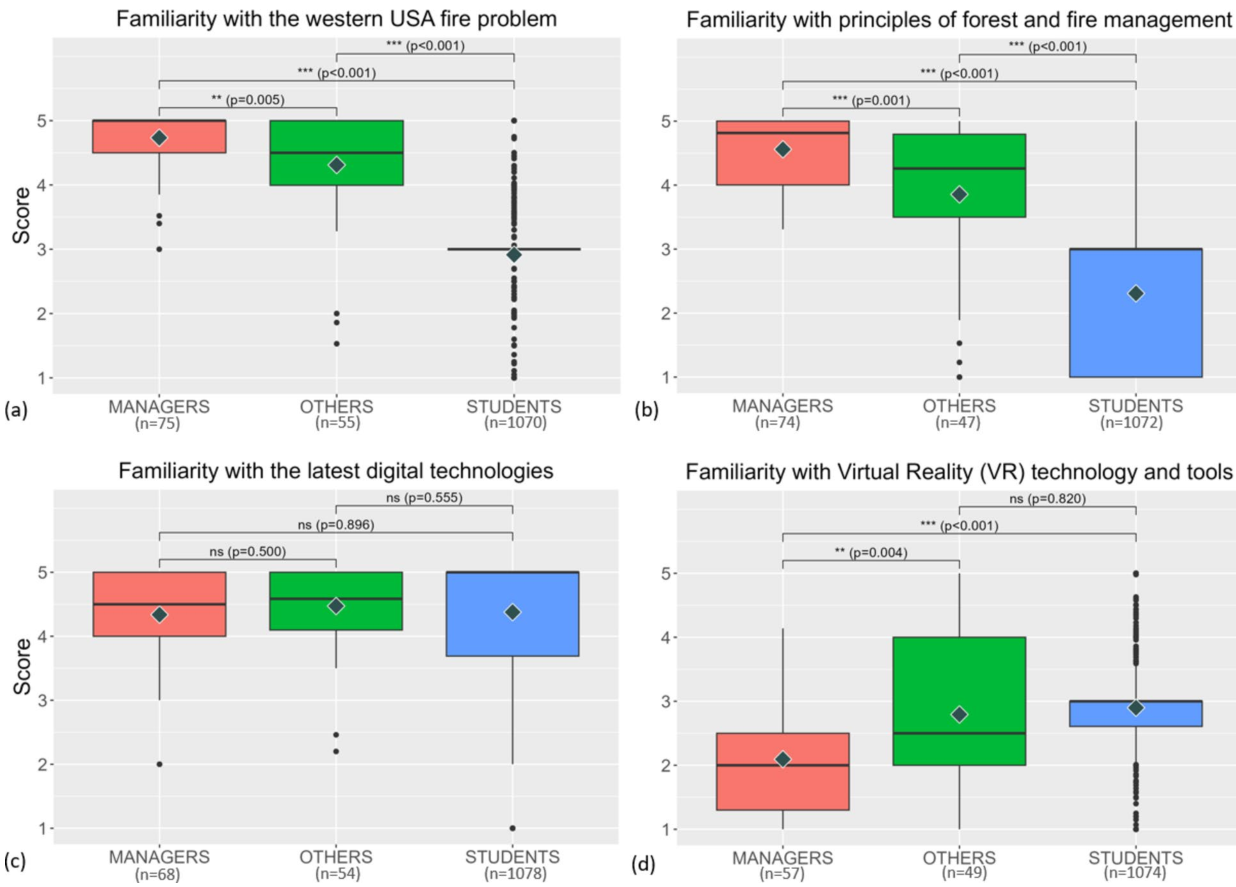


**Fig. 3** Scores for familiarity-related questions (see Table 1) by participant group, including significance of results. The dark horizontal line within boxes shows the median, while the upper and lower bounds of the box indicate the first (25%) and third (75%) quartiles. The mean is denoted with a diamond symbol. Vertical lines connect the largest and smallest values within 1.5 times the interquartile range, with outliers shown as individual points. For *p*-values: ns ($p > 0.05$), * ($0.05 \geq p > 0.01$), ** ($0.01 \geq p > 0.001$), and *** ($p \leq 0.001$)

differences ($p < 0.001$) in the perception of changes produced by treatments were noted among groups. Stronger differences were perceived by Managers than by Students for all three questions (Fig. 5a–c). Perception of differences scores for the Others group were intermediate, but significantly lower than scores for Managers only for the "differences between untreated and treated with mechanical thinning" question (Fig. 5a–c). Significant differences in scores were also noted among groups for the question of whether "High Variability" thinning and prescribed fire appeared more natural than other treatments or untreated controls ($p < 0.001$), with scores for Managers and Others significantly higher than scores for Students (Fig. 5d).

### Perceptions of VR tour and VR technology

All occupational groups strongly agreed that if a field tour was not an option, the VR tour would be a good substitute (mean scores ranging from 4.89 to 5.19 out of 6) (Fig. 6a). There were significant differences among groups ($p = 0.008$), with Others providing higher scores than Students. Scores for Managers did not differ significantly from Others or Students (Fig. 6a). All three groups also strongly agreed that VR technology could be useful for enhancing public understanding of forest management options, land management planning discussions among stakeholders and the public, and for stimulating dialog, with mean scores ranging from 4.67 to 5.60 out of 6 (Fig. 6b–d). Scores for these latter three questions differed significantly among groups ($p < 0.001$ for the first two, $p = 0.002$ for the last). Scores for Managers and Others did not differ from each other, but were significantly higher than those for Students (Fig. 6b–d).

