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ABSTRACT

There is increasing interest in the unequal socio-spatial distribution of environmental 'goods' and 'bads' and the associated implications for geographical inequalities in health. Until recently, research in this area has focused on solitary environmental characteristics and has been hindered by the absence of geographically-specific measures that recognise the multifactorial nature of the physical environment. However, recent work in the United Kingdom has developed an area-level multivariate index of health-related physical environmental deprivation that captures both pathogenic and salutogenic environmental characteristics. Applications of this index have demonstrated that, at the national level, multiple environmental deprivation increased as the degree of income deprivation rose. Further, after adjusting for key confounders, there was a significant association between multiple environmental deprivation and the health outcomes of local residents. In the current study we tested the methods developed in the UK to create the New Zealand Multiple Environmental Deprivation Index (NZ-MEDIx) for small areas across the country (n=1860). We considered whether socially disadvantaged places in New Zealand had higher levels of multiple environmental deprivation, and if environmental disadvantage exerted an influence on health after adjustment for key confounders such as socio-economic status. We found that although neighbourhoods with higher levels of multiple environmental deprivation tended to have greater social disadvantage, this association was not linear. Further, multiple

environmental deprivation tended to exert a modest effect on health that was independent of the age, sex and socio-economic structure of the population. These findings demonstrate that it is possible to develop an index of multiple environmental deprivation in an alternative national context which has utility in epidemiological investigations.

Key words:

New Zealand; Health inequalities; Environmental deprivation; Environmental justice.

INTRODUCTION

Health outcomes vary substantially across neighbourhoods with the residents of socio-economically disadvantaged places tending to have significantly poorer health than those living in more advantaged areas (Thomas, Dorling, & Smith, 2010). It is likely that a component of these geographical differences in health is affected by characteristics of the environments in which people reside. There is an abundance of studies suggesting that area-level attributes are related to health, wellbeing and related behaviours even after accounting for the variation in individual-level characteristics that occurs between populations residing in different places (Pickett & Pearl, 2001). Nonetheless, the features of places that affect health and health inequalities remain poorly understood. This limitation has been an important impediment for researchers and policy makers working in the field of health inequalities.

One set of area-level characteristics that may be significant in influencing geographical differences in health are various features of the physical environment. In this context, we define the physical environment as all physical, chemical and biological factors, and exclude social and cultural factors. Many previous studies have used an 'environmental justice' framework to consider firstly whether socially disadvantaged populations are exposed to physical environments that are disadvantageous for health, and secondly the social and political processes that have led to this socio-spatial arrangement. There is a multitude of evidence from countries such as the United States, Canada, Sweden, New Zealand and the UK to demonstrate that low income neighbourhoods tend to have poorer quality physical environments (Brainard, Jones, Bateman, & Lovett, 2002; Brulle & Pellow, 2006; Bullard, 1983; Chaix, Gustafsson, Jerrett, Kristersson, Lithman, Boalt et al., 2006; Jerrett, Burnett, Kanaroglou, Eyles, Finkelstein, Giovis et al., 2001; Pearce & Kingham, 2008). In most countries, environmental characteristics such as air pollution, climate, noise, flooding, location of industrial facilities and provision of green space all tend to be distributed to the benefit of more socially advantaged neighbourhoods. Various explanations for the social distribution of environmental goods and bads have been implicated including: the unequal capacity to influence decision making processes such as the investment in environmental infrastructure; historical trends in industrial development, labour markets, suburbanisation and segregation; and economic restructuring including the accompanying organisational shift in the production of pollution (Morello-Frosch, 2002). Given that there is a burgeoning literature documenting the geographical distribution of health-related environmental attributes, it is perhaps surprising that few studies have evaluated the implications of unequal exposure to characteristics of the physical environment for

inequalities in health status. A notable exception has been the North American literature considering the role of exposure to air pollution in establishing and maintaining inequalities in pollution-related health outcomes (e.g. Jerrett, Burnett, Brook, Kanaroglou, Giovis, Finkelstein et al., 2004). Nonetheless, despite calls in the literature (Evans & Kantrowitz, 2002) there has been less consideration given to detailing the spatial distribution of *multiple* features of the physical environment, and the health implications of exposure to multiple environmental deprivation. Whilst there are numerous examples of area-level measures that capture multiple dimensions of the social environment, including some that include a physical environment domain, the constituent variables are not selected exclusively for their health relevance. To our knowledge there have been no attempts to develop a health-specific multiple environmental deprivation index. We define multiple environmental deprivation as a concept analogous to multiple socioeconomic deprivation: it relates to the health-damaging confluence of various pathogenic environmental conditions as well as the absence of salutogenic environmental conditions.

