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Comparison of methods to estimate the rate of CO_2 emissions and coal consumption from a coal fire near Durango, CO

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ABSTRACT

Subsurface fires in coal beds consume coal resources and contribute to the global emissions of CO_2 and air pollutants. Many of these fires are found in China, India, Indonesia, and the United States. Combustion product gases at these coal fires exit through surface fissures that form over fires. These fissures are created when subsurface subsidence causes preexisting fractures in the area to widen. Fissures act as both inlets for air and exhaust for combustion gases. While remote sensing approaches have been used to quantify the rate of coal consumption and CO_2 emissions at large scale fires that extend over large distances, methods for estimating the coal consumption and CO_2 emissions values based on surface observations are less well established. In this paper, a coal fire near Durango, CO, is described. A combination of fissure mapping, thermocouple temperatures, and a cesium-vapor magnetometer survey was used to delineate the aerial extent of the current combustion zone and previously burned zones.

Three methods were then used to estimate combustion rates at an active region at the site. In the first method, time-lapse, high-resolution topographic surveys were used to relate surface volumetric losses over the active region to coal consumption and rates of CO_2 emission. In the second method, measured temperatures, gas compositions, and dimensions of an exhaust fissure were used in a simple natural convection chimney model to estimate rate values. The third method estimated coal consumption and CO_2 emission rates by measuring the velocity of exhaust gases, gas compositions and exhaust fissure dimensions. For the second and third methods, ^{13}C isotope signatures were used to determine the fractions of CO_2 that were emitted from coal and CH_4 combustion or from CO_2 in the native gas in the coal seam. A flux accumulation chamber was also used to quantify CO_2 leakage rates from non-fissured regions over an active fire region. The three methods produced roughly consistent estimates of coal combustion and CO_2 emission rates.

1. Introduction

Uncontrolled subsurface fires in coal beds account for significant releases of CO_2 to the atmosphere. A single coal fire documented in Wuda, China is estimated to consume approximately 200,000 tons of coal per year (Kuenzer et al., 2005), equivalent to around 0.60 Mt of CO_2. In addition to the problem of CO_2 emissions, gases released into the atmosphere from these fires are often toxic. Furthermore, the loss of coal volume in the subsurface can lead to significant surface subsidence and fissures, resulting in damages to near-surface or surface infrastructures.

Coal bed fires are burning in many locations in China, Indonesia, India, and the United States (Stracher and Taylor, 2004). They can be started naturally by forest fires that burn near a coal outcrop, by lightning strikes that ignite trees that subsequently ignite an outcrop, by human activities, or by spontaneous exothermic reactions of pyrites (DeKok, 1986). Spontaneous combustion of coal can occur when coal oxidizes slowly in air, which generates heat. When this heat accumulates–usually in confined settings–it can cause volatiles to evolve from the coal. These volatiles can then react with available O_2 to provide more heat to sustain and propagate combustion. This type of ignition is more likely in coal refuse piles in which coal particles are surrounded by air.

Forest fires in Indonesia in 1997 and 1998 ignited hundreds of coal fires at outcrops (Brown, 2003). In the U.S., a subsurface fire near Centralia, Pennsylvania, was started in 1962, when the local government decided to burn an unregulated trash dump in an abandoned strip mine to reduce trash volume and control rodents. The fire ignited an anthracite outcrop, eventually connected to and spread through underground tunnels, and has been burning since. A combination of subsidence and emissions from fissures has caused the town of Centralia to be abandoned (DeKok, 1986; GAI Consultants, 1983). Fires that occur in abandoned coalmines such as the one in Centralia obtain their supply of oxygen and convect exhaust gas away

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from the combustion region through mine tunnels and shafts (GAI Consultants, 1983; Kim and Chaiken, 1993).

Subsurface fires can also occur in unmined coal beds when an outcrop ignites, and the resulting combustion front subsequently burns into the formation away from the outcrop. In these natural fires, O_2 inlets and exhaust gas outlets are not as well defined as those in mine fires. Exchanges of gases between the surface and the coal seam occur through fissures that connect the surface and the coal seam. Fissures are formed when ash and void areas that result from coal combustion and gasification collapse under the overburden pressure (Ide et al., 2010).

Most abandoned underground mine fires stay close to old mine tunnels, but they can sometimes burn away from the old mining network and burn into the formation (GAI Consultants, 1983). Once the fire burns into the formation, surface features similar to those of natural coal bed fires are observed. In the United States, nearly 100 abandoned underground mine fires, excluding natural coal bed fires, across 10 states were documented by the Department of Interior (DOI) in 1988. The costs to control or extinguish these fires were estimated to cost around $741 million at that time (Kim and Chaiken, 1993). Since natural coal bed fires do not fall under the category of Abandoned Mine Land (AML), these fires are often not monitored by the DOI.

Several authors have suggested a range of CO_2 emission rates from coal fires in China (Kuenzer et al., 2005; Rosema et al., 1993). For large coal fires that use remote sensing methods such as Landsat-7 ETM+, an infrared satellite, to quantify CO_2 emissions is appropriate (Prakash and Gupta; 1998, Kuenzer et al., 2007a). When the fires are small, however, satellite images typically do not offer sufficient spatial resolution to quantify coal combustion accurately. In this paper we consider a small coal fire located along the Hogback Monocline of the San Juan Basin that spans an area of roughly 600 m × 200 m. The best deformation information that could be obtained for this area using InSAR satellite data is at a resolution of 50 m × 50 m. That resolution is too coarse to allow accurate estimates CO_2 emission or coal consumption rates.

