

recycling processes (converting HBr to BrO) are likely to be very efficient under the conditions in a volcanic plume. We conclude that local ozone depletion and small ozone 'holes' are likely to occur in the vicinity of active volcanoes, because 1 p.p.b. of BrO can destroy about 10 p.p.b. of ozone per minute. Ozone measurements close to the plume should be performed to investigate this effect. (We note that bromine-related total ozone losses in the polar troposphere and the Dead Sea basin have been observed at much lower BrO mixing ratios of ~30 parts per trillion (p.p.t.) and 180 p.p.t., respectively^{7–12}.) We also point out that the amounts of bromine emitted from volcanoes²⁵ are sufficiently large to play a role not only in the stratosphere²⁶, but also in tropospheric chemistry. Once released to the free troposphere, the lifetime of reactive Br is sufficiently long⁸ to allow regional and perhaps hemispheric mixing.

The relative abundance of BrO and SO₂ in the gas carries information about changes in the geophysical state of the volcano, which is of great importance for risk assessment. This information has been derived from HCl/SO₂ ratios determined by ground-based solar Fourier-transform infrared (FT-IR) spectroscopy²⁷. However, BrO/SO₂ measurements can be made simultaneously by optical spectrometers (described here), which are simpler than FT-IR spectrometers, are more easily deployed and automated, and allow a time resolution (~5 minutes) comparable to the time constants of variations in seismic signals. □

Methods

Data acquisition

The sequential scanning Mini-MAX-DOAS differs from the system described in ref. 11 in that a miniature spectrometer was used (OceanOptics Inc. USB2000, crossed Czerny-Turner arrangement, $1/f = 2.2$, 2,400 grooves mm⁻¹ grating, spectral range 251–402 nm, resolution 0.7 nm FWHM, CCD detector (2,048 elements at 12.5 μm centre-to-centre spacing) coupled to a 12-bit ADC connected to a PC via a USB interface). A Hoya U330 filter blocked the visible light at wavelengths >400 nm to reduce the stray light. The telescope was attached to a stepper motor mounted on a tripod to allow pointing it at angles between 10° and 90° above the horizon under computer control. In order to reduce the CCD dark current and temperature drift of the electronic offset signal and to stabilize the optical bench, the complete USB2000 spectrograph was kept at a temperature of 8 °C by Peltier cooling. To avoid water condensation, the whole unit was sealed in an argon-filled metal Dewar vessel; silica gel was added to keep the interior dry in case of leakage. The entire system (notebook PC, cooling system, spectrometer and stepper motor) operates on 12 V for about 24 hours from a car battery.

Data analysis

The SCDs of BrO and SO₂ were derived from the recorded spectra by the DOAS algorithm implemented in the WinDoas V2.10 software package from IASB (Belgium Institute for Space Astronomy)²⁸. In the case of scattered sunlight as light source, the solar Fraunhofer lines (modulating $I_0(\lambda)$) have to be removed carefully in order to allow sensitive measurements of trace species. A Fraunhofer reference spectrum (FRS, $I_0(\lambda)$) was recorded each day, and care was taken that the FRS did not contain absorption by the volcanic plume. For the BrO evaluation, a spectral range containing eight absorption bands of the A²Π_{3/2} ← X²Π_{3/2} transition of the BrO molecule (320–360 nm, 542 spectral channels) was chosen. Literature reference spectra of BrO, NO₂, O₃, SO₂ and O₄ (all degraded to match the spectral resolution of our instrument by convolution with the instrumental function), a calculated 'Ring spectrum' (to compensate for reduction of the observed optical densities of solar Fraunhofer lines on long atmospheric light paths, that is, large solar zenith angles, due to rotational Raman scattering²⁹), a polynomial of fifth order (to remove broadband structures and the effects of Rayleigh and Mie scattering), and the FRS were simultaneously fitted to the measurement spectra using a nonlinear least-squares method³⁰. Sulphur dioxide was determined in the range from 307.5 to 316 nm (115 channels) encompassing four SO₂ absorption bands. Besides SO₂, reference spectra of NO₂, O₃, ClO, BrO, FRS and the 'Ring spectrum' as well as a second-order polynomial were included in the fit.