In our recent work in the UK we began to address this research niche. We examined how multiple features of the physical environment act simultaneously to influence geographical differences in health. We developed a UK-wide area-level measure of multiple environmental deprivation that was akin to the various measures of the social environment (e.g. the Carstairs Index, the Townsend Index, or the New Zealand Deprivation Index) that summarise key social concepts such as income, unemployment and social class. Rather than measuring the social environment, the newly created index captured a combination of both pathogenic and salutogenic

4

environmental characteristics for small geographical areas (UK Census Area Statistic wards; n=10,654, average population=5,518). The Multiple Environmental Deprivation Index (MEDIx) combined area-level data on the relative levels of exposure to air pollution, cold climate, industrial facilities, green space and UVB radiation into a single value for small geographically-defined populations (see Richardson et al. (2010) for further details). We appended MEDIx to a measure of area-level social disadvantage and individual-level mortality data and assessed firstly whether multiple environmental deprivation was unequally distributed across areas differentiated in terms of social deprivation, and secondly the extent to which inequalities in mortality in the UK were explained by differential exposure to multiple environmental deprivation. We found firstly that residents of socially disadvantaged places face higher levels of multiple physical environmental deprivation (Pearce, Richardson, Mitchell, & Shortt, 2010). Further, after adjustment for key confounders (age, sex and income deprivation) multiple environmental deprivation had a significant association with health and health inequalities (Mitchell, Richardson, Pearce, & Shortt, 2011). We argued that such measures have significant potential in assisting researchers and policymakers to better understand the role of the environment in shaping health outcomes. It is therefore useful to test whether it is feasible to apply these new methods in different national contexts. Further, if it is possible to develop measures of multiple environmental deprivation elsewhere then it is important to examine whether environmental disadvantage exhibits a similar socio-spatial arrangement and has associations with health that are consistent with the UK findings.

In the current paper, we test the transferability of our earlier UK research to an alternative national context. We apply methods that are comparable to our UK work to develop a measure of multiple environmental deprivation for small areas across New Zealand. We employ New Zealand as an exemplar comparator because, similar to the UK, it is a country with significant and increasing spatial inequalities in health. Regional inequalities in life expectancy increased by approximately 50 percent over the 1980s and 1990s (Pearce & Dorling, 2006). Further, the unequal distribution of environmental characteristics that potentially affect health to the disadvantage of deprived communities has been noted. For example, air pollution levels and contaminated sites have been found to be distributed in this way (Pearce & Kingham, 2008; Salmond, Howden-Chapman, Woodward, & Salmond, 1999), although for other environmental characteristics such as beaches and usable greenspace the opposite social gradient is apparent (Pearce, Witten, Hiscock, & Blakely, 2007; Richardson, Pearce, Mitchell, Day, & Kingham, 2010). To consider whether multiple environmental deprivation is socially and geographically distributed in a similar way to the UK, we examine the relationship between the New Zealand measure and an area-level measure of social disadvantage. We then evaluate whether multiple environmental deprivation is related to health.

METHODS

This study was completed in five stages. First, to inform our choice of environmental variables, we reviewed the national and international literatures to identify attributes of the physical environment that were pertinent in influencing health in New Zealand. In the second stage we acquired relevant spatial datasets relating to

6

the physical environment. The relationship of these environmental attributes with health was confirmed in stage three. Fourth, we constructed our index of multiple environmental deprivation and then finally evaluated whether the index was associated with health in New Zealand. We detail the steps taken below.

