**Characterizing Smoke Intrusions from Prescribed Burning in Bend, OR, USA**

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**ABSTRACT**

Smoke from prescribed burns can have negative health and safety impacts in downwind communities. This is the case in and around Bend, Oregon, USA, where burning in the wildland-urban interface on the Deschutes National Forest has resulted in smoke intrusions. To better understand the conditions that lead to these intrusions, we deployed an array of portable weather and particulate monitors over the autumn of 2014 and spring of 2015, to augment the permanent monitors in place. We used the data collected to characterize the winds, and to compare with meteorological and smoke dispersion models. The primary results from this study were: (1) most of the intrusion events were the result of terrain-driven, down-drainage winds carrying smoldering smoke into Bend, after active burning was complete; (2) fuels prone to smoldering (duff, dead logs, basal accumulations) are underestimated and their consumption and emissions are not well modeled; (3) dispersion modeling can be useful for anticipating smoke intrusions, but significant errors in wind speed and direction of the underlying meteorological models can lead to complete “misses” of smoke intrusion events; and (4) using higher resolution meteorological and dispersion models can improve the prediction of both timing and location of these events.

**Introduction**

Wildland fire is a naturally occurring ecological process, and many forests in the western United States (U.S.) were shaped by the periodic occurrence of fire (Covington and Moore 1994). Timber harvesting, grazing and decades of fire suppression have altered the historical role fire played on the landscape and in some cases caused shifts in the vegetation structure and composition (Hessburg et al. 2005). These changes have allowed fuels to accumulate on the landscape which can enhance the severity and destructiveness of wildfires (Graham et al. 2004). Planned (also called prescribed) burns are one of the many tools used by land managers to improve forest health and create a diversity of plant and wildlife habitat (Covington et al. 1997, Edmonds et al. 2010) as well as reduce forest fuels to mitigate the intensity and effects of severe wildfires. These planned burns, however, present challenges that make it difficult to rely solely on them to solve the problem of ecosystem restoration.

Increased burning may be beneficial for the ecosystem, but the smoke generated from all fires (wild and planned) has negative health impacts (Delfino et al. 2009, Morgan et al. 2010, Rappold et al. 2011). Costs associated with those impacts are also significant (Kochi et al 2010). Given that fine particulate matter (particles smaller than 2.5 micrometers in aerodynamic diameter – hereafter referred to as PM2.5) is the pollutant of most concern within smoke, the U.S. Environmental Protection Agency (EPA), through the Clean Air Act (1970), has set standards (National Ambient Air Quality Standards or NAAQS) to protect the public. The maximum allowable level of PM2.5 averaged over a 24-hr period is 35 μg/m3.

In the U.S., states also implement their own regulations, in addition to the NAAQS specified by EPA. The state of Oregon Administrative Rules include regulations regarding smoke intrusions, where a “smoke intrusion” is defined as the verified entrance of smoke from prescribed burning into designated smoke sensitive areas at ground level (http://arcweb.sos.state.or.us/pages/rules/oars\_600/oar\_629/629\_tofc.html). An intrusion is characterized by the one-hour average PM2.5 concentration above the previous three-hour average PM2.5 concentration in the clean air background.

Fire management agencies, such as the Deschutes National Forest (DNF), west of Bend, OR, are increasingly moving away from fire exclusion towards policies that balance modified suppression with the use of prescribed fire, to achieve ecological objectives (Miyanishi 2001). The DNF is located in the Cascade Mountains of central Oregon, U.S. They use prescribed fire in the Wildland-Urban Interface (WUI) as part of a project designed to meet those objectives while protecting the public and quality of life in nearby communities. Therefore, predicting smoke impacts and probably more importantly, predicting conditions that will prevent smoke impacts is becoming increasingly necessary.

