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The contribution of duff consumption to fire emissions and air pollution of the Rough Ridge Fire

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Abstract. It is typically difficult to burn duff because of high fuel moisture; however, under persistent drought conditions, duff will burn readily. This study investigates the burning of a deep duff layer by the 2016 Rough Ridge Fire, in the southern United States, under drought conditions and evaluates the contribution of duff consumption to fire emissions and air pollution. Fuel loading was measured and used to evaluate the BlueSky framework. Smoke was simulated for three fuel loading and moisture scenarios of field measurement, BlueSky estimated fuel loading, and a hypothetical moist condition. The measured fuels had a very deep duff layer that had accumulated over decades due to the lack of historical fires, most of which was burned by the fire. The burning of this deep duff layer contributed substantially to the increased fire emissions at the fire site and the air pollution in metro Atlanta. In contrast, BlueSky under-predicted duff loading and fire emissions. As a result, no major air pollution episodes were predicted for metro Atlanta. The high-moisture scenario also failed to produce a major air-pollution episode within Atlanta, which highlights the contribution of the drought to the air-pollution episode within Atlanta.

Additional keywords: BlueSky, drought, FCCS, fuel sampling, HYSPLIT, United States.

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Introduction

Wildfires can significantly degrade air quality in metropolitan regions (Riebau and Fox 2010; Goodrick *et al.* 2013; Liu *et al.* 2014). Negative air quality impacts of wildfires are often produced by high-severity fires, which are characteristic of many western US regions (Liu *et al.* 2017). For example, the 2013 Rim Fire in California had long-distance impacts on several larger urban areas (Navarro *et al.* 2016). The 2017 northern California wildfires also led to smoke covering many large cities, including San Francisco (Mass and Ovens 2018; Alrick 2018).

Although most wildfires in the south-eastern US are small and do not produce much smoke at the regional scale (Goodrick *et al.* 2013), some large wildfires do cause air pollution that affects metropolitan regions. One example is the Rough Ridge Fire (RRF), one of the large wildfires that occurred in the fall (autumn) of 2016 in the southern Appalachians. The 2016 fall Appalachian wildfires burned more than 100 000 ha of forests, caused the loss of 14 lives, and destroyed or damaged thousands of structures (McDowell *et al.* 2017). The RRF burned 11 278 ha in the Cohutta Wilderness, GA, USA, from mid-October to late November 2016 (https://inciweb.nwcg.gov/incident/5078/, accessed 17 September 2019). The fire was ignited by a lightning strike during a prolonged drought (Konrad and Knox 2017; Williams *et al.* 2017). In Atlanta, GA, USA, unhealthy air quality conditions were reported, with a peak particulate matter with diameter <2.5 μm ($PM_{2.5}$) concentration of 153 μg m^{-3} during the RRF (https://amp.georgiaair.org/, accessed 17 September 2019).

Smoke-modelling systems such as the BlueSky smoke-modelling framework (Larkin *et al.* 2009) have been developed to simulate the air-quality impacts of wildland fires. BlueSky uses the Fuel Characteristic Classification System (FCCS) (Prichard *et al.* 2015) to specify a detailed, six-layer description of vegetation, and it incorporates 16 categories of fuels (duff, litter, grass, shrub, trees, and woody debris by size, etc.) across the contiguous US. The Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin *et al.* 2012) indicated that estimates of fuel characteristics had the greatest uncertainty among the various BlueSky components.

Duff, whose depth varies widely across the US (Keane 2016), may be one of the greatest challenges among the various fuel types for FCCS to estimate in the south-eastern US. The duff layer accumulates quickly in the southern Appalachians (Ottmar and Andreu 2007; Mitchell *et al.* 2009). The warm and moist climate of the south-eastern US supports highly productive forests and high decomposition rates that yield substantial litter input into the duff layer. In a long-unburned forest, fuel structures and functions can be changed dramatically, including the accumulation of a deep duff layer (Varner *et al.* 2016). Decades of fire exclusion in many forests throughout the South-east have resulted in the significant accumulation of duff on the forest floor, as deep as 20 to 30 cm in long-unburned stands in certain spots, such as those around trees (Varner *et al.* 2005; Kreye *et al.* 2014). The accumulation of duff is an important legacy of fire exclusion in ecosystems that are dependent upon frequent fire (O'Brien *et al.* 2010).

Because of high moisture, duff consumption by fire occurs primarily during the smouldering phase (Frandsen 1987, 1997; Varner *et al.* 2009; Ottmar 2014); however, duff can burn substantially under drought conditions. When a drought develops, the duff layer gradually dries out and becomes increasingly flammable, starting with the leaf litter on top. When conditions remain dry for long periods (e.g. weeks to months), the duff layer may dry out and greatly add to the fuel load (Hille and Stephens 2005).

There have been no significant wildland fires over the past four decades in the Cohutta Wilderness. Thus, a deep duff layer was likely present before the RRF. The lack of precipitation and record warmth in the summer of 2016 (Williams *et al.* 2017) created conditions that desiccated the forest floor across the south-eastern US. These prolonged and severe drought conditions prevailed for ~6 months before fire ignition, which lead to duff that was very dry and flammable. In fact, whereas a duff layer is typically consumed during the smouldering phase of combustion, the monitoring and images taken during the RRF indicated that a large portion of the duff layer burned during the flaming phase of combustion. In addition, satellite remote-sensing maps overwhelmingly indicated low burn severity across the burned area of the RRF (Reilly 2017). Interviews with the local fire manager, photos taken during the fire, and evidence from the post-fire survey all support the contention that the predominate type of fire spread was limited to surface and ground fire. This information is another indicator that duff was a major fuel source that combined with surface litter to enhance combustion.

The FCCS provides fuel loading of various fuel types, including duff. However, because the FCCS specifies typical fuel beds of a region under regular fire history and fire management, it may not adequately represent the deep duff in the South-east US. Thus, more fuel sampling is needed in this region to evaluate the FCCS and the entire BlueSky framework. The information on duff is critical for estimating the RRF emissions and simulating the air quality impacts. Other work has reported the $PM_{2.5}$ impacts from the 2016 southern Appalachian fires, and their modelling system showed a tendency towards under-prediction in comparison with the AirNow (a system developed by the U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, National Park Service, tribal, state, and local agencies to provide the public with easy access to national air quality information) $PM_{2.5}$ data (Pouliot *et al.* 2017). These authors suggested several possible causes for the differences, including fire emissions that were too low.