Received 13 November 2002; accepted 1 April 2003; doi:10.1038/nature01625.

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Acknowledgements We thank the staff of Montserrat Volcano Observatory, in particular G. Thomson, P. Dunkley and M. Edmonds, for their support during the field measurements.

Competing interests statement The authors declare that they have no competing financial interests.

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Parallel extinction risk and global distribution of languages and species

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There are global threats to biodiversity with current extinction rates well above background levels¹. Although less well publicized, numerous human languages have also become extinct, and others are threatened with extinction^{2,3}. However, estimates of the number of threatened languages vary considerably owing to the wide range of criteria used. For example, languages have been classified as threatened if the number of speakers is less than 100,

Table 1 Comparisons of the threats to birds and languages in relation to population size and decline

Population size	Languages		Birds	
	Not declining	Declining	Not declining	Declining
Extinct	306 (4.4%)		125 (1.3%)	
1–49	256 (4.1%) CR	101 (1.6%) CR	39 (0.40%) CR	19 (0.20%) CR
50–249	379 (6.1%) EN	81 (1.3%) CR	30 (0.31%) EN	59 (0.61%) CR
250–999	691 (11.2%) VU	77 (1.2%) EN	67 (0.69%) VU	97 (1.0%) EN
1,000–2,499	634 (10.3%)	50 (0.8%) EN	?	103 (1.1%) EN
2,500–9,999	1,064 (17.2%)	41 (0.7%) VU	?	438 (4.5%) VU

Threat status (CR, critically endangered; EN, endangered; VU, vulnerable) is shown and was defined by using standard biological classification⁴. The proportion extinct is in relation to the number currently extant; the proportion threatened is in relation to the number assessed (that is, excluding deficient data).

500, 1,000, 10,000, 20,000 or 100,000 (ref. 3). Here I show, by applying internationally agreed criteria for classifying species extinction risk⁴, that languages are more threatened than birds or mammals. Rare languages are more likely to show evidence of decline than commoner ones. Areas with high language diversity also have high bird and mammal diversity and all three show similar relationships to area, latitude, area of forest and, for languages and birds, maximum altitude. The time of human settlement has little effect on current language diversity. Although similar factors explain the diversity of languages and biodiversity, the factors explaining extinction risk for birds and mammals (high altitude, high human densities and insularity) do not explain the numbers of endangered languages.

Species extinction risk is conventionally assessed by using standard quantitative criteria⁴ based on population size, actual or suspected population decline, range size changes and habitat fragmentation. Table 1 shows how these standard biological definitions⁴ of ‘critically endangered’, ‘endangered’ and ‘vulnerable’ relate to whether a population is declining and to population size. Species with small populations sometimes persist for long periods but have a considerably enhanced risk of extinction⁵ as a result of demographic stochasticity, environmental stochasticity, the Allee effect⁶ or genetic stochasticity⁷.

To compare the threats to biodiversity with those to languages, I used data⁸ on the estimated number of mother-tongue speakers along with any information on whether population declines have occurred to classify the extinction risk for all 6,809 living languages in the world, with the standard biological definitions (Table 1). I also counted the number of extinct languages, where documented, excluding any that went extinct before AD 1600 (the date conventionally used in species extinctions). For comparison I show the data⁹ on 9,797 species of birds analysed in exactly the same manner, except that they also include inferred declines, such as those due to habitat deterioration. Each data set is likely to have similar problems: the population sizes are estimates, some data are out of date, and some species and languages have undoubtedly gone extinct since the data were compiled (46 of the languages were classified as having just one speaker). This comparison suggests that the risks to languages greatly exceed those to birds: there are many more recorded language extinctions and substantially more rare languages. For example, 357 languages have fewer than 50 speakers.

