

Project Title: Injury and Mortality Risks from Wildland Fire Smoke and Heat Exposures for Endangered Indiana Bats (*Myotis sodalis*) in Maternity Roosts

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For further information go to www.firescience.gov

Abstract

Our project focused on the effects of smoke on tree roosting bats, in particular the endangered Indiana bat and the effects of fire on foraging and roosting behavior and habitat. The project, to date, has resulted in two papers published in the peer-reviewed literature, one peer-reviewed paper published in a USFS document, and one submitted manuscript. The published papers can be found on the project website at www.firescience.gov. Three additional papers are expected. Results of our project can be categorized into those concerned with the direct effects of fire on roosting bats and the effects of fire on bat foraging and roosting behavior and habitat. In brief, our results suggest that 1) bats roosting in burn units are at risk from smoke, but that mitigation measures are available and 2) fire can improve foraging habitat through its effects on insect prey abundances.

Background and purpose

The endangered Indiana bat is one of a group of bats that roost in trees during the warmer months of the year in a broad range of eastern US habitats including the extensive mixed-oak forests. In mixed-oak forests, burning has been practiced by humans for millennia for ecosystem management and other reasons and prescribed fire today is gaining acceptance as a means of restoring and perpetuating oak (*Quercus*) dominance. The Endangered Species Act requires that land management agencies work closely with the U. S. Fish and Wildlife Service to avoid, or minimize and mitigate, adverse effects to threatened and endangered species as they implement habitat improvement projects and conduct other activities. Both because the Indiana bat is Federally listed as endangered and because there is a lack of knowledge about its response to forest fires, it is important that the understanding of risk to Indiana bats be improved so that land management practices can be developed that reduce risks for tree-roosting bats while allowing the use of fire for oak ecosystem management and, potentially, for improving bat habitat. More detail on background can be obtained from the publications.

Study description and location

The smoke toxicology portion of the study was a modeling study supplemented by data from fires in southern Ohio and eastern Kentucky. Our work on bat foraging and roosting behavior and habitat was conducted in eastern Kentucky on the northerly Cumberland District of the Daniel Boone National Forest. More information on study design and locations can be obtained from the publications.

Key findings with one-two paragraph discussion of each

Smoke plume and toxicology modeling (see following paper)

Our modeling efforts suggest that the effects of gases (esp. carbon monoxide) are of much less concern for tree roosting bats than the effects of heat in the plume. A submitted manuscript (attached) describes that research along with ways that fire managers can mitigate risk. Key for quantifying risk will be a better understanding of bat torpor dynamics during fire season and during fires themselves. Torpor is a daily hibernation-like state from which bats must arouse before flight can occur. Our current understanding suggests that bats, particularly male bats, will generally be in torpor during daytime burning and females may be in torpor during cool conditions when foraging is poor. Arousal from torpor takes longer the cooler the weather and, for one common tree-roosting bat, is cued by the smell and sound of smoke. Risk mitigation tactics include varying ignition practices, choice of burn weather and date, and ensuring that large, tall roost trees are available on forested landscapes.

Effects of fire on habitat – literature synthesis and data

A review of the effects of fire on bat foraging and roosting behavior and habitat identifies considerable gaps in our understanding. For instance, no data exist on whether bats prefer forests with reduced “clutter” from forest burning, though studies on this issue are ongoing. Before our project, no published data existed on the effects of fire on insect prey populations. Our published work suggests that insects attracted to newly dead wood in burned stands thinned by fire improve bat foraging conditions. Published data from the Daniel Boone National Forest show that northern bats, a tree-roosting bat that is

similar in its behavior to the endangered Indiana bat was little affected in foraging and roosting behavior by two burns on the Daniel Boone National Forest. The fires were unique in that they were ridge ignition burns designed to produce a pattern of burned ridge habitat interspersed with unburned habitat at lower elevation, wetter parts of the landscape. Thus, immediate effects of fire (e.g., displacement) were mitigated. More studies on forest “clutter” and insect prey populations are needed, particularly during fall and spring when bats are entering and leaving hibernation, respectively, and high quality habitat is crucial.

Management implications with one-two paragraph discussion of each

Key management implications include the following:

1. Our work on the toxicology of smoke and the use of daily torpor by bats suggests that bats will often be at risk from heat exposures in prescribed fires. Mitigation measures include burning at low intensities, burning before bats leave hibernation or on warm days when bats are out of hibernation, and ensuring that sufficient numbers of large, tall roost trees are available to provide low-risk roosting sites.
2. Our work on bat foraging and roosting behavior and insect prey populations suggest that fires that leave a mixture of burned and unburned habitat may result in little displacement of bats over the short term and may enhance insect prey populations over the medium term. However, significant gaps in understanding of fire effects on bat habitat exist, gaps that are being addressed by ongoing projects and that should be further addressed by future projects.

Future work needed (one to two pages)

Smoke plume and toxicology modeling

A key need is to obtain more data on bat torpor (a daily hibernation-like state) during fire seasons. Whether the fire cues used by eastern red bats to elicit arousal and flight are applicable to other species, particularly the endangered Indiana bat, is unclear. As well, it is unknown how often female bats use torpor during fall and spring burning seasons in

eastern mixed-oak forests. More verification that bats routinely flush during prescribed fires, and thus avoid the effects of smoke are needed.

Effects of fire on habitat

On-going projects are looking at effects of fire on insect prey abundance during summer months and on the potential benefit of forest thinning from fire in mixed-oak forests.

However, studies on habitat use and the effects of fire during the critical fall and spring periods when bats are entering and leaving hibernation, respectively, are needed. It is hoped that fire can improve habitat for bats during these critical periods. Studies on tree roost (snag) population dynamics in burned forest are also needed in the eastern mixed-oak forests. Fires may create preferred roosts by killing large trees, yet also removes them from the population through smoldering combustion. How fire can be used over the long-term and over landscapes to manage snag populations is unknown.

Deliverables

Also see the project website.

Type	Status	Description
Peer-reviewed publication for managers	Published	Dickinson, M. B., Lacki, M. J., Cox, D. R. 2009. Fire and the endangered Indiana bat. In: T. Hutchinson, ed., Proceedings of the Fire in Eastern Oak Forests Conference. USFS, Northern Research Station, GTR-NRS-P-46.
Refereed publication	Published	Lacki, M. J., Cox, D. R., and Dickinson, M. B. 2009. Meta-analysis of Summer Roosting Characteristics of Two Species of Myotis Bats. American Midland Naturalist 162:321-329.
Refereed publication	Published	Lacki, M. J., Cox, D. R., Dodd, L. E., and Dickinson, M. B. 2009. Response of northern bats (<i>Myotis septentrionalis</i>) to prescribed fires in eastern Kentucky forests. Journal of Mammalogy 90:1165-1175.
Manuscript	In review	Bova, A. S., Bohrer, G., Dickinson, M. B. 2009. Ventilation of animal shelters in wildland fire scenarios.
Presentation to managers	Delivered	Dickinson, M. B. 2009. Fire and the endangered Indiana bat (<i>Myotis sodalis</i>) – direct and habitat effects. Talk at Wayne National Forest and concurrent video conference with the eastern Bat Focus Group. 18 August. Podcast and presentation at: http://fsweb.wayne.r9.fs.fed.us/public_affairs/podcast.shtml
Presentation to managers	Delivered	Dickinson, M. B. Fire and the endangered Indiana bat. Raccoon Environmental Management Area Research Advisory Council (REMA RAC). 20 January 2009.
Presentation to managers/Workshop	Delivered	Dickinson, M. B. Prescribed Fire and the Indiana Bat on the Daniel Boone National Forest. Cumberland Plateau Prescribed Fire Workshop, Slade, Kentucky, August 12, 2008.
Presentation to managers	Delivered	Dickinson, M. B, M. J. Lacki, and D. R. Cox. Fire and the Indiana Bat. Fire in Eastern Oak Forests Conference, Carbondale, Illinois, May 20-22, 2008.
Presentation to managers	Delivered	Dickinson, M. B. 2009. Fire and the endangered Indiana bat (<i>Myotis sodalis</i>) – direct and habitat effects. Talk at Daniel Boone National Forest wildlife biologist’s meeting. 14 October.
Presentation at scientific meeting	Delivered	Dickinson, M. B., Norris, J., Bova, A. S., Kremens, R. L. Modeled effects of prescribed surface fires on an endangered tree-roosting bat – a biophysical and toxicological approach. Ecological Society of America, 2-7 August, Albuquerque, New Mexico.
Manuscript	In review	Dickinson, M. B., Norris, J., Bova, A. S., Kremens, R. L., Young, V., Lacki, M. J. 2009. Modeled effects of forest fire smoke on tree roosting bats – application of mammalian dose-response relationships. Canadian Journal of Forest Research, internal review.
Manuscript	In preparation	Bova, A. S., Dickinson, M. B., Bohrer, G. 2009. Modeled faunal smoke exposures in burrows, cavities, and roosts.

Manuscript	Planned	An article in Fire Management Notes summarizing our results on fire effects on bats for a management audience.
Manuscript	Planned	A paper exploring the effects of different ignition tactics on bat exposures to smokes in mixed-oak forest prescribed fires.

Modeled effects of forest fire smoke on tree roosting bats – application of mammalian dose-response relationships

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Abstract

Using a combination of data from prescribed fires in southeastern Ohio and eastern Kentucky, an integral plume model, and models of carbon monoxide (CO) and heat effects, we found that tree-roosting bats (bats which roost in foliage, crevices, or cavities) that could not escape smoke exposures would be at risk from heat, but not gas, effects in prescribed fires typical of the region. Tree roosting bats are of interest to fire management primarily because of the endangered Indiana bat and the need to mitigate potential effects of management activities. Predicted blood carboxyhemoglobin (COHb) accumulation only approached critical levels just above flames in the most intense fires. In contrast, a model of bat ear burns driven by plume model output suggested that bat ear injury would often occur at similar heights above ground as foliage necrosis, a common effect of prescribed fires. Both the risk of COHb accumulation and ear injury increase with fireline intensity (kW m^{-1}) and decrease with height above ground and with ambient wind. A main limitation of our risk assessment is that limited information exists on bat arousal and behavior during fires. Approaches to mitigating risk to bats from smoke exposures would include a use of ignition tactics that reduce fireline intensities (e.g., ridge ignition), burning when ambient temperatures are elevated, and ensuring that large roost trees (in which bats roost higher above ground) are available in forested landscapes.

Introduction

Understanding and predicting the relatively direct effects of wildfires and prescribed fires on vegetation and fauna requires consideration of both the behavior of fires (both flames and smoldering combustion) and the response of the organism of interest to the heat (Johnson and Miyanishi 2001) and gas (Guelta and Balbach 2005, O'Brien et al. 2006) exposures that it experiences. Over decades, biophysical process models have been developed to predict the effects of heat on trees (*e.g.*, Gill and Ashton 1968, Dickinson and Johnson 2001, Jones *et al.* 2006, Michaletz and Johnson 2006 and 2007) and soils (*e.g.*, Ashton and Gill 1976, Steward *et al.* 1990, Campbell 1995), yet the mechanisms by which fauna are injured or killed by heat and gas exposures during wildland fires have not received attention, though, clearly, faunal mortality in fires can be significant (Simons 1989, Esque *et al.* 2003). Of particular concern are threatened and endangered fauna which, although they may have evolved under regimes of frequent fire may be vulnerable to direct mortality from fires (Gross 1923, Lunney *et al.* 2004). The endangered Indiana bat (*Myotis sodalis*) is one such species that hibernates in mines and caves and, during the warmer months of the year, resides in a broad range of eastern US habitats including the extensive mixed-oak forests (USFWS 2007). In mixed-oak forests, burning has been practiced by humans for millennia for ecosystem management and other reasons and prescribed fire today is gaining acceptance as a means of restoring and perpetuating oak (*Quercus*) dominance (Nowacki and Abrams 2008). The Endangered Species Act requires that land management agencies work closely with the U. S. Fish and Wildlife Service to avoid, or minimize and mitigate, adverse effects to threatened and

endangered species as they implement habitat improvement projects and conduct other activities (e.g., USFWS 2007).

Both because the Indiana bat is Federally listed as endangered and because there is a lack of knowledge about its response to forest fires, it is important that the understanding of risk to Indiana bats be improved so that land management practices can be developed that reduce risks for bats while allowing the use of fire for oak ecosystem management and, potentially, for improving bat habitat (Dickinson *et al.* 2009). Indiana bats roost below bark and in crevices in trees in mixed-oak forests, often selecting dead trees (snags) for roosting, in particular, those snags that are above average in size (Lacki *et al.* 2009). Simulations of gas and heat exchange into bark flap roosts showed that the relatively small roost volumes considered offered little protection (unpublished data and Guelta and Balbach 2005). Although roost sites below large areas of sloughing bark may provide more protection, we assumed that bats would be exposed to the full effects of the plume, that is bats would be exposed to gases at a temperature, concentration, and velocity dependent only on smoke transport processes in the plume above a surface fire and not mitigated by sheltering effects.

Adult bats use torpor (a diurnal hibernation-like state in which body temperatures approach roost temperatures) extensively for energy conservation outside of the hibernation period (e.g., Kurta *et al.* 1991, Willis *et al.* 2006). The time to arousal from torpor (to a body temperature at which flying can occur) may take 10's of minutes and shows a negative relationship with ambient temperature (Layne 2009). Male bats use torpor routinely while female bats that are either pregnant or nursing young may only use torpor when foraging conditions are poor (e.g., cool and wet weather, Dickinson *et al.*

2009). Arousal may occur from a combination of olfactory and aural cues (Scesny and Robbins 2006). Neonatal bats that cannot fly and are too heavy to be carried by their mothers during flight would likely be at highest risk (USFWS 2007).

Carbon monoxide, a major component of wildland fire smoke (e.g., Andrae and Merlet 2001, Wiedinmyer 2006) causes buildup of carboxyhemoglobin (COHb) in blood, interfering with oxygen transport and exchange and, at high levels leading to incapacitation and death. Carbon monoxide is expected to be the most significant toxicant in wildland fire smoke (Purser 1988). Irritants (e.g., acrolein and formaldehyde) are a class of combustion products that cause depression in respiratory rates and the volume of air inhaled with each breath. The product of the rate of respiration and the volume of air inhaled determines the respiratory minute volume (L min^{-1}). Irritants in smoke tend to mitigate risk from gas exposures because they depress respiratory minute volume (Kane and Alarie, 1977, Nielson *et al.* 1984). Tissue burning is determined by both imposed heat flux from conduction, radiation, and convection and the properties of the tissue being heated (e.g., Diller *et al.* 1991). Sweating in humans reduces tissue heating in humans (Purser 1988), a mechanism not available to bats. Hair reduces heat fluxes to and from skin (Gates 1980), but bat ears and wing membranes are often nearly hairless and exposed when bats are in roosting conformation.