Stage 1: Identifying health-relevant dimensions of environmental deprivation

Given the limited quantity of evidence in New Zealand we drew on a combination of national and international research findings to identify characteristics of the physical environment that were pertinent for explaining geographical differences in health. We augmented our UK-based review of the environment and health literature (Richardson, Mitchell, Shortt, Pearce, & Dawson, 2009) in order to identify additional factors that may have relevance in the New Zealand context. We searched literature databases for health-relevant environmental factors (see Richardson et al. (2009) for more details). For each factor identified, evidence of health effects was appraised based on prevalence of the health outcome(s), rigour of the study design, and the strength of association established. For population health relevance we required that at least 10 percent of the New Zealand population were exposed to each environmental factor; the environmental factors that did not meet this threshold were excluded from our analyses. Four New Zealand-specific factors were identified by our literature review, however none of these satisfied the inclusion criteria and were therefore excluded from our analyses (these are shown in Table 1 which give further details). We also assessed whether factors identified to be of consequence to the UK were also relevant to the New Zealand context (Table 2). We sought to balance the international evidence and the often sparse New Zealand research. For example, whilst there is support from the international evidence that local access to

greenspace is related to health, the only study conducted in New Zealand did not find a significant association (Richardson, Pearce, Mitchell et al., 2010). We chose not to exclude greenspace from our index on the basis of the results from a solitary study with a cross-sectional ecological study design.

[Tables 1 and 2]

Based on our assessment of the literature, five environmental factors were identified: air pollution (PM_{10}), climate (average temperature), industrial facilities, UV radiation levels and green space availability. Country-wide data on industrial facilities or emissions were not available hence this factor was excluded from our index.

Stage 2: Dataset acquisition and processing

The most appropriate datasets (Table 3) were carefully selected in order to ensure scientific validity and maximise future utility and reproducibility of the summary measures (Nardo, Saisana, Saltelli, Tarantola, Hoffman, & Giovannini, 2008; Sol, Lammers, Aiking, de Boer, & Feenstra, 1995). Using ESRI ArcMap GIS we rendered each environmental dataset to 2001 Census Area Units (CAUs). CAUs are the second smallest unit for the dissemination of census data in New Zealand, and are the geographical identifier provided with most health datasets including mortality records. In 2001 there were 1860 CAUs, with an average population of approximately 2300.

[Table 3]

Stage 3: Preliminary analysis of associations with health

A preliminary ecological analysis of individual environmental factors was conducted to assess data validity, by confirming that each factor had the expected associations with health outcomes (e.g. air pollution with respiratory disease), after adjusting for relevant confounders. Given the empirical evidence of detrimental health effects at both high and low extremes of UV and temperature this analysis helped identify which extremes were of greatest significance for health in New Zealand.

Individual-level mortality data (including age, sex, cause of death and domicile of residence at death) were obtained from the Ministry of Health for the 5-year period 1999 to 2003, and were matched to CAUs. Mortality counts for leading causes of death (excluding external causes) in New Zealand were generated by age group (0-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65-74, 75-84, 85+), sex and CAU. Age- and sex-specific population counts were extracted for each CAU from the 2001 census. The total study population was 3,734,985 (in 2001), with 129,645 deaths from all causes combined (excluding external) over the 5-year period. Socioeconomic deprivation scores from the 2001 New Zealand Deprivation Index (NZDep2001) (Salmond & Crampton, 2002) were extracted for the CAUs. NZDep2001 is an area-level metric that is well used in epidemiological studies in New Zealand and combines nine variables taken from the census relating to income, employment, communication, support, transport, qualifications, living space and home ownership.

We tested whether each environmental factor had a significant independent association with mortality rates, after adjusting for the influence of age group, sex,

9

and NZDep2001 quintile. Due to over dispersion of the mortality data negative binomial regression models were used (Hilbe, 2007). The models utilised robust standard errors to allow for spatial clustering (Williams, 2000). Models were run in Stata v.10.

