2016

Conditions inside fisher dens during prescribed fires; what is the risk posed by spring underburns?

Craig M. Thompson
USDA Forest Service, cthompson@fs.fed.us

Kathryn L. Purcell
USDA Forest Service

Forest Ecology and Management 359 (2016) 156–161

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Conditions inside fisher dens during prescribed fires; what is the risk posed by spring underburns?

Craig M. Thompson *, Kathryn L. Purcell

USDA Forest Service, Pacific Southwest Research Station, 2081 E Sierra Av, Fresno, CA 93710, United States

ARTICLE INFO

Article history:
Received 6 August 2015
Received in revised form 29 September 2015
Accepted 1 October 2015
Available online 15 October 2015

Keywords:
Fisher
Pekania pennanti
Prescribed fire
Temperature
Carbon monoxide

ABSTRACT

The use of spring prescribed fires to reduce accumulated fuel loads in western forests and facilitate the return of natural fire regimes is a controversial topic. While spring burns can be effective at reducing fuel loads and restoring heterogeneous landscapes, concerns exist over the potential impacts of unnaturally-timed fires to native species. To protect native wildlife from disturbance during critical periods, limited operating periods (LOPs) are often implemented. However when LOPs for multiple species are combined into an integrated management plan, very few time windows for implementing prescribed fires remain. The use of spring burns is often effectively eliminated, thereby reducing land managers' opportunities to implement what can be their most effective tool for forest restoration. To help guide the design of LOPs for fishers in the western United States, and to help identify opportunities to mitigate the risks posed by spring prescribed burns, we evaluated conditions within tree cavities during five prescribed fires in the Sierra National Forest and Yosemite National Park, CA. This relatively simple experiment was designed to provide much-needed and timely answers to crucial questions regarding the short-term impacts of prescribed fire on fishers and other wildlife species using cavities. Temperatures were remarkably stable within cavities, averaging 20.03 °C during burns. Carbon monoxide accumulation posed a greater threat, averaging a maximum of 170.8 ppm during burns and remaining elevated for >30 min, conditions potentially hazardous to fisher neonates. We discuss how these risks can be interpreted, and recommend that measures to mitigate smoke accumulation in tree cavities be implemented where spring burns are conducted in areas potentially occupied by fishers.

Published by Elsevier B.V.

1. Introduction

Nationwide, efforts to reintroduce fire into natural ecosystems to reduce fuel loads and restore ecological function are ongoing. However this presents a challenge as decades of fire suppression have created fuel-laden landscapes where low-intensity underburns are no longer safe or practical during the traditional fire season of summer and fall (Knapp et al., 2009). Instead, managers often rely upon a combination of mechanical thinning and off-season burns, when weather and fuel moisture content are more favorable for forest operations and controlled burning. These tactics are employed until the fuel load is reduced to the point where a summer/fall fire, either prescribed or natural ignition, can be allowed to burn safely. However the equation is further complicated by the presence of threatened or endangered species, whose reproductive or migratory patterns must be taken into account.

Prescribed burning in the spring is a controversial approach to fuel reduction in western forests, offering managers a number of benefits over later season burns while at the same time presenting a variety of risks. For example, while summer/fall burns typically result in greater overall consumption of surface and ladder fuels (Perrakis and Agee, 2006), spring burns may more closely mimic the patchy distribution of fuel consumption characteristic of historical, fire-adapted landscapes (Knapp et al., 2005). In turn, this mosaic of fuel conditions supports the recruitment and persistence of a more diverse species assemblage (Roberts et al., 2008; Turner et al., 1997). Additionally, spring burns tend to cause lower tree mortality (Kaufman and Martin, 1989; Thies et al., 2005; Perrakis and Agee, 2006), result in greater retention of coarse woody debris (Knapp et al., 2005; Stephens et al., 2009), and may result in reduced air quality impacts (Cahill et al., 1996). At the same time, while many species are adapted to living in fire-prone landscapes, historically the majority of fires occurred in the warmer and drier months (Knapp et al., 2009). Spring fires could put dependent young at risk before they are mobile enough to escape (Robbins and Myers, 1992; Lyon et al., 2000; Knapp et al., 2009). Spring

* Corresponding author.
E-mail address: cthompson05@fs.fed.us (C.M. Thompson).

http://dx.doi.org/10.1016/j.foreco.2015.10.003
0378-1127/Published by Elsevier B.V.

burns also coincide with the peak period of surface activity and migration for many amphibians (Pilliod et al., 2003), thereby putting these species at additional risk (O'Donnell et al., 2015) though this risk may be moderated by their use of moist microclimates and the patchy nature of spring burns (Bagne and Purcell, 2009). Different approaches to mitigating these risks have been taken, however the use of spring limiting operating periods (LOPs) is the most common.