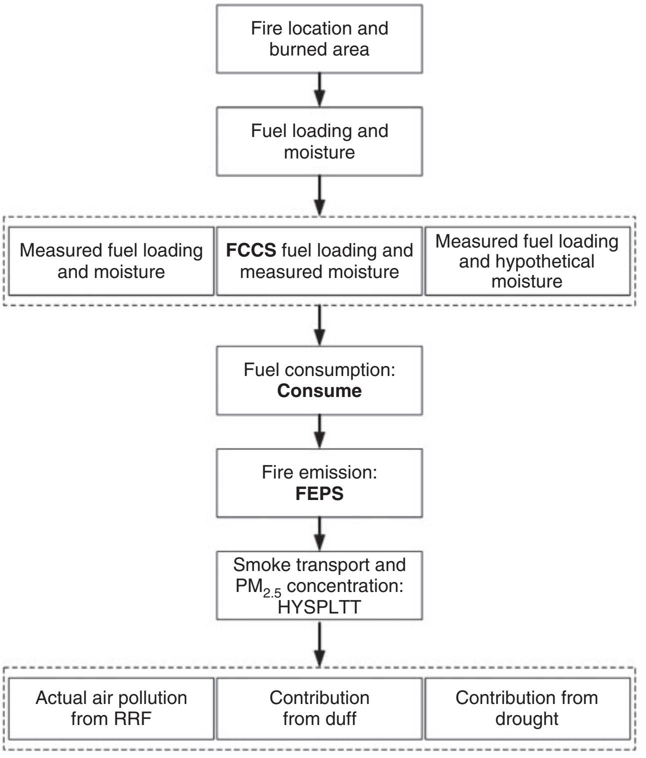

Fig. 1. A flowchart showing the progression of modules in BlueSky. The modules in bold were evaluated using field fuel samplings. The top dotted-line boxes indicate three fuel loading and moisture scenarios. The bottom dotted-line box shows the corresponding roles in air pollution modelling. FCCS, Fuel Characteristic Classification System; FEPS, Fire Emission Production Simulator; HYSPLIT, Hybrid Single-Particle Lagrangian Integrated Trajectory; $PM_{2.5}$, particulate matter with diameter <2.5 µm; RRF, Rough Ridge Fire.

The present study investigates duff properties at the RRF site and their impacts. The objectives are to (1) evaluate the BlueSky fuel loading, consumption, and emissions based on field sampling of duff and other fuels; (2) understand the contribution of duff consumption to emissions at the RRF site and air pollution in metropolitan Atlanta; and (3) understand the contribution of prolonged drought to fuel availability and fire emissions.

Methods

Modelling tools

The BlueSky smoke-modelling framework (Larkin *et al.* 2009) was used to specify fuel type and loading, estimate fuel consumption and fire emissions, and simulate smoke transport. The BlueSky implementation procedure and analysis is shown in Fig. 1. BlueSky integrates existing datasets and models into a unified structure. The data include fire (locations and burned areas) and meteorology (temperature, humidity, wind field, etc.). In addition to the FCCS for fuel types and loading, the modules in BlueSky include Consume (Prichard *et al.* 2006), Fire Emission Production Simulator (FEPS) (Anderson *et al.* 2004), and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph 2003). It also includes the Weather Information Management System

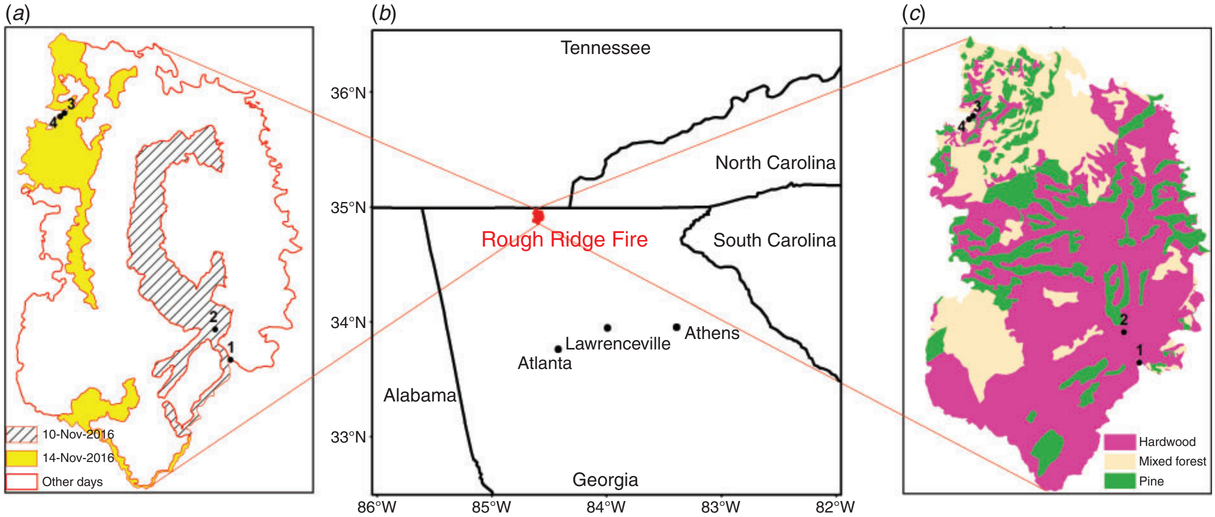

Fig. 2. Location of the Rough Ridge Fire, including (*a*) fire perimeters on 10 and 14 November 2016 and fuel measurement sites 1-4; (*b*) location of fire site; and (*c*) vegetation types.

(https://famit.nwcg.gov/applications/WIMS, accessed 17 September 2019) to determine fuel moisture.

The Consume model predicts the amount of fuel consumption, emissions and heat release from the burning of logged units, piled slash and natural fuels based on weather data, fuel loading and fuel moisture content, as well as several other factors. Consume was developed empirically from pre- and post-burn plots that included a variety of vegetation types and fire conditions. The FEPS manages data concerning the consumption, emissions and heat release characteristics of prescribed burns and wildfires. The HYSPLIT model is a complete system for computing simple air-parcel trajectories and complex dispersion and deposition simulations. This model uses a hybrid modelling approach of either puffs, particles or a combination of the two. In the particle model, which was used in this study, a fixed number of initial particles are advected over the model domain by the combined mean and turbulent wind fields. The plume rise is calculated by the model based on the $PM_{2.5}$ emissions and heat release. The BlueSky (ver. 3.5.1) framework with the components of FCCS (ver. 2), Consume (ver. 4.1), FEPS (ver. 2) and WIMS (ver. 1) was used for this study.

Datasets

Fire

The RRF occurred in the Cohutta Wilderness of northern Georgia at ~34.88°N and 84.63°W (Fig. 2). From 10 to 15 November 2016, the daily burned areas were respectively 1586, 1206, 1463, 1000, 858 and 900 ha (3920, 2980, 3615, 2472, 2119 and 2224 acres). This period accounted for 72% of the total burned area. The fire was primarily a surface fire with flaming occurring both during the day and at night.