Each of the environmental factors had expected associations with mortality, and the results for temperature and UV informed our treatment of these variables. Increased temperature was associated with significantly reduced risks for most causes of death (e.g., cardiovascular disease incidence rate ratio for interquartile increase = 0.95, 95% CI 0.92-0.97, $p < 0.001$). Accordingly, cold temperatures were included in the index as an indicator of pathogenic environments. Increased UV was associated with significantly reduced risks of all-cause and all cancer mortality (e.g. all cancer mortality IRR for interquartile increase = 0.96, 95% CI 0.95-0.98, $p < 0.001$). UV radiation might have been expected to be a pathogen in New Zealand, because it is the key risk factor for melanoma. However, UV radiation also has a consistent protective effect against a number of health outcomes, including non-skin cancers which are more frequently fatal (Krause, Matulla-Nolte, Essers, Brown, & Hopfenmüller, 2006; Reichrath, 2006; van der Rhee, de Vries, & Coebergh, 2006). Given the evidence from the literature and the protective associations found in our analysis, high UV levels were treated as salutogenic.

Stage 4: Constructing the index

In order to measure the burden of environmental deprivation in each CAU we developed an index on a continuous scale. The New Zealand Multiple Environmental Deprivation Index (NZ-MEDIx) was constructed by combining information on the

relative levels of exposure to factors that were considered to be detrimental (air pollution, cold climate) and beneficial (UV radiation and green space) for health into a single value for small geographically defined populations. For the air pollution and cold climate variables we identified the CAUs in the 'worst' (in terms of health) 20% of New Zealand neighbourhoods and assigned a score of +1. For the UV radiation and green space scores we assigned a score of -1 to the CAUs in the 20% 'best' New Zealand neighbourhoods. Summing the scores for each CAU provided a total NZ-MEDIx value of between -2 and +2, with a higher score indicating a more environmentally deprived area.

Stage 5: Analyses with social deprivation and health data

To examine the socio-spatial arrangement of multiple environmental deprivation, we calculated the mean NZDep2001 score for each NZ-MEDIx category. We then used mortality records to examine the association between our area-level measure of multiple environmental deprivation and population health status in small areas across New Zealand. We focussed on all-cause mortality (excluding external causes) and three leading causes of death in New Zealand: female breast cancer (International Classification of Disease: ICD-9 code 174; ICD-10 code C50), cardiovascular disease (ICD-9 390-459; ICD-10 I00-I99) and respiratory disease (ICD-9 460-519; ICD-10 J00-J99). Based on their established aetiological pathways we expected that mortality from cardiovascular disease and respiratory disease would be associated with multiple environmental deprivation. Breast cancer was included as a test for residual confounding, as a risk factor involving physical environmental conditions has not been established for this health outcome and we would therefore not expect to find a relationship with environmental deprivation.

Using these data we calculated Standardised Mortality Ratios due to all-causes (excluding external) and cause-specific mortality for each of the NZ-MEDIx categories with NZ-MEDIx category 0 as the base category. In order to test the effect of NZ-MEDIx after adjustment for age, sex and socioeconomic deprivation, we used negative binomial regression models to investigate the relationship between NZ-MEDIx and risk of cause-specific mortality, with the age- and sex-specific population for each CAU set as the exposure variable. All models also took account of spatial clustering of the data using robust standard errors, and adjusted for area-level socioeconomic deprivation using NZDep2001.

Given that there are clear geographical differences in smoking rates in New Zealand, it is feasible that the effects of environmental deprivation may be partially accounted for by variations in smoking behaviour (and the upstream 'determinants' of smoking). Therefore, we used data from the 1996 and 2006 New Zealand Censuses that queried respondents about their current smoking practices to derive the proportion of smokers in each CAU. CAUs were divided into quintiles according to the mean smoking rate and this variable was included in the final set of regression models.

RESULTS

Geographical distribution of NZ-MEDIx

Higher levels of multiple environmental deprivation were found in more southerly regions and urban areas of New Zealand (Figure 1). In total 68 CAUs had a NZ-MEDIx

score of +2 (highest level of multiple environmental deprivation) and these were predominantly found in urban localities on the south of the South Island with the main concentrations in the towns of Invercargill, Dunedin, Timaru, and Oamaru. This geographical distribution is likely driven by the lower UV levels and average temperature in southern parts of the country and low green space availability and high PM_{10} levels in urban neighbourhoods. The CAUs with the lowest level of multiple environmental deprivation (NZ-MEDIx score -2, $n = 46$) were in rural parts of the North Island, north of Auckland.