My extinction risk classification for languages is conservative. The language database⁸ is excellent but lacks systematic data on range size, on whether quantified rapid declines have occurred, on

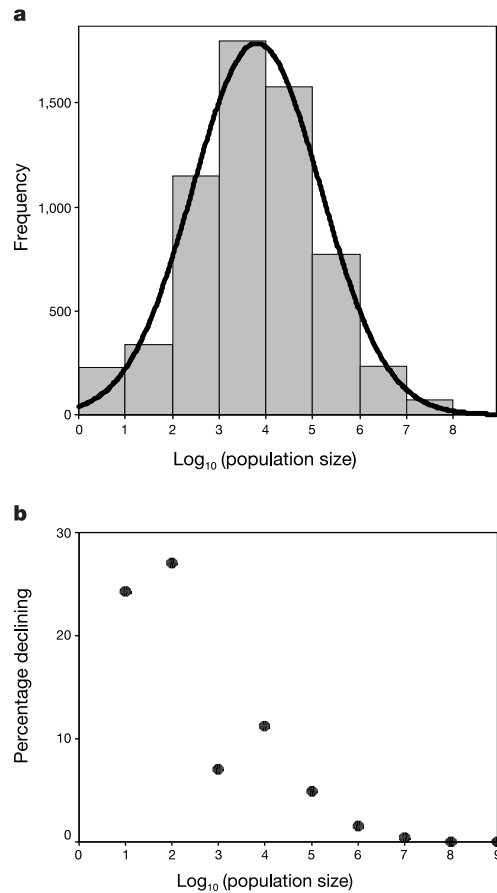


Figure 1 Language abundance and changes. **a**, Frequency distribution of extant global languages on a log₁₀ scale with a fitted normal distribution (mean 3.80, s.d. 1.38). **b**, Percentage of languages that are documented as declining in relation to the number of speakers.

whether the range is fragmented and on likely future declines—all of which are used by biologists to categorize extinction threats⁴. Of the birds classified as critically endangered on the basis of the entire data set⁹, only 64% (117 of 182) would have been classified as such on the basis of just population size and whether population decline is occurring. The equivalent figures are 58% (186 of 321) of endangered and 74% (505 of 680) of vulnerable birds. In the absence of more extensive information the threat status of many languages are similarly likely to be underestimated.

Table 2 compares the threat status of birds and mammals (based on all criteria: population size, decline, rapid decline, range size, habitat fragmentation and inferred threats) and languages, using the analysis from Table 1 (based just on population size and whether population decline is occurring). As described in the previous paragraph the analysis in Tables 1 and 2 underestimates the number of endangered languages. Even with this conservative comparison it is clear that the risks to languages exceed those to birds and mammals. Table 2 also shows that languages are at greater risk, both as a proportion of the total number and in absolute numbers.

Table 2 Comparisons of the threats to languages, birds and mammals: frequency distribution of languages, birds and mammals in each threat category

Category	Extinct	Critical	Endangered	Vulnerable	Data deficient	Total described extant
Languages	306 (4.5%)	438 (7.1%)	506 (8.2%)	732 (11.9%)	639	6,809
Birds	125 (1.3%)	182 (1.9%)	321 (3.3%)	680 (7.0%)	79	9,797
Mammals	87 (1.9%)	180 (4.1%)	340 (7.7%)	610 (13.9%)	240	4,630

Threat status of birds and mammals was assessed by using the complete IUCN criteria⁴, whereas the classification of languages is based solely on population size and decline, and is therefore underestimated. The proportion extinct is in relation to the number currently extant; the proportion threatened is in relation to the number assessed (that is, excluding deficient data).