The motivation for this study was to characterize the conditions under which smoke intrusions occur so they could be better predicted and avoided in the future. Smoke from one prescribed burn in October 2014 and five prescribed burns in 2015 intruded into Bend. 1-hr PM2.5 concentrations during these episodes ranged from 11 μg/m3 to 245 μg/m3. The U.S. Forest Service (USFS) Research Team AirFire collaborated with the USFS DNF on a field measurement and modeling project to study the complex interaction of fire, fuels, topography and wind patterns to understand how smoke intrusions into Bend occur. Another motive was to identify burn conditions that protect public health and safety. This study is unique because few case studies bring all these factors together, especially for prescribed fires. Wildfires tend to be more well-studied and large scale evaluation of air quality prediction systems that include wildfire emissions have been done, for example, by Strand et al. (2012).

Fewer studies have been conducted for smoke impacts from prescribed burns (Rorig et al.2013; Garcia-Menendez et al. 2013) There have been comprehensive fuel, fire behavior and smoke measurements on prescribed burns (e.g. RxCADRE – Ottmar et al. 2015); however, these data have not yet been used to evaluate and improve smoke modeling systems. The relationship between winds, fire behavior, and smoke dispersion is especially complex in areas of complex terrain. Wind speed and direction are affected by topography, and vegetation moisture can change at time scales of hours, minutes, and even seconds (Andrews 2012). Topography can directly affect fire behavior and smoke transport (Edmonds *et al*. 2010; Hardy *et al*. 2001). Understanding how fire, fuels, topography and wind patterns interact for a particular region can improve the ability to predict how and where smoke will disperse.

To investigate the spatial variability in meteorological conditions and analyze smoke dispersion in the area surrounding Bend, we 1) deployed a suite of PM2.5 and meteorological measurement stations for approximately 9 months, during which 5 smoke intrusions occurred, 2) collected fuels data from two locations on the DNF, 3) analyzed the performance of one modeled case with different spatial resolutions by comparing with observational data, 4) conducted smoke modeling of the intrusions, and 5) conducted a seasonal analysis of the detailed wind patterns of the region and prescription window analysis to identify burn window opportunities. This allows us to 1) identify meteorological conditions leading to smoke intrusions, 2) evaluate existing meteorological and smoke modeling systems performance for these intrusions, 3) characterize the local wind field seasonally and burn window parameters to finally 4) identify how often conditions occur that can successfully allow for prescribed burning within the DNF without impacting the town of Bend. This is one of the few studies gathering a comprehensive dataset of meteorological measurements, PM2.5 measurements, and documented burn information. Results will improve smoke dispersion modeling and support the planning of prescribed fires, leading to better predictions and fewer smoke intrusions.

**Methods**

The study area is located in central Oregon, near the cities of Sisters, Bend, and Sunriver. Figure 1 shows a map of the area, including locations of permanent and portable weather stations and particulate monitors. The DNF lies approximately 6 km to the west of Bend. Annual precipitation in Bend is about 288 mm/year, with the majority of precipitation occurring between November and February (Western Regional Climate Center; http://www.wrcc.dri.edu). The climate of Deschutes County is classified as moist subtropical mid-latitude climate with a dry and warm summer season (Köppen climate classification). These climates have generally warm and humid summers and mild winters. Prescribed burning in the DNF is typically conducted in the spring (April – June) and fall (September – November) months. Wildfires are a concern during the summer months (July, August, and into September) and prescribed burning is typically restricted during these periods.

**Smoldering Fuel Consumption Measurements**

Accurate fuel loadings and consumption are critical for smoke dispersion modeling. Ottmar et al. (2014) performed post-fire fuel consumption measurements of stumps, logs and basal accumulations (litter and duff deposits at the base of standing trees) at two sites in the DNF (Figure 1) – the West Bend unit (located less than 5 km WSW of downtown Bend) and the Glaze Meadow unit (approximately 40 km NNW of downtown Bend). The smoldering combustion of these fuel elements was thought to have contributed to a smoke intrusion in spring 2014. Because this was a retrospective study, estimates of the timing and duration of smoldering combustion could not be determined.

