Burning of forest materials under late Paleozoic high atmospheric oxygen levels

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ABSTRACT

Theoretical models suggest that atmospheric oxygen reached concentrations as high as 35% O_2 during the past 550 m.y. Previous burning experiments using strips of paper have challenged this idea, concluding that ancient wildfires would have decimated plant life if O_2 significantly exceeded its present level of 21%. New thermochemistry and flame-spread experiments using natural fuels contradict these results and indicate that sustained burning of forest fuels at moisture contents common to living plants does not occur between 21% and 35% O_2. Therefore, the fires under atmospheres with high oxygen concentrations would not have prevented the persistence of plant communities. Times of high O_2 also agree with observations of concurrent fire-resistant plant morphology, large insects, and high concentrations of fossil charcoal.

Keywords: Paleozoic, atmospheric oxygen, wildfire, flame spread, fire ecology.

INTRODUCTION

Two independent geochemical models (Berner and Canfield, 1989; Berner et al., 2000) suggest that the percentage of gaseous oxygen in Earth's atmosphere has varied over Phanerozoic time (542 Ma to the present). According to the models, during Pennsylvanian and Early Permian time (ca. 300 Ma), oxygen comprised ~35% of the atmosphere, a value significantly higher than the 21% of today. Recent research extends the duration of this peak forward to the end of the Permian Period (Berner, 2002).

An increase in ambient oxygen facilitates fuel ignition and increases combustion rates and, thus, heat flux from burning fuels (Watson et al., 1978; Tewarson, 2000). Subsequent work shows that natural fuels exposed to increasing heat fluxes show higher heating rates, decreasing times to ignition, and increased heat release rates once ignition has occurred (Yang et al., 2003). Therefore, in conditions of elevated oxygen, forest fires can be expected to exhibit more rapid rates of flame spread, leading to higher intensity fires (kW m^{-1}; Van Wagner, 1965).

Large masses of fossil charcoal in Pennsylvanian and Permian strata lead to the inference that fires during this time were large, frequent, and intense (Scott and Jones, 1994; Glasspool, 2000; Uhl and Kerp, 2003), and suggest a correlation of large fires with the high oxygen peak. Moreover, existing theory suggests that elevated oxygen had a substantial effect on Paleozoic fire ecology, evidenced by fire-resistant morphological traits in numerous unrelated clades of fossil plants, such as the lepidodendrids, *Calamites*, *Psaronius*, lyginopteridaleans, medullosans, and the cordaites. Among these adaptations are very thick bark, deeply imbedded vascular cambia, sclerified or fibrous outer cortexes, a sheath of fibrous roots surrounding the stem (cf. Stewart and Rothwell, 1993; Taylor and Taylor, 1993), and ephemeral crowns in trees of the *Lepidodendron* group, which were dominants of early and middle Pennsylvanian peat swamps (Phillips and DiMichele, 1992).

We are aware of just one effort to experimentally assess the effect of elevated atmospheric oxygen on wildfires. In this work, the authors assessed the minimum energy needed to ignite strips of paper and found that ignition has a strongly positive correlation with the concentration of oxygen. They inferred that, at levels above 25% O_2, lightning strikes during rainstorms could have ignited a wildfire. They asserted that this level of fire frequency would have been catastrophic for plant life, so they concluded that atmospheric O_2 could never have exceeded 25% (Watson et al., 1978; Lenton and Watson, 2000), since forest communities have persisted over the past 370 m.y. (DiMichele and Hook, 1992).

In this paper we present evidence to refute this conclusion. Paper strips do not represent natural forest materials (Robinson, 1991); fuel characteristics are important in determining ignition by lightning (Latham and Williams, 2001). Ignition is only the first step in the generation of a forest fire. Ignition without spread of fire to adjacent fuel would have a minimal impact on vegetation. It is therefore necessary to compare natural fuels to the previous study and also to examine the spread of fires under varying levels of atmospheric O_2 concentration and moisture content.

OXYGEN AND FUEL CHEMISTRY EFFECTS ON MASS-LOSS RATES

Primary factors affecting the spread rate of present-day wildfires include fuel loading, fuel-bed geometry, fuel thermochemistry, fuel-particle dimensions, fuel moisture, wind, and terrain (Williams, 1982). For forest fires over geologic time, ambient oxygen concentration must also be included. We conducted thermogravimetric analysis (TGA) experiments to evaluate the rate of combustion of plant-matter samples with known fuel chemistry in ambient and elevated oxygen concentrations. In addition, paper combustion was studied to compare it with that of natural plant materials.