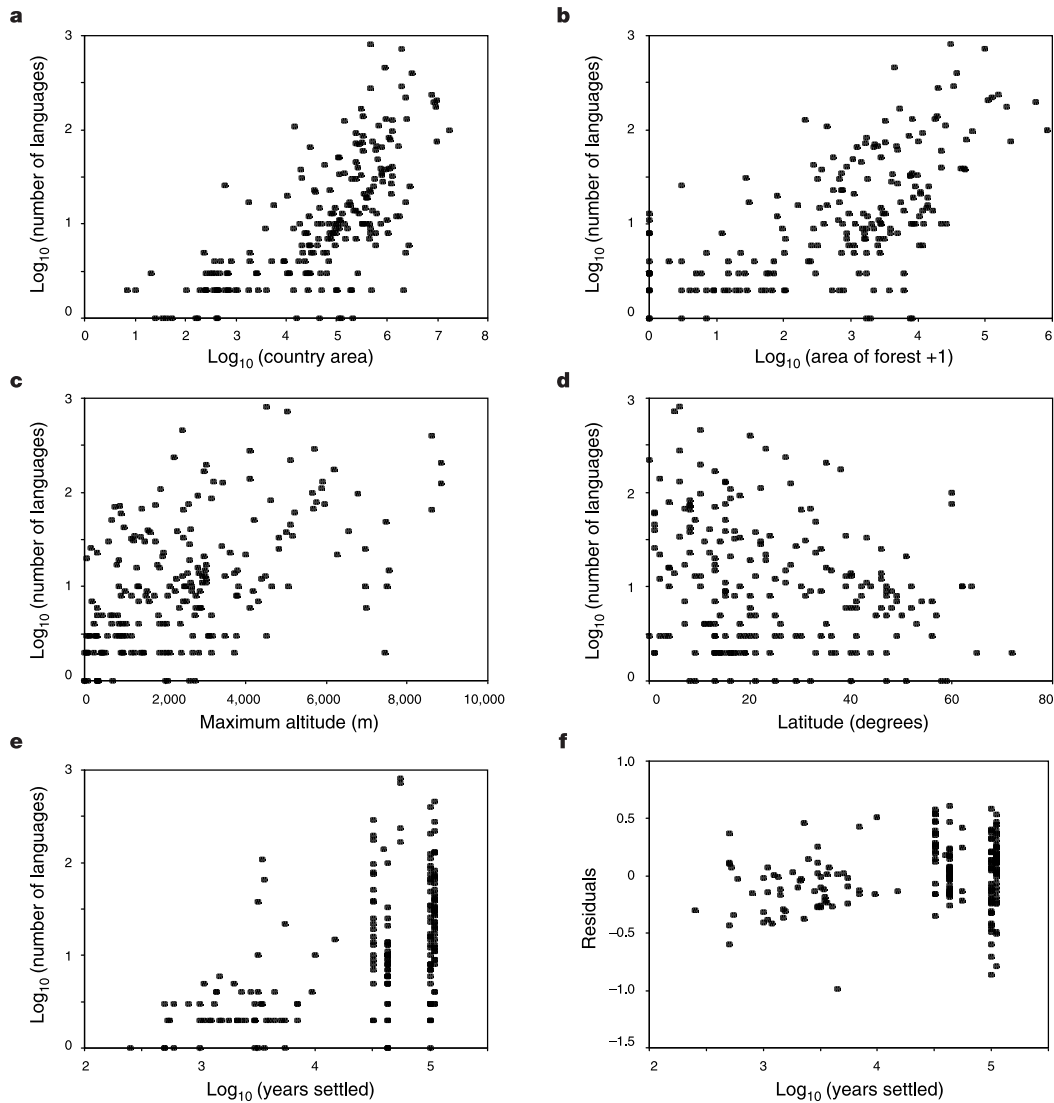


Figure 2 Factors correlating with language diversity. Relationships between \log_{10} (number of languages) and \log_{10} (area) ($r = 0.69$, $n = 214$, $P < 0.001$) (a), \log_{10} (area of forest + 1) ($r = 0.63$, $n = 199$, $P < 0.001$) (b), maximum altitude ($r = 0.52$, $n = 214$, $P < 0.001$) (c), latitude ($r = -0.24$, $n = 214$, $P < 0.001$) (d), \log_{10} (number

of years since first settlement) ($r = 0.48$, $n = 210$, $P < 0.001$) (e) and unstandardized residuals of the area relationship shown in a against \log_{10} (years settled) ($r = 0.14$, $n = 209$, $P < 0.041$) (f).

The frequency of languages of a given population size approximates to a log normal distribution (Fig. 1) with a small number of very abundant languages—a median of 6,300 mother-tongue speakers per language—although it is actually significantly different from normality (Kolmogorov–Smirnov test with Lilliefors significance correction = 0.24, d.f. = 6,168, $P < 0.001$) with a detrended Q–Q plot showing more very rare languages than expected.