Fuels

The Cohutta wilderness has a mosaic of habitats (Fig. 2). Cove forest (hardwood) and low- to mid-elevation mixed oak pine forest are the two main forest types. Hardwoods generally occur on mesic sites with a canopy composition that include tulip trees (*Liriodendron tulipifera*), basswood (*Tilia americana*), white ash (*Fraxinus americana*), American beech (*Fagus grandifolia*), northern red oak (*Quercus rubra*), eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*) and sourwood (*Oxydendrum arboreum*). Low- to mid-elevation mixed oak–pine forest occur on drier sites that support rock chestnut oak (*Quercus prinus*), white oak (*Q. alba*), southern red oak (*Q. falcata*), northern red oak (*Q. rubra*), scarlet oak (*Q. coccinea*) with conifers such as loblolly pine (*Pinus taeda*), Virginia pine (*P. virginiana*), white pine (*P. strobus*) and eastern hemlock (*Tsuga canadensis*).

The default forest type number of the FCCS for the Cohutta District is 275 (chestnut oak, white oak and red oak). This type of forest represents the dominant hardwoods (primarily oak species) very well, but it does not adequately represent the conifer species.

To obtain more realistic fuel information to evaluate the FCCS fuel types and loading, we collected fuel samples at four sites (Figs. 2, 3), primarily during 22–23 June 2017. Sites 1 and 2 were respectively located outside and inside the cove forest (hardwood)-dominated area that burned on 10 November 2016, and Sites 3 and 4 were respectively located outside and inside the mixed oak pine forest-dominated area that burned on 14 November 2016. The fuels measured at Sites 1 and 3 were used to represent the pre-fire fuel conditions at Sites 2 and 4 respectively.

The geographic features and the properties of stands at the measurement sites are provided in Table 1. The stand structures between Sites 1 and 2 were similar, as were those between Site 3 and Site 4. Each site had three measurement plots of 45.7 × 18.3 m (~150 × 60 ft). Different fuel layers (e.g. woody material, litter and duff) were measured separately. In addition, woody materials were classified according to their size following the standard time lag fuel descriptions, i.e. 1-, 10- 100- and 1000-h.

Fig. 3. Duff layers measured in unburned areas (Sites 1 and 3) and burned areas (Sites 2 and 4).

Table 1. Geographic features and stand structure of the measurement sites
DBH, diameter at breast height

	Slope (°)	Species	Number (stems ha^{-1})	DBH (cm)	Height (m)
Site 1	<20	Pine	59	5.6	5.4
		Broad-leaf	1286	16.0	13.1
		Total	1345	15.5	12.8
Site 2	<20	Pine	79	5.3	6.6
		Broad-leaf	1323	15.8	12.9
		Total	1401	15.5	12.5
Site 3	<5	Pine	1059	13.0	13.3
		Broad-leaf	824	14.4	12.9
		Total	1883	13.6	13.1
Site 4	<5	Pine	804	13.1	13.1
		Broad-leaf	927	14.5	12.9
		Total	1731	13.7	13.0

Meteorology

The surface meteorological conditions (e.g. air temperature, air relative humidity, wind speed, precipitation and 10-h fuel moisture) from the Remote Automatic Weather Station (RAWS) (https://raws.d.ri.edu, accessed 17 September 2019) in Cohutta District were used to analyse the drought conditions. The three-dimensional meteorological fields for the HYSPLIT simulations were from the Weather Research and Forecasting (WRF) model simulations, with 3-km resolution and 1-h frequency provided by the National Oceanic and Atmospheric Administration (NOAA) (see https://ready.arl.noaa.gov/HYSPLIT_data2arl.php, accessed 17 September 2019).

$PM_{2.5}$

The hourly $PM_{2.5}$ data for Atlanta, Lawrenceville and Athens from the Georgia Air Monitoring Program (https://amp.georgiaair.org/airvision/, accessed 17 September 2019) were used to estimate the background $PM_{2.5}$ concentrations and evaluate the simulated diurnal variations. The background concentrations were the averages over November 2015 and 2017.

Smoke modelling

The domain of smoke modelling with HYSPLIT covered Georgia and its surrounding areas with a resolution of 0.1°. There were no hourly fire-progression data available.

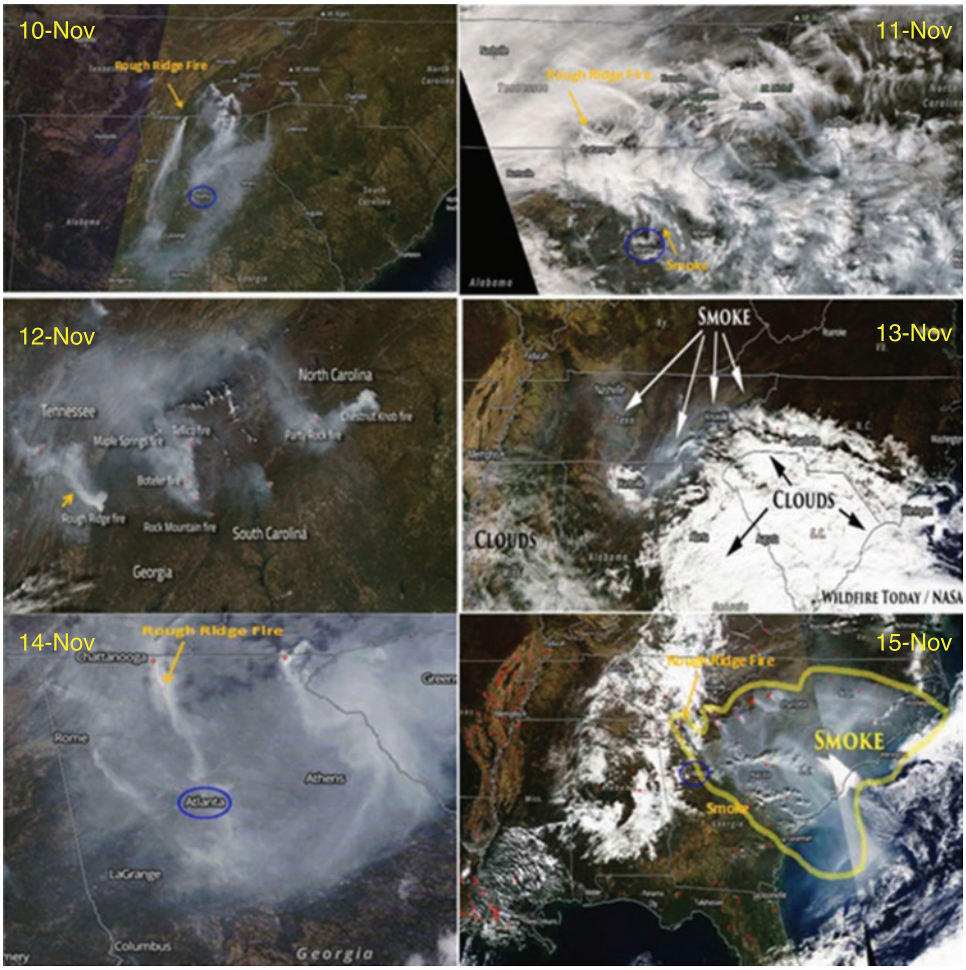

Fig. 4. Satellite images on 10–15 November 2016. (Sources: National Aeronautics and Space Administration, NASA, and National Oceanic and Atmospheric Administration, NOAA.)

