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Vulnerability to the mortality effects of warm temperature in the districts of England and Wales

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Warm temperatures adversely affect disease occurrence and death, in extreme conditions as well as when the temperature changes are more modest[1,2]. Therefore climate change, which is expected to affect both average temperatures and temperature variability, is likely to impact health even in temperate climates. Climate change risk assessment is enriched if there is information on vulnerability and resilience to effects of temperature. Some studies have analysed socio-demographic characteristics that make individuals vulnerable to adverse effects of temperature[1–4]. Less is known about community-level vulnerability. We used geo-coded mortality and environmental data and Bayesian spatial methods to conduct a national small-area analysis of the mortality effects of warm temperature for all 376 districts in England and Wales. In the most vulnerable districts, those in London and south/southeast England, odds of dying from cardiorespiratory causes increased by more than 10% for 1 °C warmer temperature, compared with virtually no effect in the most resilient districts, which were in the far north. A 2 °C warmer summer may result in 1,552 (95% credible interval 1,307–1,762) additional deaths, about one-half of which would occur in 95 districts. The findings enable risk and adaptation analyses to incorporate local vulnerability to warm temperature and to quantify inequality in its effects.

Events such as the 2003 European heatwave showed the need to identify people and communities vulnerable to the adverse effects of current weather as well as those of a changing climate[5,6]. Some studies have investigated whether the effects of temperature depend on individual sociodemographic characteristics, for example, their age or gender[3,4]. There has been less work on community-level vulnerability because studies tend to quantify, or at least pool and report, effects for whole countries or large geographical units. Community-level analysis is important for risk and adaptation assessment for a number of reasons: first, some determinants of vulnerability are related to community characteristics. Second, community-level analysis helps measure inequalities in effects, which are important above and beyond aggregate impacts. Third, if the units of analysis are administrative units such as districts, the results map directly to the scale of resource allocation and policy/programme implementation. As there are few local analyses of the effects of temperature, and none covering a whole country, assessments of the health effects of climate change have typically assumed that the observed relationships between temperature and health are transferrable across communities[7].

Some studies have constructed indicators of community vulnerability to weather and climate change based on theoretical considerations[8–10], but have not assessed whether these indicators are associated with smaller or larger health effects. Some recent studies have analysed variations in health effects of temperature at finer spatial resolutions[11–16]. A few of these have focused on short-term episodes[11,12]; others were in small regions[13–16], possibly limiting generalizability. To identify vulnerable and resilient communities, we analysed the effects of warm temperature on mortality in a national study with high spatial resolution.

We quantified the effects of warm temperature on mortality from cardiorespiratory causes for all 376 local authority districts in England and Wales for the period 2001–2010. Cardiorespiratory diseases form a parsimonious set of causes of death that have been consistently linked with increased temperature[1]; they account for about half of all deaths in England and Wales. In sensitivity analysis, we used all non-injury deaths.

We adjusted for other factors that also vary daily and may affect cardiorespiratory mortality, including air pollution[17] (particulate matter below 10 μm in aerodynamic diameter, PM_{10}, concentration in the main analysis; PM_{10} and ozone in sensitivity analysis) and whether a case/control day was a national holiday as differences in behavior and provision of health service may affect mortality on holidays. We conducted separate analyses for men and women and by age group, because both the effects of temperature and their spatial patterns may differ by age and gender. The analysed age groups were <75, 75–84 and 85+ years. The youngest age group was not further divided because only 26% of cardiorespiratory deaths occurred below 75 years and only 4% below 55 years.

To examine vulnerability and resilience, we allowed the magnitude of effect to vary by district. We used a Bayesian spatial model, which uses the empirical similarity of the effects of temperature in neighbouring districts to borrow strength across districts. This approach balances between unstable district-specific estimates (due to the relatively small number of daily deaths in each district) and overly aggregated large-area (for example, regional/national level) estimates that mask local variation. The Bayesian framework estimates both the magnitude of effect and how confident we are about its differences from the national response. We conducted a number of sensitivity analyses, detailed in the Methods, to examine the robustness of our results to analytical choices.