In this paper, we report results from 1) field experiments on CO concentrations at 2.4 and 6.1 m above ground during prescribed surface fires in mixed-oak forests and 2) plume model simulations of CO concentrations, gas temperatures, and plume velocity and residence times. Carbon monoxide and associated irritant concentrations (acrolein and formaldehyde) were used as inputs to a COHb accumulation model and plume gas

temperatures, velocities, and residence times were used as inputs to a tissue burn model. The plume model data were also used to provide replacement values for CO measurements from saturated sensors. We use the COHb and tissue burn models and knowledge about fire behavior and bat roosting behavior to assess the risk to tree roosting bats from prescribed fires in mixed-oak forests and consider how those risks could be mitigated.

Methods and Materials

1. Modeled plume

An integral plume model was used to simulate gas concentrations and temperatures and their durations in a two-dimensional plume rising from a flame front (line source of heat) on flat terrain (Mercer and Weber 1994, Figure 1). The model involves solution of six coupled differential equations based on the conservation of mass, momentum, and energy. We included wind in our simulations because gas concentrations at a given height are expected to be reduced when there is an ambient wind because of horizontal displacement and down-wind distortion of the plume (*e.g.*, Mercer and Weber 1994). The coupled differential equations were solved with the Bulstoer function in MathCad (Mathsoft 2001i Professional).

A Gaussian profile was fit to the top-hat results (Mercer and Weber 1994) and the average gas concentrations and temperatures over the residence time (travel time from edge to edge) of the plume were calculated horizontal to the ground across the plume at 1 m increments in height above the flame tip (Figure 1). Flame height was determined

from fireline intensity (kW m^{-1} , Byram 1959) as described in Weise *et al.* (1996). The residence times and average gas concentrations and temperatures were determined at the range of heights through the canopy as the surface fire and plume spread.

To generate gases and heat, the model was run over a range of relevant fireline intensities (kW/m , Byram 1959) prescribed by simultaneously increasing fuel loading and rate of spread (Table 1). Heat of combustion for convective heat release was constant at 16000 kJ kg^{-1} (Nelson 2002). Boundary conditions for the plume model include flame velocity (w_i), plume half-width (b_i), flame-tip (or, initial plume) temperature (T_{p0}), and flame density (ρ_i)(Table 1). Flame density was proportional to temperature from the ideal gas law. For this calculation, ambient air pressure at 500 m above sea level (Campbell and Norman 1998) was used to represent the Daniel Boone National Forest, Kentucky and, given flame temperature, flame density was 0.31 kg m^{-3} . Flame velocity was calculated from Nelson (2002) and plume half-width was one-half of flame depth. Flame depth was calculated from

$$D_f = \frac{RW}{c} \quad [1]$$

where R is rate of spread (m s^{-1}), W is fuel consumption (kg m^{-2}), and c is combustion rate ($\text{kg m}^{-2} \text{ s}^{-1}$) determined from experimental plot burns over a range of fuel consumption from 0.3 to 3.4 kg m^{-2} (Bova and Dickinson 2008). The range in fuels loads used to estimate combustion rate was selected to span the range found in mixed-oak forests.

Products of combustion (POCs) were assumed to mix immediately into a flame zone control volume defined in two dimensions by flame depth (D_f) and length. Flame

length (equivalent to height with no wind) was estimated from fireline intensity (Byram 1959). The two-dimensional flux of a POC ($\text{kg m}^{-1} \text{s}^{-1}$) was determined from

$$\dot{m}_j = \frac{W_{2D} R Y_j}{D_f} \quad [2]$$

where W_{2D} is two-dimensional loading (kg m^{-1}) and Y_j is yield of the POC (kg kg^{-1}).

Yield estimates for biomass burning were taken from the literature (Table 2).

Gas concentrations in the flame control volume were calculated as follows:

$$Cf_j = \frac{n_j}{n_{CV}} \quad [3]$$

where Cf_j is the concentration of POC j , n_j is the number of moles of the POC, and n_{CV} is the number of moles of all gases in the control volume. The number of moles of a POC in the two-dimensional control volume is calculated as

$$n_j = \frac{\dot{m}_j (h_f D_f) \frac{1}{2}}{M_j w_i} \quad [4]$$

where h_f is flame height (m) and M_j is the molecular weight of the POC (Table 2). The number of moles of all gases in the two-dimensional control volume is determined from the ideal gas law and ambient temperature

$$n_{CV} = \frac{p_a (h_f D_f) \frac{1}{2}}{R_{2D} T_f} \quad [5]$$

where p_a is ambient air pressure, R_{2D} is the gas constant for the two-dimensional control volume ($8.314 \text{ m}^2 \text{ Pa K}^{-1} \text{ mol}^{-1}$), and $T_f = 1000 + T_a$ (K) is the average temperature

(above ambient, T_a) of flames from biomass burning through their continuous and intermittent zones (from Depuy *et al.* 2003). Ambient temperature was set to 298 °K.

Plume model output includes plume velocity, plume temperature, and concentrations of gas species at 1 m increments along the plume centerline. Because mixing is turbulent, we assume that mass and heat transfer rates between the plume and ambient air are similar. Thus, gas concentrations decline with height above the flame in proportion to declines in plume temperature

$$C_{jh} = Cf_j \left(1 - \frac{Tp_0 - Tp_h}{Tp_0 - T_a} \right) \quad [6]$$

where C_{jh} is concentration of POC j at height h above the flame, $Tp_0 = 860 + T_a$ (K) is flame tip temperature above ambient (i.e., initial plume temperature, Depuy *et al.* 2003), and Tp_h is flame temperature at height h above the flame. A Gaussian profile is fit to centerline velocities, temperatures, and gas concentrations for the purpose of calculating averages horizontally across plumes (Figure 1). Averaging in the horizontal simulates exposures experienced by entities (such as bats) that do not move during the exposure (such as bats which remain in roosts during a fire).

2. Prescribed fire behavior and carbon monoxide concentrations

Carbon monoxide data were obtained from four prescribed fires on dissected terrain in southeastern Ohio and eastern Kentucky to provide exposure data for comparison with model output. The Clark Hollow burn in Tar Hollow State Park (93 ha) was conducted by the Ohio Department of Natural Resources Division of Forestry on April 20, 2007. Control lines were ignited by drip torch and the interior of the unit was

ignited by a helicopter dispensing ping-pong balls containing potassium permanganate injected, just before they were dropped into the unit, with ethylene glycol. Three additional burns were monitored on the Cumberland District of the Daniel Boone National Forest (DBNF), all of which were conducted by DBNF staff. All three DBNF burns were hand ignited with drip torches, involving ignition along key control lines in combination with ridge ignition, where igniters walked ridges conducting point and line ignition with drip torches. In ridge ignition, much of the area is burned by fires burning down slopes at low intensities. The Powder Mill burn (~790 ha) was conducted on April 10, 2007, the Bear Waller burn (~200 ha) on April 30, 2007, and the Wolf Pen burn (~100 ha) on April 8, 2008. Neither the Powder Mill nor Bear Waller unit had a history of prescribed burning; however, there are reports of “numerous fires having burned” within the original Cumberland purchase area prior to 1930 (Collins 1975:195). The Wolf Pen unit is a frequently-burned replicate of an ongoing research project on fire effects on vegetation and fuels (Loucks *et al.* 2008).

Twenty-foot towers were used to elevate instruments and sample locations on the interior of units (Tar Hollow N = 4 , Powder Mill N = 3 , Bear Waller N = 3, Wolf Pen N= 4) and >50 m from unit boundaries except for one tower at Tar Hollow inadvertently placed 20 m from a control line. Sixth Sense, Inc., Eco-Sense 2e electrochemical sensors, with a custom electronics signal conditioning board (that also measured sensor temperature), were placed at 2.4 m (8 ft) and 6.1 m (20 ft) to monitor CO concentrations above fires. The heights chosen were standard for fire weather and meteorological measurements, respectively. The maximum concentration that can be measured by these sensors is nominally 500 ppm. The Eco-Sense series of electrochemical sensors is

temperature compensated and responds linearly over the relevant concentration range (see sensor documentation at www.sixth-sense.com). The sensors are not sensitive to orientation and were mounted on arms that extended 30 cm from the tower. Each sensor is individually calibrated at the factory, however, to remove any variations due to electronic component tolerances we calibrated the sensor-electronics package using 100 and 250 ppm calibration gases supplied by MESA Industries. The background carrier in the calibration gas was nitrogen, which has no effect on the electrochemical sensors. Maximum concentrations after this second calibration step were below 500 ppm (see Results).

Towers were located in areas within the interior of units that we anticipated would have a high probability of burning during the fires. The tower sites tended to be on ridges and slopes with a southerly aspect, sites where one would expect relatively dry fuels. Because all units also had areas with northerly exposures, the fire intensities and rates of spread and, thus [CO] would be expected to be above the average for the units as a whole.

Modeled values used to replace saturated values were the average [CO] calculated from the plume model for the fireline intensity, wind speed, and sensor height appropriate for the tower and sensor from which the saturated measurement was obtained. Data from a series of plot burn experiments (Bova and Dickinson 2008, Kremens *et al.* 2009) were used to estimate peak fire radiative power (FRP, kW m⁻²) for the area flaming within the view area of a dual-band infrared radiation sensor and to derive a relationship between fireline intensity and peak FRP

$$I = 43.78FRP^{0.89} \quad [7]$$

where fireline intensity was estimated using measured rates of spread and consumption and a heat of combustion of 18,700 kW m⁻¹ intended to describe both convective (flaming) and smoldering heat release (Johnson 1992)(R² = 0.73). Equation 7 was then used to estimate fireline intensity from peak FRP estimates made for each plot in the field (unpublished data). Next, plume model average [CO] output from the simulations described in Table 1 was related to fireline intensity, ambient wind, and height above ground through a relationship describing temperature rise (excess) above ambient. Temperature excess ($\theta = Tp_h - T_a$, where T_a was set to 25 °C, the average ambient temperature observed in the prescribed burns) at height in the plume has been described for a line-source plume by Van Wagner (1973)

$$\theta \propto \frac{0.239I^{\frac{7}{6}}}{z_g (0.026I + U^3)^{\frac{1}{2}}} \quad [8]$$

where z_g is height above ground (m) and U is wind speed (m s⁻¹) and conversion factors and coefficients are combined. Fireline intensities for the plume model (Table 1) were based on a heat of combustion for convective heat release alone (16,000 kW m⁻¹, see above) and were adjusted upward to 18,700 kW m⁻¹ for use in Equation 8 (see Equation 7). Finally, model CO concentrations at height were described by a combination of Equation 8 and an added group of variables to obtain the best possible fit to model output (see Results).

As a means of further describing prescribed fire behavior, fuel consumption was estimated from time-integrated peak FRP (Kremens *et al.* 2009). Wooster *et al.* (2005) found that fuel consumption was proportional to total radiative energy release (fire radiative energy, FRE), a finding validated by Kremens *et al.* (1990). Ambient

temperature and wind at 6.1 m were averaged for the 10 minutes preceding fire arrival (as indicated by an initial increase in CO concentrations).

3. Modeling incapacitation from prescribed fire CO exposures

Incapacitation from smoke exposures was modeled from the combined and counteracting effects of CO and irritant exposures on carboxyhemoglobin (COHb) concentrations (%) in the blood. We assumed that COHb accumulation from CO exposures in bats was similar to that for rats, an assumption supported by the similarity in dose-response relationships seen across a wide range of taxa and body masses (*e.g.*, Spietel 1996). Accumulation of COHb was modeled for field [CO] exposure data through a relationship developed by Hartzell *et al.* (1985) based on data from rats. Hartzell *et al.*'s (1985) relationship was applied to each time step and the effects of sequential time steps summed to provide a cumulative COHb concentration (%) at the end of an exposure as follows:

$$COHb = \sum_{j=1}^n (12.5 \ln([CO]_j) - 22.9) (1 - e^{(-kt[CO]RMV_j)}) \quad [9]$$

where the summation occurs from time step $j=1$, k is the time constant ($4.057 \times 10^{-4} \text{ min}^{-1}$), t is the time step (0.17 min), and RMV is respiratory minute volume (L min^{-1} , see below). We applied Equation 9 to the main exposure period (when flames were passing below towers), ending COHb accumulation once CO concentrations had fallen towards background levels characteristic of post-fire residual combustion (see below) and COHb dissociation would be expected to result in relatively rapid (~30 min half-life) decline in COHb levels (*e.g.*, Kim *et al.* 1991).

In order to determine a lower threshold [CO] to include in COHb accumulation calculations and to serve as an initiation trigger for COHb dissociation (see below), we employed the rule of thumb that human hemoglobin affinity for CO is ≥ 200 times that for O₂ (Armin and Zibrak 1998). In the model, O₂ was 200 times more abundant than CO and, thus, became competitive with CO for binding with hemoglobin, when CO concentrations were ~ 100 ppm. Thus, only [CO] ≥ 100 ppm were included in the summation in Equation 9.

Data on time-to-incapacitation for rats as a function of [CO] from Kaplan and Hartzell (1984) were used in Equation 9 to calculate the COHb concentration associated with incapacitation. These results suggest that the COHb concentrations necessary for inducing incapacitation range between 70 to 93%. To provide a margin of safety, a threshold value for incapacitation of 50% COHb was chosen for assessing the potential effects of prescribed fire smoke exposures. Data from humans suggest greater sensitivity to COHb, with loss of consciousness predicted at 40% or lower and death at 50% or greater (Purser 1988).

In our analysis, we assumed that the affinity of the bat hemoglobin for CO was similar to that for rat hemoglobin. The basis for this assumption was the similarity of the P₅₀ values for rodent hemoglobin and bat hemoglobin. The P₅₀ value is the oxygen partial pressure at which 50% of the hemoglobin is saturated with oxygen. Thus, it is an indication of the hemoglobin affinity for oxygen; a lower P₅₀ value means a higher affinity of hemoglobin for oxygen. The P₅₀ value for *Phyllostomus discolor* was 28.6 Torr while the P₅₀ value for two other bats, *Rousettus aegyptiacus* and *Myotis myotis*, were 30.8 and 33.3 Torr, respectively (Jürgens *et al.* 1981). Conversely, the P₅₀ value for

white mice has been reported to be 42 Torr, and a value of 36 Torr for white rats (Lahiri 1975). Another reported P_{50} value for the laboratory mouse was 44 Torr which was similar in size to the *Phyllostomus discolor* (Schmidt-Nielsen and Larimer, 1958). Wild caught mice, *Clethrionomys glareolus* and *Apodemus sylvaticus*, had P_{50} values of 33.2 and 33.5 Torr, respectively (Jürgens *et al.*, 1981).