Considering that the RRF spread actively both during the day and at night, fire emissions were allocated equally each hour throughout the day. An experiment of emissions allocated equally each hour during the day was conducted to assess the impacts of this assumption on air pollution.

The simulation periods were determined by examining the WRF wind modelling and the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images (Fig. 4) during 10–15 November. Winds on 10 November were northerly to north-easterly, carrying smoke from the fire site to western metro Atlanta. On 11 November, the winds shifted slightly towards north-westerly, bringing smoke to the eastern metro Atlanta. The winds on 12 and 13 November were from the south or east and, therefore, no smoke plumes were transported towards metro Atlanta. North-westerly winds returned on 14 and 15 November, bringing smoke back into eastern metro Atlanta. Therefore, we simulated the two periods of 10–11 and 14–15 November when the smoke was transported into metro Atlanta. The measured fuel conditions on 10 and 14 November were used for those on 11 and 15 November respectively.

The following three smoke simulations were conducted with different fuel scenarios.

Simu_Sample

This simulation used fire emissions estimated based on the measured fuel loads of woody materials, litter and duff. Fuel consumption was estimated as the difference of the measured fuel loading between Sites 1 and 2 for the burn on 10 November and between Sites 3 and 4 for the burn on 14 November. Fire emissions were further estimated and used as inputs for the smoke simulations. The southern Appalachian region typically has a wet climate, which keeps the fuel moisture at a high level (Yarnell 1998; Flatley *et al.* 2013; Liu 2017). Consequently, it is rare to have many fires during a season in this region (Delcourt and Delcourt 1997). However, the Keetch–Byram drought index (KBDI) (Keetch and Byram 1968) was ~700 during the first 3 weeks of November 2016 (Fig. 5), and this value represented a level of extreme fire potential. The 10-h fuel moisture measured at the RAWS was 5–8%. We used the dry level of moisture in BlueSky, which has a 10-h fuel moisture defined as 8%.

The simulated $PM_{2.5}$ concentrations were compared with the ground measurements to evaluate model performance. The simulated values were compared with the United States Environmental Protection Agency (EPA)'s National Ambient Air Quality

Standards (NAAQS) to indicate whether the RRF caused air pollution in metro Atlanta, which spans 39 counties in northern Georgia with an estimated population of nearly 7 million in 2017.

Simu_BlueSky

This simulation used fire emissions estimated based on the fuels specified in the FCCS. As in Simu_Sample, the dry level of moisture was used. A comparison of the simulated $PM_{2.5}$ concentrations between Simu_BlueSky and Simu_Sample was used to indicate the role of deep duff burning in the formation of air pollution in metro Atlanta due to the RRF.

Simu_Moist

This simulation used the fire emissions estimated for fuels under normal moisture conditions. We used the moist level of moisture in BlueSky, which has a 10-h fuel moisture of 12%.

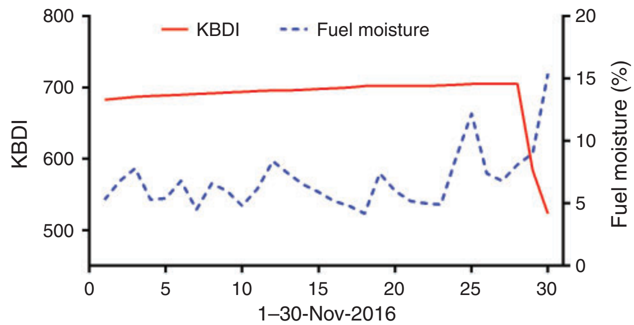

Fig. 5. The Keetch–Byram drought index (KBDI) and 10-h fuel moisture in the Cohutta Wilderness during November 2016.

The fuel loads were the same as those in Simu_Sample. A comparison of the simulated $PM_{2.5}$ concentrations between Simu_Sample and Simu_Moist was used to indicate the role of drought in the formation of air pollution in metro Atlanta due to the RRF.

The EPA uses a colour code to measure air quality conditions based on the air quality index values (https://www3.epa.gov/airnow/aqi_brochure_02_14.pdf). The corresponding respective $PM_{2.5}$ concentrations are 0–12 $\mu g\ m^{-3}$ (green) and 12–35 $\mu g\ m^{-3}$ (yellow) for good and moderately healthy conditions, 35–55 $\mu g\ m^{-3}$ (orange) for unhealthy to sensitive groups (e.g. young and elderly people and those with respiratory problems), 55–150 $\mu g\ m^{-3}$ (red) for the unhealthy to general public, and respectively 150–250 $\mu g\ m^{-3}$ (purple) and above 250 $\mu g\ m^{-3}$ (brown) for very unhealthy and hazardous conditions. Green and yellow colours are used to represent clean air, whereas other colours represent various levels of polluted air.

Results

Fuel loading

At Site 1, the measured total fuel loading was 67.9 Mg ha^{-1} (Fig. 6, Table 2). The duff layer was 4.6 cm deep with a loading of 31.5 Mg ha^{-1}, which accounts for nearly half of the total fuel loading. The fuel loading of litter was 20.23 Mg ha^{-1}. The fuel loading of dead woody materials was 16.06 Mg ha^{-1} (including 2.2, 5.4, 4.0 and 4.4 Mg ha^{-1} for 1, 10, 100 and 1000 h respectively). The measured total fuel loading at Site 3 was 79.4 Mg ha^{-1}, and the contrition of the duff layer, which was 6.5 cm deep, was even larger (more than 2/3). In comparison, the FCCS under-predicted fuel loading by ~1/2 for the total, 1/2 to 2/3 for the duff layer, ~1/4 for litter and ~1/2 for woody materials.