### Geographic and gender differences within groups

Within the Students group, significant differences were noted in scores between respondents from Penn State University (PSU) and Cal State University Fullerton (CSUF) for some questions. PSU students reported higher familiarity with principles of forest and fire

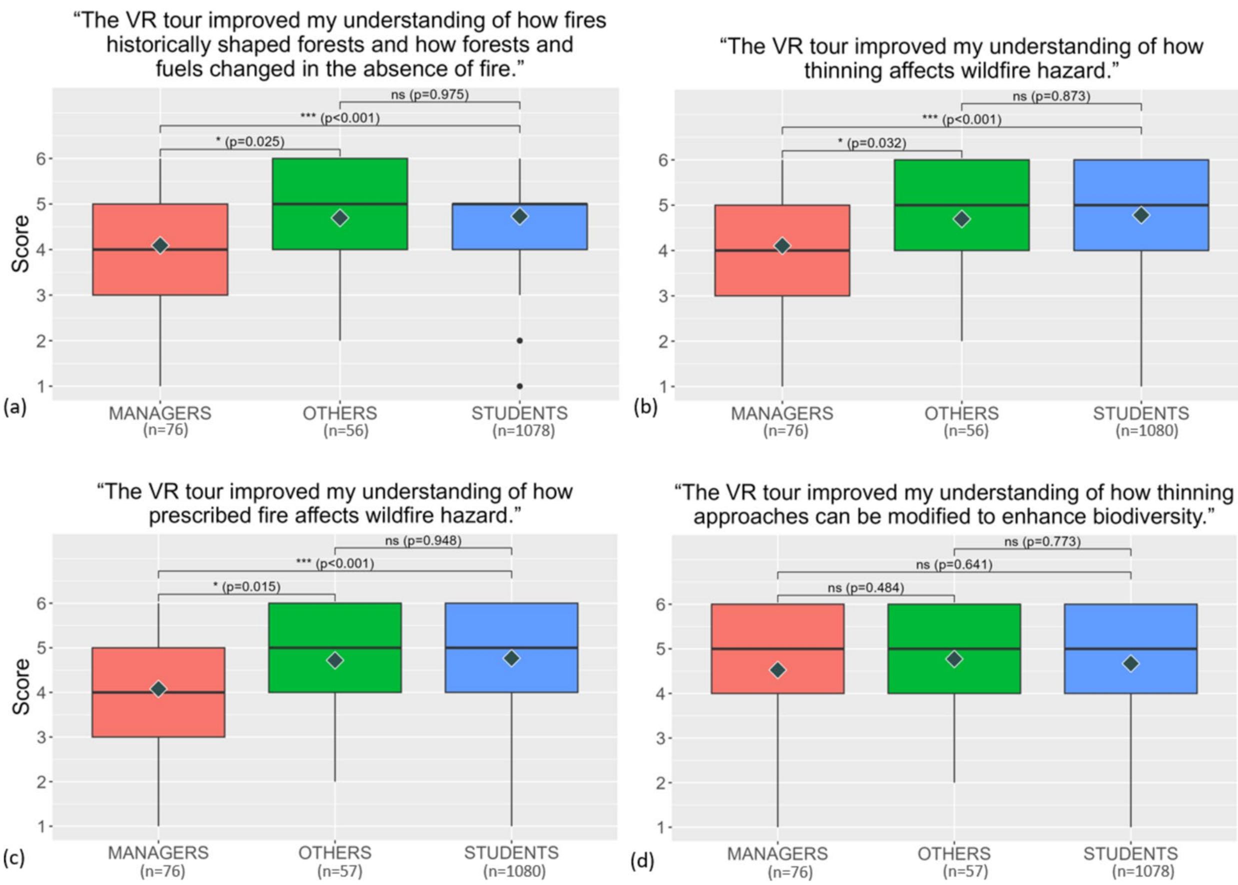


**Fig. 4** Scores for understanding-related questions (see Table 1) by participant group, including significance of results. The dark horizontal line within boxes shows the median, while the upper and lower bounds of the box indicate the first (25%) and third (75%) quartiles. The mean is denoted with a diamond symbol. Vertical lines connect the largest and smallest values within 1.5 times the interquartile range, with outliers shown as individual points. For *p*-values: ns ($p > 0.05$), * ($0.05 \geq p > 0.01$), ** ($0.01 \geq p > 0.001$), and *** ($p \leq 0.001$)

management prior to the tour (2.33 *vs* 2.05 out of 5; $p = 0.008$). Yet, CSUF students perceived greater differences between the "Low Variability" and "High Variability" thinning treatments (4.59 *vs* 4.24 out of 6; $p < 0.001$). Moreover, CSUF students agreed more strongly that "High Variability" thinning followed by prescribed fire had a more natural look (4.59 *vs* 4.19 out of 6; $p < 0.001$).

Gender differences were evident in the self-assessment scores within occupational groups for some questions. Among Managers, there was a stronger perception of differences between treatment types for women than men (5.59 *vs.* 5.10 out of 6; $p = 0.012$). Among students, women self-assessed significantly lower VR familiarity than men (2.80 *vs.* 3.09 out of 5; $p < 0.001$), but had significantly higher scores for three of the four improved understanding questions (improved understanding of how fire historically shaped forests: 4.81 *vs* 4.67 out of 6, $p = 0.017$; improved understanding of thinning effects: 4.88 *vs.* 4.67 out of 6, $p < 0.001$; improved understanding of modifying thinning: 4.74 *vs* 4.60, $p = 0.050$). Moreover, among students, women perceived (1) stronger differences between the two thinning types (4.41 *vs.* 4.20 out of 6; $p = 0.003$); (2) that the VR tour would be a more suitable option if in-person tours were not available (5.00 *vs.* 4.79 out of 6; $p = 0.005$); and (3) greater value of the VR tour as a tool for enhancing public understanding (5.43 *vs.* 5.02 out of 6; $p < 0.001$) and promoting management planning discussions (5.04 *vs.* 4.86 out of 6; $p = 0.011$).