Effects of irritants in smoke were incorporated through their effect of reducing RMV, a variable describing the combined effects of breathing rate and volume per breath. Resting RMV averaged 0.021 L min^{-1} for the rats in Hartzell *et al.* (1985). Estimated respiratory minute volume for a 15 g big brown bat (*Eptesicus fuscus*) at 37 C was 0.023 L min^{-1} (Szewczak & Jackson 1992) and Chappell and Roverud (1990) reported a RMV of 0.023 L min^{-1} at 37 C for *Noctilio albiventris* (mean mass 40 g). Accordingly, we use an RMV of 0.023 L min^{-1} as the base value in our assessments of COHb accumulation. In our model, we assume that RMV is the basal rate even though bat metabolic rates and breathing rates during torpor are lower than those at the basal body temperature (37 C) and increase with body temperature during the torpor arousal process (Hayward and Ball 1966). Our assumption of a basal RMV would tend to overestimate COHb.

Two irritants, acrolein and formaldehyde, were selected for analyses based on their presence in forest combustion products and their known effects on RMV. Equations relating formaldehyde and acrolein mole fractions (ppm) to percent decrease in respiration rate (breaths min^{-1}) were determined by nonlinear least squares regression using Matlab on data from the literature. Under an assumption of a constant tidal volume (L), a decrease in respiration rate translates directly into a decrease in RMV. The

relationship describing percent decrease in respiration rate as a function of formaldehyde concentration $[\text{CH}_2\text{O}]$ is based on data from Chang *et al.* (1981) for mice

$$\% \text{ decrease} = \frac{72.57[\text{CH}_2\text{O}]}{1.96 + [\text{CH}_2\text{O}]} \quad [10]$$

From the literature, the respiratory rate changes for acrolein were measured over the concentration range of 0.404 to 7.3 ppm (Nielsen *et al.* 1984). The relationship describing percent decrease in respiration rate as a function of acrolein concentration $[\text{C}_3\text{H}_4\text{O}]$ is based on data from Nielsen *et al.* (1984) for mice

$$\% \text{ decrease} = \frac{89.96[\text{C}_3\text{H}_4\text{O}]}{2.09 + [\text{C}_3\text{H}_4\text{O}]} \quad [11]$$

The irritancy of the bats was assumed to be the same as for mice with both acrolein and formaldehyde. We assume that acrolein and formaldehyde effects are additive (Casseo *et al.* 1996) and, thus, the percent decrease in respiration rates for acrolein and formaldehyde were added together in the equation for the calculation of carboxyhemoglobin percentages. Acrolein is a somewhat more potent irritant with an RD_{50} value (irritant concentration at which there is a 50% decrease in respiration rate) of 1.7 ppm after 10 minute exposures to a range of concentrations in comparison with formaldehyde with an RD_{50} value of 3.1 ppm after 10 minute exposures (Kane and Alarie 1977). The concentrations of irritants were determined to be below lethality levels given the relatively short exposure times for these gases (see below) and, hence, consideration was only given to the irritants' effects on breathing rates and accumulation of COHb.

When CO exposures cease, a process of dissociation of COHb and elimination of CO begins. To get a sense of the rate of this process and identify where exposures could be said to end, we implemented dissociation when measured CO concentrations fell

below 100 ppm. We estimated the rate constant for this process from data in Kim *et al.* (1991)

$$\text{COHb}_{(t+1)} = \text{COHb}_{(t=0)} \exp^{-lt} . \quad [12]$$

where $\text{COHb}_{(t+1)}$ is COHb concentration at the end of the time step, $\text{COHb}_{(t=0)}$ is COHb concentration at the beginning of the time step, l is the time constant (0.0003 s^{-1}), and t is our 10 s sampling interval. In Kim *et al.*'s (1991) dataset, rats were exposed to 3700 ppm CO for 30 minutes and COHb concentrations were $>50\%$.

6. Modeling burns caused by elevated plume temperatures

Not having data on plume gas temperatures in the prescribed fires, we used plume model data to assess risk from exposures to elevated temperatures. We modeled thermal effects on bats by considering the heating of bat ears, thermally-thin appendages that are exposed while bats are roosting in their typical head-down position. We chose this approach because no models or data specific to bats exist regarding thermal effects and no appropriate models or data were available for other small mammals. We did not feel that models or data based on human exposures (*e.g.*, Blockley 1965, Purser 2005) would be defensible given differences in thermal mass between humans and bat appendages and the ability of humans to use sweating as a heat sink to reduce the effects of exposure.

If an object can be assumed to exhibit a minimal temperature gradient from the surface of the object to its interior during heating, a simplified lumped-capacitance approach can be applied (see derivation in Holman 1986). The lumped capacitance model has been applied to predicting the heating of small buds and twigs (*e.g.*, Michaletz

and Johnson 2006) and cones (Gutsell and Johnson 1996) in wildland fires. The criterion for applying the model is the Biot number

$$Bi = \frac{cV}{h} \quad [13]$$

where c is the heat capacity of the material ($\text{J kg}^{-1} \text{C}^{-1}$), V is the volume (kg m^{-3}), and h is the convection heat-transfer coefficient ($\text{W m}^{-2} \text{C}$). The Biot number provides a ratio of internal resistance to heating to external heat flux and internal thermal gradients can be assumed to be small enough to ignore when $Bi < 0.1$. The ears of the Indiana bat are nearly hairless. Ear skin thickness in *Myotis septentrionalis*, a species with similar body size and hairless ears of similar morphology, was 0.16 mm (N=3 bats). As a first approximation for calculations of convective heat-transfer coefficients, we assume that the head of a roosting bat is approximately spherical in shape. The average convection heat transfer coefficient for a sphere is a function of head dimension and gas temperature and flow rate and can be estimated by solving the following relationships for h (Gates 1980)

$$Nu = 0.37 Re^{0.6} \quad [14]$$

and

$$Nu = \frac{hD}{k} \quad [15]$$

and

$$Re = \frac{VD}{\nu} \quad [16]$$

where Nu is the Nusselt number (dimensionless), Re is the Reynolds number (dimensionless), D is the diameter of the bat's head (15 mm for Indiana bat, NatureServe 2009), k is air thermal conductivity ($\text{W m}^{-1} \text{C}^{-1}$), ν is kinematic viscosity of air ($\text{m}^2 \text{s}^{-1}$),

and V is plume velocity (m s^{-1}). Air thermal conductivity and kinematic viscosity are dependent on plume gas temperature and are calculated from Sutherland's formula (Rogers 1992) assuming a constant heat capacity of air of $1030 \text{ J kg}^{-1} \text{ K}^{-1}$ (at 500 K). As with CO exposures, we assume that the roosting bat experiences the full temperature and velocity of the plume with no sheltering.

The lumped capacitance model can be arranged to provide the time to burn injury

$$t_N = \ln \theta_N \left(\frac{\rho c V}{h A} \right) \quad [17]$$

where t_N is time to necrosis (s), θ_N is the temperature excess at necrosis $((T_N - T_{ph})/(T_a - T_{ph}))$, where T_N is set to $60 \text{ }^\circ\text{C}$ and T_a to $25 \text{ }^\circ\text{C}$, ρ is density of the skin (1040 kg m^{-3} , Diller *et al.* 1991), c is skin heat capacity ($4000 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$, Diller *et al.* 1991), and V and A are volume and area, respectively, of a $1 \times 10^{-4} \text{ m}^2$ patch of skin ($1 \times 1 \text{ cm}$). Residence times required for necrosis were compared with plume residence time to determine whether burn injury was expected.

Results

1. Plume model output

General relationships between modeled plume characteristics, height above ground, and fireline intensity for no-wind plumes are shown in Figure 2a-d. For a given fireline intensity, mixing of the plume with ambient air results in falling CO concentrations, gas temperatures, and velocities with height above ground, while residence times increase with height above ground as the plume expands (Figure 1). Modeled plume velocities showed marked declines just above the height of the flames, but were relatively stable thereafter. At a given height above ground, temperatures, CO

concentrations, and velocities increased with fireline intensity while residence times fell. Cross-winds caused plume distortion from the no-wind case and led to lower temperatures and CO concentrations and longer residence times at a give height. At a given height, wind tended to increase plume velocities at the lowest intensities and reduce velocities at the highest fireline intensities as plume centerline curvature increased (see Figure 1). Residence times were generally short. For no-wind fires, the range was 15 s near the flame tip (0.7 m above ground) for the lowest intensity fire (133 kW m^{-1}) up to 10 minutes for the same fire at 31 m above ground. Residence times for higher intensity fires fell within that range over all heights. For fires burning in a 2 m s^{-1} cross-wind, the range in residence times was 1 min for the highest intensity fire (2133 kW m^{-1}) near flame tip (3.6 m) and 78 min at 31 m height. Residence times for the 1 m s^{-1} cross-wind were intermediate between the no-wind and 2 m s^{-1} simulations. Results for low intensity fires in cross-winds are not reliable because of plume distortion (Van Wagner 1973), particularly for predictions high into the canopy. However, plume model CO concentrations were toxicologically significant only for high intensity fires where sensor saturation occurred and for heights below which plume temperatures and velocities were sufficient to cause ear injury (see below).

Plume model average CO concentrations from simulations described in Table 1 were related to fireline intensity, ambient wind, and height above ground for use in correcting for sensor saturation (see below). Equation 8 describing temperature excess θ was used along with an added group of variables to tailor the relationship to [CO]

$$[CO] = 59.8 \left(\frac{\theta}{((U + 1)z_g)^{1/3}} \right) \quad [18]$$

where the denominator was chosen for best fit ($R^2 = 0.98$). Equation 18 was used to replace saturated values by mean modeled [CO] values ranging from 484 to 1817 ppm for sensors at 2.4 m height and from 377 to 1650 ppm for sensors at 6.1 m height. Model values at 6.1 m height for a few low-intensity fires were less than saturated values and, in this situation, saturated values were not replaced. Formaldehyde and acrolein concentrations estimated from emission factors in Table 2 are shown for the range of CO concentrations predicted by the plume model for the fire scenarios in Table 1 (Figure 4).

2. Prescribed Burns

General prescribed fire conditions are summarized in Table 3 and conditions at each tower are summarized in Table 4. Three to five monitoring towers were deployed in each fire. Fireline intensities estimated from peak FRP ranged from 894 to 90 kW m⁻². Fuel consumption estimated from integrated FRE ranged from 1.56 to 0.13 kg m². Ambient temperatures when fires burned by towers averaged from 18 to 33 °C. Relative humidities from nearby fire weather (RAWS) stations ranged from 21 to 45 %. Measured peak CO concentrations and, where saturated, modeled average CO concentrations are given. Saturation values ranged from 334 to 436 ppm. In general, CO exposures near the ground (2.4 m) are higher than at 6.1 m as expected from the plume model as products of combustion are mixed with ambient air.

Time courses of CO concentrations are provided for fires with the highest, near-median, and lowest fireline intensities as a means of illustrating the range in exposures (Figure 3a-c). The rapid rise and saturation of sensors in the highest intensity fires along with a long period of residual combustion and smoke transport from outside the

immediate area of the tower is illustrated for the Powder Mill tower (Figure 3a). The gradual rise and fall of exposures shown in Figure 3b and 3c resulted from relatively weak plumes. Carboxyhemoglobin accumulates most rapidly where [CO] where highest and, as described in the methods, [CO]<100 ppm are not included in calculations.

3. Incapacitation from Carbon Monoxide

Modeled COHb concentrations only approached the 50% threshold at 2.4 m above ground at two towers (Table 3). The towers in question were the locations of the most intense burning for which we had CO exposure data. For all towers, modeled COHb values were lower at 6.1 m than at 2.4 m except for one case where values were equal at the two heights. There was a general positive relationship between fireline intensity and modeled COHb (Table 3, see below).

Modeled COHb is used as the basis for comparison between plume model and field carbon monoxide exposures (Figure 5). Modeled COHb is plotted against Van Wagner's (1973) temperature excess variable (Equation 8) which, as can be seen, provides a reasonable description of variability in the data. The highest COHb estimates from the prescribed burn CO exposures are higher than those arising from the plume model exposures even for more intense fires. None of the COHb concentrations calculated from CO exposures and residence times generated by the plume model approached the 50% threshold for incapacitation. Because CO concentrations are not higher in the plume model output than in the datasets derived from the field data, we can conclude that short model plume residence times (Figure 2d) are the cause of low blood COHb concentrations.

4. Gas temperature effects

Biot numbers were always ≤ 0.08 so we used the lumped capacitance model to assess ear injury. Figure 6 shows the heights above ground to which bat ear burns would be predicted for fires of increasing intensity burning in a range of ambient wind velocities. For a given fireline intensity, cross-winds tended to decrease the heights up to which ear burns would occur. As fireline intensity increases, the modeled height up to which ear injury is predicted increases linearly over the range of interest. Shown are the average and minimum roost heights recorded for Indiana bats along with the range of fireline intensities observed at towers within the prescribed burns in Table 4. Under our modeling scenario, with bats being exposed in roosts to the full effect of the plume, ear injury would often be predicted at the mean roost height and for typical fireline intensities. The height of ear injury corresponded approximately to the height at which 60 °C was reached in the plume (Equation 17).

Discussion

Based on prescribed fire CO exposures and the associated modeling of COHb concentrations, CO toxicity for tree-roosting bats, such as the Indiana bat, that cannot fly is not likely to be a concern at fireline intensities below 900 kW m⁻¹ (~1.6 m flame length, Table 3). Because of short residence times, our plume model CO exposures led to even lower predicted COHb concentrations than those determined for the field data (Figure 5). Higher fireline intensities than those we observed at our towers in four prescribed fires (Table 3) occur during prescribed burning in our region, but, often,

attempts are made to avoid high intensities because of the injury they cause to trees. In contrast to CO effects, our results suggest that Indiana bats would often be vulnerable under typical prescribed-fire conditions to tissue burns on their ears because of their head-down roosting orientation and the fine ear structure (Figure 6). As a rule of thumb, bat injury would be expected at the same height as foliage necrosis, which has been successfully described as the height at which 60 °C is reached in the plume (Van Wagner 1973). The 60 C rule of thumb results from both our chosen necrosis temperature (60 °C) and the short residence times required to cause necrosis of thin ear tissue (Equation 17).