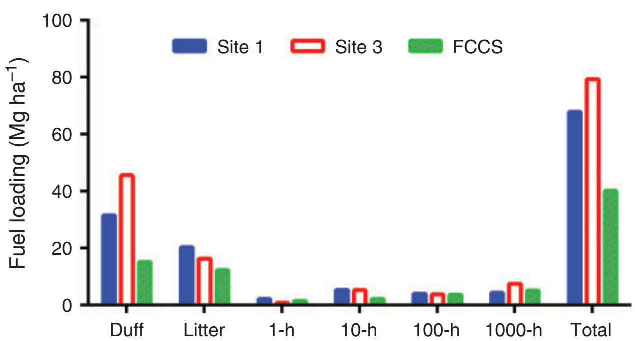

Fig. 6. Fuel loading measured at Site 1 and Site 3 and from the Fuel Characteristic Classification System (FCCS).

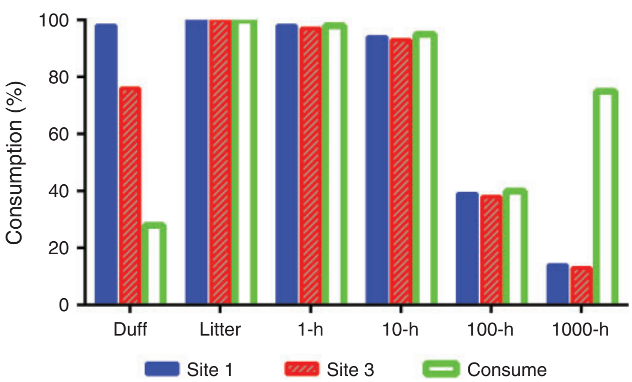

Fig. 7. The measured percentage of fuel consumption.

Table 2. A comparison of fuel loading (Mg ha^{-1}) between measurements and Fuel Characteristic Classification System (FCCS)
DIF 1 and DIF3 are the relative differences (%) between the FCCS and Site 1 and Site 3 respectively

Fuel loading	Site 1	Site 3	FCCS	DIF 1	DIF 3
Total	67.9	79.4	34.8	−48.7	−56.2
Duff	31.5	45.6	15.1	−52.1	−66.9
Litter	20.2	16.4	12.3	−29.1	−25.0
Dead woody	16.1	17.5	7.4	−54.0	−57.7

The fuel loadings at Sites 2 and 4 (not shown) were reduced dramatically by the RRF. The total loading at Site 2 was 6.61 Mg ha^{-1}, mainly from the 100- and 1000-h woody materials with the litter and duff layer burned out, and the total loading at Site 4 was 24.88 Mg ha^{-1}, including 15.67, 0.00 and 9.21 Mg ha^{-1} from the duff, litter and woody materials respectively.

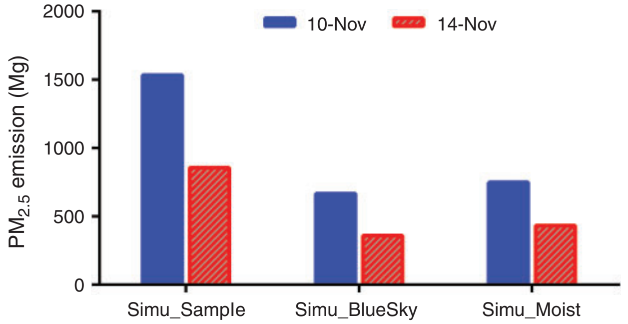

Fig. 8. Daily particulate matter with diameter <2.5 μm ($PM_{2.5}$) emissions for three fuel scenarios.

Fuel consumption and fire emissions

Using the fuel measurements, the percent consumption of the duff layer at Site 1 was 98% and over 75% at Site 3 (Fig. 7). The litter, 1-h and 10-h woody fuel bed components were consumed almost completely, with respective consumption percentages of 100, 98 and 94% at Site 1 and 100, 97 and 93% at Site 3. The 100- and 1000-h fuels were consumed by respectively 39 and 14% at Site 1 and 38 and 13% at Site 3. In comparison, the consumption percentages estimated by BlueSky were close to the measured values for the litter, 1-, 10- and 100-h fuels, but they were much lower for duff (28%) and much higher for 1000-h fuel (75%).