After removing 205 deaths whose postcodes could not be matched to any district, there were 921,288 cardiorespiratory deaths in May–September of 2001–2010 (47% of all deaths in England and Wales over this period). Of these, 441,788 were among men and 479,500 among women. Of these deaths, 26% were below 75 years of age, 35% between 75 and 84 years and 39% in those aged 85 years or older. Nationally, women aged 85+ years were the most vulnerable to the effects of warm temperature, that is, had a larger response (Table 1), consistent with most previous

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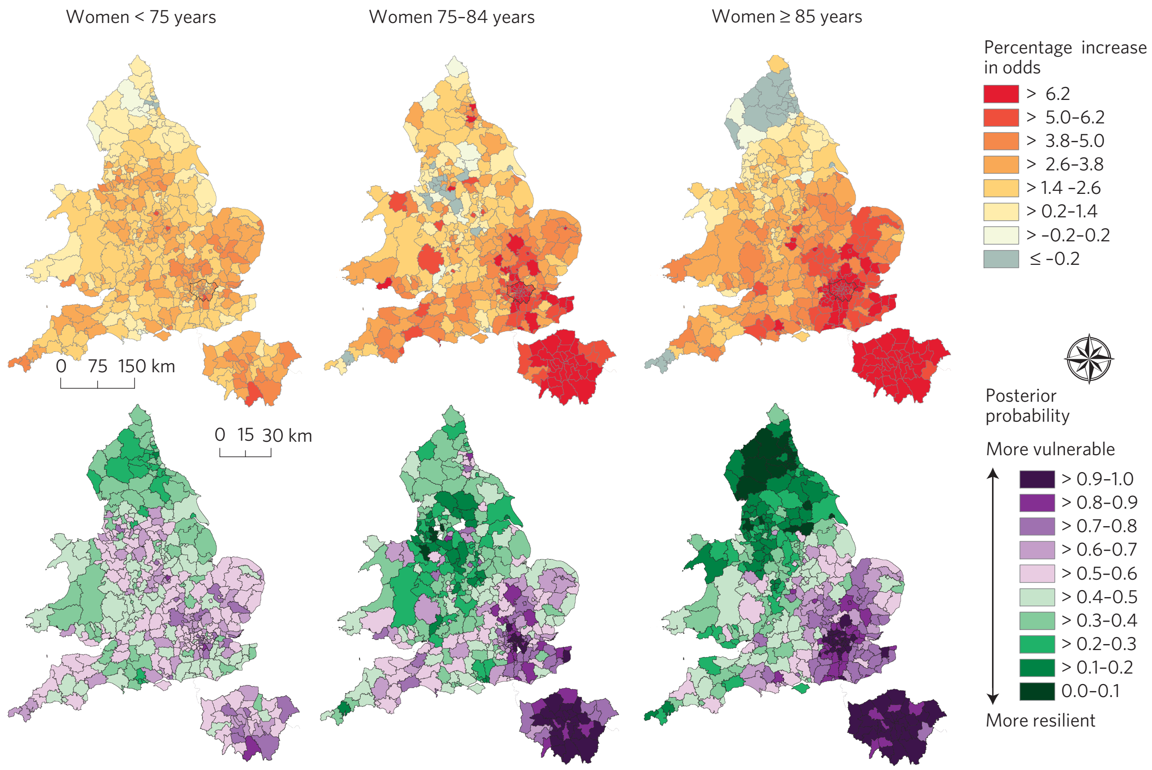

Figure 1 | Percentage increase in the odds of cardiorespiratory death (women) for 1 °C increase in mean daily summer temperature above district-specific thresholds and the posterior probabilities that the estimated effect size is different from the national average. Posterior probability ranges between 0 and 1, with a value close to 0 indicating high confidence in resilience (that is, effect size smaller than the national average) and a value close to 1 indicating high confidence in vulnerability (that is, effect size larger than the national average). A posterior probability of 0.5 indicates an effect that is indistinguishable from the national average. Below each map of England and Wales is an enlarged map of Greater London. See Supplementary Fig. 2 for results with a common temperature threshold. See Supplementary Fig. 4 for winter results.

analyses[3,4,18,19]. Above 75 years of age, women were somewhat more vulnerable to warm temperature than men, consistent with other studies of temperature[3].