The risk to tree-roosting bats is contingent on their presence in forests during periods when burns are being conducted and, if present, their ability to fly to escape heat and gases. A review of dates at which Indiana bats emerge from hibernation and begin using forest habitats shows that females tend to emerge earlier than males (U. S. Fish and Wildlife Service 2007). Depending on weather and climate, peak emergence for females ranged from early to mid-April and peak emergence for males ranged from the end of April to early May (e.g., , Cope and Humphrey 1977). Emergence was found to begin as early as late March (e.g., Hobson and Holland 1995). In the fall, males are active for long than females (e.g., Cope and Humphrey 1977). Most bats have entered hibernation by the end of November (mid-October in northerly hibernacula, Kurta et al. 1997). Indiana bat populations at some hibernacula may increase throughout fall and into January (Clawson et al. 1980). Currently, most prescribed fires in the central hardwoods region are conducted during the late winter and early spring, yet, for most National Forests, burning is not extended into May (Dickinson et al. 2009).

For Indiana bats, there is an approximately 2 week period during which newborn bats are flightless and, within that period, 1 week in which they are too large to be carried by their mothers (USFWS, 2007). The vulnerability of adult bats to smoke outside of the hibernation period is contingent on torpor dynamics, for which too little is known to make reliable assessments. Key issues are the cues that serve to initiate arousal for a given species, the time required for flight once the arousal process is initiated, and the gender differences in torpor behavior during the burning season (review in Dickinson *et al.* 2009). Information on arousal cues and times for red bats (Scesney 2006, Scesny and Robbins 2006, Layne 2009) provide useful guidance, but need to be confirmed for other tree roosting species. Because red bats hibernate in the leaf litter during cold periods, and have been observed flushing in front of fires (Moorman *et al.* 1997), their populations may have experienced greater selective pressures for smoke sensitivity. As well, more information on bat torpor, arousal, and flushing during prescribed fires is needed. Currently, only one study on the behavior of bats fitted with transmitters during a single prescribed burn has been conducted (Dickinson *et al.* 2009).

Because of the reduced sheltering, bats roosting in foliage would be expected to be as or more vulnerable to smoke effects than Indiana bats that show a preference for roosting below sloughing bark (e.g., Lacki *et al.* 2009). Bats that are known to roost in foliage include eastern red bats, hoary bats (*Lasiurus cinereus*), silver-haired bats (*Lasionycteris noctivagans*) (NatureServe 2009). Bats that preferentially roost in crevices (e.g., the northern bat, Lacki *et al.* 2009) and cavities would appear to be somewhat less vulnerable to smoke effects than other tree roosting bats because of the reduced rates of gas mixing into cavities (Guelta and Balbach 2005).

Eastern red bats have been shown to use both the sound and smell of fires as cues for arousal (Scesny 2006). Red bats hibernate on the ground during cold periods in oak forests, where fire is frequent. In their study, bats aroused from smoke exposure alone and, more rapidly, from the combination of smoke and playback of sound recordings of fire. Bats did not arouse from the sound of fire alone. Without further data, we must assume that tree-roosting bats, such as the Indiana bat, respond to fire cues in a way similar to red bats.

Figure 7 summarizes the literature on times to arousal from torpor. The most relevant data are from eastern red bats (*Lasiurus borealis*) from Layne (2009). In Layne (2009), the time to flight was measured after the bats were exposed to smoke from nearby small-scale leaf litter burns. The only field measurement is from Dickinson *et al.* (1990), indicating that, during a warm day (31 C, Tar Hollow, Table 3), bats flew within 10 minutes of prescribed fire ignition. It was not known whether these bats were in torpor at the time of the fire. Arousal time in a small insectivorous marsupial was found to increase exponentially as body temperatures fell with declining ambient temperatures (Geiser 1986); a pattern roughly captured when arousal times from Layne (2009) are plotted against inverse time (Figure 6).

It would be expected that pregnant or lactating female Indiana bats would use torpor less often than males and nonreproductive females because of a need to sustain high metabolic rates. Data from Kurta *et al.* (1996) demonstrated that adult female Indiana bats in Michigan sustained body temperatures of 35 °C for up to 12 hrs inside diurnal roosts and some bats sustained temperatures at that level for up to 6 consecutive days, suggesting that these individuals would be able to respond fairly quickly to an

oncoming fire. High solar exposure and aggregations of bats at Indiana bat maternity roosts is thought to aid in maintaining high body temperatures (USFWS 2007). On the other hand, studies on other bat species have demonstrated declines in body temperatures in reproductively active female bats after diet restriction, such as would happen after poor foraging success (Kurta 1991, Audet and Thomas 1997). Willis *et al.* (2006) demonstrated multi-day bouts of torpor in pregnant female bats during spring storms just prior to giving birth. Thus, at least periodically, maternity colonies may be at increased risk from fire because adult females may be in torpor during cool weather. Rainy periods when foraging is poor would not be of concern since these periods do not provide good burning conditions.

Field studies found that male and nonreproductive female big brown bats (*Eptesicus fuscus*) select cooler roosts than reproductive females (Hamilton and Barclay 1995) and males enter torpor more regularly than reproductive females (Grinevitch *et al.* 1995). Given that male Indiana bats have a tendency to roost in smaller trees that are less exposed to solar radiation (Kurta 2005), we may assume that male Indiana bats also use torpor regularly. More data on roost microclimates and torpor dynamics for bats inside tree roosts and their relation to prescribed burn prescriptions are needed to address issues of roost site selection and vulnerability of bats to prescribed fire (Boyles 2007).

Because appropriate plume model validation data are scant in the literature, the accuracy of our integral plume model is uncertain. A comparison of predicted COHb concentrations from field and plume model CO exposures (Figure 5) indicates that plume model residence times are short compared with residence times of high smoke concentrations in the field. There are at least two reasons for this result. First, the

integral plume model characterizes plumes as arising from a line source of heat generated by flaming combustion. However, a portion of the heat release and smoke emissions from real fires includes those arising from smoldering combustion occurring over long time periods after the passage of flaming combustion. Second, our towers were in the interior of prescribed fire units and were thus exposed to smoke transported from outside the immediate vicinity of the tower. A particularly large contributing area, and prolonged exposures to smoke, would be expected where heat release in the interior of burn units creates a single, powerful convective column (Achte-meier et al. 2004). In contrast, the source area for smoke from the integral plume model is local as determined by fire rate of spread, flame depth, and plume distortion by wind.

The shorter plume model residence times would lead to shorter exposures to CO and, thus less COHb accumulation. In contrast, the rapid heat release envisioned by the plume model would be expected to result in an overprediction of bat burn injury. This is because the residence times required for injuring bat ears (where thickness is a thin 0.16 mm) are short and rapid heat release results in high plume velocities (and, thus, higher convection heat-transfer coefficients) and higher gas temperatures at a given height. Because distortion of the plume by ambient winds result in lower temperatures and gas concentrations at height we expected that wind would ameliorate any heating or gas effects of plumes on bats. Our results with ear burns support this expectation (Figure 6) and, in addition wind reduced COHb concentrations predicted from plume model data (results not shown). More field data and more realistic plume models are required to increase confidence. The effects of wind in reducing vegetation heating are well known,

both from field and model studies (Van Wagner 1973, Mercer and Weber 1994) and among fire practitioners (e.g., E. J. Bunzendahl, personal communication).

Uncertainty in our approach to modeling COHb accumulation arises not only from limitations in our field data and uncertainty in our plume model predictions of gas concentrations, but also from the lack of information on bat toxicology. It was not possible for us to employ models designed for time-varying CO exposures (e.g., Benignus *et al.* 1984) because estimates for bats of key parameters and functional relationships do not exist. For instance, metabolic and breathing rates of bats and other small mammals increase with body temperature during arousal (Haywood and Ball 1966, Fons *et al.* 1997), though the effects of irritants on those rates can only be surmised. Given a lack of information on irritant effects during torpor, our analysis of COHb accumulation (Equation 9) assumes that RMV during arousal from torpor is the higher resting value. Because of elevated RMV's, our approach may overpredict COHb accumulation. On the other hand, dissociation of COHb typically occurs by a two stage process where the first stage is characterized by more rapid dissociation (Shimazu *et al.* 2000). We chose to characterize dissociation by a simpler single-stage model and, thus, may underestimate dissociation rates and, thereby, overestimate COHb concentrations. Finally, because of a lack of data in the literature, we extrapolated Equation 9 to CO concentrations well below 2000 ppm, the lowest CO concentrations in the dataset on which Equation 9 was based.

Clearly, more information on torpor during prescribed fire seasons and on toxicological responses to smoke during torpor would be needed to better assess risk beyond our current analysis. However, given that our results point to heat effects as the

main concern and gas exposures as a secondary risk, it is not clear whether more research on toxicology is warranted for purposes of informing fire management. Clearly, however, more work is needed on torpor dynamics of roosting bats and the behavior of bats during prescribed fires.

Fire management and risk mitigation

Fire managers will be interested to consider how they can mitigate risk to tree roosting bats during prescribed burn operations. Several mitigation tactics suggest themselves. First, ignition operations that proceed slowly at first and, if possible, ensure that smoke is transported over the burn unit, may provide bats with the sound and smell cues that elicit arousal from torpor. Second, fire managers are well versed in modifying fire behavior through manipulating ignition practices and choosing burning days that reduce fireline intensity (Dickinson et al. 2009). One obvious tactic is to avoid a coincidence of up-slope wind and up-slope spread on dry, south-facing slopes that would produce the most intense burning. Ridge ignition is a tactic used on the Daniel Boone National Forest wherein ignition occurs by hand along ridgelines and fires are allowed to spread downhill often against a generalized flow towards the ridgeline. Ridge ignition results in a reduction in average fireline intensities over other ignition tactics. For instance, helicopter ignition with ping-pong ball incendiary devices combined with hand ignition around burn unit boundaries results in a mix of heading, flanking, and backing, and converging fire and can lead to a wide range of fire behavior. Our Tar Hollow prescribed fire was one such burn. Strip head-firing by hand can also lead to intense

behavior, but fireline intensity can be controlled through varying the distance between strips and their placement on the landscape.

Choice of season-of-burn may also allow fire managers to reduce fire intensities and otherwise reduce risk for bats. National Forests in the central hardwoods region currently have various timing restrictions on prescribed burning in their Forest Plans, generally directed at the spring when maternity colonies are forming and the summer when newborn young may be present in tree roosts (Dickinson et al. 2009). Currently, most burning in the mixed-oak forest region within the range of the Indiana bat occurs during the dormant season, especially late winter and early spring, coinciding generally to the period when Indiana bats, particularly females, are leaving hibernacula and temperatures are cool. Burning during the growing season, as opposed to the dormant season, has been proposed as a way to accomplish the same vegetation management objectives (*e.g.*, reduction in competition for oaks from fire-intolerant species) at lower fire intensities (Mike Bowden, personal communication). Burning during the spring after deciduous species have leafed out would mean that burning would generally occur on warmer days in which arousal from torpor occurs quickly (Figure 7).

In areas with hibernacula, a late winter and early spring constraint is potential disturbance of hibernating bats by smoke (Dickinson et al. 2009). Fire managers in Mammoth Cave National Park attempt to conduct fires on days warm enough to avoid smoke aspiration into hibernacula, that is, when daytime temperatures are > 10 C, which is the average cave temperature (U. S. Department of Interior, 2001). Because their prescribed burning season extends from mid-November through April, it may be possible in some years to burn before any bats have emerged from hibernation.

Finally, a review of the literature on Indiana bat roosting behavior suggests that having large trees on landscapes that, in turn, create large (dead) snags for roosting would reduce risk for bats (Dickinson et al. 2009). Figure 6 shows that bats roosting high up in the canopy are at lower risk from exposures to plumes than bats roosting lower on trees. The literature shows that bats roost higher up in taller trees and, where appropriate data are available, choose larger than average trees from the pool of suitable snags. Thus, it is reasonable to conclude that allowing more trees to get large on landscapes in which tree-roosting bats live would reduce their risk from fires and, in addition, generally improve maternity habitat.

Efforts to mitigate risks of smoke exposure to bats may often cause conflict with smoke and vegetation management. For instance, relatively high fire intensities are often used during the dormant season to accomplish vegetation management objectives such as killing trees that compete with fire-tolerant oaks and opening the canopy for oak regeneration (*e.g.*, Iverson et al 2008). Also, prescribed fire units are often ignited rapidly and in a way that encourages a rapid release of heat and smoke in order to ensure that smoke is transported away from the burn unit as effectively as possible. Adding considerations for reducing risk to wildlife contributes to what is already a complicated fire management situation in the eastern US.

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Tables

Table 1. Characteristics of the fires used to generate boundary conditions for the plume model and the boundary conditions themselves. There is no interaction between wind and fire behavior in our model, only effects of wind on plume behavior and flame tilt (i.e., flame height) and, thus, the height above ground at which the plume begins. Fuel consumption (W), rate of spread (R), and heat of combustion determine fireline intensity (I). Flame length and initial plume velocity (w_i) are determined by I and initial plume half-width (b_i) is determined by rate of spread and total and rate of fuel consumption.

W	R	I	L_f	w_i	b_i
kg m ⁻²	m min ⁻¹	kW m ⁻¹	m	m s ⁻¹	m
0.5	1	133	0.7	1.9	0.10
1.0	2	533	1.4	3.1	0.42
1.5	3	1200	2.0	4.0	0.94
2.0	4	2133	2.6	4.9	1.68

Table 2. Yield and molecular weights (M) of products of combustion from biomass burning. Carbon monoxide yields are for deciduous forest fuels. Yield of water vapor is based on a fuel moisture content of 5% of dry weight, the fuel moisture content prescribed for plume simulations. Yields are used to calculate concentrations (see Equations 2-6).

POC	Yield (gm kg ⁻¹)	M (gm mol ⁻¹)	Source
CO	94	28	Wiedinmyer 2006
Acrolein	0.24	56	Andrae and Merlet 2001
Formaldehyde	2.2	106	Andrae and Merlet 2001
Water	609	18	Byram 1959

Table 3. General characteristics of prescribed fires in southeast Ohio and eastern Kentucky. Averages across towers at 6.1 m are provided for temperature and wind speed except for Wolf Pen where estimates are from the nearest fire-weather station (Remote Automated Weather Station, RAWS). Relative humidity values are the midafternoon value (1500 hrs) from the nearest RAWS except for Tar Hollow, for which the Zaleski RAWS was more representative. Data specific to individual towers are provided in Table 4. All fires in Kentucky were on the Cumberland District of the Daniel Boone National Forest. The unit size is larger than the area burned, particularly for fires in the Daniel Boone National Forest where ridge ignition was practiced. The Tar Hollow burn in Tar Hollow State Forest was ignited by hand and helicopter.