Is there any evidence that languages might have a minimum viable size similar to the minimum population sizes of animal and plant populations? Figure 1b shows that the proportion of the languages that are documented as declining or predominantly elderly is negatively correlated with population size ($r_s = -0.966$, $n = 9$, $P < 0.001$). As with the Allee effect^{5,6}, this could mean that rarer languages will become even rarer and so go extinct. An obvious mechanism for such an Allee effect is that as languages become rare they become less attractive for people to learn and use.

There has been considerable interest in identifying areas of greatest biodiversity^{10,11}, and various factors affect global patterns of language diversity^{12–15}. I therefore sought to examine whether global linguistic

diversity and biodiversity are correlated and explained by the same variables. Countries with high language diversity also have high bird diversity ($r = 0.75$, $n = 204$, $P < 0.001$, both \log_{10} transformed) and mammal diversity ($r = 0.69$, $n = 197$, $P < 0.001$, both \log_{10} transformed). This analysis is obviously confounded by area, but the correlations remain once the effect of area has been removed: the residuals from the relationships between \log_{10} (number of languages or species) and \log_{10} (area) are correlated for both languages and birds ($r_s = 0.41$, $n = 204$, $P < 0.001$) and languages and mammals ($r_s = 0.41$, $n = 197$, $P < 0.001$).

The number of languages per country increases with country area (Fig. 2a), area of forest (Fig. 2b) and maximum altitude (Fig. 2c) but decreases with increasing latitude (Fig. 2d). Table 3 shows the results of a general linear model of the factors influencing numbers of languages and the number of bird and mammal species per country. Once the area effect has been incorporated, languages, birds and mammals are all more diverse in low-latitude countries, in countries with large areas of forest and, for birds and languages, in mountainous countries. Island countries have significantly fewer

Table 3 Correlates of the abundance of languages, birds and mammals

Variable	Languages		Birds		Mammals	
	F (sign)	P	F (sign)	P	F (sign)	P
Log ₁₀ (area)	39.09 (+)	0.001	33.45 (+)	0.001	20.61 (+)	0.001
Latitude	77.46 (-)	0.001	60.20 (-)	0.001	37.62 (-)	0.001
Log ₁₀ (forest area)	16.12 (+)	0.001	82.73 (+)	0.001	26.62 (+)	0.001
Altitude	4.12 (+)	0.044	4.68 (+)	0.032	0.40 (+)	0.530
Insularity	0.00 (+)	0.957	54.35 (-)	0.001	74.12 (-)	0.001
R ²	0.63		0.81		0.72	

GDP per person, growing season and date of modern human settlement were all considered in the full model but were not significant.

Table 4 Correlates of threatened languages, birds and mammals

Variable	Languages		Birds		Mammals	
	F (sign)	P	F (sign)	P	F (sign)	P
Total diversity	24.53 (+)	0.001	28.38 (+)	0.001	79.37 (+)	0.001
Log ₁₀ (area)	5.09 (+)	0.026	38.99 (+)	0.001	47.88 (+)	0.001
Growing season	8.76 (+)	0.004	14.93 (+)	0.001	1.10 (+)	0.296
Human density	0.04 (-)	0.851	13.83 (+)	0.001	4.57 (+)	0.034
Maximum altitude	0.03 (+)	0.868	19.85 (+)	0.001	7.49 (+)	0.007
Insularity	0.56 (-)	0.454	29.83(-)	0.001	18.71 (-)	0.001
R ²	0.38		0.73		0.76	

Latitude, GDP per person, and log₁₀ forest area, were all considered but were not significant in the model for the number of languages. The numbers of endangered languages and species were square-root transformed prior to analysis.

birds and mammals but similar language diversity to non-island countries.

It has been suggested¹² that the length of the growing season (defined as the number of months in which the temperature exceeds 6 °C and rainfall in millimetres twice exceeds the average temperature in degrees Celsius¹²) influences language diversity but there was no evidence for this in this analysis. Furthermore, neither Gross Domestic Product (GDP) per person nor number of televisions per 1,000 people (as an index of national and global communication) was significantly related to the number of languages in a country.