#### *Manager open-ended assessments*

Open-ended assessments by managers on what they liked on the tour were very favorable (Table S1). Positive comments mentioned the tour content in a general sense (32%), the tour controls including the ability to navigate around the forest treatments with a computer mouse (25%), the ability to clearly distinguish differences between treatments because of narration, imagery, or in combination (25%), and the quality of the visuals including 360° images (20%). Specific responses included: "Often, a single picture is not enough to explain

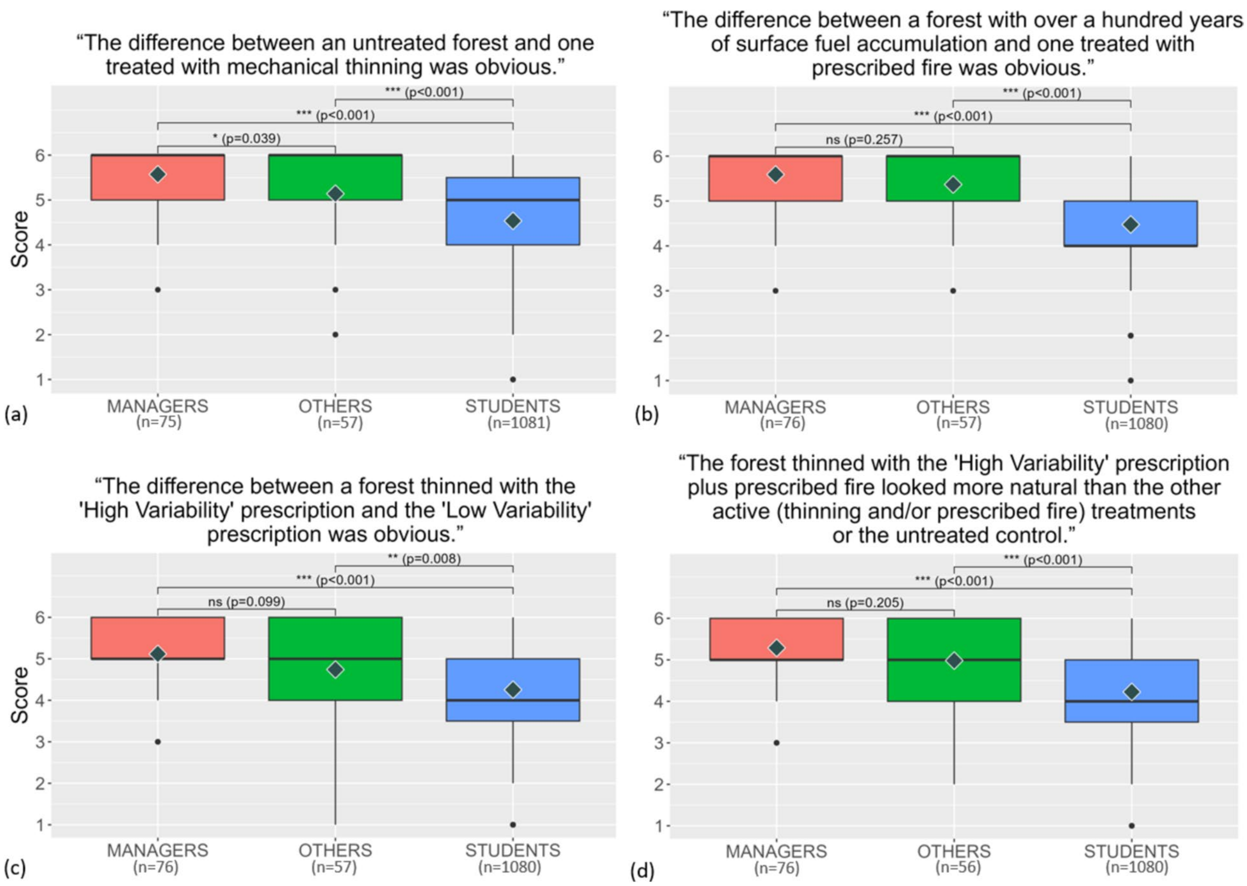


**Fig. 5** Scores for perception of obvious treatment differences (see Table 1) by participant groups, including the significance of results. The dark horizontal line within boxes shows the median, while the upper and lower bounds of the box indicate the first (25%) and third (75%) quartiles. The mean is denoted with a diamond symbol. Vertical lines connect the largest and smallest values within 1.5 times the Interquartile Range, with outliers shown as individual points. For *p*-values: ns ($p > 0.05$), * ($0.05 \geq p > 0.01$), ** ($0.01 \geq p > 0.001$), and *** ($p \leq 0.001$)

stand treatments. This 3D immersive experience will be extremely helpful in future projects… much easier than coordinating field visits with dozens of different partners, adversaries, and the general public, and concisely shows what forest managers are trying to accomplish in an easy-to-digest format"; "It feels like you're in the forest. The technology is amazing."; "I loved the "big picture" perspective that VR technology allows. Visualizing a stand not only at eye level really highlights differences in the landscape at a larger scale."

Fewer managers responded to the question of what they liked least (Table S2). Respondents commented about features (often less a criticism than constructive feedback of an additional feature(s) that might improve the tour (21%), technology issues—mainly the long load time for the app (12%), content information (e.g., disagreement with information or the way it was presented, or pointing out missing information), and the passive nature of the tour (e.g., no interaction with the narrator (9%).