[Bob, please use use your GIS skills to estimate area for PM, BW, and WP]

Burn unit	Date	State	RAWS	Area ha	Ta C	RH %	U m s ⁻¹
Powder Mill	04/10/2007	KY	Koomer	~790	18.5	21	0.43
Tar Hollow	04/20/2007	OH	Zaleski	98	22.5	31	0.70
Bear Waller	04/30/2007	KY	Koomer	~200	32.0	26	0.40
Wolf Pen	04/08/2008	KY	Triangle	~100	26.0	45	-

1 Table 4. Characteristics of prescribed fires at towers in mixed-oak forests of southeastern Ohio and eastern Kentucky. Table is sorted
2 by peak fire radiative power (*FRP*). Fires are Powder Mill (PM), Bear Waller (BW), Tar Hollow (TH), and Wolf Pen (WP).
3 Sampling towers were placed in landscape positions that were expected to burn, so are not representative of burn unit averages. See
4 text for descriptions of fireline intensity and fuel consumption calculations. Ambient temperatures (T_a) and winds (U) were estimated
5 for the 10 minutes preceding fire arrival. General fire behavior below towers was determined from video (where available), with
6 heading, flanking, and backing referring to fires burning with the wind, perpendicular to the wind, and against the wind, respectively,
7 while uphill, across slope, and downhill referring to fire spread direction relative to the prevailing slope. Maximum measured [CO]
8 exposures are provided for the two sensor heights and, where sensor saturation occurred, the corresponding average [CO] from the
9 plume model is also provided. Partial or complete sensor system failures are indicated by dashes. Modeled COHb concentrations
10 were derived from upper bound carbon monoxide exposures (i.e., where saturated values were replaced with plume model average
11 values where those values were large than saturated values).
12

1 Table 4, continued.

									Max [CO] ppm COHb (%)			
									_____		_____	
4	Fire	Behavior	FRP	FRE	<i>I</i>	W	U	Ta	Height		Height	
5			kW m ⁻²	kJ m ²	kW m ⁻¹	kg m ⁻²	m s ⁻¹	°C	6.1 m	2.4 m	6.1 m	2.4 m
6	_____											
7	PM	Heading uphill	29.1	3770	894	1.39	0.4	18	524 ¹	1817 ¹	-	45
8	BW		21.6	875	685	0.32	-	-	-	-	-	-
9	BW		19.5	4231	623	1.56	0.4	32	407 ¹	1410 ¹	16	43
10	TH	Flanking across slope	17.3	3806	562	1.40	0.5	22	377 ¹	1308 ¹	7	25
11	TH	Heading across slope	12.5	1563	418	0.58	0.7	23	205	1013 ¹	1	13
12	PM		8.9	1661	308	0.61	0.4	19	367 ²	883 ¹	3	11
13	PM	Flanking downhill	5.4	1922	198	0.71	0.5	-	297	-	2	-
14	TH	Backing downhill	3.4	1128	130	0.41	0.5	23	243	264	1	2
15	BW		3.2	925	125	0.34	0.4	33	353 ²	484 ¹	4	16
16	PM		3.2	2886	122	1.06	-	-	-	-	-	-

1 Table 3, continued.

									[CO] ppm		COHb (%)	
									_____		_____	
4	Fire	Behavior	FRP	FRE	<i>I</i>	W	U	Ta	Height		Height	
5			kW m ⁻²	kJ m ²	kW m ⁻¹	kg m ⁻²	m s ⁻¹	°C	6.1 m	2.4 m	6.1 m	2.4 m
6	_____											
7	WP	Backing downhill	3.0	1670	117	0.61	-	-	115	212	0	1
8	TH	Flanking across slope	2.7	1594	107	0.59	1.1	22	375	335 ²	4	4
9	BW	Heading uphill	2.4	1811	97	0.67	0.4	31	360	436 ²	4	5
10	WP		2.4	1745	95	0.64	-	-	158	313	1	6
11	WP		2.3	362	91	0.13	-	-	103	214	0	1
12	WP	Backing downhill	2.2	1384	90	0.51	-	-	5	179	0	2
13	_____											

14 ¹Saturated [CO] measurement is replaced by model average [CO].

15 ²Modeled average [CO] value was lower than saturated [CO] measurement and, thus, measured maximum value is given.

1 Figure captions

2

3 Figure 1. A two-dimensional plume rising above a line-fire in a crosswind. The wind
4 comes from the left, causing plume deflection to the right. Flame spread is also to the
5 right, causing objects in the canopy to experience a plume residence time that is a
6 function of flame spread rate, wind velocity, and the object's height above ground.
7 Flame conditions determine initial gas concentrations, temperatures, velocities, and
8 densities. A Gaussian profile is fit to the top-hat (averaged) output of the plume model
9 and used to calculate average plume properties. We do not consider deflection of the no-
10 wind plume (not shown) in our model because flame spread is slow relative to plume
11 velocity.

12

13 Figure 2. No-wind plume characteristics predicted from the integral model. CO
14 concentration (a), gas temperatures (b), plume velocities (c), and residence times (d) are
15 shown as a function of height above ground and fireline intensity (see Table 1). Note that
16 residence times increase with height while CO concentrations, temperatures, and
17 residence times (to a lesser extent) fall.

18

19 Figure 3. Representative CO exposures and blood COHb concentrations from prescribed
20 fires in southeastern Ohio and eastern Kentucky. Shown are the time courses of CO
21 exposures at 6.1 m (top) and 2.4 m (bottom) above ground. Modeled COHb
22 accumulation is calculated where no sensor failures occurred (*e.g.*, Figure 3a at 6.1 m)
23 and where $[CO] \geq 100$ ppm. Data are from towers that captured the highest, near-median,

1 and lowest median fireline intensities (see Table 3). Saturated CO concentrations were
2 replaced by model average values (see methods). The CO sensor saturation limits are
3 indicated for the Powder Mill tower by arrows. Note that the vertical scale changes
4 among figures.

5
6 Figure 4. Proportionality between CO and irritant concentrations determined from the
7 yields (emission factors) in Table 2. The ranges are those used for the fire behavior and
8 plume model scenarios in Table 1.

9
10 Figure 5. Comparison between prescribed fire and plume model blood COHb (%)
11 predictions. By capturing functional relationships among explanatory variables, the
12 temperature excess variable (Equation 9) reduces variability in the data.

13
14 Figure 6. Modeled relationship between the height in the canopy up to which bat ear
15 burns would be expected and fireline intensity for three ambient wind speeds (U , $m\ s^{-1}$).
16 The range in fireline intensities estimated across four different prescribed fires is
17 indicated (see Table 3). The minimum (2 m) and mean roosting heights (9.1 m) along
18 with its variability (1 std. dev. = 2.1 m) are shown for male and female Indiana bats (see
19 Dickinson et al. 2009). Approximate flame lengths corresponding to given fireline
20 intensities are provided to facilitate interpretation.

21
22 Figure 7. Time to arousal and flight for a range of bat species. Data are for the little
23 brown bat (*Myotis lucifugus*, Thomas et al. 1990), big brown bat (*Eptesicus fuscus*,

1 Hayward and Ball 1966), northern long-eared bat (*Myotis septentrionalis*, Dickinson et
2 al. 2009), and eastern red bat (*Lasiurus borealis*, Scesney 2006, Layne 2009). For
3 convenience, the 10 and 30 minute arousal times are indicated. The solid line is an
4 extension of the linear fit to Layne's (2009) data on time to flight. The only field
5 measurements are for the northern long-eared bat indicating that two bats with radio
6 transmitters flew within 10 minutes of ignition (Dickinson et al. (2009), consequently, 10
7 minutes is an underestimate of time-to-flight as indicated by the upward-pointing arrow.
8 Data from Scesney (2006) and Hayward and Ball (1966) are for 5 °C and are offset for
9 clarity.
10

