Lichens, air pollution and lung cancer

The relationship between lung cancer and atmospheric pollution remains controversial[1–3] despite 50 years of discussion, partly because studies are frequently restricted to small, well-monitored areas. In contrast to instrumental monitoring, bioindication techniques allow the mapping of pollution effects over wide areas with a high sampling density. We have compared a biodiversity map of pollution-sensitive organisms, the lichens[4], with mortality maps of a large part of northeastern Italy, the Veneto region (18,364 km^2, population ~4 million). Our results strongly support a relationship between air pollution and lung cancer.

The lichen study (data from 1991)[5] was based on 2,425 measurements of epiphytic lichen biodiversity at 662 locations, calculated as the sum of frequencies of all species in a sampling grid of 10 units[6]. The mortality data at municipal level (1981–88) derive from the Italian National Institute of Statistics. Kernel indicators for the estimate of density functions[7,8] were used for the analysis.

Biodiversity shows low, if any, correlation with several types of cancer (including larynx cancer, $r = 0.016$), and with mortality by chronic bronchitis ($r = 0.15$) because of the high mortality in mountain areas. There is no correlation with lung cancer in male migrants ($r = 0.07$), or in resident women ($r = 0.12$). Municipal data concerning women have a poor statistical quality because lung cancer deaths in women are relatively few (13% of total lung cancer deaths), and there are pronounced differences in the smoking habits of women from rural and urban areas[8].

However, biodiversity (Fig. 1a) and lung cancer in young (aged under 55 years) native male residents (Fig. 1b) are highly correlated ($r = 0.82$, Fig. 2), even when corrected for spatial autocorrelation with bayesian analysis[7]. When all age-groups are included, the correlation becomes lower ($r = 0.6$), owing to higher mortality of older men in mountain areas, many of whom emigrated between 1950 and 1970 to coal mines in Belgium.

We tested the hypothesis that lung cancer is correlated with lichen biodiversity as a result of air pollution, using pollution data recorded in nine municipalities since 1986. In these regions the correlation between biodiversity and lung cancer in young male residents was high ($r = 0.95$, $P < 0.001$). Furthermore, there was a high correlation with common anthropogenous pollutants, such as SO_2, NO_3, dust and SO_4^{2-} ($r = 0.93$, 0.87, 0.86 and 0.85, respectively; $P < 0.01$ in all cases); and no correlation with non-anthropogenous substances such as Cl^-, Ca^{2+}, Mg^{2+}, HCO_3^-, K^+, Na^+, or with all other types of cancer.

Lichens are notoriously sensitive to sulphur dioxide[4], but the low SO_2 concentrations recorded in the survey area are unlikely to produce carcinogenic effects.

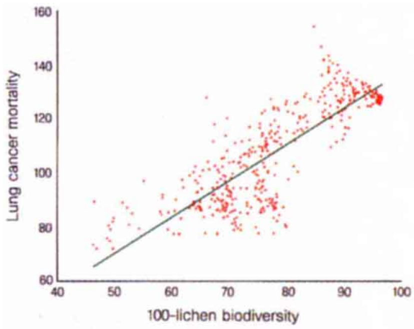

Figure 2 Scatter diagram relating lichen biodiversity (100 − sum of frequencies) and lung cancer mortality (observed/expected cases × 100; males aged under 55 years) in all municipalities of the Veneto region ($r = 0.82$, $F = 845.9$, $P < 0.0001$).

However, the patterns of SO_2 concentration revealed by lichens do reflect the long-distance transport of different pollutants that may be emitted with SO_2, some of which may have carcinogenic effects.

The densely populated eastern and western parts of the Veneto plain are upwind and downwind of the main pollution sources, which may explain the low correlation between lung cancer in young males and population density ($r = 0.23$). Pollution was higher between 1960 and 1980, but the main patterns of atmospheric transport have remained constant, indicating that time-lag factors are irrelevant.