The proportional effects of warm temperature on mortality varied substantially across districts, especially among women. In some districts, there was no increase in mortality on warmer days; at the other extreme, the odds of dying increased by more than 10% per 1 °C warmer temperature for older women in some districts (Fig. 1). In every age group, women in districts in London and in south and southeast England were more vulnerable to the effect of warm temperature than the national average. The most resilient communities were those in the far north. In the most vulnerable districts (for example, the deprived districts of Hackney and Tower Hamlets in London), the odds of dying would more than double on hot days such as those of August 2003. There was relatively high statistical confidence in the observed vulnerability and resilience patterns for the two older age groups, with an 80% or more posterior probability that the effects were lower/higher than the national effects (Fig. 1). Men in and around London were also more vulnerable to the mortality effects of warm temperature (Fig. 2) but there was less statistical confidence in the findings than there had been for women; some London districts nonetheless reached the 80% posterior probability for men as well. The larger effects of warm temperature in the south do not support the hypothesis that people living in typically warmer areas of England and Wales have (physiologically or behaviourally) adapted to their local temperature as observed in some urban studies in the USA[20]—had there been adaptation, for example, by use of air conditioning, effect sizes for each 1 °C would be smaller where temperatures are regularly higher.

Table 1 | National-level per cent increase in the odds of cardio-respiratory death for 1 °C increase in mean daily summer temperature above district-specific thresholds.

Age group	Men	Women
< 75 years	2.7 (1.6, 3.8)	2.4 (1.0, 3.9)
75–84 years	2.2 (1.1, 3.2)	3.4 (2.3, 4.6)
85+ years	2.4 (1.2, 3.6)	3.9 (3.0, 4.8)

Numbers in brackets show 95% credible intervals, which are the 2.5th and 97.5th percentiles of the posterior distributions of effect size parameters from the Bayesian model. See Supplementary Table 2 for winter results.

If the estimated associations are causal, there would be an additional 1,552 (95% credible interval 1,307–1,762) cardio-respiratory deaths in a single summer that is warmer by 2 °C (Table 2; Fig. 3); 2 °C is about the range of annual summer mean temperatures over the decade of our analysis. Of these deaths, 38% would be in men and 62% in women. Just under one-half would be above 85 years of age, where both the effect sizes and the total number of deaths are largest. These deaths would be distributed unevenly among districts, with 95 of 376 districts accounting for one-half of all deaths. This uneven distribution is both because these districts are more populous and because they have larger death rates (Supplementary Fig. 1) and/or proportional effect sizes. For comparison, a winter warmer by 2 °C would see 6,255 (5,963–6,581) fewer deaths, with a weaker spatial pattern than those of summer effects (see Supplementary Methods for details of winter analysis).

Variations in the mortality effects of temperature across districts may be either due to concentration of vulnerable individuals or