Figure 1

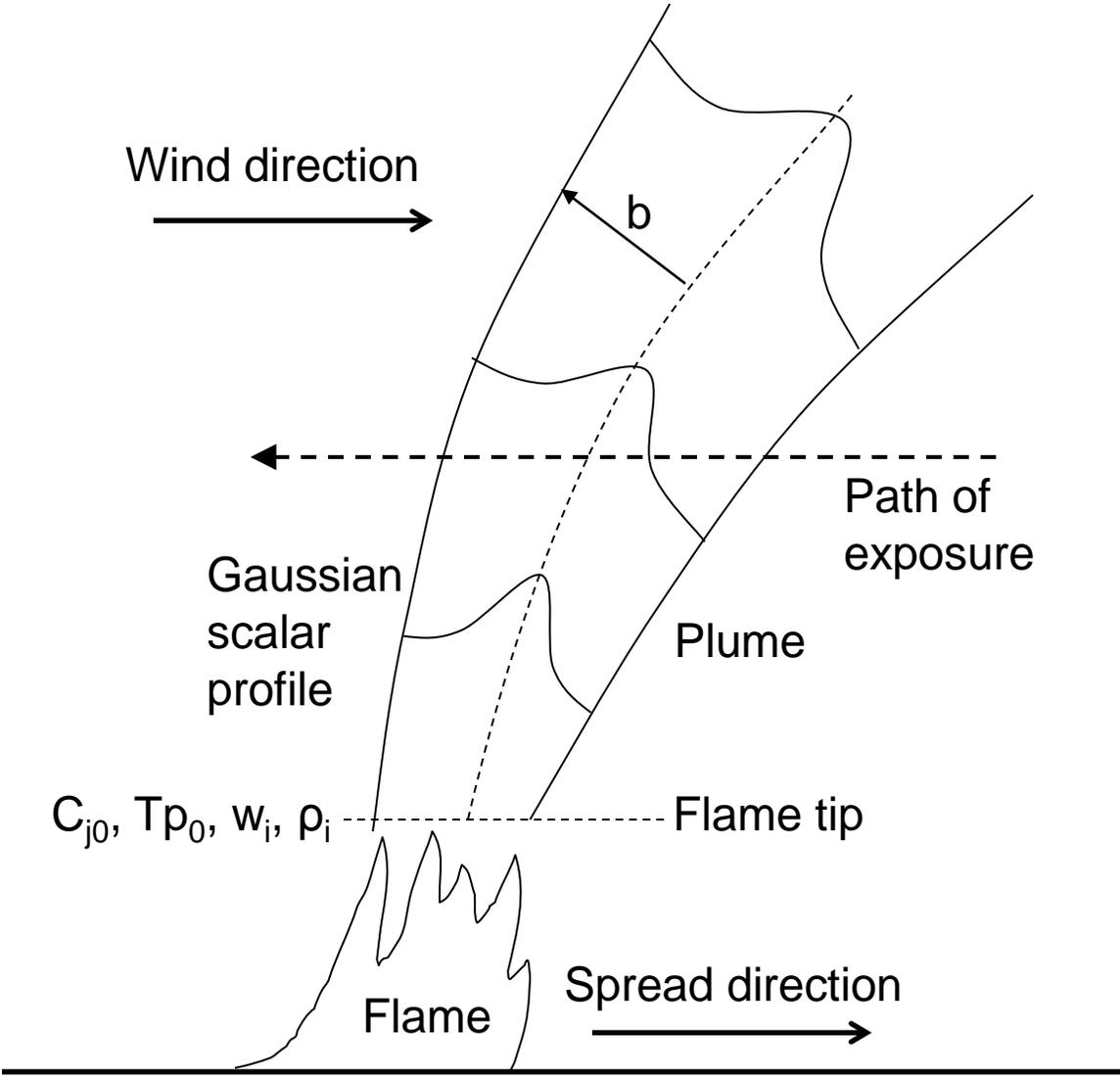


Figure 2a

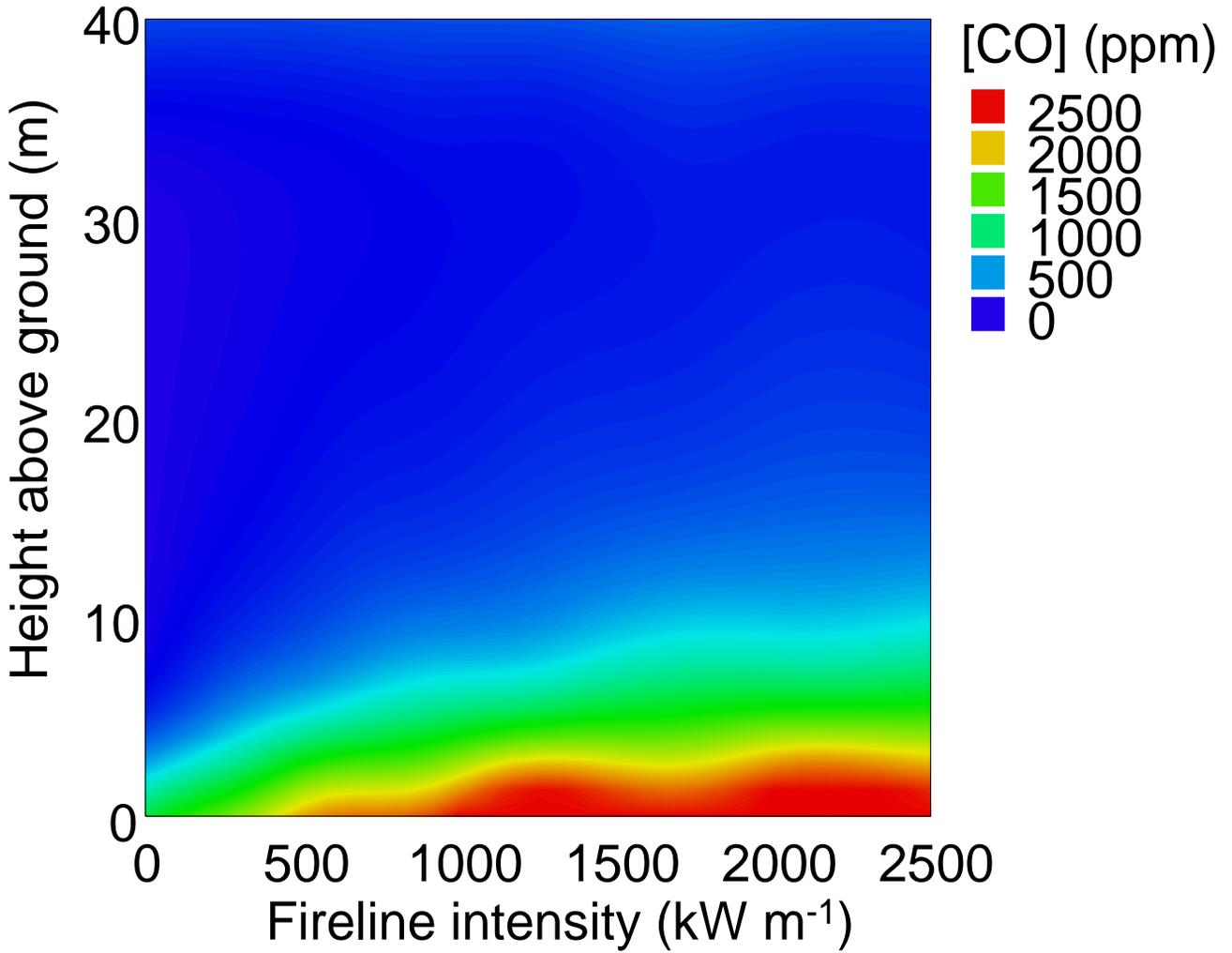


Figure 2b

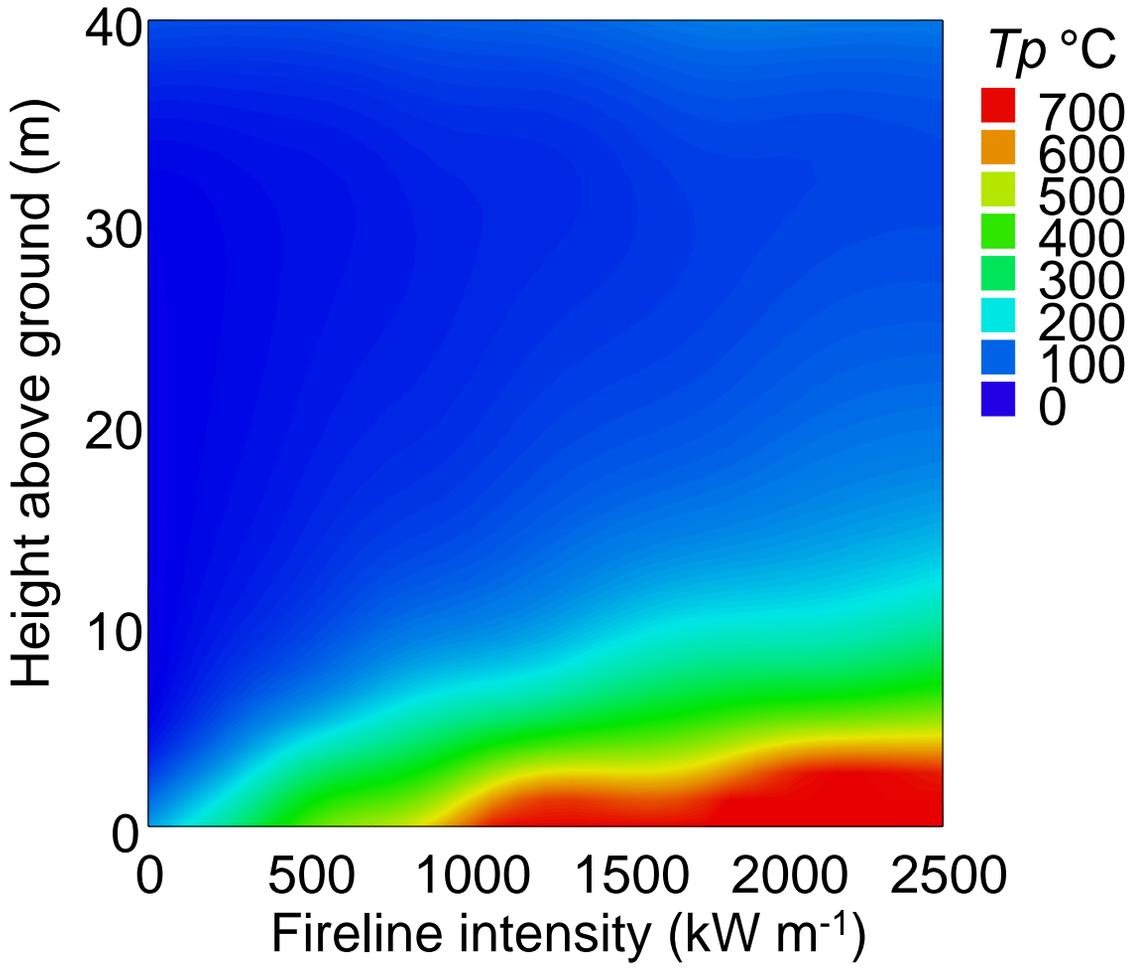


Figure 2c

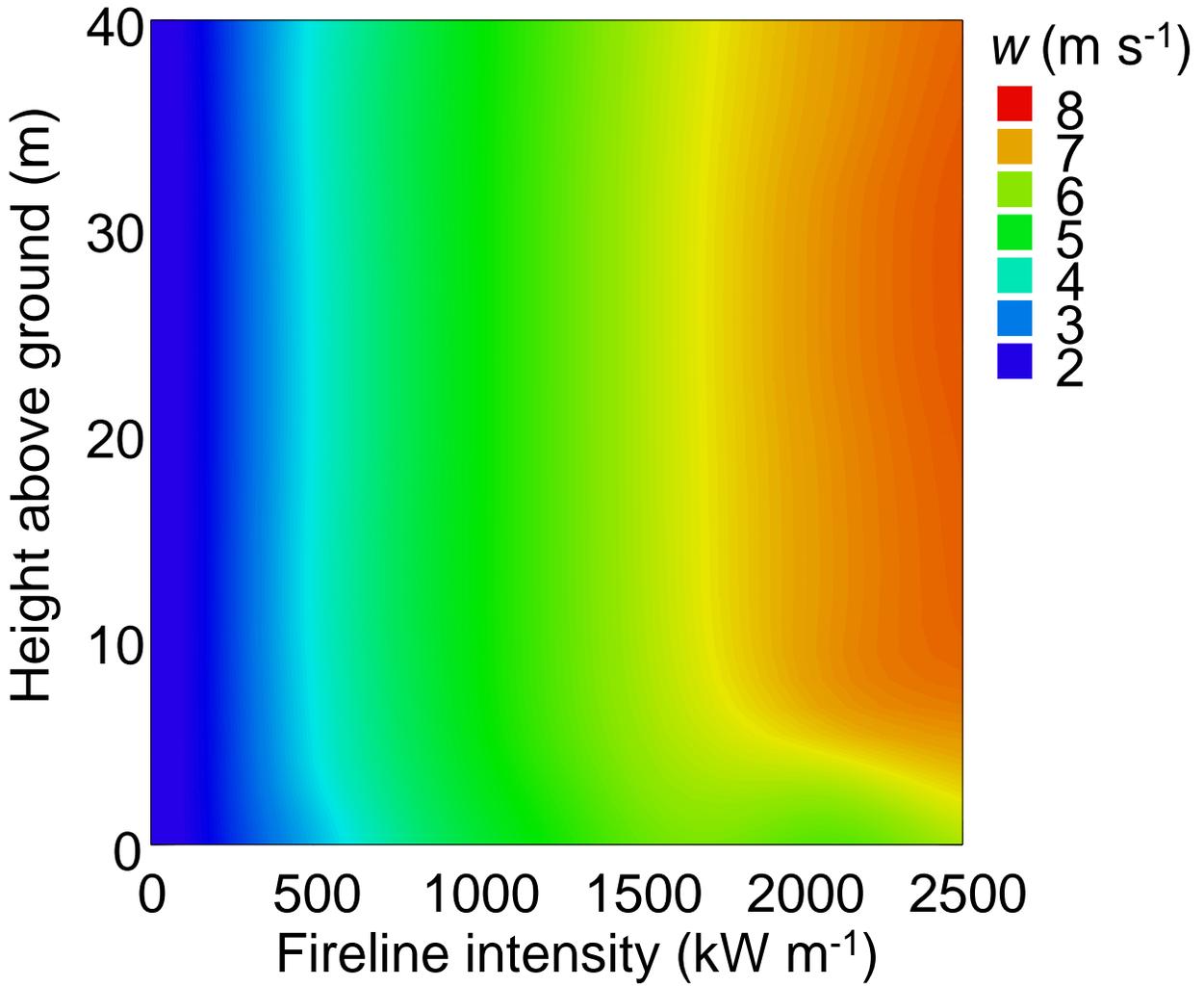


Figure 2d

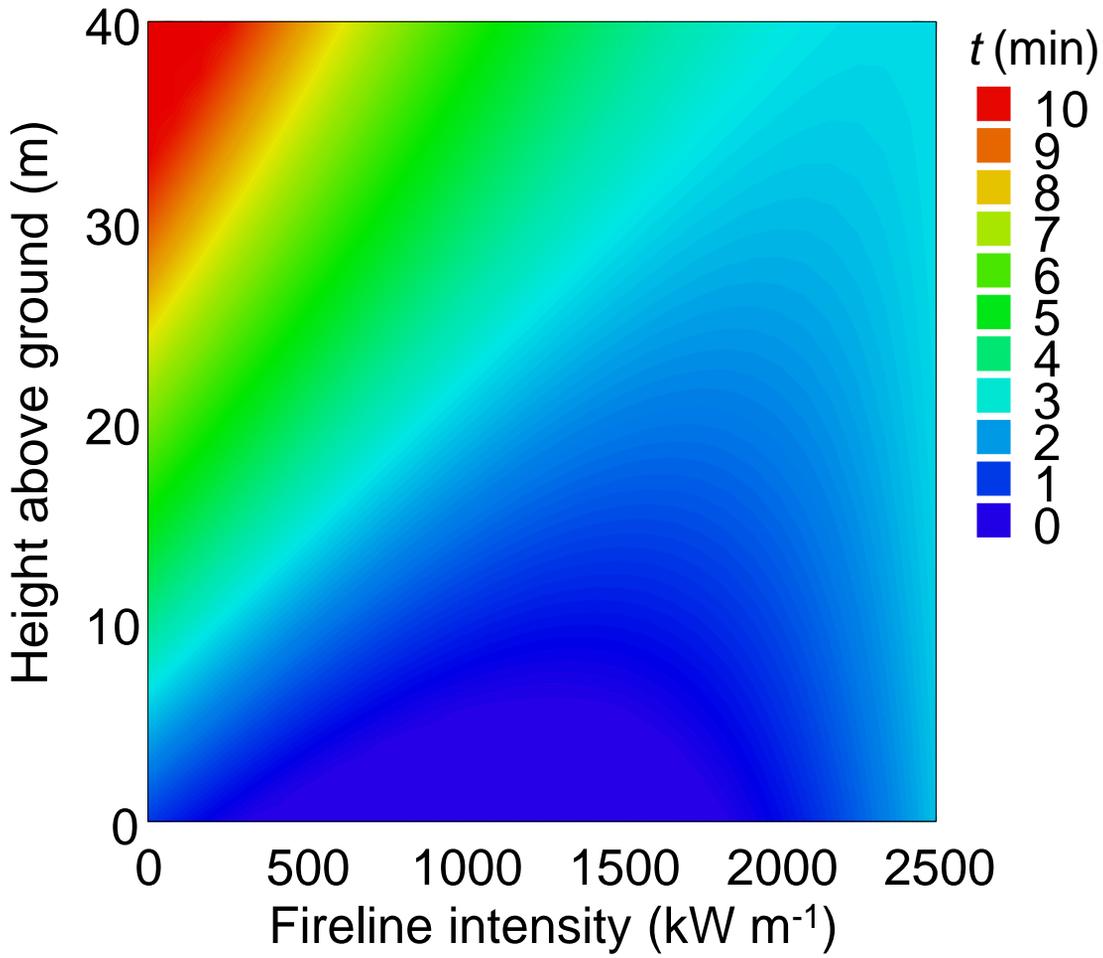


Figure 3a

Powder Mill, $I = 894 \text{ kW m}^{-1}$

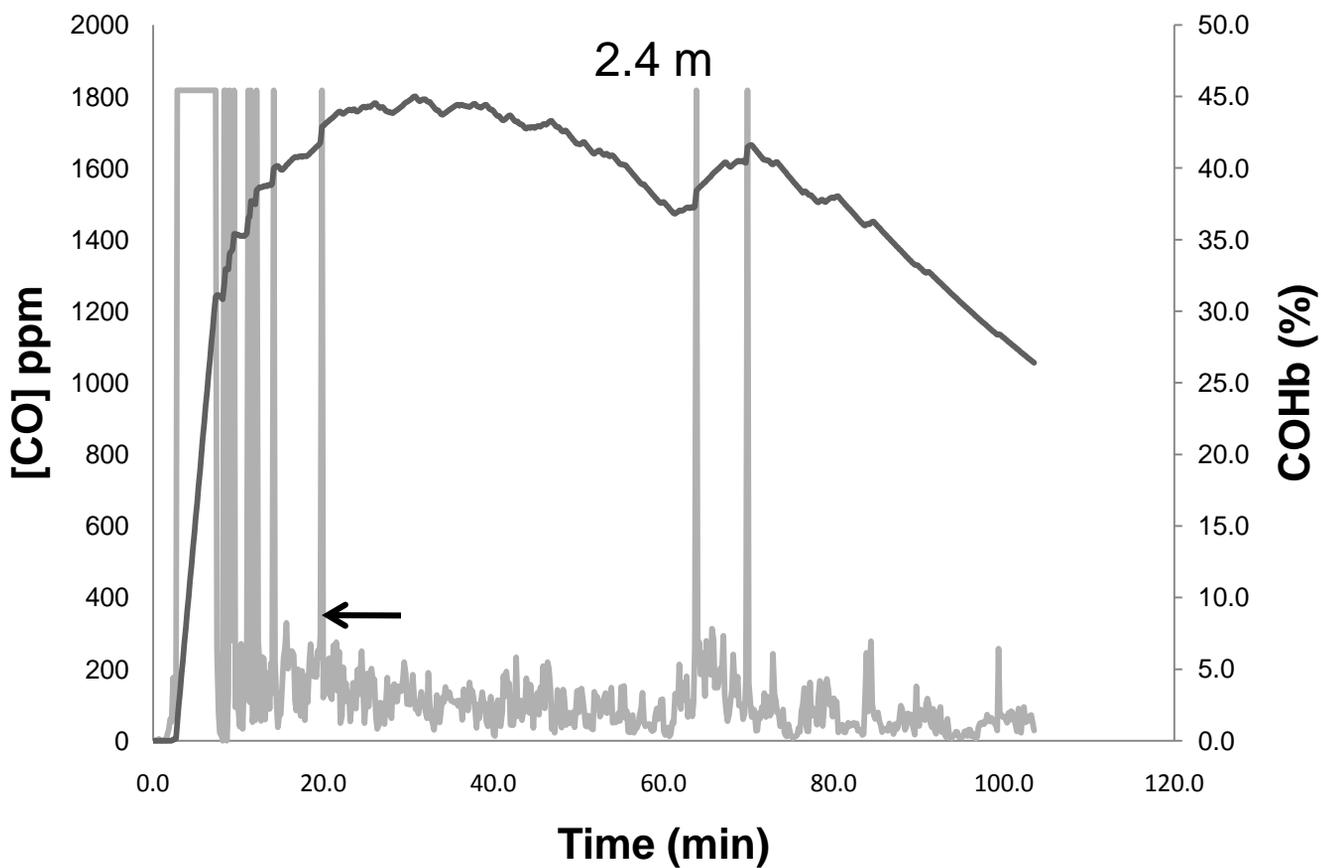