Despite these concerns, there is very little systematic information on the actual risk of spring fires to threatened and endangered species, or guidance on how mitigation might be accomplished (Dickinson et al., 2010). In a recent meta-analysis of the impacts of fire severity on wildlife, Fontaine and Kennedy (2012) noted that while numerous published articles were available on avian response, only 13 reported the impacts of fire severity on small mammals and only one study on larger carnivores met their criteria for inclusion in the analysis (raccoons; Jones et al., 2004). In a comprehensive review of the ecological impacts of fire, Knapp et al. (2009) noted that the majority of information regarding the impacts of fire season on wildlife in the western United States is either anecdotal or based on interpreting multiple burned/unburned comparisons; e.g. fall burn vs. unburned or spring burn vs. unburned, lacking a direct comparison of seasonal influence such as fall burn vs. spring burn. And of 1082 species listed in the USFS Fire Effects Information System website (http://www.feis-crs.org/beta), 128 are animals, including 48 mammals and 4 amphibians; only 4 species have actual research studies linked to the management recommendations. This lack of information or guidance creates uncertainty for managers as they try to balance conservation and fuel reduction objectives.

Fishers (*Pekania pennanti*) are of particular concern in the western United States. The have been proposed for listing as threatened under the Federal Endangered Species Act (USDI Fish and Wildlife Service, 2014) and the California Endangered Species Act, and are listed as endangered in Washington. There is concern that fishers' need for structurally complex forests may conflict with efforts to counter decades of fire suppression through fuel reduction (Scheller et al., 2011). Females have large home ranges in which they travel extensively, but in early spring female fishers focus their activity on a small area centered on a den cavity (Higley and Matthews, 2006). This first den, known as a natal den, is utilized for a period of weeks to months. As the kits mature, the females generally move them to subsequent cavities known as maternal dens. By June when the kits are becoming active and agile, the females begin utilizing large logs in addition to tree cavities, and their residence time at each maternal den decreases until the family is moving frequently again (R. Green, USFS, unpublished data).

Concerns that spring prescribed burns may pose risks to denning females and their young have led to a number of management guidelines and recommendations. For example, the 2004 Sierra Nevada Forest Plan (USDA, 2004) stipulates that fisher den sites will be protected (1) by a 700 acre buffer site around each known den, (2) with a limited operating period (LOP) from March 1 to June 30 within that buffer, and (3) when a conflict between fisher den sites and human safety occurs (dens within the wildland urban interface zone), fuel reduction will be achieved using mechanical means whenever possible. While comprehensive, several weaknesses exist within these guidelines. Protection depends on managers knowing where den sites are located, however a huge disparity in knowledge exists depending on whether or not research and monitoring programs are located within a particular forest district. A few forest districts with ongoing fisher research projects have extensive information while most have no verified den locations at all. Identification of dens requires a fairly intensive effort involving trapping fishers and fitting them with radio collars, followed by tracking radio-collared fishers to their den trees in the spring. These intensive studies provide valuable information on fisher reproductive ecology and habitat requirements, but are expensive to implement and difficult to maintain. The definition of den buffers also varies by forest, some only account for active dens while others retain buffers associated with past years' dens. Finally, denning females may use up to 6 dens each denning season (R. Green US Forest Service, unpublished data). This means that in areas of high-quality habitat within districts hosting intensive research programs, den buffers accrue quickly and can eventually make up a significant portion of the landscape, greatly limiting managers' ability to apply prescribed fire within that critical spring window and thereby placing the high-value habitat at risk of high-severity fire.

To help address the perceived conflict between fisher conservation and fuel management in western forests, we evaluated what the true risk of spring prescribed fire to unborn or young fishers might be. In areas where prescribed fires were planned, we equipped any known, historic fisher den cavity with temperature and carbon monoxide dataloggers to evaluate conditions inside the tree during the burn. We worked extensively with the Sierra National Forest and Yosemite National Park prescribed fire staff to safely deploy and recover dataloggers. Given the small number of actual den sites that overlapped with spring prescribed fire locations, we also outfitted similar tree cavities without documented fisher use as well.