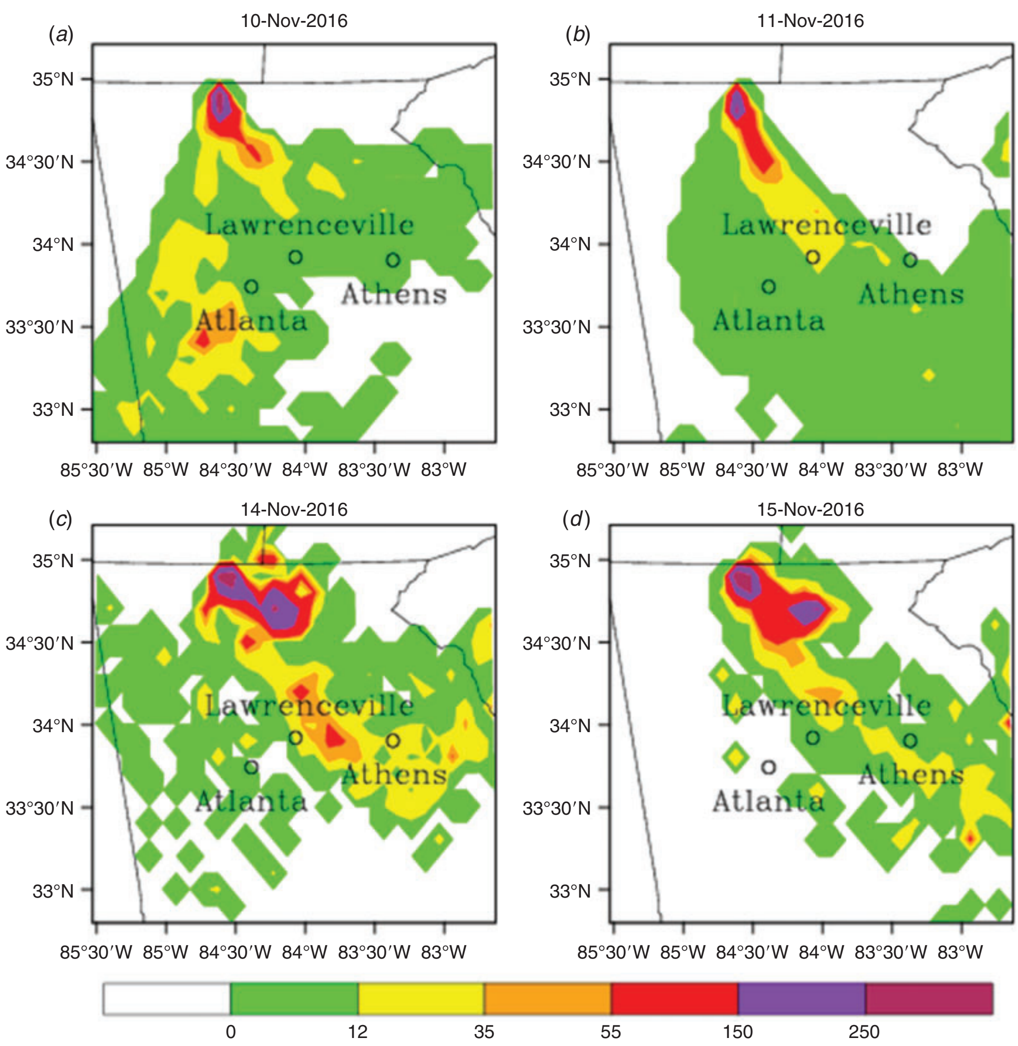

Fig. 9. Simulated daily particulate matter with diameter <2.5 μm ($PM_{2.5}$) concentrations (μg m^{-3}) for the Simu_Sample fuel scenario. Panels (*a*)–(*d*) are for 10, 11, 14, and 15 November 2016 respectively.

The fire $PM_{2.5}$ emissions from the fuel consumption calculated based on the fuel measurements were nearly 1600 Mg on 10 November and 860 Mg on 14 November (Fig. 8). The fire emissions from the fuel consumption calculated based on the FCCS fuels were nearly 670 and 360 Mg, which were ~40% of the corresponding values calculated from the measured fuels. The fire emissions from the fuel consumption calculated based on the hypothetical moist fuels were ~800 and 430 Mg, which were half the corresponding values calculated from the measured fuels under drought conditions.

Air quality impacts

Simu_Sample

The spatial patterns of the daily $PM_{2.5}$ concentrations from Simu_Sample showed two smoke plumes drifting from the fire site on 10 November (Fig. 9*a*). One plume moved southward to south-western Atlanta, and the other plume moved south-eastward to the Lawrenceville area of north-eastern metro Atlanta. On 11 November, the first plume disappeared, while the second extended further south-eastward (Fig. 9*b*). The hourly spatial smoke patterns (not shown) indicated that smoke first went south-westward to central Alabama (a state west of Georgia) and then moved towards the east. The spatial patterns of the simulated daily $PM_{2.5}$ concentrations on 14 and 15 November showed a single plume from the fire site to Lawrenceville and further eastward to Athens, GA, USA (a city ~116 km east of Atlanta) (Fig. 9*c*,*d*).

The simulated $PM_{2.5}$ concentrations produced air-pollution episodes in two areas on 10 November (Fig. 8*a*). One area was the fire site and its surroundings, which had hazardous conditions (brown). The other area was south-western metro Atlanta, mostly with USG (orange). On 14 November (Fig. 8*c*), in addition to the hazardous condition near the fire site, USG (orange) and unhealthy (red) conditions appeared in a large area between Lawrenceville and Athens. The results indicated that the smoke from the RRF caused air-pollution episodes in metro Atlanta.

The spatial patterns of the simulated daily smoke plume were similar to those shown in the MODIS imagery (Fig. 4). In comparison with the hourly $PM_{2.5}$ measurements in Atlanta (10–11 November) and Lawrenceville (14–15 November), the simulation basically reproduced the diurnal cycle and the concentration magnitude of the corresponding air pollution centres (Fig. 10). However, the simulated duration of the peak values on 10 November was shorter. Moreover, the concentrations during night were under-estimated on 14–15 November. The causes are yet to be understood; however, one possible cause is the impacts of another fire, the Tatum Gulf fire (http://wildfiretoday.com/tag/tatum-gulf-fire/, accessed 17 September 2019) in north-western Georgia close to the Alabama–Georgia border, which carried smoke that moved through metro Atlanta starting on the afternoon of 14 November. Nevertheless, this fire was not included in our simulation.

Simu_BlueSky

Although the spatial patterns of the daily $PM_{2.5}$ concentrations from Simu_BlueSky (Fig. 11) were similar to those from Simu_Sample, the magnitudes were reduced dramatically. On 10 and 11 November, the simulated $PM_{2.5}$ concentrations near

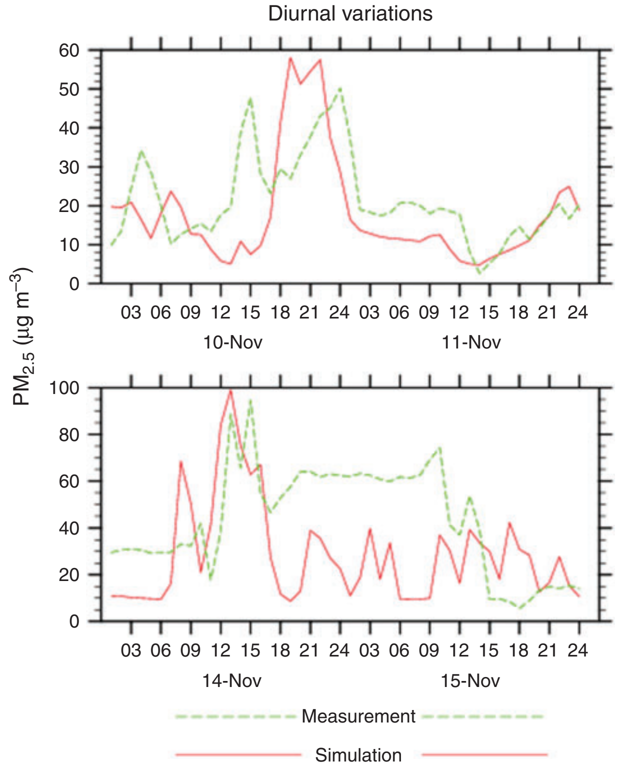

Fig. 10. Simulated (Simu_Sample fuel scenario) and measured hourly particulate matter with diameter <2.5 μm ($PM_{2.5}$) concentrations (μg m^{-3}) for 10–11 November 2016 at Atlanta (top) and 14–15 November 2016 at Lawrenceville (bottom). The background hourly concentrations were added to the simulated values, which were smaller during the day and higher during the night, with daily averages of ~10 μg m^{-3}.

the fire site were reduced by one level, from very unhealthy in the Simu_Sample case to unhealthy in the Simu_BlueSky case. On 14 and 15 November, the simulated $PM_{2.5}$ concentrations decreased from hazardous in the Simu_Sample case to very unhealthy in the Simu_BlueSky case. More importantly, the $PM_{2.5}$ concentrations were at good or moderate levels throughout metro Atlanta in the Simu_BlueSky case on all days. The difference between the Simu_BlueSky case and the Simu_Sample case indicates the critical importance of how the burning of the deeper duff layer produced air pollution episodes in metro Atlanta during the RRF.

