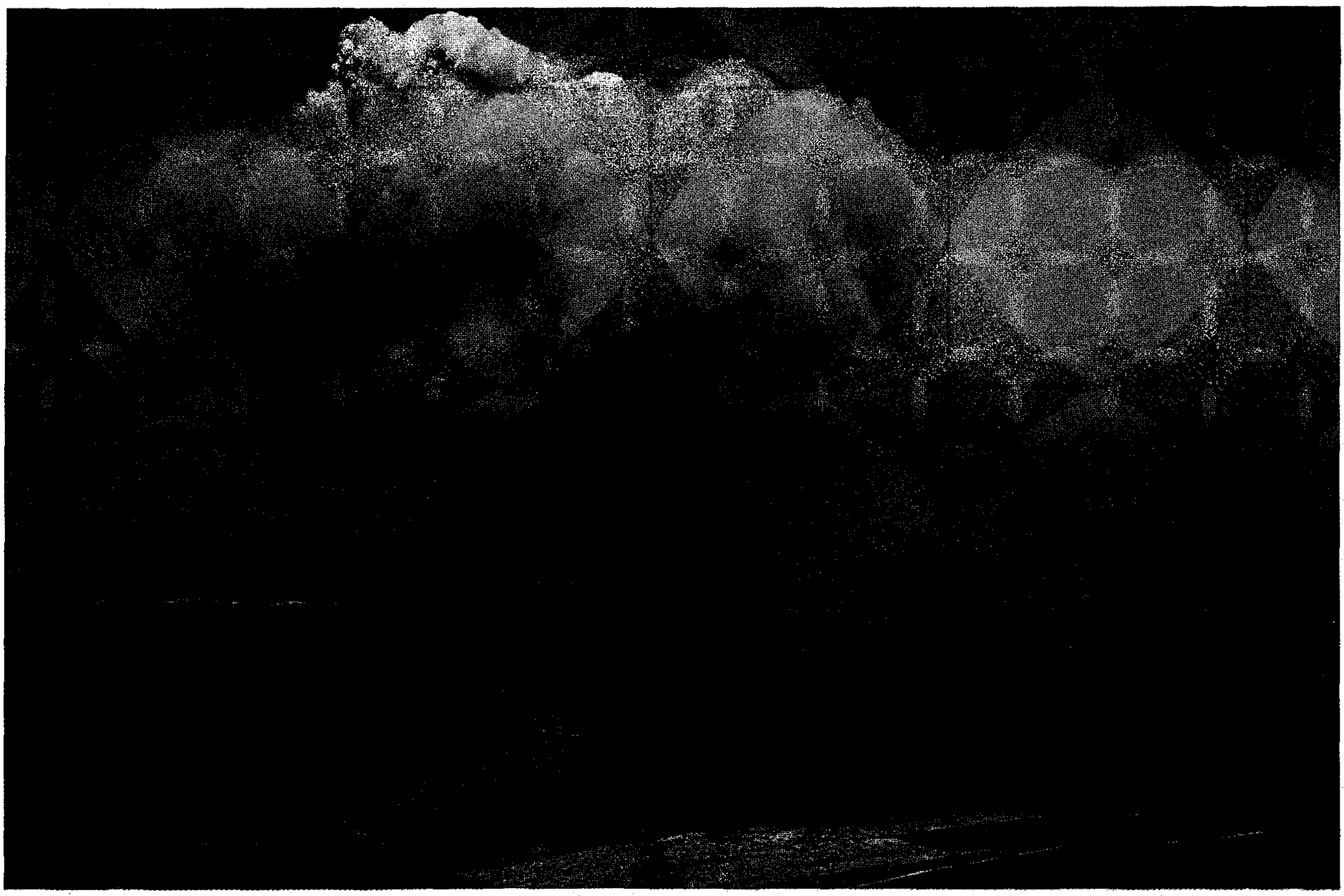


A mushroom-shaped plume, drawing in air from all directions.

Looking into smoke

Forest fires pour enormous amounts of smoke into the air over Australia each year. A day's prescribed burning in a forest—to reduce the bushfire risk by removing forest fuel—can send up more than 1000 tonnes of smoke. The devastating Victorian bushfires of 1939 produced enough to discolour the sky as far away as New Zealand.

We can't stop smoke from pouring into the sky, just as we can't prevent the Australian bush from burning. But people planning prescribed-burning operations and other forest and farm burns can time their fires so that the smoke causes the fewest possible problems. And the prescribed-burning programs, by reducing the incidence and intensity of summer bushfires, cut back the output of smoke from unplanned fires.