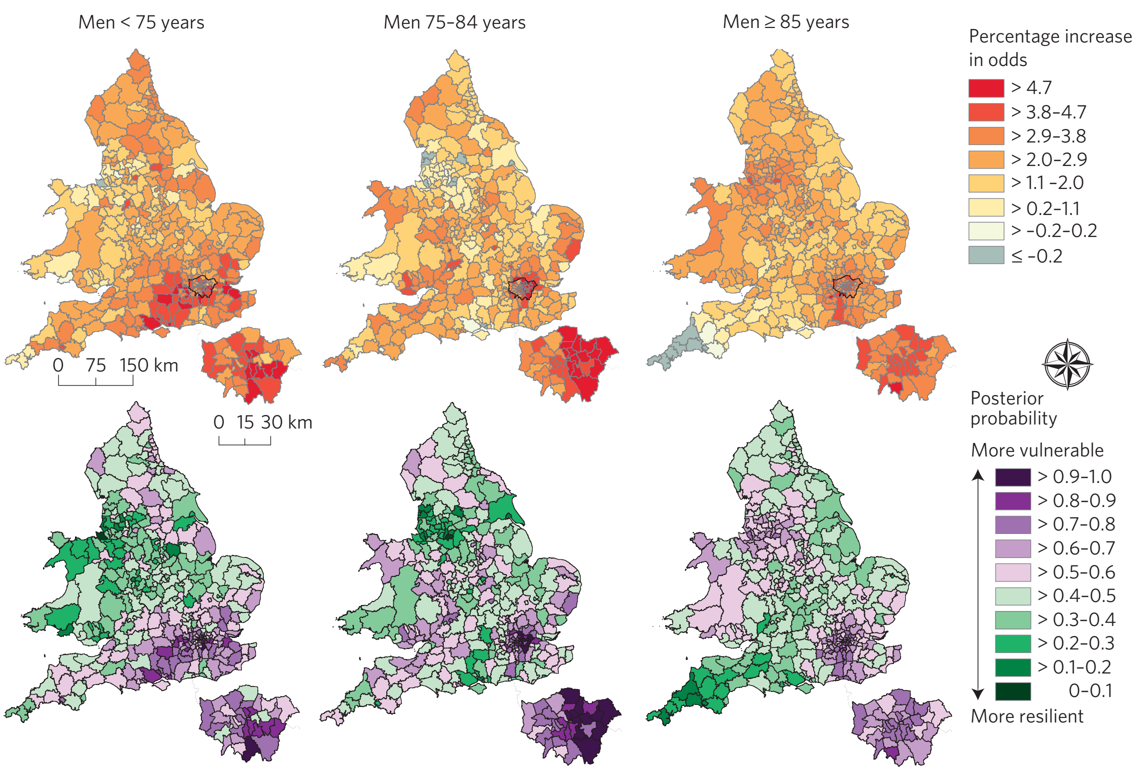

Figure 2 | Percentage increase in the odds of cardiorespiratory death (men) for 1 °C increase in mean daily summer temperature above district-specific thresholds and the posterior probabilities that the estimated effect size is different from the national average. Below each map of England and Wales is an enlarged map of Greater London. See Supplementary Fig. 3 for results with a common temperature threshold. See Supplementary Fig. 5 for winter results.

differences at the community level (noting that some individual lifestyle and psychosocial factors are themselves related to the local physical, food and social environments). We examined whether the proportional effect is itself associated with rural versus urban status, deprivation and green space in the community of residence. These characteristics may modify the mortality effects of temperature because they may dampen (for example, green space) or exasperate, through the so-called urban heat island, the ambient temperature[21], or because they are indicators of certain services that mitigate the effects of temperature on mortality (for example, emergency response time and quality of care). The mortality effects of temperature were not statistically significantly different between rural and urban areas, perhaps because our fine-grid temperature data had already accounted for the urban heat island effect and hence had internalized this phenomenon in the temperature data. The increase in the odds of mortality was generally smaller where there was more green space[4], although this role was not statistically significant in most age–sex groups. There was no consistent or statistically significant relationship between deprivation quintile and the proportional effect of temperature on mortality, although the effects on women tended to be larger in more deprived districts. The lack of a relationship with community deprivation, compared with the USA for example[20], may be partly because the use of air conditioning, an important means of combating heat, is universally low in the UK. If healthcare utilization is a mechanism for reducing the mortality effects of heat, the role of deprivation may also be attenuated due to the universal health coverage in the UK. Despite having similar proportional effects, deprived districts experience a larger absolute effect of temperature, because there are more deaths in deprived districts. For example, of the additional deaths in a 2 °C warmer summer, around 254 would be in the least deprived quintile of districts and around 407 in the most deprived quintile.

Table 2 | Number of additional cardiorespiratory deaths that would be expected during 5 summer months if temperatures were warmer by 2 °C by broad regions.

Region	Number of deaths (95% credible interval)
Southern England (South East, South West, London and East of England)	960 (835, 1,089)
Midlands (East Midlands, West Midlands)	236 (178, 284)
Northern England (North East, North West, Yorkshire and the Humber)	267 (151, 376)
Wales	89 (48, 125)
Total	1,552 (1,307, 1,762)

See Supplementary Table 3 for winter results.

In sensitivity analyses, our results were robust to analytical choices (Supplementary Table 1): the estimated effect sizes had the same spatial patterns when we used district-specific temperature thresholds (main analysis) and a common threshold in all districts (Supplementary Figs 2 and 3); the correlation coefficients of the two sets of effect sizes ranged between 0.83 and 0.98 for different age–sex groups. The results were very similar when we adjusted for ozone in addition to PM_{10}, when analysis was restricted to the three warmest months (June–August), when the daily maximum temperature was used instead of daily average and when we used different lags for temperature and air pollution as done in some previous analyses[18,19,22,23]. The effect sizes were generally smaller when we used all non-injury deaths, possibly because these deaths consist of those associated with temperature (mainly cardiorespiratory) and those that are unrelated to it.