Simu_Moist

Similar to Simu_BlueSky, the $PM_{2.5}$ concentrations from Simu_Moist were reduced dramatically compared with those of Simu_Sample (Fig. 12). The $PM_{2.5}$ concentrations were at good or moderately healthy levels in metro Atlanta on all days. The difference between these cases indicates that the RRF still occurred, but under more typical moisture conditions; this scenario means the reduced fuel consumption and lower fire emissions from burning of the wetter fuels would change the impacts on air quality from producing air-pollution episodes in metro Atlanta under drought conditions to no air-pollution episodes under more normal moisture conditions.

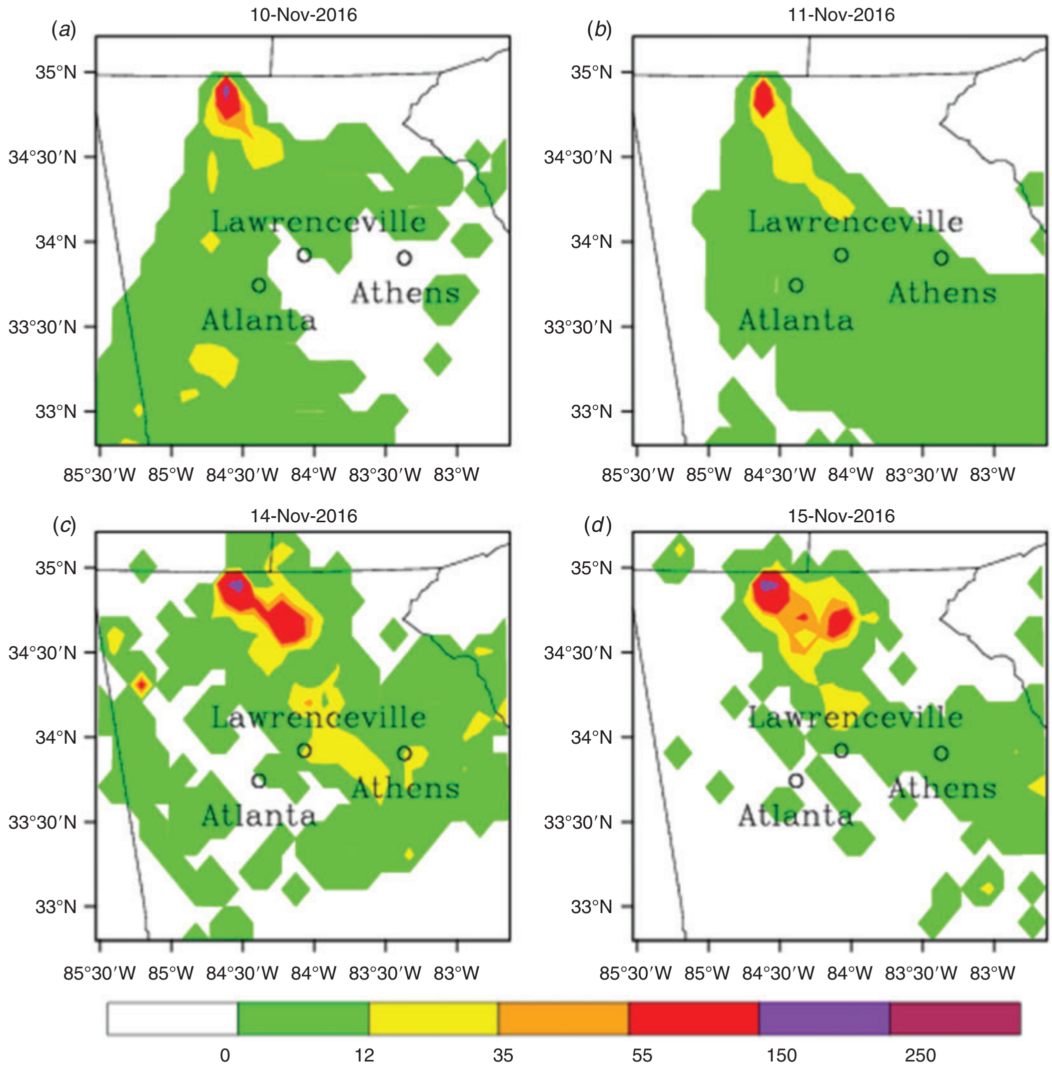

Fig. 11. Simulated daily particulate matter with diameter <2.5 μm ($PM_{2.5}$) concentrations (μg m^{-3}) for the Simu_BlueSky fuel scenario. Panels (*a–d*) are for 10, 11, 14, and 15 November 2016 respectively.

Conclusions and discussion

Fuel measurements were conducted at sites in and around the RRF. The measured fuel loading at both burned and unburned sites was used to calculate and simulate the fuel consumption, fire emissions and air-quality impacts under drought conditions. Duff consumption was found to be the largest contributor to the $PM_{2.5}$ emissions of the RRF. Duff consumption played a critical role in the production of air pollution episodes in the metro Atlanta area. The extended period of drought that preceded the fire also contributed as the dry conditions led to higher fuel consumption and subsequent emissions than those that would be expected under more normal conditions. By contrast, BlueSky was able to predict the consumption rates of litter and fine dead fuels; however, it under-estimated the duff loading and consumption rate. As a result, fire missions and $PM_{2.5}$ concentrations were under-predicted. No air-pollution episodes were predicted in metro Atlanta by the model using the BlueSky fuel information. The simulations using measured fuels but under more typical fuel moisture conditions also failed to predict observed air quality conditions in metro Atlanta.

The different air-quality impacts between the deep duff layer measured in the southern Appalachians and the duff amounts assigned by the FCCS fuel types suggest that smoke simulations using fire emissions based on popular fuel and fire emission tools such as BlueSky would likely underestimate the air-quality of wildfires in this region. Under normal moisture conditions, the difference in fuel loading may lead to minimal differences in air-quality impacts, but drought conditions will amplify potential errors. These results suggest that the better quantification of the duff layer in areas such as the southern Appalachians could lead to greatly improved air quality predictions.