## Discussion

VR tour effectiveness was evaluated for three occupational groups and each group gave high scores for the capacity of this visual and interactive approach for improving self-reported understanding of current forest conditions relative to historic conditions, and for distinguishing among forest fuel reduction treatment options. All occupational groups also gave high scores for the value of the VR tour approach for enhancing public understanding of fuel management treatments and engaging audiences in land management planning discussions. Differences in scores among occupational groups are likely the result of varying familiarity with western US forests and principles of forest and fire management. Managers, particularly those working in western US forests who were targeted in our outreach, were more likely to be well-versed in forest and fuel changes that contribute to fire hazard, and approaches used to improve forest resilience to fire. Most university students, on the other hand, had little or no experience with land management.

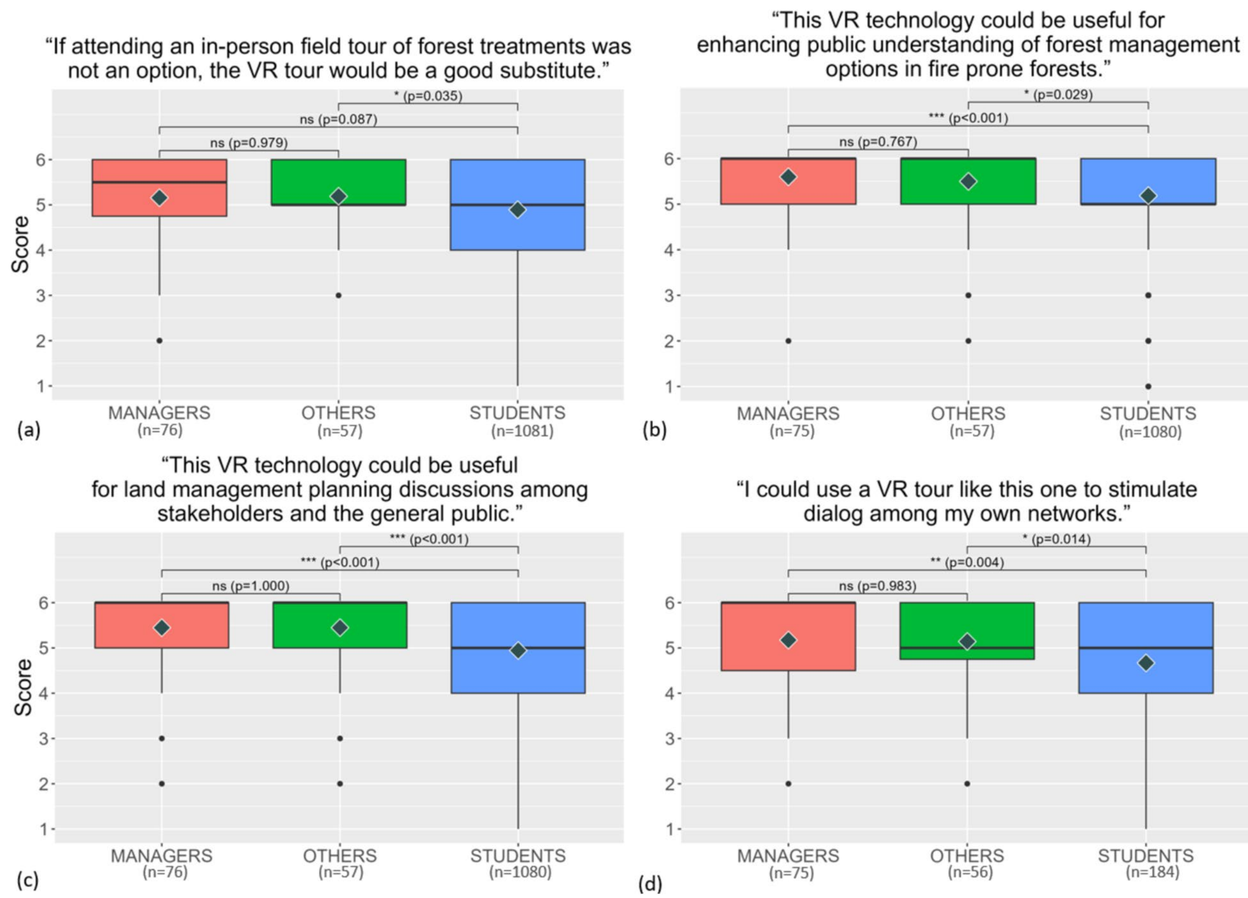


**Fig. 6** Results from overall perception-related questions (see Table 1) by participant groups, including significance of results. The dark horizontal line within boxes shows the median, while the upper and lower bounds of the box indicate the first (25%) and third (75%) quartiles. The mean is denoted with a diamond symbol. Vertical lines connect the largest and smallest values within 1.5 times the interquartile range, with outliers shown as individual points. For *p*-values: ns ($p > 0.05$), * ($0.05 \geq p > 0.01$), ** ($0.01 \geq p > 0.001$), and *** ($p \leq 0.001$)

Many (89%) student respondents also came from a university where students live in proximity to a very different forest type (eastern deciduous hardwood forest), which burns infrequently and is biogeographically distinct from the fire prone conifer-dominated forests depicted in the tour. Respondents in the Others (non-student and non-manager) group likely had less direct experience with forest or fire management than the Managers group. However, the methods used to attract non-student respondents were oriented towards individuals with a general interest in and familiarity with western US forest and fire management. Moreover, a substantial proportion of respondents in the Others group self-identified as "retired/other" to the question about occupation. Those who were retirees could have been managers prior to retirement. Consequently, it is unsurprising that scores from the Others group were often intermediate between Managers and Students, and generally closer to the Managers group. Lower self-assessed improvement in understanding scores by Managers for questions about current *vs.* historical forest conditions or how thinning and prescribed fire reduce fire hazard likely stem from higher pre-tour familiarity with these topics. Consequently, there was less room for improved understanding from the VR tour for Managers. This interpretation is supported by the similarity of understanding scores among groups for the question on how thinning approaches can be modified to enhance biodiversity. Manager scores for this question were higher than the Manager scores for the other "improved understanding" questions. The High Variability thinning treatment is a novel silvicultural technique focused on increasing spatial heterogeneity in tree group and gap structure, with the goal of increasing habitat diversity for a wide range of species (Knapp et al. 2012). Here, all, including the Managers group, had room for improved understanding.