**Weather Stations & Smoke Measurement Stations**

WatchDog Weather Stations (Spectrum, Inc.) were deployed at six sites in 2014 and four sites in 2015. These weather stations collected observations of temperature, precipitation, relative humidity (RH), wind speed, wind direction, wind gust speed, wind gust direction, and dew point at 10- or 15-minute intervals. E-samplers (Met One Instruments, Inc.) were deployed at five sites in 2014 and three sites in 2015. These monitors are nephelometers that collect PM2.5 concentration data in addition to temperature, RH, wind speed, and wind direction. All the sensors were 1.5 m to 2 m above ground level (AGL). Four of the E-samplers recorded at 1-hr averages and one at 10-min averages in 2014. All three used 15-min averages in 2015. The State of Oregon operates two permanent nephelometers in the DNF, one at the Sisters, Oregon District Ranger Station in Sisters, and the other at the Bend Pump Station. These instruments measure light scattering due to particulate matter in the atmosphere. Four Remote Automated Weather Stations (RAWS) are also located in the region and maintained by the DNF and the Western Regional Climate Center (WRCC). These are permanently located stations, with sensors higher above the ground than the portable stations. Wind sensors on the RAWS are typically placed at a height of 6 m AGL. Most RAWS units are owned by wildland fire agencies and placed in locations where they can monitor fire danger (<http://raws.fam.nwcg.gov>, accessed 13 October 2016). Three of these RAWS were employed in this work. See Table 1 for a list of instrument locations and instrument details and Figure 1 for instrument locations during spring 2015.

**Smoke Dispersion Modeling**

The BlueSky smoke modeling framework (Larkin et al. 2009) was used to model the smoke intrusions into Bend. BlueSky is a framework linking together datasets and models of fire location and growth, fuel loadings and consumption, emissions from consumed fuels, plume rise, and smoke dispersion. The dispersion model requires meteorological model output to predict movement and concentration of smoke. Table 2 lists the models used in the framework. For the current study, we used actual fire location and size for each of the prescribed burns. This information was obtained from the intrusion reports prepared by the DNF District Office that was responsible for the burn. Table 3 contains the dates, times, locations, sizes, and fuel loadings in kg/ha, and Table 4 lists the intrusion start time and length (in hours), the maximum 1-hr and 24-hr average PM2.5 concentrations, and the direction and distance of the burn from Bend. Because the intrusion reports did not specify fuel loadings by category (1-hr, 10-hr, shrub, etc.), fuel loadings were obtained from the Fuel Characterization Classification System (FCCS) mapped at a 1-km resolution (Prichard et al., 2013). FCCS fuel models and total loadings used in the model runs are given in Table 3.

A three dimensional wind field from the Weather Research and Forecast (WRF) model (Michalakes et al. 2001; Skamarock et al. 2005) was used in BlueSky, and the Hybrid Single Particle Langrangian Integrated Trajectory (HYSPLIT) model was used for the dispersion simulations (Stein et al. 2015; Draxler and Hess 1998). The spatial and temporal resolutions of the BlueSky runs are determined by the meteorological model. In this case, we used the hourly 4-km resolution WRF model provided by the University of Washington Department of Atmospheric Sciences (Mass et al. 2003). Additionally, we had available a 1-km resolution meteorological model from the National Centers for Environmental Prediction (NCEP) North American (NAM) weather model (Rogers et al. 2009) for the October 4-5, 2014 smoke intrusion period. Both models provide hourly predictions. The suite of portable meteorological and PM2.5 monitors were not deployed for the October 2014 episode, but smoke dispersion modeling was possible and the modeled meteorological wind fields were compared with those obtained from RAWS stations. Modeled PM2.5 values were compared with PM2.5 measurements at the Bend Pump Station.