TGA subjects samples to a standard heating regime, allowing the determination of the effects of fuel chemistry, fuel-particle dimensions, and atmospheric composition on the rate of burning. In a TGA trial, a sample is placed in a pan hung on a microbalance. A furnace surrounds the sample and heats at a steady rate while the changing mass of the sample is recorded. Since ignition of the sample is ensured, sample fuel chemistry and response to heating, not ignition, is the focus of the measurement. A TA Instruments 2950 unit was used. Sample pans of

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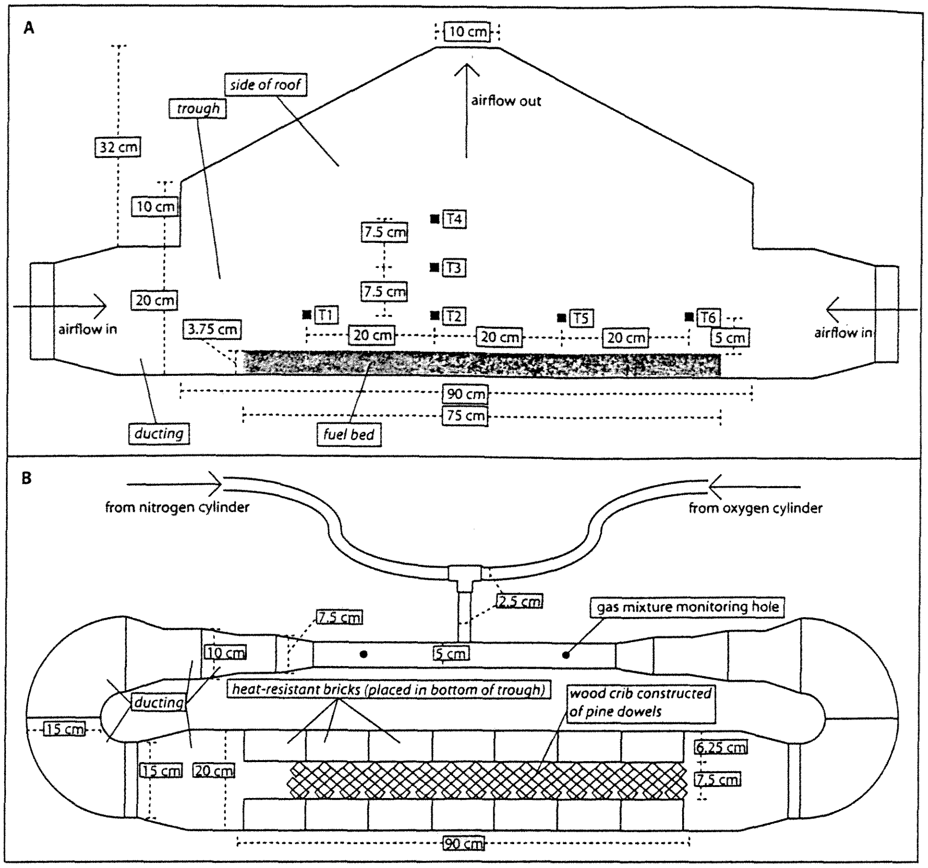

Figure 1. A: Side view (cutaway) of flame-spread apparatus. Gas flows in from ends of trough and out through hole in top of roof. Roof was removable to allow access to bottom of trough for construction of fuel beds. Squares labeled T1–T6 represent six thermocouples, which were inserted through holes drilled through trough walls and heat-resistant bricks (see B) such that their tips were suspended above middle of fuel bed. Bricks and door used to access fuel bed for ignition (located approximately at "3.75 cm" label location) are omitted for clarity. B: Top view of flame-spread apparatus. Gas entered from gas cylinders (not shown), and mixing was verified at gas mixture monitoring holes. Gas then flowed into ends of trough and out hole in top of roof (not shown). Wood crib fuel bed is shown constructed between two rows of heat-resistant bricks, needed to protect sheet metal. Thermocouples are not shown for clarity.

