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Authors

Liang, Shuang
Hurteau, Matthew D
Westerling, Anthony L

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Large-scale restoration increases carbon stability under projected climate and wildfire regimes

Shuang Liang[1†], Matthew D Hurteau[2*], and Anthony L Westerling[3]

Changing climate and increasing area burned pose a challenge to forest carbon (C) storage, which is compounded by an elevated risk of high-severity wildfire due to long-term fire suppression in the western US. Restoration treatments that reduce tree density and reintroduce surface fire are effective at moderating fire effects and may help build adaptive capacity to changing environmental conditions. However, treatment implementation has been slow and spatially limited relative to the extent of the area affected by fire suppression. Using model simulations, we quantified how large-scale restoration treatments in frequent-fire forest types would influence C outcomes in the Sierra Nevada mountain range under projected climate–wildfire interactions. Our results indicate that large-scale restoration treatments are an effective means of reducing fire hazard and increasing C storage and stability under future climate and wildfire conditions. The effects of implementation timing suggest that accelerated implementation of large-scale restoration treatments may confer greater C-storage benefits, supporting California's efforts to combat climate change.

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Changing climate and accelerating disturbance frequency, size, and intensity are increasing temperate forest mortality to unsustainable levels (Millar and Stephenson 2015). In the fire-prone forests of the western US, these factors are compounding the effects of long-term fire suppression, challenging the use of forests for carbon (C) sequestration to mitigate climate change (Hurteau *et al.* 2014a; Taylor *et al.* 2016). Despite having had limited effect on infrequent-fire forests (mean fire return interval of decades to centuries), fire suppression in dry, fire-prone forests (mean fire return interval <40 years) has altered tree density and fuel loads, leading to increased wildfire hazard in the Sierra Nevada mountain range in California and Nevada (Stephens *et al.* 2016). In frequent-fire forests, restoring surface fire regimes that approximate the historical fire return interval, which may also involve thinning to reduce tree density, could effectively reduce extreme fire behavior and tree mortality, potentially enhancing adaptive capacity to changing climate and wildfire regimes (Collins *et al.* 2013; Loudermilk *et al.* 2016).

Despite their potential benefits, implementation of restoration treatments has been slow due to a combination of political, financial, and social constraints (North *et al.* 2015; Stephens *et al.* 2016). Efficacy of individual treatments is often scale-dependent and may be diminished by fires ignited during extreme fire weather conditions if only a limited part of the landscape is treated (Lydersen *et al.* 2014). In light of the pervasive fuel problem, as well as the increasing extent and frequency of large wildfires in the Sierra Nevada, large-scale restoration treatments that include targeted mechanical removal of smaller trees and widespread fire use have been proposed (North *et al.* 2012; Stephens *et al.* 2016). Yet the removal (eg thinning) and emission (eg prescribed fire) of stored C through treatments can be substantial and will require evaluation to quantify their effects on forest C dynamics (Campbell *et al.* 2012; Krofcheck *et al.* 2017).

Implementation of large-scale restoration treatments must also be evaluated in the context of accelerating climate change, which is projected to increase wildfire area burned (Westerling *et al.* 2011). As fire hazard intensifies, delayed implementation of restoration treatments increases the potential for untreated areas to burn at uncharacteristically high levels of severity, and ongoing climate change may then affect post-fire forest recovery (Liang *et al.* 2017a).

Given the uncertainties regarding the stochastic nature of wildfire, the effects of projected changes in climate on forests, and known impacts of large-scale restoration treatments on forest C, we sought to quantify how large-scale treatment efforts applied to low- and mid-elevation forests could influence C dynamics in the Sierra Nevada. Specifically, we asked: how does the implementation timing of restoration treatments alter C outcomes in Sierra Nevada forests under projected climate–wildfire interactions? Using climate and area burned projections from

[1]*Intercollege Graduate Degree Program in Ecology and Department of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA;* [†]*current address: Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL;* [2]*Department of Biology, University of New Mexico, Albuquerque, NM* [*]*(mhurteau@unm.edu);* [3]*Sierra Nevada Research Institute, University of California–Merced, Merced, CA*