The main innovation and contribution of our study is a national small-area analysis of the effects of temperature on mortality, which

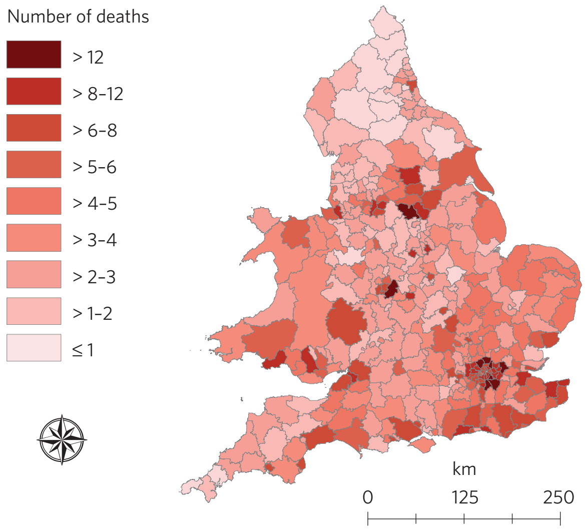

Figure 3 | The number of additional cardiorespiratory deaths in the districts of England and Wales that would be expected during five summer months if temperatures were warmer by 2 °C. See Supplementary Fig. 6 for winter results.

reveals vulnerability and resilience across all communities. There are also some limitations to our analysis. The use of fine-grid temperature lessened exposure misclassification compared with regional temperature and incorporated the urban heat island effect in the exposure. Despite this improvement, a limitation shared with all studies of environmental risks is that exposures assigned through residential address may not reflect people's true exposure if they spend significant time away from home. This concern is likely to be less relevant in older ages, when people spend more time at or near their residence, than in working ages. Although we accounted for the non-linearity of temperature–mortality association and the role of temperature on previous days through a threshold model with lagged average temperatures, more flexible models exist[24]. These models are not currently integrated in a Bayesian spatial framework. Piecewise linear models with lagged average temperatures have been found to describe the data equally well[1,3,19,23–25], also confirmed in our exploratory analysis and in our sensitivity analyses around lags. National distributed-lag analysis indicates that the strongest effect is from the current day's temperature with statistically significant effects continuing for two to three days[24]. Finally, although we could assess vulnerability and resilience in relation to age, gender and selected community characteristics, our results should initiate further investigation of vulnerability and resilience factors, especially those that may be directly used for adaptation, for example housing and healthcare access and quality. To do so for individual characteristics other than age and gender would require record linkage, for example, linking deaths with the census and general practice and hospitalization records.

Although weather and climate change are predominantly large-scale phenomena, resilience and vulnerability to their effects are highly local and therefore should be accounted for in our analyses of risk and policy responses. Our small-area spatial framework and methods can also be applied to other countries with geo-coded mortality and temperature data. The former is now available in many high-income countries and some middle-income countries. Small-area data on environmental variables can be obtained using a combination of ground-based monitoring and remote sensing, together with models that interpolate throughout the whole country as done in the gridded data used here. The high-resolution findings on health effects of temperature allow local interventions that reduce the adverse impacts of current and future weather in vulnerable districts, such as alerts to the public and nursing homes, and health service planning to respond to emerging warm temperatures.

Methods

Data. Death records were from national vital statistics held by the UK Small Area Health Statistics Unit. Age, postcode of residence at time of death and date of death were available for each record. We used deaths that occurred in May–September. In sensitivity analysis, we restricted the analysis to the warmest three months (June–August).