2. Study area

The study was conducted primarily in the High Sierra Ranger District of the Sierra National Forest, located approximately 80 km northeast of Fresno, CA. The landscape ranges from montane hardwood at the lower elevations to mixed conifer and red fir at the higher. Fishers typically occupy the mixed conifer/montane hardwood band between 3000 and 7000 feet, and prescribed burning is most often done in the lower two-thirds of that band. Primary tree species within that elevational band include California black oak (*Quercus kelloggii*), incense cedar (*Calocedrus decurrens*), white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), and canyon live oak (*Quercus chrysolepis*). Common shrubs and tree-like shrubs include whiteleaf manzanita (*Arctostaphylos viscida*), greenleaf manzanita (*Arctostaphylos patula*), Bear clover (*Chamaebatia foliolosa*), bush chinquapin (*Chrysolepis sempervirens*), mountain whitethorn (*Ceanothus cordulatus*), and snowberry (*Symphoricarpos mollis*). Limited data were also collected during a prescribed burn in the southern portion Yosemite National Park, also a region dominated by mixed conifer/montane hardwood habitat as outlined above.

3. Methods

Between 2012 and 2014, we evaluated conditions inside den cavities during prescribed burns by equipping historic dens and similar tree cavities with sensor packages 3–7 days prior to a planned prescribed burn. Two types of tree cavities were used; actual and surrogate fisher dens. Whenever possible, actual historic den sites within the burn perimeter were used. Since 2007, the USFS Pacific Southwest Research Station has been actively monitoring fisher reproduction in the High Sierra District using a combination of live trapping, radio telemetry, den climbing, and remote camera surveys. As part of this effort, USFS technicians regularly locate and mark trees selected as den sites by female fishers. UTM coordinates and tree tags were used to relocate historic (currently unoccupied) dens within planned burn perimeters, and these cavities were prioritized for monitoring. Flagging was placed near the cavity entrance to facilitate relocation and retrieval, however no marking was placed at ground level to reduce the chance of altered behavior on the part of the fire crew that might affect burn conditions at the tree.

Because there was limited overlap between known den sites and prescribed burn efforts, surrogate cavities, similar in height and size to actual dens, were selected when no known historic dens were located within the planned burn perimeter. Only cavities in oak species, California black oak and canyon live oak, were used. While fishers do den in conifers and other tree species, the majority of dens on the High Sierra District occur in oaks and we feared that results could vary between hardwood and conifer species. Similarly, while fishers in the Sierra National Forest do den in snags which are often inaccessible due to safety concerns, the majority of dens are located in live trees (R. Green, unpublished data). Given the small sample size and the safety concerns associated with climbing snags, we therefore choose to focus on cavities in live oaks exclusively for this initial effort.

Sensor packages consisted of one Onset Hobo 4-channel temperature logger and one Lascar EasyLog CO monitor. Two temperature probes were attached to the Hobo logger, one resting at the bottom of the cavity and one extending just outside the cavity entrance. The Lascar CO monitor registered carbon monoxide level at the cavity floor. While smoke consists of a variety of potentially harmful gases and particulate matter, CO is the primary cause of hypoxia due to its affinity for hemoglobin (Winter and Miller, 1976). All loggers were set to record at 1 min intervals, providing approximately 21 days of operation for the temperature loggers and 15 days of operation for the CO monitor. All sensors were removed 3–7 days after the prescribed burn was completed, when the area was determined safe to enter.

As a fire approaches and passes a den tree, it is difficult to determine precisely when the internal environment may begin to be impacted (Fig. 1). We therefore defined the impact period as 10 min before and after the peak external temperature was reached. We compared the average internal and external temperature during that 20-min window to the average temperature inside and outside the cavity during the same 20-min window the day before and after the prescribed fire using paired *t*-tests. Our goal was to compare the stability of the internal cavity temperature to the stability of the external temperature before, during, and after prescribed burning.

The hazard of carbon monoxide accumulation depends on both the maximum concentration reached as well as the length of time that a minimum threshold is exceeded. In developing fetuses, oxygen deprivation occurs because CO crosses the placental barrier and binds to fetal hemoglobin, resulting in CO-induced hypoxia (Storm and Fechter, 1985). Permanent learning and memory impairment has been shown in rats exposed in utero to 75 ppm for an extended length of time (Mactutus and Fechter, 1984; Giovanni et al., 1993). We therefore looked at both the maximum CO concentration reached, and the length of time that the concentration within the cavity exceeded 75 ppm.