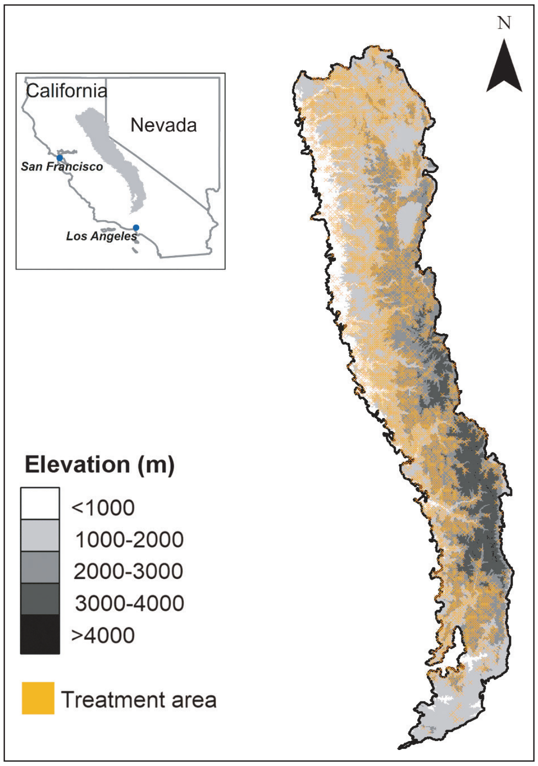

Figure 1. *Map of study area and restoration treatment area.*

three climate models based on the A2 (medium–high) emissions scenario, we ran 90-year simulations of three different treatment implementation scenarios: accelerated (treatments implemented during the first half-century), distributed (treatments implemented throughout the century), and control (no restoration). We hypothesized that (1) large-scale restoration treatments would shift the majority of fire events toward low-severity surface fires and mitigate C loss from wildfire relative to the control; (2) the accelerated scenario would incur larger C loss from treatments but total cumulative loss would be lower than would occur in the distributed scenario over the simulation period; (3) the accelerated scenario would confer a greater increase in live tree C with higher stability across the region toward the end of the century.

Methods

Study area

This study encompassed approximately 3.4 × 10^6 ha of forest land in the Sierra Nevada mountain range of California and Nevada (Figure 1) and covered a substantial elevation gradient (165–4230 m). The climate is Mediterranean with dry summers and wet winters; most of the annual precipitation occurs in the form of snowfall (Fites-Kaufman *et al.* 2007), and snow cover persists into summer, depending on elevation. Temperature and total precipitation vary as a function of elevation and latitude, and influence fire activity, with wildfire events primarily occurring during the dry months (Syphard *et al.* 2011).

The Sierra Nevada range supports a diversity of tree species and forest types that sort by elevation, with low-elevation forests and woodlands generally composed of conifer and broadleaved species, and mid- and high-elevation forests primarily composed of conifer species (Liang *et al.* 2017a; see WebPanel 1 for additional details). Historically, fire events were frequent (fire return interval: 5–20 years) at lower elevations and frequency decreased with increasing elevation due to shorter snow-free seasons (Van de Water and Safford 2011). Selective timber harvest and subsequent fire suppression beginning in the early 20th century disrupted historical fire regimes at low and mid-elevations, and led to an increase in tree density and forest fuel loads, as well as a shift in composition toward more fire-intolerant species (Taylor *et al.* 2016). Conversely, fuel loads have not markedly deviated from historical conditions in high-elevation forests, where fires were infrequent (Mallek *et al.* 2013).

Simulation model description and development

We used LANDIS-II (www.landis-ii.org/home) – a spatially explicit landscape model with a core-extension structure – to simulate forest C dynamics in response to different treatment scenarios under projected climate–wildfire interactions. In conjunction with the LANDIS-II core, we used four extensions, consisting of Century Succession, which simulates C pools and fluxes; Dynamic Fire and Fuels (two distinct extensions), which simulate stochastic wildfire behavior/effects and classify the landscape by generalized fuel types, respectively; and Leaf Biomass Harvest, which simulates management (Scheller *et al.* 2011; see WebPanel 1). We leveraged previous model parameterization, calibration, and validation efforts, which are described in detail in Liang *et al.* (2017a), for this study.