Socio-spatial distribution of NZ-MEDIx

Multiple environmental deprivation and area-level social deprivation were not strongly correlated ($r = 0.10$). The mean NZDep2001 score was lowest in neighbourhoods with a NZ-MEDIx score of -2 or -1 (low multiple environmental deprivation) and higher in areas with NZ-MEDIx scores of 0, +1 and +2. However, there was no evidence of a linear relationship (Figure 2). Similarly, the highest level of physical environmental deprivation (NZ-MEDIx score of +2) was experienced by approximately equal numbers of the most and least socially disadvantaged populations (NZDep2001 quintiles 1 and 5), as was the lowest level of environmental deprivation (Table 4). However, the CAUs with low environmental deprivation (NZ-MEDIx -2 and -1) were slightly more affluent (NZDep2001 quintiles 1 and 2), and those with greater environmental deprivation (NZ-MEDIx +1 and +2) were generally more socially disadvantaged (NZDep2001 quintiles 3 and 4).

Multiple environmental deprivation and health

In the final stage of the analyses we considered whether health varied across areas characterised by different levels of multiple environmental deprivation. We found that after adjustment for age and sex differentials, there were systematic differences in health between groups of areas with the same NZ-MEDIx score. All-cause mortality SMRs (excluding external) were lowest (SMR = 0.94, i.e. best health) in the least environmentally deprived areas, and highest (SMR = 1.14) in the most environmentally deprived areas (Figure 3). Further, these differences were statistically significant and there was an approximately linear association across the NZ-MEDIx categories. This association remained after adjustment for area-level social deprivation (Figure 3).

We then used regression to consider the relationship between multiple environmental deprivation and all-cause and cause-specific mortality. The incidence rate ratios (IRRs) indicated the mortality rate for each NZ-MEDIx value relative to CAUs at an intermediate level of environmental deprivation (NZ-MEDIx = 0; Figure 4, Table 5). We found that after adjustment for potential confounders, there was some evidence that multiple environmental deprivation had an independent association with all-cause mortality, as well as deaths from cardiovascular disease and respiratory disease. The IRRs in NZ-MEDIx +2 (high multiple environmental deprivation) were significantly elevated for all-cause, cardiovascular disease and respiratory disease (1.14, 1.17 and 1.17 respectively). Some evidence of a dose-response trend was found for the plausibly related causes of death: mortality rates worsened as environmental deprivation increased. However, few of these findings

were statistically significant. As anticipated, NZ-MEDIx was not significantly associated with breast cancer mortality.

In the final stage of the analyses we repeated this modelling procedure but with the addition of the area-level smoking prevalence variable (quintiles). Whilst the smoking variable had some relationship with most of the health outcomes (but not breast cancer) the main effects (those of NZ-MEDIx) were largely unattenuated. This finding suggests that variations in smoking behaviour across different environments in New Zealand are unlikely to account for the observed associations between multiple environmental deprivation and health.

DISCUSSION

Considering multiple exposures to harmful and beneficial environmental characteristics offers significant opportunities for researchers and policy makers who are concerned with identifying the key mechanisms that underpin the uneven distribution of health outcomes (Evans & Kantrowitz, 2002; Jerrett, 2009). In this New Zealand study we constructed an index of multiple environmental deprivation and tested whether the methods developed previously in the UK can be readily transferred to an alternative national context. To do this we identified dimensions of physical environmental deprivation that were pertinent to population health in New Zealand and then constructed the New Zealand Multiple Environmental Deprivation Index (NZ-MEDIx) for small areas across the country. NZ-MEDIx provided an ordinal measure of environmental deprivation (from 'least' to 'most'). We then evaluated

whether there is evidence that multiple environmental deprivation exerted an influence on health in New Zealand.