However, before they can plan burns to keep smoke problems to a minimum, the people lighting them must be able to predict how much smoke will be produced and where it will go. Also, useful assessments of the problems can only be made if the composition of the smoke is known.

Over the past 7 years, CSIRO teams from Melbourne have gathered a great deal of information on forest fire smoke. They have observed the behaviour of plumes from the ground and air, and have flown through the smoke to measure its composition and gather samples for tests on the ground.

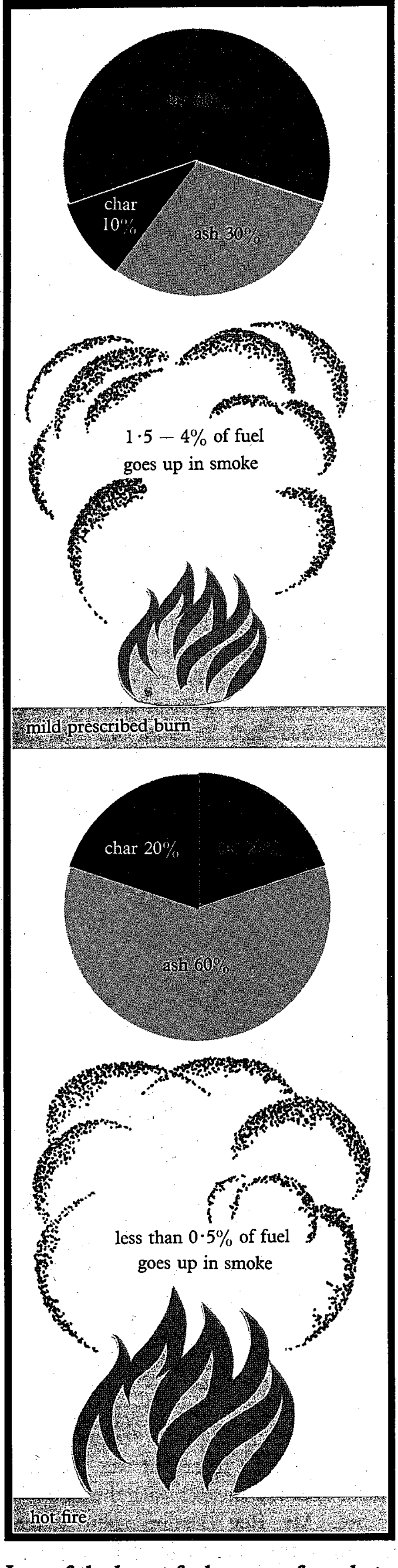
Most of the work has been done in the jarrah and karri forests of Western Australia, to the east and south of Perth. Using the research results, foresters can now successfully predict how much smoke any prescribed burn will produce, where it will blow to, how quickly it will disperse, and the effects it will have on visibility. The tests on its composition indicate that smoke returning to the ground is very unlikely to be a health hazard.

One question that still lacks a firm answer is whether forest smoke blowing over a city could increase the city's photochemical smog hazard. Another is whether any burning practices may send enough nutrients up in the smoke to cause a rundown in a forest's nutrient supply. Also still to be determined is how the dispersed smoke particles are finally removed from the air.

The smoke rises

The first matter looked at was the ways smoke and heat interact with the air above a fire. Mr Reg Taylor, who retired recently from the Division of Atmospheric Physics, did the work with scientists from the former Division of Applied Chemistry's Bushfire Section. One of their aims was to find ways to predict how high smoke will rise above any fire.

What goes up in smoke



Less of the burnt fuel goes up from hot fires than from mild ones, but a hot fire's total smoke output is likely to be greater because more fuel burns. Smoke composition varies, but the breakdowns shown are typical.

Smoke from an experimental intense fire in Western Australia.

The scientists studied three intense fires specially lit for the experiments by the Western Australian Forests Department in poor-quality jarrah forest, and a very hot land-clearing burn near Darwin. They made their observations from a light aircraft flying through the smoke plume and from ground observation points.

All the fires produced mushroom-shaped plumes. Winds at ground level changed direction as air flowed into the smoke columns.

The scientists measured temperatures in the smoke as they flew through it. Then they compared these with temperature predictions based on the rates of heat output from the fires. The measurements were always considerably lower than the estimates; this is because wind dilutes the smoke and the air drawn into the smoke columns cools the plumes. Very large amounts of air are involved—more than 400 cubic kilometres for each of the Western Australian fires.

When the smoke and captured air from these three fires reached heights between 1370 and 2200 metres, more heat was released into the smoke columns. It came from the water vapour in the columns condensing to liquid. This heat gave a big boost to the upward movement of the smoke—a push ranging from about one-third up to nine-tenths of that produced by the heat of the fires themselves.