The Century Succession extension drives simulations with monthly climate distributions created from means and standard deviations of monthly temperature and precipitation. Consistent with prior work (Liang *et al.* 2017a), we used downscaled (12-km) climate projections from three regionally representative general circulation models (GFDL, CCSM3, and CNRM) under the A2 emissions scenario to develop monthly climate distributions.

The Dynamic Fire and Fuels extension assigns fuel types based on tree species and age cohorts, and re-classifies fuel types at each time-step to account for succession, disturbance, and management activity. Wildfire fire size is determined by user-defined fire size distributions, fire weather conditions (eg wind speed, fine fuel moisture), topography, and fuels (eg amount, composition, distribution). Most of our study area maintains adequate fuel to carry large fires throughout the simulation period (Liang *et al.* 2017b). Fire severity class is scaled from 1 to 5, with

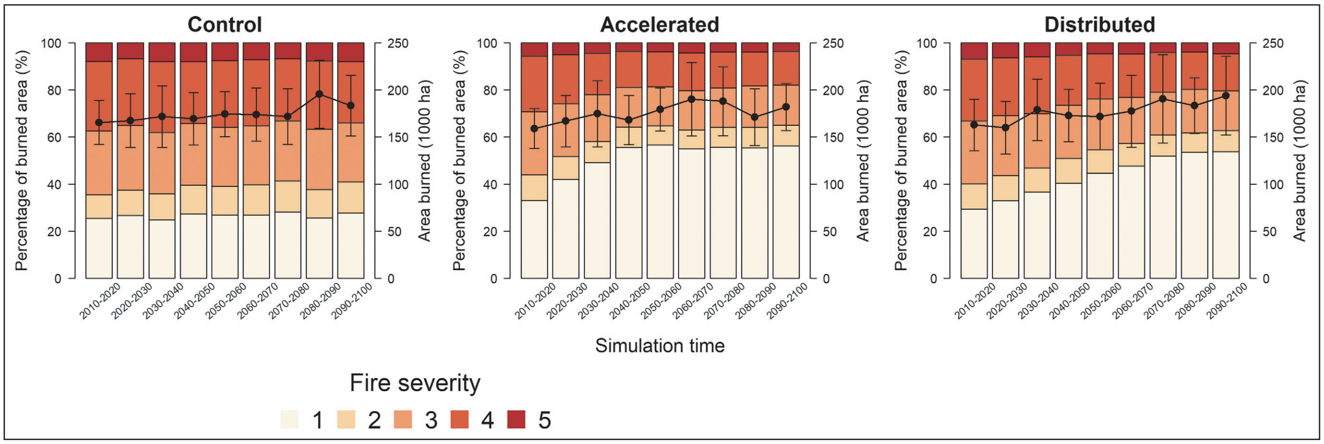

Figure 2. *Temporal changes in fire severity distributions within the burned area under each treatment scenario. Colored bars represent the percentage of burned area by fire severity classes at each time-step (left y axis), whereas the superimposed line plots represent the trend in area burned (right y axis). Values are averaged across 10 replicate simulations of each of the three climate–wildfire scenarios for a given treatment scenario. Error bars represent ± 1 SD of area burned. Fire severity class is scaled from 1 to 5, with 5 being stand-replacing fire. See WebFigure 1 for climate-model–specific results.*

severity classes 1 and 2 being surface fires, 3 and 4 involving some torching of overstory trees, and 5 being stand-replacing. To simulate area burned, we derived decadal fire size distributions based on the climate-model–specific projections of area burned by large wildfires (>200 ha) developed by Westerling *et al.* (2011) (see WebPanel 1).

Fuel treatment implementation

We used the Leaf Biomass Harvest extension to simulate not only thinning from below but also prescribed fire treatments that are commonly practiced in low- and mid-elevation forests to reduce fire hazard in the Sierra Nevada, following Syphard *et al.* (2011) and Krofcheck *et al.* (2017). The thinning and prescribed fire treatments were designed to remove a greater proportion of the youngest cohorts and shift the age distribution toward older cohorts. Across the landscape, treatments were implemented in fire-prone forests that currently have a greater risk of high-severity fire (Figure 1). The potential treatment area accounted for 57% of the total study area and excluded federally designated wilderness, riparian conservation areas, and infrequent-fire forest types (eg high-elevation forests).