Visual differences in treatments were more obvious to individuals with previous experience in fire or forest management. The higher scores for the Managers and Others for perception of treatment differences and applicability of the VR tour technology for land management decision-making were probably related to their overall higher familiarity with western forests and forest management compared to Students. Thus, among group variation in how the same images and other content were interpreted may be related to variation in the capacity of participants to link visual cues to life experiences and past learning (Chiesi et al. 1979; Smith et al. 2021), which is widely found in visual perception research (Mead et al. 2019; Vandelli et al. 2024). Managers and many in the Others group were also likely more familiar with contested narratives (e.g., Prichard et al. 2021; Jones et al. 2022) around public lands management, and thus had a better understanding of how our VR tour could facilitate dialog and promote successful collaborative approaches for fire hazard reduction on forest lands.

Geographic proximity and familiarity are also potential explanations for differences in responses within the Students group. Forests near the PSU campus, and in the mid-Atlantic region where the bulk of this student population comes from, are deciduous and oak-dominated and rarely burn, with little visible evidence of fire effects (charred stems, low surface fuels). Consequently, PSU students may be less likely to perceive visible cues of fire effects in photographs. Conversely, CSUF, although located in an urban setting, is less than an hour drive from mountains with mixed conifer forest that has burned frequently in the last few decades. Other non-geographic explanations are also possible. The small number of courses from which students were drawn not only differed between universities but may have included students with widely varying majors and backgrounds, which could have factored into varying answers to the questionnaire.

Interestingly, Managers, who had the lowest pre-tour familiarity with VR technology, had a high appreciation of the potential utility of the technology, indicating that low familiarity with VR was not a barrier for implementation. This interpretation is reinforced by the similarity in scores for survey questions for those with high and low familiarity with VR within the Managers group. Stronger differences between those with low and high VR familiarity were seen among students, but students with high VR familiarity also tended to have greater pre-tour familiarity with the western US fire problem and principles of forest and fire management, which may have driven responses more so than familiarity with VR.

While the VR tour content was designed for people interested in forest management issues or practicing forest management, the very high "improved understanding" scores for Students indicate the VR tour was also highly effective at increasing understanding among those with initially low interest and familiarity with forest ecosystems, suggesting high potential for improving understanding of forest management by the public. This result supports previous research that shows educational materials, including immersive virtual field tours (Mead et al. 2019; Wallgrün et al. 2021), raise public knowledge of management practices (Loomis et al. 2001; Toman and Shindler 2006). Our results indicate that VR tours like the one we developed can be an effective educational tool for audiences without a background in forest management, enabling them to understand the pros and cons of different fire hazard reduction treatment options.

Our study cannot distinguish the role immersive technology played in the uptake of the material because we did not compare the VR tour with other non-immersive methods of delivery. However, evidence from previous research suggests a benefit. While Steidle et al. (2023) noted no difference between 2D (regular photographs and text) and 3D immersive media (360° photographs) for changing public attitudes about forest management and prescribed fire, the 3D immersive media in their study significantly improved an esthetic appreciation of forest habitat.The 3D immersive media was also better at changing attitudes towards management interventions among the subset of individuals who were initially opposed or neutral (Steidle et al. 2023). Another limitation of our study is that scores were self-assessed, so the questions did not test the actual extent of learning or how attitudes towards different treatment options changed because of the tour. Such evaluations, including different user groups with varying backgrounds and familiarity with forest and fire management, would be a logical next step.

The use of VR and immersive experiences in the natural resources fields has thus far been quite limited. Our development of a virtual tour was intended as a prototype—an early-stage demonstration to land managers of what might be possible with current and future VR technologies for environmental education and decision-making. The VR tour employs principles of place-based learning in that it uses a real-world context to scaffold the learning content and by using analog simulations (different forest management practices and resulting forest structures), it provides access to experiencing the outcomes first-hand. For example, during the land-management planning process, managers could use VR technology to illustrate to interested parties the condition of untreated stands, and what proposed thinning and/or prescribed fire treatments will look like by transporting audiences into similarly treated stands. Showing how treated stands change over time or illustrating the reduction in severity with wildfire, relative to untreated stands, are additional possibilities. Furthermore, the decision space in federal-lands fire and fuels management is frequently narrowed by misinformation (Jones et al. 2022) and controversial terms such as 'clear-cutting' or 'commercial logging' that are used by opponents of forest thinning to generate distrust of federal land management. The use of immersive high-resolution 360° imagery utilized in a VR platform enables audiences to 'experience' the treatments with their own eyes, adding an immersive visual context to words. So long as the imagery used is an unbiased representation of reality, immersive experiences could aid consensus-building among groups with diverse perspectives and break down societal barriers to treatment implementation, thereby helping to increase the pace and scale of fuel management activities.

The development of virtual and immersive reality applications is evolving rapidly. The application tested here was an improved version, incorporating viewer suggestions (Wallgrün et al. 2021) to increase interactivity. Much more is possible, including greater user control (such as more freedom of movement and allowing the user to determine the length of time spent on each scene) and more embedded content. Guided VR experiences are also possible, where viewers can interact directly with the narrator. While a VR field tour will never fully match the sensory experience and relationship building possible in a field setting, guided tours could alleviate one downside identified by managers of virtual tours—the lack of two-way interaction.