**Burn Day and Seasonal Wind Analyses**

To determine how frequently land managers can expect conditions that are favorable for prescribed burning, we compiled the number of days fuel and meteorological parameters meet required conditions. Table 5 lists conditions necessary for conducting prescribed burns on the DNF. The days were identified by data measured and calculated from the RAWS in the area, and include temperature, RH, mid-flame wind speed, and 1-hr, 10-hr, and 100-hr dead fuel moistures. Using Fire Family Plus (Bradshaw and McCormick 2000), daily (13:00 PST) data from the Tumalo Ridge RAWS (7 km west of Bend at an elevation of 1220 meters; Bend elevation is 1105 meters), Lava Butte RAWS (15 km south of town at an elevation of 1344 meters), and Round Mountain RAWS (47 km southwest of Bend at an elevation of 1800 meters) were used to identify days when burning would be within prescription for the ten-year period including 2006-2015. We also used only wind data from the Tumalo Ridge RAWS (the station closest to Bend) to determine how frequently daytime and nighttime winds were from a direction that would carry smoke away from Bend.

In addition to determining the frequency of days in prescription, we also generated seasonal wind roses, both for day and night, to better understand the winds in this area. We followed the methodology used by the Western Regional Climate Center to define “day” and “night” (<http://www.wcc.nrcs.usda.gov/climate/windrose.html>, accessed 13 October 2016). Time windows for “daytime” winds include the interval from 11:00 am – 18:00 pm PST, and nighttime windows include the interval from 01:00 am – 07:00 am PST. These time periods capture the general wind patterns during the day and night and attempt to reduce the inclusion of transitions associated with sunrise and sunset. Additionally, the times generally cover daytime and nighttime hours throughout the year and minimize the difference between winter and summer.

**RESULTS AND DISCUSSION**

**Fuel Consumption Estimations**

Accurate estimates of fuel loadings and types are necessary for consumption and emissions predictions. Data on preburn fuel information for the three targeted fuelbed components were unavailable, so postburn data were collected approximately two months later to reconstruct the potential contribution of stumps, logs and basal accumulations to smoldering combustion and to smoke production (Ottmar et al. 2014)**.** Total maximum smoldering fuel component consumption was estimated at 3094 kg/ha in West Bend and 17553 kg/ha in Meadow Glade with over 50% of that consumption from smoldering stumps. West Bend had minimal smoldering of logs (247 kg/ha) while Meadow Glade had 6882 kg/ha. Consumption of basal accumulation was similar at 695 kg/ha and 852 kg/ha at West Bend and Meadow Glade respectively. This information about the smoldering combustion components is used in the smoke modeling to improve predicted PM2.5 concentrations from the intrusions analyzed in this work.

**Seasonal and Diurnal Wind Patterns**

Because smoke intrusions are wind-driven events, we characterized typical wind patterns on the DNF near Bend, using the three RAWS stations located closest to Bend: Tumalo Ridge, Round Mountain, and Lava Butte (see Figure 1). One of the motivating questions prompting this study was whether the smoke intrusions were the result of smoke transported up-drainage at the time of active burning during the day, with a “return flow” down-drainage at night, or if it is primarily night-time smoldering combined with down-drainage winds that resulted in the intrusions.

 Hourly weather observations for the years 2006-2015 were collected from the three RAWS sites. To help understand the diurnal weather patterns around Bend, we created wind roses from the RAWS winds for every season, day and night, at each RAWS site, following the Northwest Coordination Center (NWCC) format (<http://www.wcc.nrcs.usda.gov/climate/windrose.html>, accessed 13 October 2016). These wind roses are shown in Appendix 1.

**Burn Window Analysis**

Land managers conduct prescribed burns when fuel and meteorological parameters meet required parameters. Table 5 lists conditions necessary for conducting prescribed burns on the DNF. Using the methodology described above (in the Methods section), the number of days when conditions would be in prescription for the 10-year period at the three RAWS sites was compiled.