We developed two scenarios for implementing large-scale restoration treatments: distributed and accelerated. The distributed scenario allocated thinning treatments at a rate of 12% of potential treatment area per decade, whereas the accelerated scenario implemented treatments at a faster rate of 25% per decade, with thinning completed by mid-century. Stands with higher fire hazard were treated first. Following each thinning treatment, prescribed fire treatments were successively applied on a 10–30-year return interval as a function of elevation band to reflect the fact that historical fire frequency generally decreased with increasing elevation (see WebTable 1 and WebPanel 1 for details). Because prescribed fire was only implemented after thinning treatments in low- and mid-elevation forests, the accelerated scenario had a greater number of prescribed fire intervals.

Simulation experiment

We simulated three treatment scenarios (control, accelerated, distributed) with three climate–wildfire scenarios, for a total of nine different scenarios over a 90-year simulation period (2010–2100) using a 10-year time-step. We ran 10 replicate simulations of each scenario to capture climate and wildfire stochasticity. Results for each treatment scenario were averaged over 30 simulations (10 replicates for each of three climate–wildfire scenarios) to summarize effects of different treatments on wildfire behavior and C balance for the entire study area (WebPanel 1).

Results

While cumulative area burned by wildfire was consistent across treatment scenarios, widespread application of restoration treatments gradually reduced the proportion of landscape burned by high-severity wildfires, with an increasingly greater proportion of the landscape burned by low-severity surface fires relative to the control (Figure 2). The reduction in wildfire severity occurred more rapidly in the accelerated scenario than in the distributed scenario, with the ratio of area burned by higher severity fires (severity class ≥ 3) to area burned by lower severity fires (severity class < 3) decreasing from 1.59 to 0.66 in the accelerated scenario and 0.87 in the distributed scenario.

Although C loss was initially higher in the restoration treatments, treatment effects on fire severity led to an