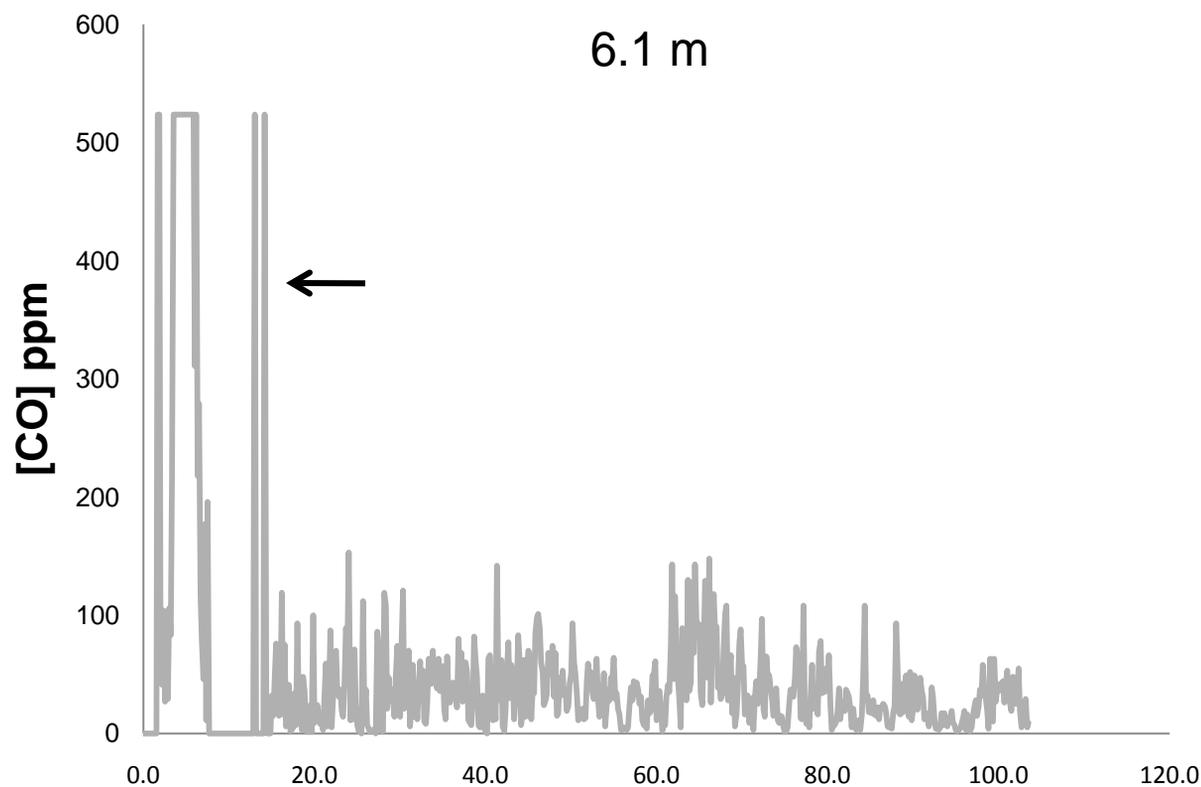
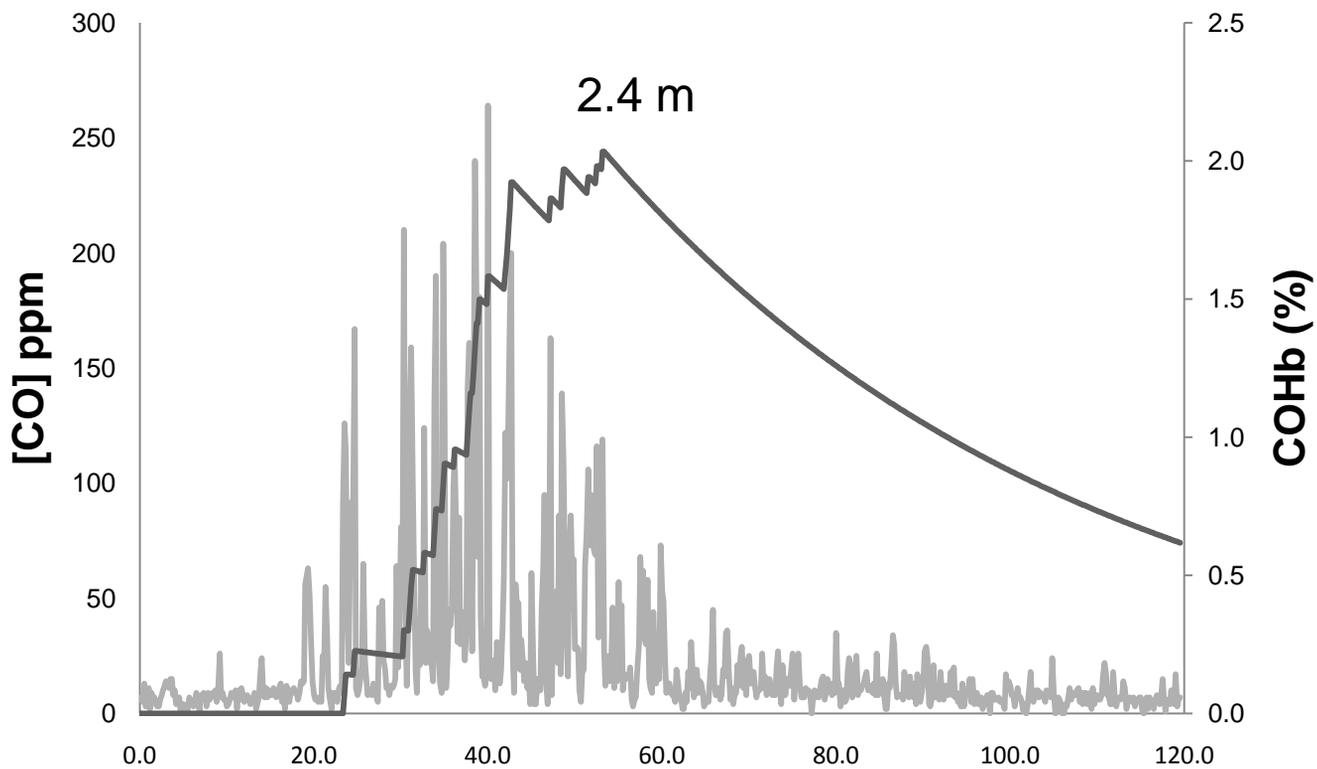
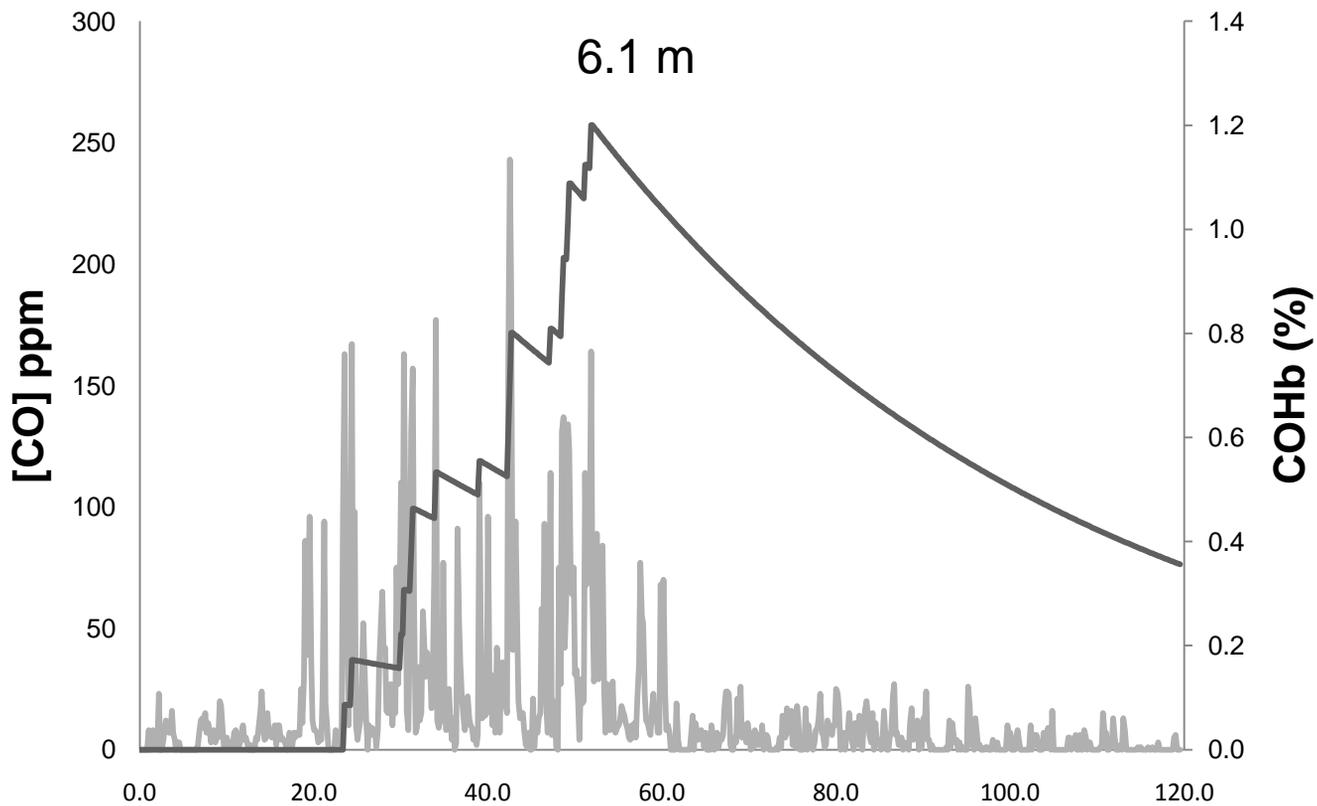


Figure 3b

Tar Hollow, $I = 130 \text{ kW m}^{-1}$



Time (min)

Figure 3c

Wolf Pen, $I = 90 \text{ kW m}^{-1}$

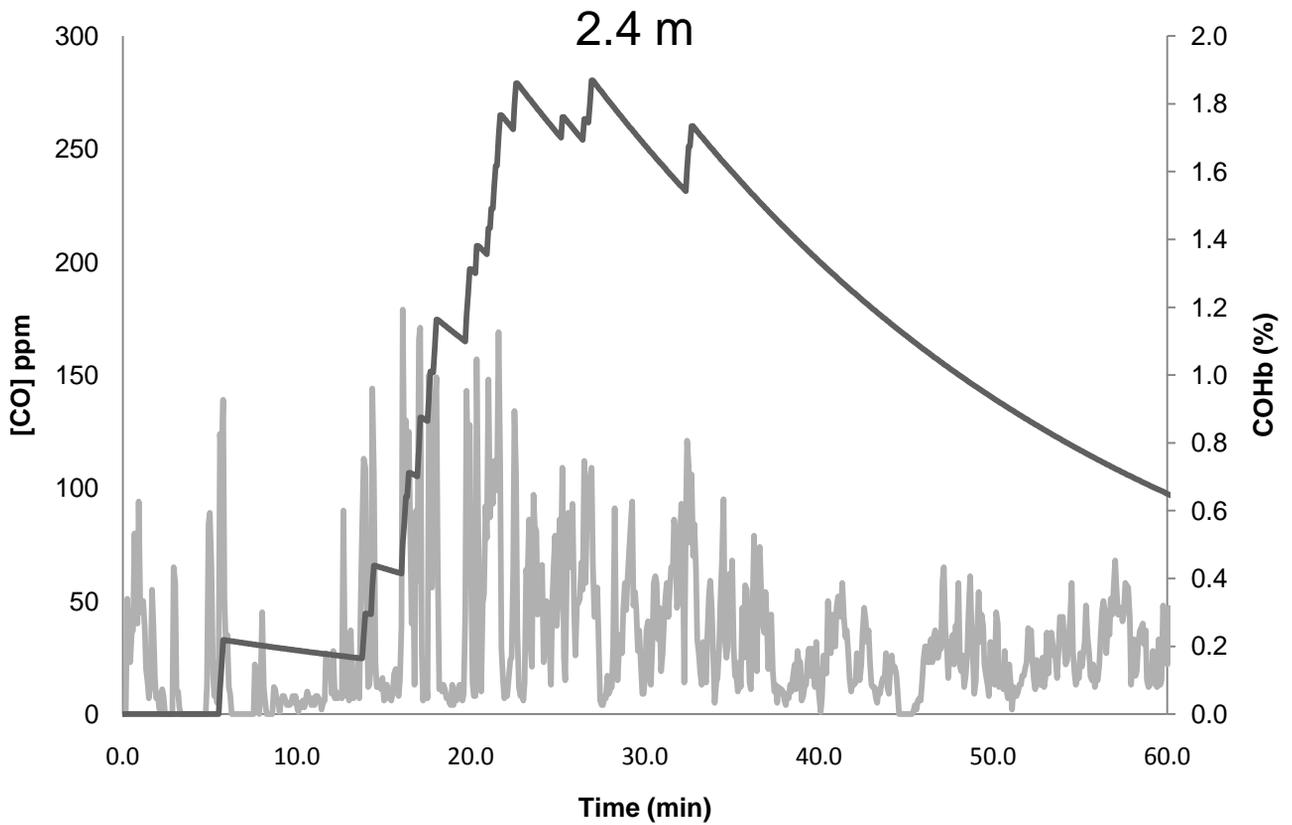
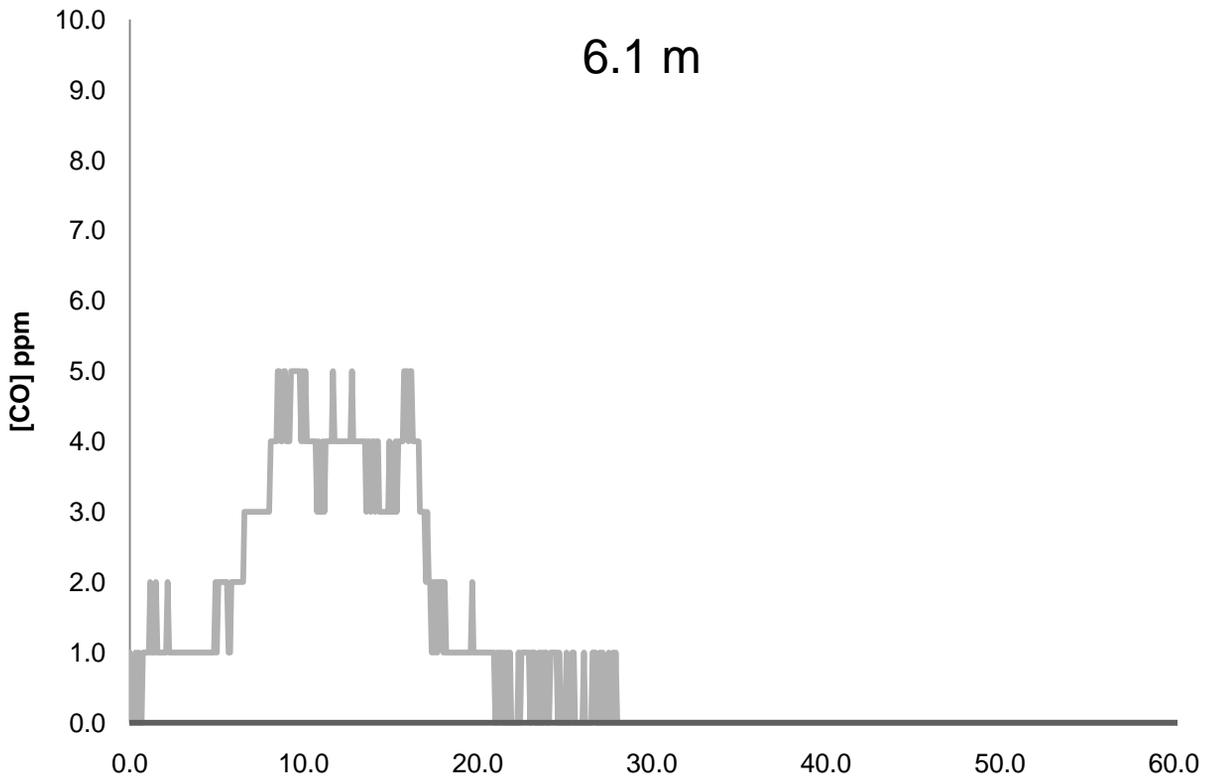