Tumalo Ridge had 259 burn days, Lava Butte had 264 burn days, and Round Mountain had 280 burn days within prescription. On average, 26-28 burn days exist every year. Figure 2 shows the average number of burn days by month for these three RAWS locations. During mostly the winter periods significant data gaps exist in the RAWS data, therefore those data are probably biased low during the winter months. Greater confidence is placed in the spring, summer and fall months of data (shown by the box around those months in Figure 2). Many of the days within prescription occur during the summer months, which coincide with wildfire season, when prescribed burning is typically not used.

The need to keep smoke away from populated areas further decreases the number of available burn days. The parameters listed in Table 5 do not include wind direction. Additional analysis was therefore undertaken using wind directions from the Tumalo Ridge RAWS, to determine how often northwesterly through northeasterly winds occur during the day (to transport smoke from the DNF West Bend projects away from town) and how often south to southwesterly winds occur during the nighttime (to determine if nighttime drainage flows are responsible for the smoke intrusions from the smoldering of the large woody fuels and basal accumulations). These numbers are summarized in Table 6. Including only those days that are in prescription (per Table 5), annually, this ideal pattern exists on 8% of the days. During spring burn days, 13% of the days have this pattern while on fall burn days, 5% of the days have this pattern. This suggests that in any given year, the number of days with weather conditions in prescription and favorable wind directions (both day and night) that will keep smoke out of Bend is very limited, making it difficult to achieve fuel treatment objectives with fire alone.

**Smoke Intrusions**

Smoke from prescribed burns intruded into Bend on one occasion in October 2014 and five occasions in May and June, 2015. An intrusion is defined as a 1-hr average PM2.5 concentration greater than the previous three hourly average PM2.5 concentrations. The intrusions are not tied to the NAAQS and may or may not exceed the NAAQS. On the DNF, over the period we studied, over-night and early morning intrusions were more frequent than daytime intrusions during active burning operations. Table 4 lists the dates of the intrusions, the maximum 1-hr PM2.5 concentration measured, the time of the maximum, and the duration of elevated PM2.5 concentrations. Figure 3 shows the locations of the fires leading to the intrusions. The May 4 intrusion was the shortest duration and lowest concentration and occurred during the daytime hours. The other five intrusions occurred in the evening, over-night, and early morning hours, with 1-hr PM2.5 concentrations up to 245 μg/m3.  The measured meteorological conditions contributing to these intrusions, and smoke modeling results from the BlueSky smoke modeling framework, are presented. Observed and modeled PM2.5 are compared only for cases where the model predicted smoke in Bend. On days when the model “missed”, there was no PM2.5 to compare with the observations.

Prescribed burns on units with fuels prone to smoldering (stumps, basal accumulations, and duff) have the potential for intrusions, especially if nighttime winds are light and down-drainage winds predominate. The May 6 intrusion was an example of underestimating the smoldering fuel loadings. The four night-time intrusions for which wind data was available showed in all cases wind speeds less than 2 m/s during the intrusion periods (Figures 4 – 6). The one intrusion that occurred during the afternoon recorded wind speeds in the range of 2.5 to 4.5 m/s, suggesting terrain was not a factor in determining the winds. The combination of high smoldering fuel types and light wind speeds is of particular concern for anticipating intrusions.

Dispersion models can help predict intrusions, however wind speed and direction errors in the meteorological models used by the dispersion models can cause “misses” in the smoke predictions, both in location and timing of smoke impacts (Garcia-Menendez et al. 2013). This was the case for the May 28 intrusion, when the dispersion model predicted no smoke in Bend. Figure 5 compares modeled wind speed and direction with measured winds from the portable weather station at Cascade Middle School, located in Bend, showing modeled winds out of the NW before and during the intrusion period, while measured winds were from the SSW at the same time. This explains the “miss” in PM2.5 concentrations by the dispersion model. Wind speed mean error and mean bias and wind direction mean error were computed at all weather monitoring sites for the 2015 intrusions (Table 7). Of particular interest are wind direction errors ranging from about 14 to over 90 degrees, which would explain the model “misses”.