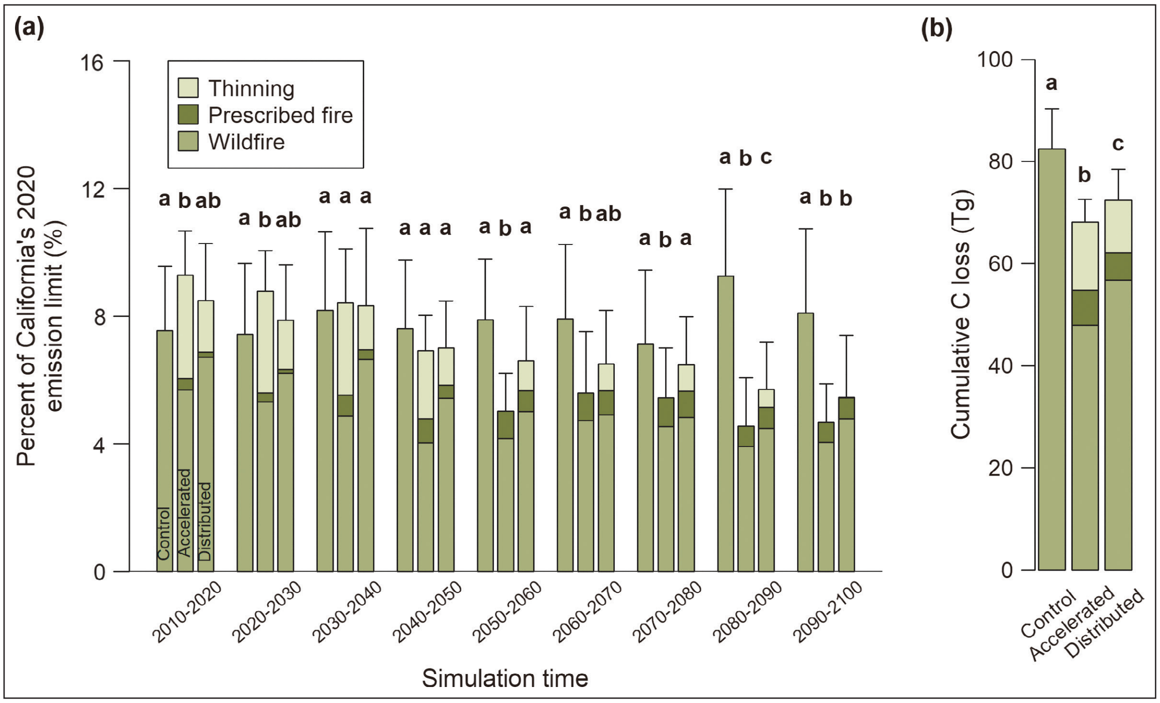

Figure 3. *(a) Temporal changes in mean carbon (C) loss from the system by treatment and source. Carbon loss is represented as the percentage of California's 2020 emission limit. (b) Total cumulative C loss across the Sierra Nevada over the 90-year simulation by treatment and source. Error bars represent ± 1 SD of total C loss for the 30 replicate simulations of all three climate–wildfire scenarios under each treatment scenario. Bars with different letters within a bar group indicate significant differences (*P *< 0.05) in total C loss between treatment scenarios. See WebFigure 3 for spatial distributions of the results in (b).*

immediate reduction in wildfire emissions and lowered cumulative C emissions and losses (Figure 3). There was little difference in total C loss between the accelerated and distributed scenarios for the first half-century, but cumulative C losses were significantly lower ($P < 0.001$) in the accelerated scenario by late-century (Figure 3b). The timing of treatment implementation had significant effects on both wildfire emissions and aboveground C (AGC). The accelerated and distributed scenarios reduced cumulative wildfire emissions by 42% and 31%, respectively. Although late-century mean AGC differences were small on a per unit area basis (accelerated = 156 megagrams of carbon per hectare [Mg C ha^{-1}], standard deviation [SD] = 1.5; distributed = 154 Mg C ha^{-1}, SD = 2.0; $P < 0.001$), by 2100 the accelerated scenario stored 6 teragrams (Tg) more C across the Sierra Nevada than the distributed scenario. Because of the timing of treatments and the stochastic nature of wildfire, C losses resulting from thinning and prescribed burning were larger in the accelerated scenario than in the distributed scenario (Figure 3b), but because the accelerated scenario rapidly restored surface fire regimes in low- and mid-elevation forests and reduced burn severity, total cumulative losses across the Sierra Nevada were significantly lower (Figure 3b).

The influence of treatments on burn severity also led to greater AGC accumulation across the landscape relative to the control. The proportion of the landscape in which C accumulation was greatest (ΔAGC > 60 Mg C ha^{-1}) over the simulation period increased from 8% in the control to 17% in the distributed scenario and 20% in the accelerated scenario, generally tracking the spatial distribution of restoration treatments (WebFigures 2 and 3). In addition, both the distributed and accelerated scenarios had lower late-century AGC coefficients of variation over the landscape, indicating more stable C storage (WebFigure 4). Because of the effects of treatments on moderating tree mortality from wildfire, the accelerated scenario substantially reduced the area that had no forest cover in 2100 due to climatic limitations on post-fire recovery (WebFigure 5).

Discussion

Reducing the risk of high-severity fire always involves short-term C costs (Campbell *et al.* 2012), which our results confirm (Figure 3). Wildfire C emissions in California are projected to increase by 19–101% in response to future changes in climate (Hurteau *et al.* 2014b). Although reducing wildfire emissions requires repeated atmospheric C emissions from more frequent prescribed fires (Hurteau 2017; Krofcheck *et al.* 2017), prescribed fire emissions are smaller and we found support for our hypothesis that large-scale treatments will lower fire severity and reduce wildfire emissions relative to the control (Figures 2 and 3). Inclusive of emissions from repeated prescribed fire, our large-scale restoration treatments reduced fire emissions by an average of 0.07–0.09 Mg C ha^{-1} yr^{-1} over the 90-year simulation, with the cumulative amount of avoided C emissions across the entire Sierra Nevada equaling 24% of California's 2020 emission limit (116 Tg; California Assembly Bill 32).