The relative risk associated with pollu-

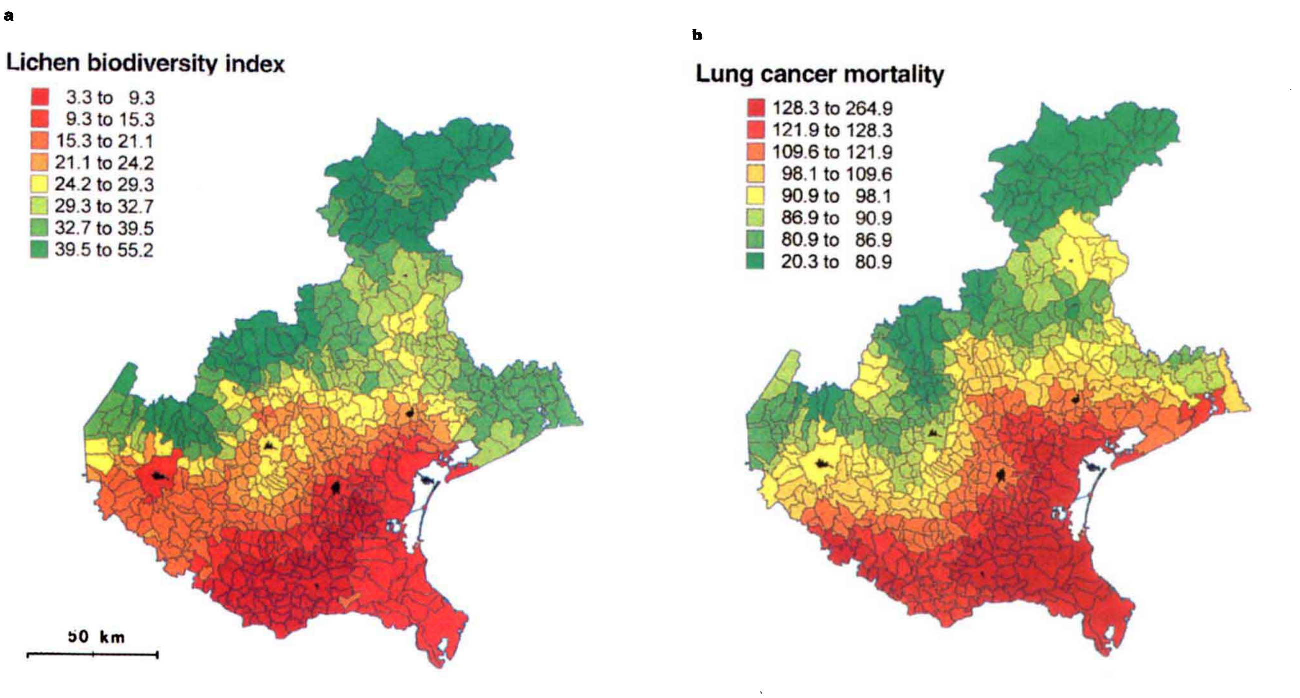

Figure 1 a, Lichen biodiversity, calculated as the sum of frequencies of all epiphytic species in a sampling grid of 10 units; and **b,** lung cancer mortality in young male residents (expressed as observed/expected cases × 100), in the region of Veneto. Scale intervals are based on percentiles of values distribution.

tion exposure is small, but the affected population is large, and thus the impact of pollution in terms of cancer mortality is important.

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Vervet monkeys as travelling salesmen

Vervet monkeys (*Cercopithecus aethiops*) forage on patchily distributed resources, visiting several sites in a single trip. When choosing a route, they face a famous optimization problem, the 'travelling salesman' problem[1]. Here we pose a question about their route-choosing mechanism: how many future destinations along the route influence the choice of the next destination? We find that at least two further destinations affect the choice of the next destination, which is remarkable considering that the monkeys never visited more than six destinations in one excursion.

Our procedure was modelled on that of Menzel[2], who studied the travelling salesman problem in chimpanzees. He carried juvenile chimpanzees around while he hid fruit in 18 different locations, then released them and recorded the route taken to collect the fruits. They collected most or all of the fruits in sequences that bore no relation to the baiting sequence and that tended to minimize the distance travelled.

Our subjects were four adult female vervet monkeys selected from a 23-member troop living in a 9.15-m square enclosure. They were carried around to watch while grapes were hidden in six or eight small holes, randomly selected from 25 holes spaced at 1.53 m intervals in a 5×5 grid. Like Menzel's chimpanzees, our vervets ignored the baiting order and tended to minimize the distance travelled (Fig. 1a). However, they never visited more than six hiding places, confirming earlier reports that monkeys and apes differ dramatically in how many potential destinations they can keep in mind at once[3].