To overcome spatial resolution issues, we first test methods to determine more precisely the current extent of the combustion zone. We used three approaches to identify the current location of the active combustion zone and the previously burned zone. In the first approach, the spatial distribution of surface fissures was mapped using a portable GPS unit, and the temperature of gas present at each fissure was measured. The second approach used subsurface temperatures measured using thermocouples installed in boreholes drilled into the coal seam. The third approach delineated the combustion region using a cesium vapor magnetometer. As we show below, the magnetometer measurements provided the most useful determination of burned, currently burning, and unburned areas. The use of magnetometer data to detect coal fire boundaries has been reported by several investigators (Bandelow and Gielisch, 2004; Gielisch, 2007; Hooper, 1987; Schaumann and Yu Change, 2005; Sternberg, 2004; Sternberg et al., 2008), though the O(1) m resolution over a coal fire of this size is more detailed than those previously described. In addition, the magnetometer results over the North Coal Fire have been corroborated using well-logs, driller's logs, core samples, and temperature measurements. Finally, data have been filtered by removal of diurnal fluctuations, by signal amplitude and by pole reduction.

Based on the estimated locations of current combustion, previously burned, and unburned zones, three methods were used to estimate quantitative rates of CO_2 emissions and coal consumption. The first method estimates coal consumption rates from time-lapse, high-resolution surface deformation measurements at different points. Data acquisition points were obtained near the hottest fissures found over the North Coal Fire. The second method uses measured velocities of exhaust gases from a fissure over an active region and combined that estimate with estimates of amounts of CO_2 seeping from the less fractured areas over the active fire. The third makes use of an analogy between coal fires and natural convection chimneys to estimate a range of CO_2 emission rates. The dimensions and the measured subsurface temperatures of the most active fissure over the site were used to set the chimney geometry and the thermal gradient. In the first method (the subsidence method), the coal consumption rate was calculated by taking the volume of subsidence and converting it to mass by using the density of coal. In the second and third methods, CO_2 emission rates were calculated first. For those methods, ^{13}C isotope signatures were used to determine the fractions of CO_2 that were emitted from coal combustion/gasification, from CH_4 combustion, and from CO_2 in the native gas in the coal seam. A simple stoichiometric relationship was then used to convert to and from coal consumption rates and CO_2 emission rates. The results presented provide first-order estimates of the rates of CO_2 production and coal consumption from this fire.

2. Fire location

A detailed description of the San Juan Basin, local geologic setting, and fire location is given by Ide et al. (2010). The fire considered here is located in the San Juan Basin, along the Hogback Monocline, about 50 km southwest of Durango, CO. There are four known fires along the Hogback Monocline. This particular fire is termed the North Coal Fire to distinguish it from a South Coal Fire that lies two miles to the south. The coal layer that is burning is in the Fruitland Formation (Fassett, 2000). It is one of three coal layers in the Fruitland separated by shales, sandstone, and clay layers, though at this location, the top two coal layers have been eroded away. The coal is overlain by fractured sandstone and shale, and is underlain by the Pictured Cliffs sandstone.

The coal layer dips to the southeast at about 11°. The depth to the top of the coal in the zone that is burning is about 12–15 m, and the coal layer thickness is approximately 5–7 m. The Fruitland Formation outcrops along the Hogback Monocline, and it is believed that trees struck by lightning or a forest fire at the outcrop ignited the coal seam. As the combustion front moved subsequently into the formation, the loss in structural integrity in the burned coal seam resulted in subsidence. Many surface fissures that formed due to subsidence are observed over the North Coal Fire today. Exhaust gases produced from the coal combustion, some as hot as 1000 °C, flow out of some of these surface fissures, while others appear to be air intakes or are inactive.

CH_4 and CO_2 are also present in the coal in areas that have not been affected by combustion. These gases desorbed from the coal, and they support coal bed methane production in the San Juan Basin. They also contribute to the observed outflow of gases from the fissures at the North Coal Fire, as the isotope signatures reported below document.

3. Extent of the North Coal Fire

3.1. Surface fissure distribution

Surface fissures observed at the North Coal Fire are similar to those observed at coal fires around the world (Cao et al., 2007; Huang et al., 2001; Kuenzer et al., 2007b; Wessling et al., 2008), and are surface manifestations of the coal fire burning below. Fissures observed over the North Coal fire have apertures ranging from 0.02 m to > ~1.5 m, and they connect the surface and the coal seam. These fissures were mapped in 2007. Fissures are observed only in areas affected by the fire, and they are not present in neighboring areas where the coal seam is intact. At the North Coal Fire, fissures with narrower apertures typically vent hot exhaust gases, while the wider fissures are at ambient temperatures at the surface. The geomechanical mechanisms of formation of these fissures are discussed in detail by Ide et al. (2010). Fissures at the North Coal Fire were mapped using a pack-mounted Trimble ProXH GPS unit, with accuracy better than 0.5 m after correction. Fig. 1 reports the spatial distribution of fissures over the North Coal Fire. The fissures shown in the figure are color coded by