Our findings suggested that it is possible to develop a small area measure of multiple environmental deprivation for New Zealand. The resulting index provided a summary measure of small area multiple environmental deprivation that is akin to previous UK work but which has been purposively designed for the New Zealand context. However, some key challenges restricted the transferability of our methods to New Zealand. In particular, it was notable that some New Zealand data sets were not readily available at the national level from routine data sources. For instance, in contrast to the UK, pollution is measured at a comparatively small number of locations in New Zealand. The measure of pollution used in the current study was a relatively crude regression-based estimate and only available for CAUs in urban areas. Particulate pollution in rural parts of the country, whilst lower than in urban areas, are likely to vary according to local road dust, agricultural practices, and other potential sources. Similarly, comprehensive data on the location of industrial facilities across New Zealand were not available. The relative paucity of environmental datasets in New Zealand points to dissimilarities in the spatial data infrastructure and different priorities in terms of the collection and availability of data between countries. These can restrict the comparative development of measures such as the one presented here.

The index is a conceptual advancement on most previous studies that rely on the use of separate environmental measures rather than recognising the reality of multiple concurrent exposures. Further the index has utility in researching spatial inequalities

in health. Our results demonstrated that multiple environmental deprivation was not strongly patterned by social deprivation in New Zealand. Although the most environmentally deprived neighbourhoods tended to have higher levels of social deprivation than the least environmentally deprived neighbourhoods the trend was not linear. Within the five NZ-MEDIx categories there was a clear distinction between those neighbourhoods with an NZ-MEDIx score in the two groups with the lowest levels of multiple environmental deprivation (where social deprivation was also relatively low) compared to neighbourhoods with zero or positive NZ-MEDIx scores (where levels of social deprivation were considerably higher). To some extent this finding is consistent with earlier studies which have tended to suggest that socially disadvantaged communities suffer from the double jeopardy of socio-economic and environmental deprivation. There is a body of evidence in the international literature which finds that in high income countries the richest and most empowered neighbourhoods disproportionately benefit from decision making affecting the allocation, location and organisation of public goods and services (Knox, 1982; Lineberry, 1977). Nonetheless, the non-linearity between NZ-MEDIx scores and the measure of social deprivation is not generally consistent with the international literature or our earlier UK work. However, previous New Zealand studies of the social distribution of neighbourhood community resources have tended to find a pro-equity geographical arrangement (i.e. favouring more disadvantaged places). More disadvantaged neighbourhoods in New Zealand tend to have better locational access to resources such as parks, schools, shops and health care provision (Field, Witten, Robinson, & Pledger, 2004; Pearce, Witten, Hiscock et al., 2007; Witten, Exeter, & Field, 2003). Explanations are likely linked to land-use planning decision making, dominant transport mode at the time of settlement,

17

patterns of agricultural and industrial development, and land ownership (Pearce, Witten, Hiscock, & Blakely, 2008).

The findings of this study also demonstrated that multiple environmental deprivation had a modest but significant association with small area variations in health in New Zealand. After adjustment for key confounders, NZ-MEDIx was associated with plausibly-related causes of death. Further, the absence of a relationship with breast cancer mortality was reassuring as it indicated that NZ-MEDIx was related only to causes of death that are theoretically susceptible to physical environmental conditions and hence confounding is unlikely to have unduly affected the results. Spatial differences in mortality in New Zealand may therefore be partly explained by multiple environmental deprivation, as measured by NZ-MEDIx. As found in the UK work (Mitchell, Richardson, Pearce et al., 2011), the association of environmental deprivation with health outcomes was modest (17% at most, seen for respiratory disease mortality) relative to the influence of socioeconomic deprivation. One of the strengths of the current study over previous work was our capacity to adjust for smoking rates in the regression modelling. Taking into account the geography of smoking behaviour did not substantially alter the association between NZ-MEDIx and health.