A computer algorithm that always chose the closest site as the next destination did as well as our subjects, suggesting that such a mechanism would be adequate. However, performance on arrays chosen specifically to test for the influence of destinations beyond the nearest showed that the choice of the next destination was strongly influenced by at least two further destinations.

In the 'diamond' experiment, monkeys visited the four vertices of a diamond, one of which was the starting point (Fig. 1b). When the experiment did not require them to return to the start, an optimal route led first to both middle locations and then to the far end, but when the start was also a food site to which the monkey had to return, the optimal route led first to a middle location, then to the far point, and next to the other middle location on the way back to the start. Our subjects took the optimal (diamond) route in 20 of 26 experiments in which they returned to the start. By contrast, they visited both middle locations before the far location on 5 of 7 routes that did not include a return to the start.

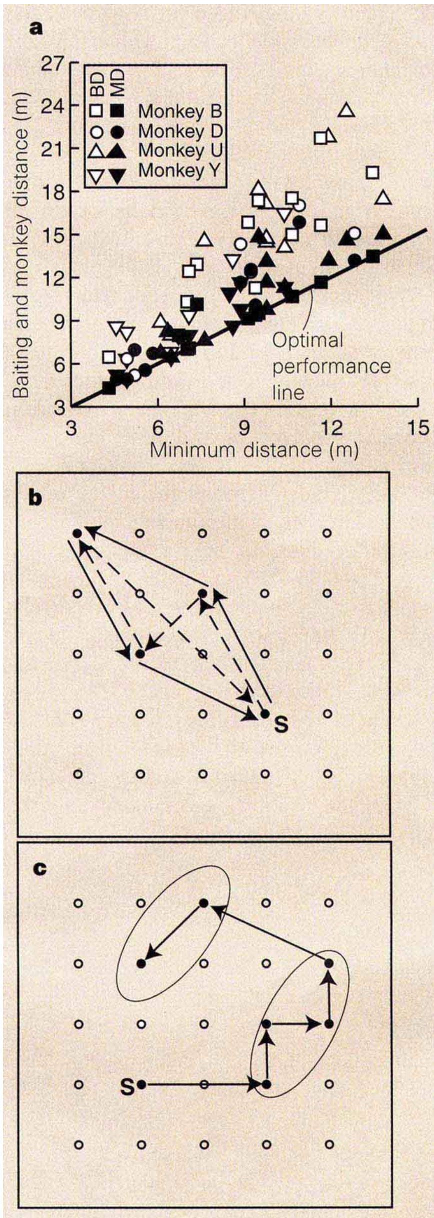

Figure 1 a, Distance travelled by the experimenter while randomly baiting food sites (BD) and the distance travelled by the monkey (MD) visiting these sites, plotted against the minimum distance by which all sites could be visited. **b,** A grape was put in the hole at the monkey's starting point (S) after it had reached the first visit site, requiring a return to the starting point later on in the visit sequence. The diamond route (solid arrows) is shorter than the zig-zag route (dashed arrows). **c,** Example of an unequal-sides configuration, with the two groups of visit sites enclosed in ellipses. Arrows indicate the monkey's route.

A third experiment used four baited locations on one side of the enclosure, and two on the other (Fig. 1c), with the nearest location in each group being equidistant from the starting point. Our subjects chose to visit the side with the greater number of foraging sites first in all of 43 experiments. The decision to go first to this side must be dictated by at least two further destinations beyond the site nearest the monkey at the start. This result also indicates that factors beyond distance minimization might be important, for example, maximizing the harvest early in the trip. These considerations also require that future destinations affect the decision on which destination to visit next.

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Even odder carbons

In commenting on our recent observation that there are more organic compounds with an even number of carbon atoms than with an odd number (*Nature* **384**, 320; 1996), P. G. Stanley (*Nature* **385**, 782; 1997) suggests that "The pronounced excess of C-even compounds among those with large numbers of carbon atoms could be explained if a significant proportion of the compounds are dimers or other polymers". In fact, only a small proportion of the seven million compounds listed in Beilstein are dimers or higher polymers.

M. Kaser in the same issue points out that "Many of the naturally occurring organic compounds… are undoubtedly derivatives either of hexose sugars or of