Measurement of duff loading like that presented in this study provides a solution for obtaining duff loading before and after a wildfire. However, this approach is feasible only for

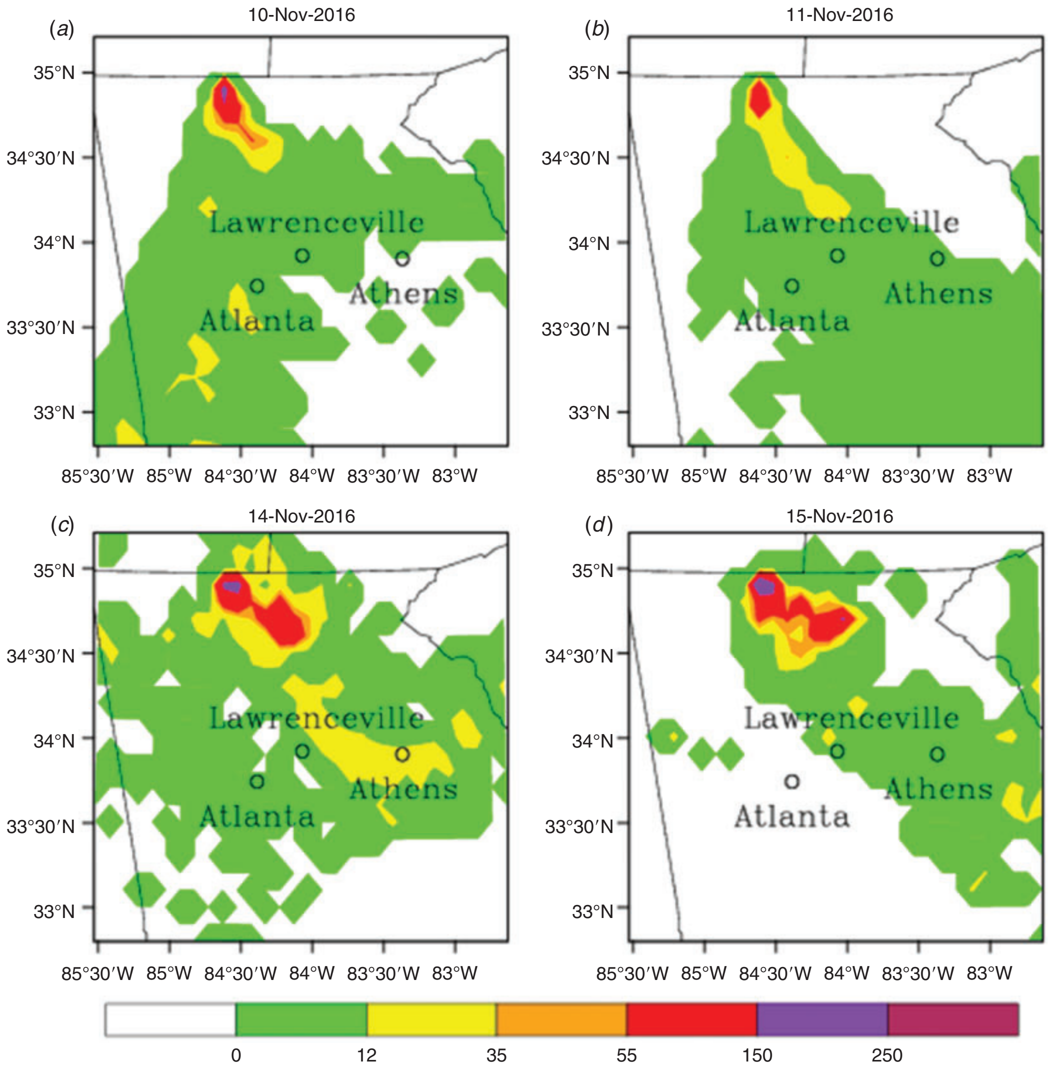

Fig. 12. Simulated daily particulate matter with diameter <2.5 µm ($PM_{2.5}$) concentrations for the Simu_Moist fuel scenario (µg m^{-3}). Panels (*a–d*) are for 10, 11, 14, and 15 November 2016 respectively.

individual fires and it is also mainly for post-fire research. For the duff information and prediction of the air-quality impacts of duff burn by wildfires at regional, continental and global scales, modelling tools, both empirically and physically based, would be an efficient and ultimate solution. Currently, there are tools for simulating and predicting duff consumption by prescribed burn and wildfire (Prichard *et al.* 2017). Further efforts are needed to develop models to simulate and predict pre-fire duff loading. Different from prediction of duff fuel moisture, which varies mainly at short time periods (daily and monthly) and is closely related to meteorological conditions (Bilgili *et al.* 2019), duff loading varies mainly at long time periods (seasonal to decadal) and is related to not only weather and climate conditions but also complex processes of ground fuel (litter, fine and coarse woody materials) accumulation, biochemical decomposition in soil, and prescribed burn and wildfire consumption.

The $PM_{2.5}$ concentrations due to the RRF simulated by Pouliot *et al.* (2017) were less than 20 µg m^{-3} in metro Atlanta on 14 November 2016, and these values were considerably lower than the measurements. The fire emissions in their simulations were obtained from the Fire Inventory from National Center for Atmospheric Research (NCAR) (FINN) (Wiedinmyer *et al.* 2011), which specifies fuel loading for each generic land use and land cover type around the world based on Hoelzemann *et al.* (2004). Duff is absent in the fuel loading estimates for the South-east US. This absence would account for the low $PM_{2.5}$ concentrations estimated for metro Atlanta by Pouliot *et al.* (2017) for the RRF.

Moisture content is the environmental variable that most overwhelmingly determines the ignition and consumption of duff (Frandsen 1987; Frandsen 1997; Robichaud and Miller 1999). Duff is normally very wet, and duff consumption by fire occurs primarily during the smouldering stage (Ottmar 2014).

Smouldering is a solid phase or glowing form of combustion that heats the surface mineral soil, imbedded roots and potentially tree basal cambium, and therefore causes tree mortality (Varner *et al.* 2009). However, the duff consumption by the RRF was different. The fire occurred under persistent drought conditions that had initiated ~6 months before fire ignition and the duff burned in both smouldering and flaming stages. In addition to the risk of tree mortality associated with smouldering duff combustion, this study indicates that flaming duff consumption may pose an additional problem, with greater air-quality effects occurring downwind. Flaming fire releases much more heat into the air than does smouldering fire. As a result, smoke particles can be lifted to higher elevations instead of being trapped near the ground. The lofted particles are more likely to be transported long distances to affect metro regions.

Prescribed fire is used extensively in the South-east US (Melvin 2012). Although prescribed fire does not typically consume large amounts of duff directly, the regular application of fire consumes the litter layer, which prevents it from decomposing and forming a deep duff layer. Arthur *et al.* (2017) indicated that duff depth in a southern Appalachian forest was reduced by 50% by a single prescribed fire and by more than 60% by repeated prescribed burning. The ability of prescribed fire to reduce duff depth suggests that prescribed fire, if implemented regularly, might reduce the potential of future air pollution episodes in metro areas due to wildfires in a southern Appalachian forest such as the Cohutta Wilderness where the current fire management plan does not specifically allow prescribed fire on wilderness and other protected lands due to the wildlife impacts of prescribed fire (Block *et al.* 2016).

Conflicts of interest

The authors declare that they do not have any conflicts of interest.

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