Daily temperatures at 5 km × 5 km resolution were from the UK Met Office with methods described elsewhere[26]. In brief, the daily temperature in each grid is estimated based on inverse-distance-weighted interpolation of monitoring data, also accounting for latitude and longitude, elevation, coastal influence and proportion of urban land use. In the main analysis, we used mean daily temperature, calculated as the average of daily maximum and minimum temperatures. In sensitivity analysis, we used daily maximum temperature. We used the average of temperature on day of death and the preceding three days in the main analysis to allow for the possibility that the health effects may be cumulative[18,19,22,23]; this duration of averaging provides near-identical results to a more flexible model of lagged temperatures[24]. In sensitivity analysis, we used alternative lag durations, including temperature on the day of death alone, which is found to have the strongest association with mortality[1,27].

We calculated daily PM_{10} concentrations by combining two data sources: annual average PM_{10} levels in 1 km × 1 km grids from the UK government Department for Environment, Food and Rural Affairs (DEFRA) Ambient Air Quality Assessment and daily monitoring data for every day of the analysis period from DEFRA's Automatic Urban and Rural Network. As PM_{10} concentrations are correlated across monitors over time, we estimated location-specific daily PM_{10} by scaling the gridded annual estimates so that they preserved the daily patterns of the data from monitors. We used an average of PM_{10} on the day of death and on preceding two days based on evidence from previous studies[28], with sensitivity analysis around lag duration.

We assigned temperature and PM_{10} on/preceding the day of death to each death record (and to control days as defined below) from the grid that contained the coordinates of the centroid of the decedent's postcode of residence (average area covered by a postcode is <0.1 km^2; median and 99th percentile of distances between centroid of each postcode and its nearest neighbour are 52 m and 760 m, respectively). Using high-resolution temperature data is advantageous to regional daily temperature because day-to-day temperature changes can be highly localized (Supplementary Fig. 7). Rural–urban status was based on the Office for National Statistics classification. Deprivation was measured using the Carstairs score, which combines indicators on unemployment, social class, crowding of housing and (lack of) vehicle ownership. These variables and green space (as the percentage of the Census ward)[29] were assigned to each death record through the coordinates of the centroid of the postcode of residence.

Statistical methods. We used a time-stratified case-crossover design, commonly used for analysing effects of short-term exposures. Temperature on the day of death (case day) and as relevant, preceding days, is compared with the temperature on control days on which the death did not occur[30]. The case-crossover design naturally controls for potential confounding factors that are time-invariant or that vary slowly over time, for example, ethnicity, socio-economic status, smoking, healthcare and obesity. We used control days on the same day of the week as the case day, to automatically adjust for day of the week, and in the same calendar month to avoid the so-called overlap bias[31].

The relationship between warm temperature and mortality is typically non-linear with virtually no effect below some threshold, and a dose-response at higher temperatures, confirmed in exploratory analysis of our data. Therefore, we analysed the temperature-mortality association using a piecewise linear model, as also used in previous national or regional analyses[1,3,19,23,25]. We set the thresholds in two alternative approaches: district-specific thresholds (main analysis) and a common threshold for all districts (sensitivity analysis). The first approach implies that the hazardous effects of temperature start at a higher temperature where the long-term temperature is warmer. The second approach implies that hazardous effects begin at about the same temperature in all districts. We selected both types of threshold empirically, by using the Deviance Information Criterion. The district-specific thresholds were the 85th percentile of each district's summer temperatures and the common threshold was 18 °C. District-specific thresholds ranged between 15.4 °C in northwest England and 19.9 °C in the City of London.

We used a Bayesian spatial model to borrow strength across districts. In this approach, the estimated effect in each district is influenced by its own data and by those of its neighbours. The extent to which neighbours influence one another depends on the variance of the estimated effects in each district and on the empirical similarity among neighbouring districts. We report the district-specific percentage change in the odds of mortality per 1 °C change in temperature, and the posterior probability that the estimated effect size is larger than the national average. We examined whether the proportional effect size itself is associated with characteristics of the community of residence by introducing these variables into the model as modifiers of the effect size. Detailed model specification is provided in Supplementary Methods.

All analyses were done in the software WinBUGS.

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Author contributions

M.E., J.E.B. and P.E. designed the study concept. J.E.B., M.B. and M.E. developed the analytical approach. J.E.B. and D.F. collated and analysed gridded environmental data. J.E.B. analysed mortality effects. J.E.B. and M.E. wrote the first draft of the paper. All other authors contributed to interpretation of results and writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.E.

Competing financial interests

The authors declare no competing financial interests.