Smoke from the jarrah forest fires reached heights ranging from 2500 to 4300 metres. The Darwin fire's plume reached a fairly constant 3000 metres, except for a period of about half an hour at the height of the blaze when it rose nearly twice as high, to 5800 metres, and then subsided again. It was a spectacular sight.

Another tower

Looking back at their Western Australian results after the Darwin fire, the scientists detected a similar but less spectacular smoke tower during the hottest of the jarrah forest burns. This big change in the smoke's behaviour at the peak of very hot fires ruled out the possibility of devising a simple way to predict the height of plumes for all fires.

Smoke from the jarrah forest fires reached heights ranging from 2500 to 4300 metres.

But the scientists found that it is quite simple to predict the plume height where towering doesn't occur. This depends on the rate at which the forest fuel burns, which foresters have well-established ways of estimating. The height of the condensation level—where water vapour turns to liquid—is another factor. It can be worked out quite accurately from meteorological measurements on the ground.

Predicting the height of the tower is a much more difficult problem, but one that should arise very rarely with deliberately lit fires. Towering is associated with intense fires and unstable weather conditions. Most deliberately lit fires are mild and are set off on calm days; in fact, for prescribed burns foresters usually choose days when a temperature inversion in the atmosphere will stop the smoke rising more than perhaps 1500 metres.

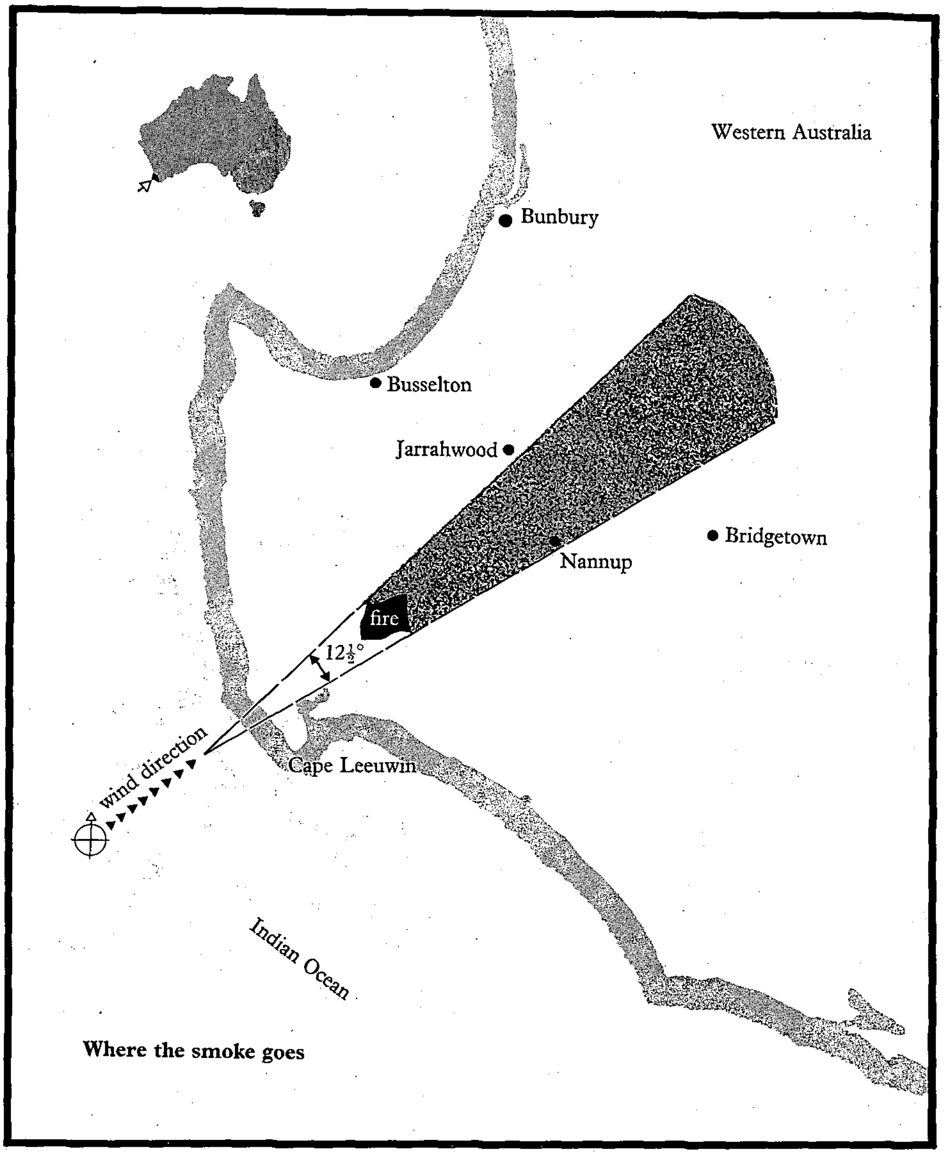
As well as being able to predict how high smoke will rise, it is useful to be able to work out beforehand where smoke from any fire will spread to. This is one of the problems a CSIRO Bushfire Section team led by Dr Bob Vines looked at in the early 1970s.