Just as colonization and speciation explain increases in species within a new site, colonization and language divergence should result in increases in the numbers of languages after a country is first occupied. To examine whether time since settlement is currently important in determining language diversity I used the best estimates from refs 16 and 17 for the settlement of continents derived from archaeological and genetic data (Asia 100,000, Australia 55,000, Europe 43,000 and America 32,000 years BP) and a wide range of archaeological and historical information for settlement dates for islands. The time of settlement of the Americas is particularly controversial with current estimates ranging from 50,000 to 14,000 years BP. Language is thought to have appeared in Africa at some time between 50,000 and 150,000 years ago^{16,17}. It is generally accepted that the origin of languages predated the global spread of *Homo sapiens sapiens* and I used a date of 110,000 years BP.

Although the number of languages per country is significantly correlated with the number of years since settlement (Fig. 2e), many of the recently settled countries with few languages are small islands, and once the effect of area is removed, the relationship is greatly weakened (Fig. 2f). Settlement date was not significant when added to the general linear model (Table 3). Thus, the period since settlement has surprisingly little effect on language diversity. For example, the Pacific country of Vanuatu has 110 languages, yet the archaeological evidence shows only about 3,500 years of occupation. The two most likely reasons for duration's being relatively unimportant on a global scale are that languages can evolve so quickly that differences in settlement times are unimportant, and that processes such as the widespread loss of languages over much of Africa, Asia and Europe as a result of the development of Neolithic agriculture¹² suggest that languages are in a state of continual flux to which settlement time makes only a small contribution. This

supports the conclusion¹⁸, based on an analysis of linguistic stocks, that the high linguistic diversity within the Americas is not incompatible with the archaeological evidence that the Americas were occupied only relatively recently, such as 14,000 years BP.

Countries with the most endangered and extinct languages also have more endangered and extinct birds ($r_s = 0.36$, $n = 215$, $P < 0.001$) and mammals ($r_s = 0.34$, $n = 200$, $P < 0.001$). However, when expressed as a proportion of total numbers, the relationships between languages and species are not significant (birds: $r_s = -0.109$, $n = 215$, $P = 0.119$; mammals: $r_s = 0.03$, $n = 200$, $P = 0.662$). A general linear model analysis (Table 4) showed that, once the total number of species and area are controlled for, the numbers of endangered languages and birds are higher in areas with a long growing season (presumably because the lower ecological risk^{12,13} allows greater diversification). The numbers of endangered birds and mammals increase with human density (presumably because of greater habitat loss). There are more endangered birds and mammals in mountainous countries but fewer on islands. By contrast, the number of endangered languages did not vary with human density, altitude or insularity. It therefore seems that although patterns of language, bird and mammal diversity are similar, the reasons for extinction risk differ between cultural and biological diversity. □

Methods

Data sources were as follows: languages⁸, birds⁹, mammals¹⁹, total number of species¹⁹, closed non-plantation forest cover²⁰ in square kilometres (expressed as log₁₀(area of forest + 1)), GDP²¹, climate²² for calculating growing season¹³, population altitude, area in square kilometres and latitude²³. Arithmetic means were taken if a range of values was given. Data for extinctions before 1600 AD were excluded. The bird data include three species classified as 'extinct in the wild', which I classified as 'extinct'. The data on bird extinctions²⁴ includes extinctions after 1500 AD. I excluded *Bulweria bifax*, *Pterodroma rupinarum*, *Arlantisia podarces*, *Porzana astrictocarpus*, *Dysmoropelia dekarchiskos* and *Upupa antaois* because these are all likely to have become extinct before 1600 AD.

Received 3 December 2002; accepted 21 March 2003; doi:10.1038/nature01607.

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Acknowledgements I thank I. Côté, C. Crockford, R. Freckleton, J. Gill, P. Stephens and A. Watkinson for very useful comments.

Competing interests statement The author declares that he has no competing financial interests.

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