4. Results

Between 2012 and 2014, we were able to install sensors in cavities prior to five prescribed fires. We equipped a total of 25 cavities, including 10 historic fisher dens and 15 surrogate cavities (Table 1). Five sensor packages in surrogate cavities were lost when the tree burned; in all cases these were surrogate cavities with a basal hollow, i.e. a cavity entrance at the base of the tree. Fire appeared to access through the basal hollow and the interior of the tree was consumed.

Temperatures within cavities were cooler and significantly more stable than exterior temperatures during burns (Table 1, Fig. 2). The mean maximum external cavity temperature during prescribed burns was 49.5 ± 23.8 °C compared to a mean maximum of 20.0 ± 9.7 °C inside cavities (Table 1, Fig. 3). Average external temperatures during burns were 32.3 °C while interior temperatures were 18.2 °C. Using an adjusted critical *p*-value of 0.0125 to control for multiple tests, the mean and maximum external temperatures were significantly higher during burns compared to non-burn periods ($P < 0.001$ in both tests). However

Fig. 1. Photos of prescribed fires burning in the vicinity of fisher dens.

Table 1
Temperatures recorded inside and immediately outside tree cavities, as well as maximum CO concentrations recorded inside cavities, during both a spring prescribed fire and adjacent days on the Sierra National Forest and Yosemite National Park. Empty cells indicate sensor malfunction and unavailable data.

ID	Type[a]	Date	Max CO (ppm)	Internal cavity temperatures (°C)				External cavity temperatures (°C)			
				Burn window[b]		Non-burn window[c]		Burn window		Non-burn window	
				Max	Average	Max	Average	Max	Average	Max	Average
UC_103	D	Feb 2013	32	4.2	4.1	2.85	2.15	24.75	13.85	4.7	2.8
UC_102	D	Feb 2013	24	19.55	14.25	3.85	2.5	26.25	17.35	9.35	5.35
UC_101	D	Feb 2013	267	5.5	5.3	7.45	4.8	50.5	15.05	10.1	5.45
UC_104	D	Feb 2013	56	19.55	18.75	9.45	8.15	20	18.6	14.35	12.65
BM_01	S	Mar 2013		41.95	33.65	14	13.25	42.3	34.85	18.95	14.8
BM_02	S	Mar 2013		33.35	22.45	12.55	12.15	102	39.65	14.15	12.75
BM_04	S	Mar 2013		12.2	11.95	13.05	12.2	47.75	30.25	16.8	15.4
BM_05	S	Mar 2013		13.95	13.7	15.3	13.9	54.05	29	18.75	15.75
FM_01	S	Apr 2013	81								
FM_02	S	Apr 2013	315	17	16.9	16.85	16.75	112.05	58.7	14.35	13.55
FM_03	S	Apr 2013	564	26.35	21.9	15	16.35	67.55	62.2	16.5	14.45
FM_04	D	Apr 2013	135	19	18.7	19.35	19.1	57.3	48.15	22.4	21
FM_06	S	Apr 2013	349	17.1	16.75	17.7	17	52.75	29.75	20.3	18.95
YNP_04	S	Mar 2015	324	14.25	13.6	15.35	14.35	42.45	24.4	18.6	17.4
YNP_01	S	Mar 2015	388	15.35	16.45	19.15	14.45	57.05	38.95	18.75	17.05
CL_193	D	May 2012	11	23	22.4	21.95	20.1	31.8	30.35	30.2	25.85
CL_506	D	May 2012	18	15.35	15.3	16.65	16.55	41.35	29.7	9.8	8.75
CL_700	D	May 2012	57	18.65	18.5	16.6	16.6	41.65	28	17.5	17.1
CL_781	D	May 2012	100	36.15	35.35	25.8	24.45	36.75	36.45	26.05	24.65
CL_000	D	May 2012	12.5	28.15	25.6	17.15	15.85	31.95	29.3	17.2	15.2
Average			170.8	20.03	18.19	14.74	13.72	49.49	32.34	16.78	14.68

[a] D = den, S = surrogate cavity.
[b] Burn window represents 10 min before and after the maximum temperature was reached.
[c] Non-burn window represents the same 20 min window as the burn window, however on the preceding and following day.