The scientists studied many Western Australian prescribed burns—lit when winds at plume level, much stronger than those at the ground, ranged from less than 30 to more than 50 km per hour. In each case the smoke spread out in a narrow fan with an angle of 12–13°. This seemed a surprising result as it might have been expected that increasing wind strengths would narrow the fan. Evidently increased turbulence along the edges of a plume in stronger winds balances out this narrowing effect.

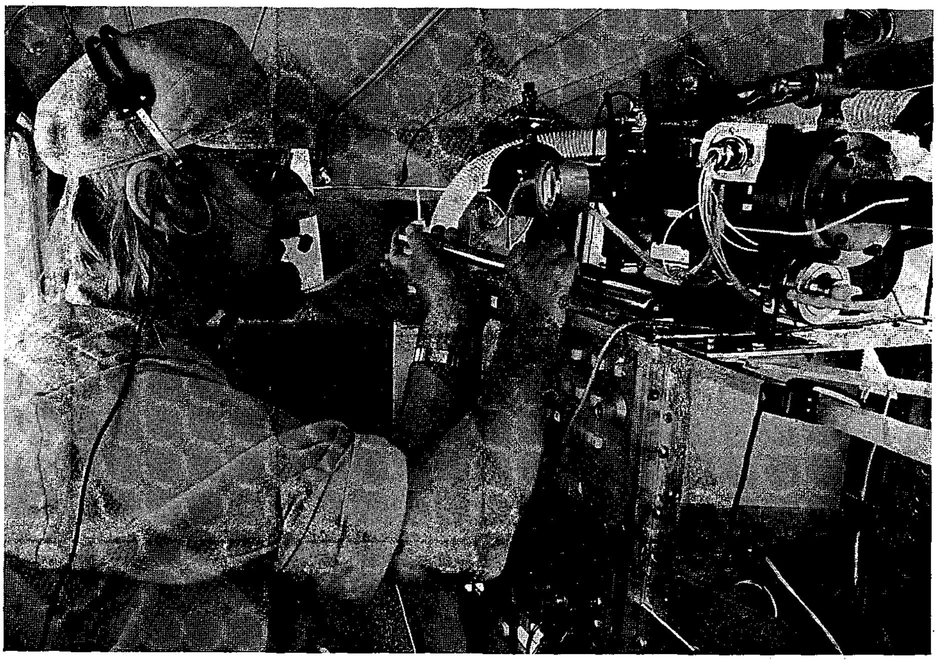
So if wind direction can be forecast for a prescribed-burning day, the areas that the plume will spread over can be predicted. This makes it possible to plan prescribed burns so that the smoke stays away from populated areas, and to warn light-aircraft pilots of smokey skies. The smoke near the centre of a plume can reduce visibility to as little as 200 metres.

What's in it

The Bushfire Section began examining the composition of forest fire smoke in 1970. The Section was disbanded in 1974, when the Division of Applied Chemistry was split into two new Divisions, but two of its members are continuing the work. They are Mr Tony Evans of the Division of Applied Organic Chemistry and Mr David Packham of the Division of Mineral Chemistry. Dr Alan McKenzie,



Smoke from this prescribed burn, inland from Cape Leeuwin, W.A., spread out as a fan with an angle of 12–13°. This spreading pattern is typical for Western Australian burns, despite differing wind speeds.



Dr Alan McKenzie watches instruments in the scientists' specially equipped aircraft.

of the Division of Process Technology, recently joined them; he is making chemical analyses of smoke particles.

One of the first things the scientists set out to discover was how much of the material in the forest fuel ends up in the smoke. The obvious, but very difficult, way to work this out is by comparing the weight of the smoke produced in a fire with the weight of the fuel burnt. They did this. They calculated the weight of smoke from measurements of smoke concentration throughout the plume and throughout the lifetime of the fire, and the fuel weight from foresters' estimates of its density.

The answer the team came up with for a typical prescribed burn was that 1·5–2% of the fuel ended up as smoke particles. Soon after making these calculations, they hit upon a much simpler way of working out the ratio between fuel and smoke.