50 μL held masses ranging from 7 to 12 mg (the recommended mass for this instrument) that were heated at a rate of 40 °C/min (the maximum of the experimental setup). Only one type of fuel was combusted during a trial. During heating, mass data were collected every 2 s.

Rates of mass loss relate directly to rates of combustion. Before and during the heating of the trial samples, the instrument's sample chamber was flushed with air or an artificial oxygen-nitrogen mixture. Because the slow heating of the TGA apparatus dehydrates the samples before combustion begins, all TGA data were collected for dry samples. Moreover, the diminutive fuel bed led to simultaneous combustion for all pieces of fuel, so there was no spreading behavior to affect the rates of mass loss.

The sample of plants used in these experiments was selected to provide a close anatomical match to those forming the bulk of the vegetation in Pennsylvanian–Permian equatorial lowland and upland settings, for which there is evidence that fires were important (Scott and Jones, 1994; Falcon-Lang and Scott, 2000). Sphagnum moss and the fibrous root matter of *Alsophila cooperi*, a tree fern, were selected for their similarity to lowland plants. The peat moss represents decaying organic matter, and tree fern fibers are inferred to be the closest modern equivalent to the outer bark of the dominant genus of Carboniferous swamp forests, *Lepidodendron*. The wood and leaves of modern *Araucaria bidwillii* were used for their close phylogenic and histological relationship to the dominant upland order of the Pennsylvanian and Permian conifers, the *Voltziales* (DiMichele and Hook, 1992).

To fit in the sample pan, leaves and paper were folded, the granules of peat moss were placed in a small pile, and the wood and tree fern fibers were broken into small chunks. Usually samples prepared for TGA measurements are finely ground, but the paper and the leaves did not lend themselves to grinding, so all samples were left unground to allow for comparison.

OXYGEN AND MOISTURE EFFECTS ON FLAME SPREAD

A separate set of experiments tested the propagation of a flame front through a fuel bed. Either pine dowels (0.95 cm × 0.95 cm × 9.31 cm) or pine needles were used, both from the species *Pinus strobus*, an upland conifer. The dowels were arranged in a criss-cross framework or crib extending down the length of a sheet metal trough (open at the top and ends, shown in Fig. 1), and the needles were spread out evenly through the trough. Steady-state, unidirectional flame spread was measured along a 7.62-cm-wide, 75-cm-long path with K-type thermocouples that recorded temperatures every 0.01 s while positioned 5 cm above a 3.8-cm-deep bed of fuel. The fuel-packing ratio (volume of fuel divided by volume of fuel bed) was held constant at 0.29 for the wood cribs and 0.04 for the pine needles. Fuel chemistry was controlled by burning the different types of fuel separately. A minimum height of at least 16.5 cm was maintained between the top of the fuel beds and the roof of the apparatus.

Both the oxygen concentration of the gas supply and the moisture content of the fuels were varied. O_2-N_2 gas mixtures were created by mixing industrial grade oxygen and nitrogen gas in the ducting behind the trough (Fig. 1B). The gas composition was verified with a handheld atmospheric oxygen meter in two monitoring holes (Fig. 1).

The flame-spread apparatus was designed to allow the fire temperature to act as the principal driver of the gas movement through the trough. With the ducting attached (as shown in Fig. 1B), an insufficient flow rate from the gas cylinders would have starved the fire of oxygen. Conversely, an excessive flow rate would also have poorly approximated natural conditions by providing more oxygen to the fire than the fire would have drawn by itself. To maximize the likelihood of sufficient airflow driven only by the fire, the Bernoulli equation was used to estimate the inverse relationship between gas flow rates and the cross-sectional areas of the apparatus openings. The general ranges of

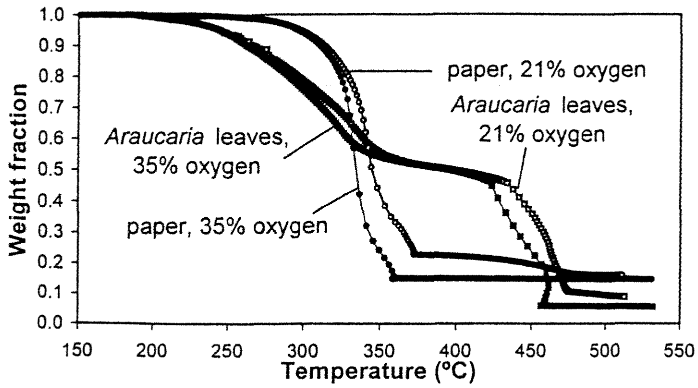

Figure 2. Results of thermogravimetric analysis experiments.

the air velocity and fire temperatures were determined in a bench-scale fire, and this allowed for the determination of the rough dimensions of the apparatus. The design allows oxygen and nitrogen gas to mix completely in a small volume and at a high speed. After the gases enter the ducting, an increase in its cross-sectional area produces a slower, less turbulent flow of gas to the fire.