## Conclusions

Our study indicates an enormous potential for VR tours to improve understanding and communication among interested parties and decision-makers in implementing fire hazard reduction treatments in fire-prone landscapes. The tour was highly regarded by all groups and was effective as a learning tool based on an initial self-assessment. The tour improved understanding in all groups and the greatest improvement occurred in the group with the lowest subject matter familiarity. This is consistent with other fire research showing that educational efforts can raise public knowledge of fire management practices (Loomis et al. 2001; Toman and Shindler 2006). However, visual differences among treatment types were most evident for groups with higher initial familiarity with fire and forest management. Yet, lack of familiarity with VR technology did not appear to be a barrier to uptake, as even the lowest VR familiarity group (Managers) expressed an improved understanding of how novel treatment types (e.g., High Variability thinning with prescribed fire) can improve biodiversity despite lower familiarity with VR technology. All groups strongly agreed that if a field tour of forest treatments was not an option, VR tours such as this one would be a good substitute. However, further research is needed to evaluate actual learning or how attitudes towards different treatment options changed because of the tour. Expanding the study to include more diverse populations (i.e., different occupations, income levels, race/ethnicity, and education levels) could help confirm our conclusions for the general public.

While actual field visits to treated and untreated areas provide unmatched experiences and opportunities for interactive learning and relationship-building compared with a VR tour, VR provides access to a much-expanded audience of potential users who otherwise could not attend a field visit. The high scores for conveying understanding given by even those viewers with the lowest familiarity with western US forests and the current wildfire problem suggest a broad benefit of VR tours for public engagement. Our findings highlight the significant potential for VR tours to become integral for delivering informational content to increase understanding and trust in environmental management decision-making (Murtiyoso et al. 2024). Trust is critical for building momentum towards landscape-scale forest and fuel management programs to reduce fire hazard and increase resilience of western US forests to wildfire.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-024-00345-0.

Additional file 1: Table S1. Results from coding the open-ended feedback by the Managers group for "What did you like most about the tour?". Table S2. Results from coding the open-ended feedback by the Managers group for "What did you like least about the tour?".

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**Authors' contributions**

Alan H. Taylor: conceptualization, methodology, Investigation, Formal analysis, Visualization, Data Curation, Writing original draft – review and editing, Funding Acquisition. Jan Oliver Wallgrün: Conceptualization, Methodology, Investigation, Visualization, Formal Analysis, Writing – review & editing. Eric E. Knapp, Conceptualization, Methodology, Investigation, Writing – review & editing. Alexander Klippel: Conceptualization, Methodology, Investigation, Writing – review & editing. José J. Sánchez: Methodology, Investigation, Writing – review & editing

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**Data availability**

Available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate
The research was approved by Penn State's Institutional Review Board (#00012992).