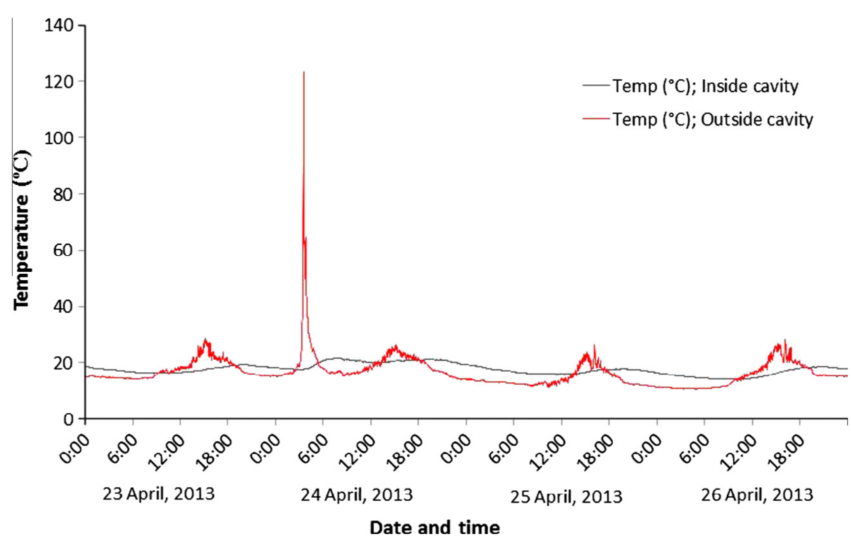

Fig. 2. Temperatures recorded inside and outside a tree cavity during a 2013 spring prescribed burn on the Sierra National Forest. Diurnal patterns of cavity warming and cooling are evident. External temperature peaked during the burn, while internal temperatures increased slightly and in a delayed manner.

there was no difference in internal temperature, either mean or maximum, between burn and non-burn periods ($p = 0.050$ and 0.055, respectively). During the burn window, external temperatures were significantly higher than internal temperatures, both for maximum temperature ($p < 0.001$) and mean temperature ($p < 0.001$).

CO concentrations within cavities typically showed a sharp but short-lived peak as the fire passed through the area. The mean maximum CO concentration within the cavity was 170.8 ± 171.7 ppm (mean ± SD, range 5.5–563.5 ppm) (Table 1, Fig. 3). For cavities that exceeded the 75 ppm threshold, the number of continuous minutes the cavity sustained a hazardous threshold averaged 38.7 ± 51.4 min, (range 2–159 min).

5. Discussion

This relatively simple experiment was designed to provide much-needed and timely answers to crucial questions regarding the short-term impacts of prescribed fire on fishers and other wildlife species using cavities. Our goal was to determine whether or not there was evidence to support concerns about the impact of spring prescribed burning on fisher reproductive success and kit survival and, if impacts were found, to suggest mitigation efforts and future research. We found that the temperature within cavities was, for the most part, remarkably stable during low intensity ground fires. In some cases, when brush or fine fuels near the base of the tree ignited, the external cavity temperature increased as

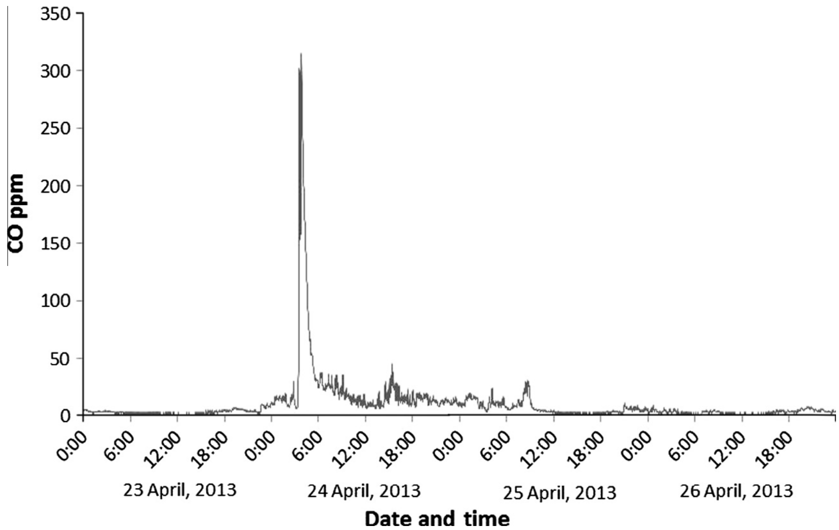

Fig. 3. Carbon monoxide (CO) levels recorded within one tree cavity during a 2013 spring prescribed burn on the Sierra National Forest. CO levels peaked during the burn, and then remained slightly elevated for approximately 24 h.

much as 150 °C over three minutes. During the same three minutes, the internal cavity temperature rose only 0.4 °C. Similar results were reported by Bova et al. (2011) in controlled experiments designed to model the conditions within single-entrance tree cavities during fires.