At the outset of the burning trials, a subset of wood and pine needles was burned in the flame-spread apparatus with the gas lines detached. This allowed the fire to create its own airflow with ambient air, and the flow rate through the ducting was measured with an anemometer to be ~70.1 ± 4.5 m/min. This flow rate was then duplicated in each of the artificial gas mixture trials performed with the gas lines attached.

All batches of wood or pine needles were oven dried to a constant mass, soaked in water to saturation, then oven dried to the desired moisture content. Fires were always started in 10 cm of dry fuel at one end of the fuel bed that led to the test fuel by using a blowtorch inserted through a small door in the side of the trough. The door was open only until ignition was verified. These procedures ensured that each batch of test fuel was heated with a fire that had achieved steady-state flame spread under stable gas mixtures.

Test fires achieved steady-state flame spread at least 20 cm before the first thermocouple. As the flame front moved through the fuel bed, each thermocouple recorded a temperature profile over time with one maximum. The time intervals between the maxima for different thermocouples indicated the rate of flame spread. Thermocouple temperatures are not reported because they were erratic, given the structure of the flames and the fineness of the thermocouples.

RESULTS AND DISCUSSION

The TGA results show that the rate of mass loss increased somewhat with an increase in the concentration of oxygen to 35%. The burning of *Araucaria* leaves is an example, as shown in Fig. 2. The beginning of mass loss is the moment the weight fraction dropped below 1.0. The temperature at which mass loss began did not vary as experimental conditions changed, but the samples combusted in 35% oxygen lost their mass faster than those burned in 21% oxygen.

An important observation relative to the results of earlier work (Watson et al., 1978; Lenton and Watson, 2000) is that fuel type affects mass-loss rates more strongly than does oxygen concentration. As an example, *Araucaria* leaves lost mass at both lower and higher temperatures than geometrically similar paper, probably because the leaves contain a considerable amount of lignin, whereas paper contains little, if any. The composition of the leaves was ~32% lignin and 63% cellulose by mass (Spain and LeFeuvre, 1987), whereas the dry paper used was 79% cellulose, 15% mineral fillers, and 6% starch compounds by mass (Bush, 2003). Paper loses ~86% of its mass in one temperature range, because it is composed almost entirely of cellulose. The remaining 14% of the paper did not burn; this residue probably represents the mineral fillers. Double flexure of the *Araucaria* mass-loss curve (Fig. 2) is thought to be caused by the different fates of cellulose and lignin during thermal decomposition and combustion. The other natural fuel samples analyzed via TGA also behaved very differently from paper and showed qualitatively similar responses to *Araucaria* leaves under varying oxygen levels.

TABLE 1. RESULTS OF FLAME-SPREAD EXPERIMENTS

Moisture content	Oxygen concentration							
	Ambient	8%	12%	16%	21%	28%	31%	35%
Wood fuel beds								
2%	Burn 3.97	Fail –	Burn 1.70	Burn 2.48	Burn 2.76	Burn 4.92	Burn 4.82	Burn 5.00
12%	Burn 1.55			Fail –	Burn 1.45	Burn 2.49	Burn 3.11	Burn 3.09
23%	Fail –				Fail –	Fail –	Burn 2.60	Burn 2.73
61%	Fail –				Fail –	Fail –	Fail –	Fail –
Pine-needle fuel beds								
0–2%	Burn 37.50		Fail –	Burn 18.75	Burn 20.69	Burn 37.50	Burn 50.00	Burn 37.50
12%					Burn 21.43			Burn 23.08
23%					Burn 15.00			Burn 42.86
42%								Burn 33.33
61%					Fail –			Fail –
193%					Fail –			Fail –

Note: "Burn" signifies that the entire fuel bed burned under the conditions indicated, and "Fail" signifies the opposite. If there was a successful burn, the number below is the rate of flame spread (in cm/min). The ambient column refers to fires burned in ambient air with gas lines detached, so that the fire drove its own airflow.