### Consent for publication
Not applicable.

### Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### References
Abatzoglou, J.T., and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113 (42): 11770–11775.
Airey-Lauvaux, C., A.D. Pierce, C.N. Skinner, and A.H. Taylor. 2022. Changes in fire behavior caused by fire exclusion and fuel build-up vary with topography in California montane forests, USA. *Journal of Environmental Management* 304: 114255.
Brambilla, E., E. Petersen, K. Stendal, V. Sundling, T.E. MacIntyre, and G. Calogiuri. 2024. Effects of immersive virtual nature on nature connectedness: A systematic review and meta-analysis. *Digital Health* 10: 20552076241234640. https://doi.org/10.1177/20552076241234639.
Brodie, E.G., Knapp, E.E., Brooks, W.R., Drury, S.A., Ritchie, M.W. 2024. Forest thinning and prescribed burning reduce wildfire severity and buffer the impacts of severe fire weather. Fire Ecology, 20:Article 17.
Calkin, D.E., J.D. Cohen, M.A. Finney, and M.P. Thompson. 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences* 111 (2): 746–751.
Chiesi, H.L., G.J. Spilich, and J.F. Voss. 1979. Acquisition of domain-related information in relation to high and low domain knowledge. *Journal of Verbal Learning and Verbal Behavior* 18 (3): 257–273.
Chow, A.T.S., Karanfil, T. and Dahlgren, R.A., 2021. Wildfires are threatening municipal water supplies. *Eos, Science News by AGU*.
Churchill, D.J., A.J. Larson, M.C. Dahlgreen, J.F. Franklin, P.F. Hessburg, and J.A. Lutz. 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. *Forest Ecology and Management* 291: 442–457.
USDA Forest Service, 2022. Confronting the wildfire crisis: a strategy for protecting communities and improving resilience in America's Forests.
Cuesta, A., D. Alvear, A. Carnevale, and F. Amon. 2022. Gender and public perception of disasters: A multiple hazards exploratory study of EU citizens. *Safety* 8 (3): 59.
Davis, K.T., J. Peeler, J. Fargione, R.D. Haugo, K.L. Metlen, M.D. Robles, and T. Woolley. 2024. Tamm review: A meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. Forest Ecology and Management 561: 121885.
Donato, D.C., J.S. Halofsky, D.J. Churchill, R.D. Haugo, C.A. Cansler, A. Smith, and B.J. Harvey. 2023. Does large area burned mean a bad fire year? Comparing contemporary wildfire years to historical fire regimes informs the restoration task in fire-dependent forests. *Forest Ecology and Management* 546: 121372.
Freina, L. and Ott, M., 2015, April. A literature review on immersive virtual reality in education: state of the art and perspectives. In *The international scientific conference elearning and software for education* (Vol. 1, No. 133, pp. 10–1007).
Guy, M., J.M. Normand, C. Jeunet-Kelway, and G. Moreau. 2023. The sense of embodiment in Virtual Reality and its assessment methods. *Frontiers in Virtual Reality* 4: 1141683.
Harris, L.B., A.E. Scholl, A.B. Young, B.L. Estes, and A.H. Taylor. 2019. Spatial and temporal dynamics of 20th century carbon storage and emissions after wildfire in an old-growth forest landscape. Forest Ecology and Management 449: 117461.
Hemes, K.S., C.A. Norlen, J.A. Wang, M.L. Goulden, and C.B. Field. 2023. The magnitude and pace of photosynthetic recovery after wildfire in California ecosystems. *Proceedings of the National Academy of Sciences* 120 (15): e2201954120.
Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications* 31 (8): e02432.
Hiers, J.K., J.J. O'Brien, J.M. Varner, B.W. Butler, M. Dickinson, J. Furman, M. Gallagher, D. Godwin, S.L. Goodrick, S.M. Hood, and A. Hudak. 2020. Prescribed fire science: The case for a refined research agenda. *Fire Ecology* 16: 1–15.
Higuera, P.E. and Abatzoglou, J.T., 2021. Record-setting climate enabled the extraordinary 2020 fire season in the western United States. Global Change Biology, 27(1).
Hurteau, M.D., M.P. North, G.W. Koch, and B.A. Hungate. 2019. Managing for disturbance stabilizes forest carbon. *Proceedings of the National Academy of Sciences* 116 (21): 10193–10195.
Jones, G.M., H.A. Kramer, W.J. Berigan, S.A. Whitmore, R.J. Gutiérrez, and M.Z. Peery. 2021. Megafire causes persistent loss of an old-forest species. Animal Conservation. 24(6): 925–936.
Jones, G.M., E.K. Vraga, P.F. Hessburg, M.D. Hurteau, C.D. Allen, R.E. Keane, T.A. Spies, M.P. North, B.M. Collins, M.A. Finney, J.M. Lydersen, and A.L. Westerling. 2022. Countering wildfire misinformation. Frontiers in Ecology and the Environment. 20 (7): 392–393.
Klippel, A., J. Zhao, K.L. Jackson, P. La Femina, C. Stubbs, R. Wetzel, J. Blair, J.O. Wallgrün, and D. Oprean. 2019. Transforming earth science education through immersive experiences: Delivering on a long held promise. *Journal of Educational Computing Research* 57 (7): 1745–1771.
Klippel, A., Zhao, J., Sajjadi, P., Wallgrün, J.O., Bagher, M.M. and Oprean, D., 2020a, March. Immersive place-based learning–an extended research framework. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 449–454). IEEE.
Klippel, A., J. Zhao, D. Oprean, J.O. Wallgrün, C. Stubbs, P. La Femina, and K.L. Jackson. 2020b. The value of being there: Toward a science of immersive virtual field trips. *Virtual Reality* 24: 753–770.
Knapp, E., North, M., Benech, M. and Estes, B., 2012. The variable-density thinning study at Stanislaus-Tuolumne Experimental Forest. Managing Sierra Nevada forests. Gen. Tech. Rep. PSW-GTR-237. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station. pp.127–140.
Kreider, M.R., P.E. Higuera, S.A. Parks, W.L. Rice, N. White, and A.J. Larson. 2024. Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. Nature Communications. 15(1):2412.
Lampropoulos, G., and Kinshuk,. 2024. Virtual reality and gamification in education: A systematic review. *Educational Technology Research and Development* 72 (3): 1691–1785. https://doi.org/10.1007/s11423-024-10351-3.
Lee, B., D. Brown, B. Lee, C. Hurter, S. Drucker, and T. Dwyer. 2020. Data viscerealization: Enabling deeper understanding of data using virtual reality. IEEE Transactions on Visualization and Computer Graphics. 27(2):1095–1105.
Loomis, J.B., L.S. Bair, and A. Gonzalez-Caban. 2001. Prescribed fire and public support: Knowledge gained, attitudes changed in Florida. Journal of Forestry.99(11):18–22.
Lydersen, J.M., M.P. North, E.E. Knapp, and B.M. Collins. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: Reference conditions and long-term changes following fire suppression and logging. Forest Ecology and Management. 304: 370–382.
Makransky, G., T.S. Terkildsen, and R.E. Mayer. 2019. Adding immersive virtual reality to a science lab simulation causes more presence but less learning. Learning and Instruction. 60: 225–236.