There were some exceptions to this pattern. In two cases the internal temperature approached or exceeded 37.7 °C (100 °F) during the burn (Table 1). In both cases, the internal temperatures closely matched the external temperatures, likely reflecting advanced internal decay and subsequent air flow throughout the structure. Female fishers are known to be highly selective in choosing natal dens (Weir et al., 2012), and internal temperature stability may help explain why only 4% of hardwood fisher dens identified during a long-term research effort were located in snags as opposed to live trees (R. Green, US Forest Service, unpublished data).

The accumulation of carbon monoxide in cavities appeared to be a greater concern. While CO concentrations did not reach levels considered hazardous to adult animals, they did reach levels potentially hazardous to unborn fetuses and neonates. Research on the effects of cigarette smoking has revealed that long-term exposure of pregnant rats to CO concentrations as low as 75 ppm can result in permanent learning and memory impairment to the offspring (Mactutus and Fechter, 1984; Giovanni et al., 1993). Similarly, brief exposure (3 h) to 5 ppm CO was shown to have similar effects in postnatal (10 day old) mice (Cheng et al., 2012). Impairment appears to be related to changes in the rate of apoptosis, naturally occurring pulses of cell death that facilitate the creation of neurons and the formation of synapses. Synaptogenesis (the formation of brain synapses) occurs explosively in the first few weeks after birth and results in 'proper wiring' (Cheng et al., 2012). A similar explosion of neural development, also governed by apoptosis, occurs early in the gestational period when a large number of neural cells are created which will eventually form neurons. Seven hour exposure to CO levels ranging from 200 to 600 ppm during this period of early gestational development has been shown to dramatically increase the rate of spinal deformities in mice (Loder et al., 2000).

In a controlled experiment designed to help parameterize a model of toxic gas accumulation in single-entrance cavities, Bova et al. (2011) reported that CO concentrations within the simulated cavity did not exceed 40 ppm. They found that wind speed had the greatest effect on CO accumulation. And in the application of their model to a red-cockaded woodpecker cavity, they estimated internal CO concentrations of 160 ppm or less. They did not directly record CO concentrations within the cavity, however, and internal estimates were based solely on external concentrations and wind speed. The fact that we recorded internal CO concentrations as high as 564 ppm suggests that additional environmental factors such as slope position or cavity orientation may play a significant role as well.

It is worth noting the five highest levels of CO accumulation also occurred in surrogate dens. This observation is confounded by the fact that these accumulations all occurred during two of the prescribed burns, on landscapes containing suitable habitat but where only one confirmed fisher den was available for testing. Both fires occurred on steep hillsides, where fire was allowed to creep downslope and possibly resulting in greater smoke exposure to upslope cavities.

The influence of prescribed fire on both internal cavity temperature and carbon monoxide accumulation will clearly depend on factors such as cavity height, slope position, weather, fuel condition, and fire intensity. Because even this small dataset was logistically difficult to generate, we did not try to control for these factors. However to effectively mitigate prescribed fire impacts and facilitate the use of spring burning in fisher habitat, a better understanding of these factors is required. One option would be to expand the efforts of Bova et al. (2011) in modelling gas accumulation to include the effects of topographic variation. In particular, a better understanding of the relationship between wind speed, slope position, and CO accumulation could allow fire managers to alter their prescriptions accordingly during periods of enhanced neurological development in unborn or neonatal fishers.

The loss of 5 surrogate structures is of concern, however it most likely represents our inability to mimic the suite of concerns a female fisher considers while selecting a den site. Certain aspects of structures used by fishers have been well documented and are consistent throughout the fisher's range (Aubrey et al., 2013), yet other considerations such as the influence of internal air flow on temperature stability are completely unknown. Based on the larger temperature dataset we collected (sensors were often in place for >20 days), we speculate that the degree of internal decay regulates both air flow within the tree and temperature stability within cavities, and therefore by selecting cavities with greater internal temperature stability, fishers inherently avoid those trees more likely to be at risk of the type of destruction we observed. Additional research is needed to test this hypothesis; given our limited dataset we were unable to conduct any robust analysis of subsets of the data.