Table 1 shows the results of the flame-spread experiments. Fires did not spread above a fuel moisture threshold that increased with oxygen concentration. Increasing fuel moisture decreases the flame-spread rate, whereas flames spread more quickly with increasing oxygen concentration in both fuels. We conjecture that at oxygen levels near and above 35%, conduction of heat into fuel might replace oxygen concentration as the rate-limiting process when fuel moisture contents are low. At low fuel moistures, flame-spread rate appears to approach an asymptote as oxygen concentrations approach 35%. As such, fire spread may be less affected by high oxygen concentrations than has been hypothesized.

A comparison of spread rates between ambient and 21% oxygen (Table 1) suggests that fires may spread more rapidly under natural aerodynamic conditions than under the imposed flow regime, while still producing the same qualitative result. We do not expect that the dampening effect of the artificial gas supply on flame spread would result in the asymptote in spread rates seen at high oxygen concentrations.

CONCLUSION

Our results suggest that oxygen levels above 30% O_2 would not necessarily have been inimical to the persistence of late Paleozoic forests, as has been suggested by earlier researchers (Watson et al., 1978; Lenton and Watson, 2000). First, prior conclusions about Paleozoic fires were based on paper strips, yet thermogravimetric analysis indicates that natural fuels are not well represented by paper strips. Second, catastrophic effects of high-oxygen fires would have been more likely if elevated-oxygen fire-spread rates did not show the asymptote that our results suggest. Finally, moisture in fuels would have strongly limited spread rates and fire intensities in high-oxygen fires, just as they do today.

Previous researchers (Watson et al., 1978) concluded that above

25% oxygen, fuels at their fiber-saturation points could be ignited into a widely destructive fire during a rainstorm. The fiber-saturation point (the moisture content of dead fuels at which all moisture is bound within cell walls) of both wood and pine needles is ~30% (Skarr, 1988). However, during a rainstorm, intercellular cavities begin to fill with water, and maximum moisture contents can rise to 102% for conifer litter (Reynolds and Knight, 1973), to >215% for hardwood litter (Helvey and Patric, 1965), and to >350% for reindeer lichen (Pech, 1989). The moisture content beyond which flames could not spread reaches a maximum of just ~42% moisture at 35% oxygen (lower portion of Table 1). Thus, our data show that at O_2 levels well above 25%, surface fires (flames spreading through fuels on the forest floor) were unlikely to have occurred at commonly attained elevated fuel-moisture levels. Crown fires (flames spreading through live foliage of trees) may represent a somewhat different situation than surface fires because crown fires commonly occur when foliage moisture exceeds 70%. However, crown fires today rarely burn except when they are supported by heat from flaming surface fuels (Van Wagner, 1977).

Thus, postulated high oxygen concentrations of the late Paleozoic probably enhanced wildfires and may help to explain the common occurrence of fire-resistant plant morphologies (Robinson, 1990) and charcoal abundance then (Scott and Jones, 1994; Glasspool, 2000; and others). We also speculate that forest-fire frequency would have been high, given increased ignition probabilities. However, our results suggest that the extent of fires would have been limited by fuel moisture, which in Carboniferous landscapes would have been determined by climate and hydrology. Fire spread would also have depended on fuel loads (kg ha^{-1}), which may have been low and patchy in upland sites because of frequent fires but high in swamps because of perennially wet fuels. We could further speculate that the more sizeable fires of this period recorded in coal deposits (Scott and Jones, 1994; Glasspool, 2000) were uncommon phenomena that resulted from drought and involved not only flaming combustion of above-ground fuels but also smoldering combustion of accumulations of organic material on the forest floor (Miyanishi, 2001).

When combined with observations of fire-resistant plants and abundant charcoal as well as experimentation concerning the effects of elevated oxygen on plant (Beerling et al., 2002) and animal growth (Frazier et al., 2001; Berner et al., 2003), these new data on wildfires are consistent with the idea of elevated levels of O_2 during the late Paleozoic (Berner and Canfield, 1989; Berner et al., 2000).

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