Marsi, S., E.A. Shenoi, D.R. Garfin, and J. Wu. 2023. Assessing perception of wildfires and related impacts among adult residents of southern California. *International Journal of Environmental Research and Public Health* 20 (1): 815.
McCaffrey, S.M. and Olsen, C.S., 2012. Research perspectives on the public and fire management: a synthesis of current social science on eight essential questions.
McCaffrey, S., J.J. Moghaddas, and S.L. Stephens. 2008. Different interest group views of fuels treatments: Survey results from fire and fire surrogate treatments in a Sierran mixed conifer forest, California, USA. *International Journal of Wildland Fire* 17 (2): 224–233.
McCaffrey, S., Toman, E., Stidham, M. and Shindler, B., 2015. Social science findings in the United States. In *Wildfire hazards, risks and disasters* (pp. 15–34). Elsevier.
Mead, C., S. Buxner, G. Bruce, W. Taylor, S. Semken, and A.D. Anbar. 2019. Immersive, interactive virtual field trips promote science learning. *Journal of Geoscience Education* 67 (2): 131–142.
Murtiyoso, A., S. Holm, H. Riihimäki, A. Krucher, H. Griess, V.C. Griess, and J. Schweier. 2024. Virtual forests: A review on emerging questions in the use and application of 3D data in forestry. *International Journal of Forest Engineering* 35 (1): 29–42.
North, M., B.M. Collins, and S.L. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *Journal of Forestry* 110 (7): 392–401.
North, M.P., R.A. York, B.M. Collins, M.D. Hurteau, G.M. Jones, E.E. Knapp, L. Kobziar, H. McCann, M.D. Meyer, S.L. Stephens, and R.E. Tompkins. 2021. Pyrosilviculture needed for landscape resilience of dry western United States forests. *Journal of Forestry* 119 (5): 520–544.
Pawlikowski, N.C., M. Coppoletta, E. Knapp, and A.H. Taylor. 2019. Spatial dynamics of tree group and gap structure in an old-growth ponderosa pine-California black oak forest burned by repeated wildfires. *Forest Ecology and Management* 434: 289–302.
Pisters, S.R., H. Vihinen, and E. Figueiredo. 2019. Place based transformative learning: A framework to explore consciousness in sustainability initiatives. *Emotion, Space and Society* 32: 100578.
Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31 (8): e02433.
R Core Team, 2021. R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria. URL https://www.R-project.org/.
Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences* 115 (13): 3314–3319.
Rasch, R., and S. McCaffrey. 2019. Exploring wildfire-prone community trust in wildfire management agencies. *Forest Science* 65 (5): 652–663.
Rogers, B.M., 2022. The Urbanization of the American West: The Processes and People in the Rise of Instant Cities and Their Evolution into the Twenty-First Century. In *The World of the American West* (pp. 267–307). Routledge.
Safford, H.D., A.K. Paulson, Z.L. Steel, D.J. Young, and R.B. Wayman. 2022. The 2020 California fire season: A year like no other, a return to the past or a harbinger of the future? *Global Ecology and Biogeography* 31 (10): 2005–2025.
Scholl, A.E., and A.H. Taylor. 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecological Applications* 20 (2): 362–380.
Schöne, B., M. Wessels, and T. Gruber. 2019. Experiences in virtual reality: A window to autobiographical memory. *Current Psychology* 38 (3): 715–719.
Schreier, M., 2012. Qualitative content analysis in practice. *Qualitative content analysis in practice*, pp.1–280.
Semken, S., E.G. Ward, S. Moosavi, and P.W. Chinn. 2017. Place-based education in geoscience: Theory, research, practice, and assessment. *Journal of Geoscience Education* 65 (4): 542–562.
Smith, R., P. Snow, T. Serry, and L. Hammond. 2021. The role of background knowledge in reading comprehension: A critical review. *Reading Psychology* 42 (3): 214–240.
Spies, T.A., M.A. Hemstrom, A. Youngblood, and S. Hummel. 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. *Conservation Biology* 20 (2): 351–362.
Steidle, S., M. Lucash, E. Nasr-Azadani, and E. Smithwick. 2023. Testing presence, assessing attitudes: Study of a 3D virtual tour in an "aesthetically challenged" landscape. *Journal of Environmental Management* 337: 117574.
Taylor, A.H., V. Trouet, C.N. Skinner, and S. Stephens. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. *Proceedings of the National Academy of Sciences* 113 (48): 13684–13689.
Toman, E. and Shindler, B., 2006. Communicating the wildland fire message: influences on knowledge and attitude change in two case studies. *In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management-How to Measure Success: Conference Proceedings. 28–30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 715–728* (Vol. 41).
Toman, E., M. Stidham, B. Shindler, and S. McCaffrey. 2011. Reducing fuels in the wildland–urban interface: Community perceptions of agency fuels treatments. *International Journal of Wildland Fire* 20 (3): 340–349.
Vaillant, N.M., and E.D. Reinhardt. 2017. An evaluation of the Forest Service Hazardous Fuels Treatment Program—Are we treating enough to promote resiliency or reduce hazard? *Journal of Forestry* 115 (4): 300–308.
Vandelli, V., P. Migoń, Y. Palmgren, E. Spyrou, G. Saitis, M.E. Andrikopoulou, P. Coratza, M. Medjkane, C. Prieto, K. Kalovrektis, and C. Lissak. 2024. Towards Enhanced Understanding and Experience of Landforms, Geohazards, and Geoheritage through Virtual Reality Technologies in Education: Lessons from the GeoVT Project. *Geosciences* 14 (5): 127.
Wagler, A., and M.D. Hanus. 2018. Comparing virtual reality tourism to real-life experience: Effects of presence and engagement on attitude and enjoyment. *Communication Research Reports* 35 (5): 456–464.
Wallgrün, J.O., J. Huang, J. Zhao, A. Masrur, D. Oprean, and A. Klippel. 2017. A framework for low-cost multi-platform VR and AR site experiences. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 42: 263–270.
Wallgrün, J.O., Knapp, E., Taylor, A., Klippel, A., Zhao, J. and Sajjadi, P., 2021, May. Place-based learning through a proxy-Variations in the perceived benefits of a virtual tour. In *2021 7th International Conference of the Immersive Learning Research Network (iLRN)* (pp. 1–8). IEEE.
Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis. 2021. Economic footprint of California wildfires in 2018. *Nature Sustainability* 4 (3): 252–260.
Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier. 2019. Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* 7 (8): 892–910.
Wilson, R.S., McCaffrey, S.M. and Toman, E., 2017. Wildfire communication and climate risk mitigation. In *Oxford Research Encyclopedia of Climate Science*.
Winter, P.L. and Cvetkovich, G.T., 2010. Diversity in Southwesterners' views of Forest Service fire management. In *Wildfire Risk* (pp. 156–170). Routledge.
Wu, H., Z.D. Miller, R. Wang, K.Y. Zipp, P. Newman, Y.H. Shr, C.L. Dems, A.H. Taylor, M.W. Kaye, and E.A. Smithwick. 2022. Public and manager perceptions about prescribed fire in the Mid-Atlantic, United States. *Journal of Environmental Management* 322: 116100.
Zhao, J., T. Sensibaugh, B. Bodenheimer, T.P. McNamara, A. Nazareth, N. Newcombe, M. Minear, and A. Klippel. 2020. Desktop versus immersive virtual environments: Effects on spatial learning. *Spatial Cognition and Computation* 20 (4): 328–363.

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