To further assess what lead to the intrusions, smoke modeling was undertaken with the BlueSky Smoke Modeling Framework using the 4-km resolution University of Washington WRF meteorological forecasting system, with a domain over the Pacific Northwest. We compared modeled with observed PM2.5 concentrations only for those cases when BlueSky accurately predicted the intrusion into Bend. For the May 4 intrusion, the modeled BlueSky PM2.5 concentrations at the Bend Pump Station were an order of magnitude less than the concentrations measured by the nephelometer, with concentrations of 0.05 to 0.47 μg/m3 predicted between 1300 and 1500 PDT, compared to the observations of 4.8 to 12.6 μg/m3. Concentrations were again underestimated on the May 6 case, with BlueSky underpredicting the PM2.5, and missing the location and timing of the smoke plume. Explanations for the model underpredictions include underestimating the default modeled fuel loadings, which do not capture the fuels likely to smolder, that Ottmar et al. (2014) identified as also being consumed and probably contributing additional smoke emitted. Increasing the preborn duff depth from 2 inches to 5 inches in the May 5 – 6 BlueSky simulation approximately doubled the fuel load burning, with most of that in the smoldering phase such that it was released close to the ground. This improved the model concentrations although the main plume was still simulated to miss Bend because there was no change in the predicted winds (Figure 3a). Note also that modeled concentrations are an average across a 4-km grid cell and thus could be lower than the observed value, which is a point observation. Finally, when the fires are very close to Bend (as in the June 5-7 cases), they are within two grid cells of the nephelometer, which is likely too close to obtain an accurate prediction.

One more intrusion occurred from a burn on October 4 2014, with the intrusion occurring in the late night and early morning hours of October 4-5. Three planned burns, between 18 and 20 ha each, were ignited approximately 44 km SSW of Bend (Figure 3d). A maximum 1-hr PM2.5 concentration of 96 μg/m3 was recorded at the Bend Pump Station at 0300 PDT, with a second peak of 94 μg/m3 at 0900 PDT (Figure 7). A 1-km resolution meteorological model domain was available from the NWS in addition to the 4-km WRF meteorological domain. Smoke modeling was therefore undertaken with the two resolutions and modeled winds compared to the three available RAWS (Tumalo Ridge, Lava Butte, and Round Mountain).

The smoke model outputs using both the 1-km NAM and the 4-km WRF show the smoke transported down the drainage from the SSW into Bend (Figure 8), with the plume arriving at 0300 PDT (in agreement with the measured data). Concentrations were low (approximately 10 μg/m3 for the NAM output and less than 1 μg/m3 for the WRF output; Figure 9) probably because BlueSky is not fully capturing the emissions from the smoldering fuels. The smoke simulation using the 4-km WRF carries smoke towards Bend overnight but weakly, while the simulation using the 1-km NAM shows a more well-defined plume (Figure 9). Similar outputs are seen in the predictions four hours later (Figure 10), at 0700 PDT. The higher resolution NAM run more accurately characterizes the smoke transport along the drainage, while the lower resolution WRF run has a less well-defined smoke plume, because the model is too coarse to adequately represent the drainages. This case shows that higher resolution meteorological models can improve smoke dispersion predictions. While this may not always the case, higher resolutions have been shown to provide better results when compared with coarser resolutions in modeling fire danger indices (Hoadley et al. 2006)

**SUMMARY/CONCLUSIONS**

A comprehensive study was undertaken of several smoke intrusion episodes in the autumn of 2014 and spring of 2015 in Bend, OR, USA. In addition to permanent RAWS (weather stations) and particulate monitors, data were collected from several portable weather and particulate monitors that were deployed for this study. State regulations prohibit smoke in populated areas, because of health and safety concerns. The goal was to better understand the conditions leading to the intrusions so they could be anticipated and prescribed burns be successfully accomplished.