The increasing occurrence of high-severity fires in the southern Sierra region (Miller and Safford, 2012; North et al., 2015, but see also Hanson and Odion, 2014) and the consequences of these fires for not only wildlife but also human health and safety makes responsible fuel management a mandatory task for any public land manager. Spring prescribed burns are an effective and low-risk option that can mimic historic landscape and fuel conditions better than mechanical alternatives (Knapp et al., 2007; Stephens et al., 2009), potentially resulting in more robust conditions and communities. For example, Bagne and Purcell (2011) found that low severity spring burns drove the forest bird community toward pre-suppression era conditions. And Knapp and Keeley (2006) found that early season burns led to patterns of landscape heterogeneity that more closely mimicked historic patchiness. At the same time, spring fires are an unnatural event posing unknown risks to many sensitive wildlife species. Our results suggest that managers can strike a balance between effective fuel reduction and fisher conservation, however until additional data on the effects of environmental and topographic variation are available, we recommend that within fisher denning habitat, prescribed fire practitioners attempt to minimize smoke accumulation during spring burns.

Acknowledgements

We are grateful to the prescribed fire staff of both the Sierra National Forest and Yosemite National Park for their willingness to help facilitate research efforts. In particular, C. Ballard, T. Gonzales, and A. Hernandez of the Sierra National Forest were instrumental in identifying research opportunities and helping coordinate activities. Funding was provided by the USFS Region 5, the Sierra National Forest, and the USFS Western Wildlands Environmental Threat Assessment Program.

References

Aubrey, K.B., Raley, C.M., Buskirk, S.W., Zielinski, W.J., Schwartz, M.K., Golightly, R.T., Purcell, K.L., Weir, R.D., Yaeger, J.S., 2013. Meta-analyses of habitat selection by fishers at resting sites in the Pacific coastal region. J. Wildlife Manage. 77, 965–974.

Bagne, K.E., Purcell, K.L., 2009. Response of two terrestrial salamander species to spring burning in the Sierra Nevada, California. Research Note RMRS-RN-41. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, p. 10.

Bagne, K.E., Purcell, K.L., 2011. Short-term responses of birds to prescribed fire in fire-suppressed forests of California. J. Wildlife Manage. 75, 1051–1060.

Bova, A.S., Bohrer, G., Dickinson, M.B., 2011. A model of gas mixing into single-entrance tree cavities during wildland fires. Can. J. For. Res. 41, 1659–1670.

Cahill, T.A., Carroll, J.J., Campbell, D., Gill, T.E., 1996. Air quality. In: Sierra Nevada Ecosystem Project, Final Report to Congress, vol. II, Assessments and Scientific Basis for Management Options. University of California Davis, Centers for Water and Wildland Resources, pp. 1227–1260.

Cheng, Y., Thomas, A., Mardini, F., Bianchi, S.L., Tang, J.X., Peng, J., Wei, H., Eckenhoff, M.F., Eckenhoff, R.G., Levy, R.J., 2012. Neurodevelopmental consequences of sub-clinical carbon monoxide exposure in newborn mice. PlosOne 7. http://dx.doi.org/10.1371/journal.pone.0032029.

Dickinson, M.B., Norris, J., Bova, A.S., Kremens, R.L., Young, V., Lacki, M.J., 2010. Effects of wildland fire smoke on a tree-roosting bat: integrating a plume model, field measurements, and mammalian dose–response relationships. Can. J. For. Res. 40, 2187–2203.

Fontaine, J.B., Kennedy, P.L., 2012. Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in U.S. fire-prone forests. Ecol. Appl. 22, 1547–1561.

Giovanni, V.D., Cagiano, R., De Salvia, M.A., Giustino, A., Lacomba, C., Renna, G., Cuomo, V., 1993. Neurobehavioral changes produced in rats by prenatal exposure to carbon monoxide. Brain Res. 616, 126–131.

Hanson, C.T., Odion, D.C., 2014. Is fire severity increasing in the Sierra Nevada, California, USA? Int. J. Wildland Fire 23, 1–8.

Higley, J.M., Matthews, S., 2006. Demographic Rates and Denning Ecology of Female Pacific Fishers (Martes pennanti) in Northwestern California: Preliminary Report to the Wildlife Conservation Society.

Jones, D.D., Conner, L.M., Storey, T.H., Warren, R.J., 2004. Prescribed fire and raccoon use of longleaf pine forests: implications for managing nest predation. Wildlife Soc. B. 32, 1255–1259.

Kaufman, J.B., Martin, R.E., 1989. Fire behavior, fuel consumption, and forest-floor changes following prescribed understory fires in Sierra mixed conifer forests. Can. J. For. Res. 19, 455–462.

Knapp, E.E., Keeley, J.E., Ballenger, E.A., Brennan, T.J., 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. For. Ecol. Manage. 208, 383–397.

Knapp, E.E., Estes, B.L., Skinner, C.N., 2009. Ecological effects of prescribed fire season: a literature review and synthesis for managers. General Technical Report PSW-GTR-224. USDA Forest Service, Pacific Southwest Research Station, Albany, CA, p. 80.