The method, devised by a recently retired member of the Bushfire Section, Mr Nick King, involves simultaneously measuring carbon dioxide and smoke concentrations in the plume. From the carbon dioxide reading, the scientists can calculate the rate of fuel combustion responsible for the measured smoke concentration. This method, as well as being much simpler, has the advantage that it allows smoke : fuel ratio assessments to be made at any time during a fire.

How much goes up

The team's latest measurements for Western Australian prescribed burns put the proportion of fuel ending up as smoke particles at 1·5–4%; both methods of calculating the ratio have consistently come up with figures in this vicinity. For high-intensity burns, the figure is lower. Measurements by the team over a very hot fire in Victoria, designed to remove as much fuel as possible from a forest site, showed that less than 0·5% of the fuel changed to smoke.

The reason for the difference is that combustion is much more complete in a hot fire than in a mild one. This shows up as well in the composition of the smoke particles.

In smoke from the prescribed burns, on average, 70% of the particles were tar and char, mostly tar. This compares with a figure of about 40% in smoke from the intense Victorian fire, where tar and char quantities were about equal. The rest of the smoke—about 60% in the case of the intense fire but only 30% for the mild fires—was mineral ash, which of course can't burn.

Thick smoke near a fire can contain as many as a million particles per cubic centimetre.

The smoke particles are very small. Measurements by the team gave most a diameter of about a ten-thousandth of a millimetre, although some of the tar particles are up to a twentieth of a millimetre across. Thick smoke near a fire can contain as many as a million particles per cubic centimetre.

Dr McKenzie's analyses of the particles, particularly the ash, should give an idea of the quantities of various mineral nutrients going up in the smoke. The quantities lost in a fire depend also on the distance particles travel from a fire before returning to the ground—for example, whether they return to the forest or are lost out to sea. Obviously this will vary greatly from fire to fire. Mr Packham hopes to begin work soon to try to trace the fate of smoke particles from prescribed burns.

Measurements by Dr Vines and his colleagues indicate that most of the ash residue from fires remains on the ground. For seven Western Australian prescribed burns, their estimate of the proportion of the ash showing up in the smoke ranges from as little as 0·1% to 10%. The lowest figures were recorded on days when temperature inversions blocked the smoke's ascent.

Nitrogen and sulphur

The gases given off when forests burn can also contribute to losses of nutrients, particularly nitrogen. The scientists sometimes detected concentrations of nitrogen oxides in smoke slightly above the natural background level, and laboratory tests indicate that more of the element is given off as nitrogen gas than as oxides.

However, nitrogen is lost continuously

from soil, and fires can only briefly speed the process. Whether any long-term loss occurs depends on how rapidly the lost nutrient is replaced, mainly by nitrogen taken from the air by leguminous vegetation.

Sulphur is another nutrient that goes up in the smoke—as sulphur dioxide. But the scientists detected none of this gas, indicating that the concentration in the smoke they examined was below 0·01 p.p.m., the lower limit of the detectors.

This is a surprising result, because calculations based on the amount of sulphur in forest fuel suggest that concentrations up to 0·04 p.p.m. could be expected. Part of the explanation seems to be that much of the sulphur remains in the ash on the forest floor; laboratory burns confirm this. Also the leaf canopy may stop some of the sulphur escaping with the smoke. Whatever the full explanation may be, the small scale of the sulphur loss is good news for the forests.

Another important question is whether any of the gases given off could return to ground level in sufficient quantities to constitute a health hazard. On all the evidence to date, the answer is no. Concentrations measured in the thickest smoke plumes were always below the accepted risk levels, and the gases are rapidly diluted.

Ozone

The only possible cause for concern seems to be ozone, formed not in the fire but at the top of the smoke plume. Ozone is the principal ingredient of photochemical smogs in cities. It forms in smoke, and in cities, when nitrogen oxides and hydrocarbons react together under the stimulus of ultraviolet radiation from the sun.

The scientists have measured ozone concentrations as high as 0·2 p.p.m. at the top of plumes from intense fires, a figure of about the size expected in severe smogs in Sydney or Melbourne. However, plume-top readings for prescribed burns are much lower, usually not exceeding 0·08 p.p.m.

They have found that maximum smoke concentrations do not coincide with maximum ozone levels. Instead, ozone seems to build up, but not indefinitely, with the length of time the smoke is exposed to the ultraviolet radiation.

For example, measurements in the plume from one prescribed burn revealed, 5 km downwind of the fire, a layer 100 m thick where ozone concentrations rose slightly above the background level of