Accurate assessments of fuel types and loadings are essential for realistic estimates of emissions. Unfortunately, current fuel models do not adequately represent the smoldering fuels that often are responsible for smoke intrusions. This was the case for several of the intrusions here, when total fuels (specifically duff) were underestimated. Those fuels continued smoldering overnight, well after the active burning had ended.

Future research is required to include pre-burn fuel loading measurements and to refine the measurement of the consumption of forest fuels during the flaming and smoldering phases of combustion, and the timing and the duration of that consumption. For smoke managers, it may no longer be enough to base burn plans on the total amount of forest fuels, fuel consumption, and total smoke produced on site. Rather, a more detailed understanding of the timing of consumption and smoke production during periods of weak atmospheric dispersal may better help manage downwind smoke effects in communities near the WUI. Furthermore, plans may need to be in place to limit the ignition of fuelbed components that have the potential of long-term smoldering, particularly if calm, clear conditions are expected overnight.

Close analyses of the predicted and observed winds and particulate matter indicated conditions that were common to all but one of the intrusions. The unique case was on May 4 2015, when daytime winds carried smoke into Bend in the early afternoon, two hours after ignition. All the other cases occurred during the late night and early morning hours, when winds were light or calm, and smoke movement was driven by terrain-induced down-drainage flows.

Smoke dispersion model results varied by intrusion. In some cases, (the daytime intrusions of May 4, and the nighttime intrusions of May 5 - 6 2015, and October 5, 2014) the model results showed smoke transport into Bend close to the time indicated by the observations. The model results for the other cases (May 28-29 2015, June 5 and 6 2015) were “misses,” with no smoke transport into Bend predicted. For the cases where both the observations and the model showed smoke in Bend, the modeled concentrations were less than observed, sometimes by an order of magnitude or more. There are a couple of explanations for this. First, model to observation comparisons are difficult because the observation is at a point location, while the model value represents an average over a grid cell. Second, as discussed above, smoldering fuels were likely underestimated, therefore emissions were also underestimated. Lastly, the dispersion model is only as good as the underlying meteorological model it is using (Garcia-Menendez et al. 2013), and if that model does not accurately represent the winds (such as sub-grid scale drainage winds), the dispersion model will not accurately locate the smoke. We found wind direction errors ranging from less than 15 degrees to over 90 degrees, and mean wind speed errors (modeled – observed) from 1 – 3 m/s. This also points to the importance of high-resolution meteorological and dispersion models. The one case where we had two resolutions available (October 4 2014, 4km and 1km), the higher resolution model better predicted the location and timing of the smoke intrusion.

Because intrusions are highly dependent on winds, we analyzed wind patterns over a 10-year period, using the three permanently sited RAWS. Wind roses were generated for all four seasons. Because the RAWS are remote, there are many “missing” days in winter. The other seasons have fewer missing data and are more reliable. In most (but not all) seasons, daytime wind directions were more variable than nighttime directions, and daytime speeds were higher than those at night. This was especially the case at the Tumalo Ridge RAWS, closest of the three to Bend. This suggests a higher frequency of light, terrain-driven winds at night just to the west of town. Also using wind direction from Tumalo Ridge, on average less than 10% of the days meet both criteria of being in prescription and keeping smoke out of Bend.

The current study was undertaken to understand the conditions that result in smoke intrusions in Bend, OR. Prescribed burning is important for improving ecosystem health, yet the number of days when conditions are optimal for burning are few. Future research into fuel characterization, and improvements in consumption and emission models, especially during the smoldering phase of the fire, will be needed. Higher resolution meteorological models are also necessary. When planning prescribed burns, especially in areas with complex terrain, land managers must learn when/how to recognize conditions that are conducive to smoldering and down-drainage flows. With improved models and better interpretation of those models, the number of smoke intrusion events can be minimized.

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