Knapp, E.E., Keeley, J.E., 2006. Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. Int. J. Wildland Fire 15, 37–45.

Knapp, E.E., Schwilk, D.W., Kane, J.M., Keeley, J.E., 2007. Role of burning season on initial understory vegetation response to prescribed fire in a mixed conifer forest. Can. J. For. Res. 37, 11–22.

Loder, R.T., Hernandez, M.J., Lerner, A.L., Winebrener, D.J., Goldstein, S.A., Hensinger, R.N., Liu, C., Schork, M.A., 2000. The induction of congenital spinal deformities in mice by maternal carbon monoxide exposure. J. Pediat. Orthop. 20, 662–666.

Lyon, L.J., Huff, M.H., Hooper, R.G., Telfer, E.S., Schreiner, D.S., Smith, J.K., 2000. Wildland fire in ecosystems: effects of fire on fauna, USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-41-v1.

Mactutus, C.F., Fechter, L.D., 1984. Prenatal exposure to carbon monoxide: learning and memory deficits. Science 223, 409–411.

Miller, J.D., Safford, H., 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Casades, California, USA. Fire Ecol. 8, 41–57.

North, M.P., Stephens, S.L., Collins, B.M., Agee, J.K., Aplet, G., Franklin, J.F., Zule, P.Z., 2015. Reform forest fire management; agency incentives undermine policy effectiveness. Science 349, 1280–1281.

O'Donnell, K.M., Thompson, F.R., Semlitsch, R.D., 2015. Prescribed fire and timber harvest effects on terrestrial salamander abundance, detectability, and microhabitat use. J. Wildlife Manage. 79, 766–775.

Perrakis, D.D.B., Agee, J.K., 2006. Seasonal fire effects on mixed-conifer forest structure and ponderosa pine resin properties. Can. J. For. Res. 36, 238–254.

Pilliod, D.S., Bury, R.B., Hyde, E.J., Pearl, C.A., Corn, P.S., 2003. Fire and amphibians in North America. For. Ecol. Manage. 178, 163–181.

Robbins, L.E., Myers, R.L., 1992. Seasonal effects of prescribed burning in Florida: a review, Tall Timbers Research Inc., Tallahassee FL, Misc. pub 8, 96pp.

Roberts, S.L., van Wagtendonk, J.W., Miles, A.K., Kelt, D.A., Lutz, J.A., 2008. Effects of fire severity and spatial complexity on small mammals in Yosemite National Park, California. Fire Ecol. 4, 83–104.

Scheller, R.M., Spencer, W.D., Rustigian-Romsos, H., Syphard, A.D., Ward, B.C., Strittholt, J.R., 2011. Using stochastic simulation to evaluate competing risks of wildfires and fuels management on an isolated forest carnivore. Landscape Ecol. 26, 1491–1504.

Stephens, S.L., Moghaddas, J.J., Edminister, C., Fiedler, C.E., Haase, S., Harrington, M., Keeley, J.E., Knapp, E.E., McIver, J.D., 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecol. Appl. 19, 305–320.

Storm, J.D., Fechter, L.D., 1985. Prenatal carbon monoxide exposure differentials affects postnatal weight and monoamine concentration of rat brain regions. Toxicol. Appl. Pharm. 81, 139–146.

Thies, W.G., Westlind, D.J., Loewen, M., 2005. Season of prescribed burn in ponderosa pine forests in eastern Oregon: impact on pine mortality. Int. J. Wildland Fire 14, 223–231.

Turner, M.G., Romme, W.H., Gardner, R.H., Hargrove, W.W., 1997. Effects of fire size and pattern on early succession in Yellowstone National Park. Ecol. Monogr. 67, 411–433.

USDA, 2004. Sierra Nevada Forest Plan Amendment, Final Supplemental Environmental Impact Statement, R5-MB-019. USDA Forest Service Pacific Southwest Region, Vallejo, CA.

U.S. Department of the Interior, Fish and Wildlife Service (USFWS), 2014. Endangered Species Program. <http://www.fws.gov/endangered/>.

Weir, R.D., Phinney, M., Lofroth, E.C., 2012. Big, sick, and rotting: why tree size, damage, and decay are important to fisher reproductive habitat. For. Ecol. Manage. 265, 230–240.

Winter, P.M., Miller, J.N., 1976. Carbon monoxide poisoning. J. Am. Med. Assoc. 236, 1502–1504.