Given the stochastic nature of wildfire and the effects of treatments on reducing large C releases (Hurteau *et al.* 2008), we hypothesized that the accelerated scenario would incur larger C losses as a result of treatment but lower cumulative losses than would the distributed scenario. In the distributed scenario, more untreated area was burned by wildfire before treatments could be implemented, leading to a larger area being affected by high-severity wildfire. In contrast, the accelerated scenario reduced cumulative C losses over the long term as a result of the trade-off between substantial C losses from wildfire and moderate C losses from treatments. These different C outcomes emphasize the necessity of weighing trade-offs between the C costs of treatments and the long-term C benefits when planning large-scale treatment implementation (North *et al.* 2009; Loudermilk *et al.* 2016).

While the effects of treatments can yield disparate responses in forest C over time (Campbell *et al.* 2012; Krofcheck *et al.* 2018), we found that by moderating fire effects under changing climate and increased burned area, the treatment scenarios had higher late-century AGC than the control (WebFigure 2). Previous studies have demonstrated that restoration treatments that focus on removing smaller trees and restoring surface fire can substantially increase canopy base height while at the same time minimizing reductions in live tree C and increasing C stability (North *et al.* 2009; Krofcheck *et al.* 2017). The temporal distribution of C losses demonstrated that large-scale restoration treatments may initially incur greater C loss from the system, with the size of this near-term C cost being a function of implementation timing (Figure 3). However, because the accelerated scenario rapidly reduced the risk of tree mortality from canopy fires, the remaining C was held in a more stable form and a greater fraction of the landscape retained forest cover as compared to the distributed scenario (WebFigures 2, 4, and 5). Given that climate change is expected to facilitate severe wildfire occurrence and drought-induced tree mortality (Allen *et al.* 2015; Jones *et al.* 2016), large-scale treatments may become more C cost-efficient in stabilizing forest C than our simulations indicate, and accelerating treatment deployment may help confer greater C benefits.

Our treatment results are conservative with respect to C losses from the system due to thinning because we treated all thinned biomass as a loss and applied treatments to all low- and mid-elevation forests. Previous research has suggested that a portion of this biomass can be converted to long-lived wood products, which reduces total C loss (North *et al.* 2009). In addition, developing treatment networks and strategically siting treatments may increase the efficacy of treatments in reducing wildfire spread and intensity (Collins *et al.* 2013), and can also facilitate the reintroduction of surface fire in areas where harvesting is limited and surface fire alone can reduce fire hazard (North *et al.* 2012). Furthermore, our results are conservative because we held fire weather conditions constant throughout the simulations. Warmer and drier conditions, as well as higher wind speeds, enhance fire behavior and can increase the probability of high-severity wildfire in untreated forests (Krofcheck *et al.* 2017), and severe fire weather conditions are becoming increasingly common in the Sierra Nevada (Collins 2014). However, treatment efficacy with respect to fire severity has been demonstrated under both current and projected extreme fire weather when surface fire regimes are restored (Krofcheck *et al.* 2017, 2018).

Other operational considerations are left unaccounted for by our simulations. Large-scale treatment implementation may be restricted by the cost of thinning small, non-merchantable trees. However, a large-scale, long-term treatment plan with an incremental deployment of treatments may form a steady and predictable flow of biomass, which could help diversify the wood products industry and improve the economics of removing small trees (Hampton *et al.* 2011; North *et al.* 2012). Although widespread prescribed fire application would contribute to degraded air quality, prescribed fire emissions can be substantially lower than those from large, severe wildfires, and management prescriptions can reduce exposure by prioritizing treatments when wind conditions are conducive to transporting emissions away from population centers (Wiedinmyer and Hurteau 2010). Moreover, restoring forests to achieve long-term C gains may require trade-offs with other management objectives (eg wildlife protection), but large wildfires also pose a major impediment to achieving these objectives (Jones *et al.* 2016; Stephens *et al.* 2016). Large-scale treatment planning therefore requires a degree of flexibility to accommodate other goals.

By accounting for climate–wildfire–vegetation interactions, our results suggest that large-scale restoration treatments in historically frequent-fire forests can be an effective strategy to moderate fire effects, as well as to manage for higher C storage and stability under projected climate change and increasing area burned. A more rapid treatment implementation schedule could confer a greater long-term C benefit and sustain more forest cover than delayed treatment implementation, with ecological and societal benefits.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1791/suppinfo