Figure 4

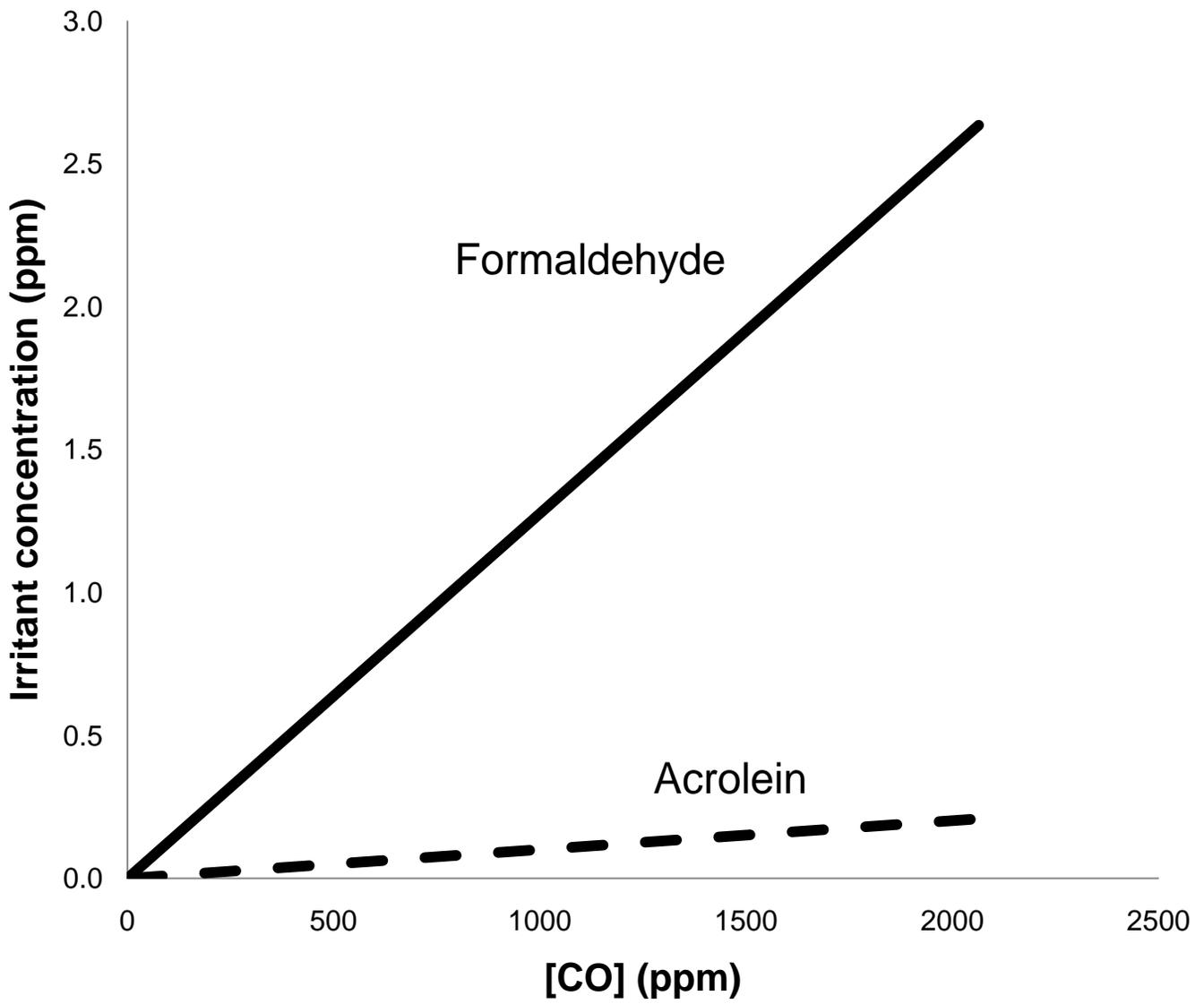
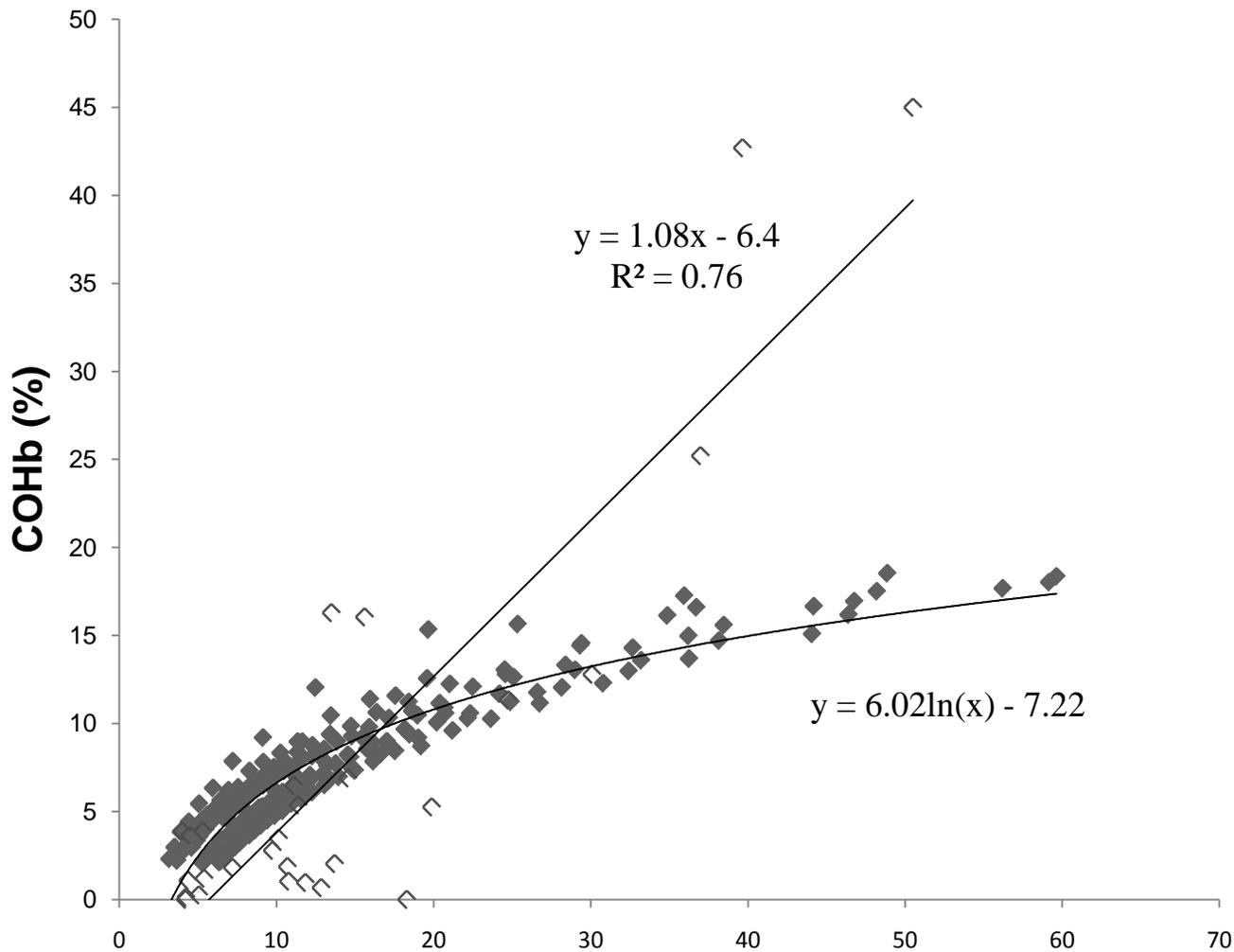


Figure 5



$$\frac{0.239I^{\frac{7}{6}}}{z_g (0.026I + U^3)^{\frac{1}{2}}}$$

Figure 6

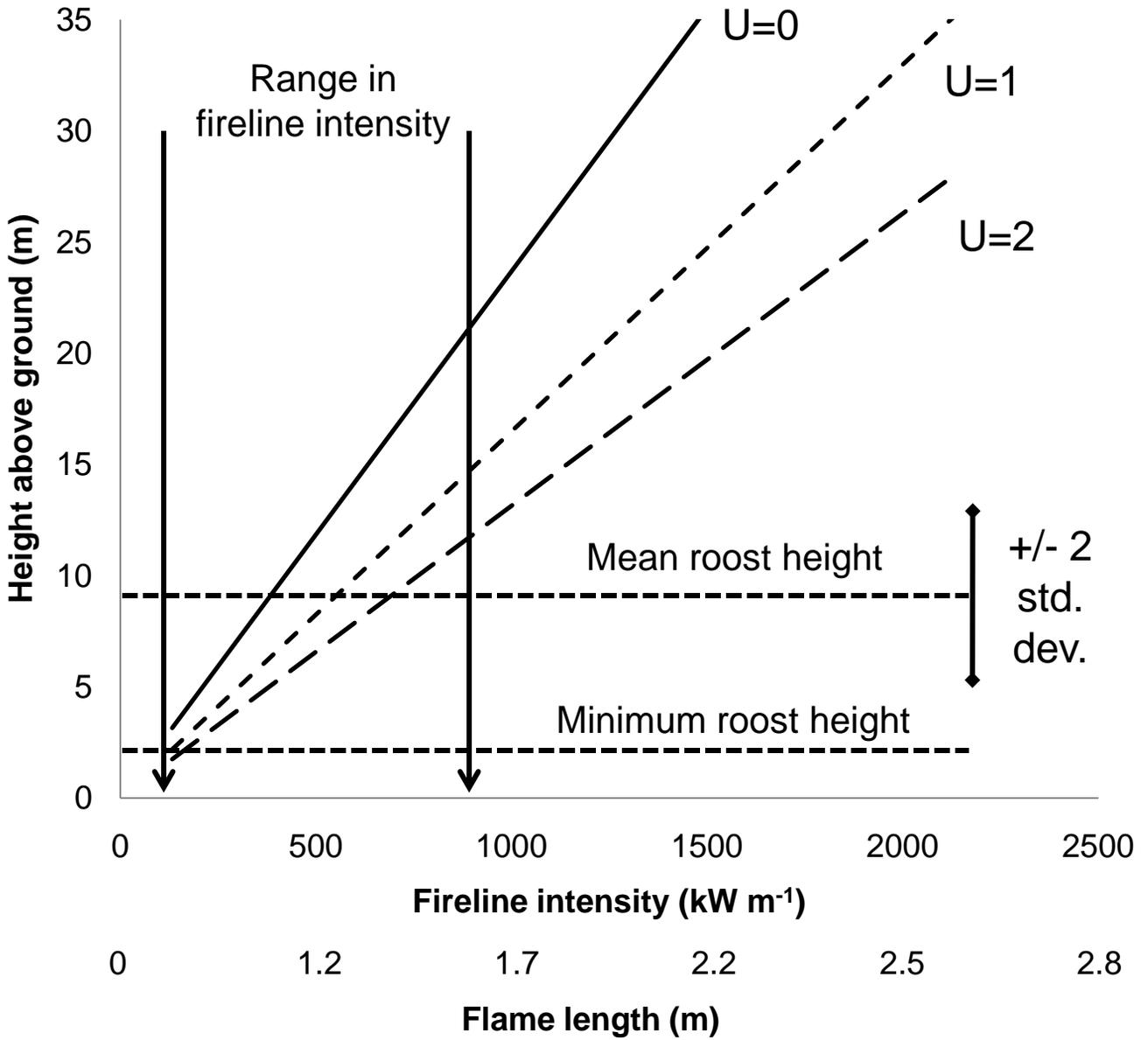


Figure 7