Our study has limitations. First, there are other environmental characteristics that are important for health for which we were unable to obtain adequate and/or geographically-specific data. For instance, the absence of national records of industrial facilities precluded our assessment of population exposure to industrial emissions, and possible inclusion of this factor in the index. As previously noted, the

absence of air pollutant monitoring sites in some parts of New Zealand also necessitated our use of empirically-modelled estimates, which were available only for urban areas (Kingham, Fisher, Hales, Wilson, & Bartie, 2008). The inclusion of additional environmental variables could have altered our findings. Second, due to the lack of New Zealand evidence on which to inform our decision making, we purposively did not apply weights to the constituent parts of the index. The different environmental domains are likely to exert unequal effects on health. Furthermore, there are also likely to be different latency effects. For instance, the health effects of extreme temperature may be more immediate than the long term effects of ambient pollution exposure. It is plausible that weighting the components of NZ-MEDIx could have affected our findings. Third, it is plausible that factors such as health-related behaviours (including alcohol consumption and physical activity) or other mediating factors including adequate home heating are likely to have distinct geographies and may affect the associations between multiple environmental deprivation and health. In the next phase of this research we will be evaluating these potential pathways and considering whether the findings of this ecological investigation are consistent with analyses that utilise individual-level data. Nonetheless, adjusting for smoking behaviour (albeit at the area-level) did not affect the results. Fourth, we assume that place of residence is an adequate surrogate for environmental exposure. It is likely that settings outside of the residential neighbourhood such as workplaces and schools are likely to contribute towards total environmental exposure. Similarly, CAUs were selected for pragmatic reasons (i.e. they are the smallest unit for which mortality records were available) yet it remains unclear whether CAUs are the most appropriate geographical unit for capturing multiple environmental deprivation. For some environmental features such as air pollution and green space measurement,

the CAU may not fully capture the high degree of local variability. Our results could be sensitive to the geographical unit adopted in the analyses. Finally, this study was cross-sectional and hence causality cannot be ascertained. Some aspects of the physical environment will have altered considerably over the lifetime of individuals at the upper end of the age range. Environmental exposures early in the life course are likely to have had a lasting effect. Air pollution and urban green space access will have changed markedly in response to amendments in the regulation of polluting facilities, and planning law affecting the availability of neighbourhood resources. In the future, climate change will present similar challenges. These changes coupled with the movement of individuals between neighbourhoods may have lead to the misclassification of environmental exposure. Integrating geographically-specific measures of the temporal course of environmental risk exposure with individual-level longitudinal health data is likely to be a fruitful line of further investigation.

In conclusion, this research has contributed to the emerging debates relating to environmental justice and health inequalities. We argue that indices of multiple environmental deprivation, such as NZ-MEDIx, provide significant opportunities for progressing our understanding of the pathways linking environmental inequality and inequalities in health outcomes. We have demonstrated that a methodology developed for the construction of health-relevant measures of multiple environmental deprivation in the UK can be applied to a different context. We produced NZ-MEDIx and have shown that it has utility in health research. We have found that although multiple environmental deprivation is not socially patterned to the same extent as in the UK, it does make a modest independent contribution to leading causes of mortality in New Zealand. We encourage researchers in other

countries to investigate the utility of indices of multiple environmental deprivation in epidemiological research.

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List of Figures

Figure 1. Spatial distribution of NZ-MEDIx scores across (a) whole of New Zealand, (b) Auckland area, (c) Wellington area and (d) Christchurch area

Figure 2. Mean NZDep2001 score for each NZ-MEDIx category (a measure of multiple environmental deprivation)

Figure 3. All-cause mortality Standardised Mortality Ratios (SMRs) by NZ-MEDIx score adjusted for a) age and sex, and b) age, sex and social deprivation (NZDep2001). Bars indicate 95% confidence intervals.

Figure 4. Associations between NZ-MEDIx scores and (a) all cause, (b) cardiovascular disease, (c) respiratory disease, and (d) female breast cancer mortality rates, relative to CAUs with an NZ-MEDIx score of 0 (IRR = 1.0). Incidence rate ratios (IRRs) were adjusted for age-group, sex and socioeconomic deprivation quintile (NZDep2001). Bars indicate 95% confidence intervals.

Figure 1. Spatial distribution of NZ-MEDIx scores across New Zealand.

NZ-MEDIx score

- -2 (least environmental deprivation)
- -1
- 0
- +1
- +2 (most environmental deprivation)
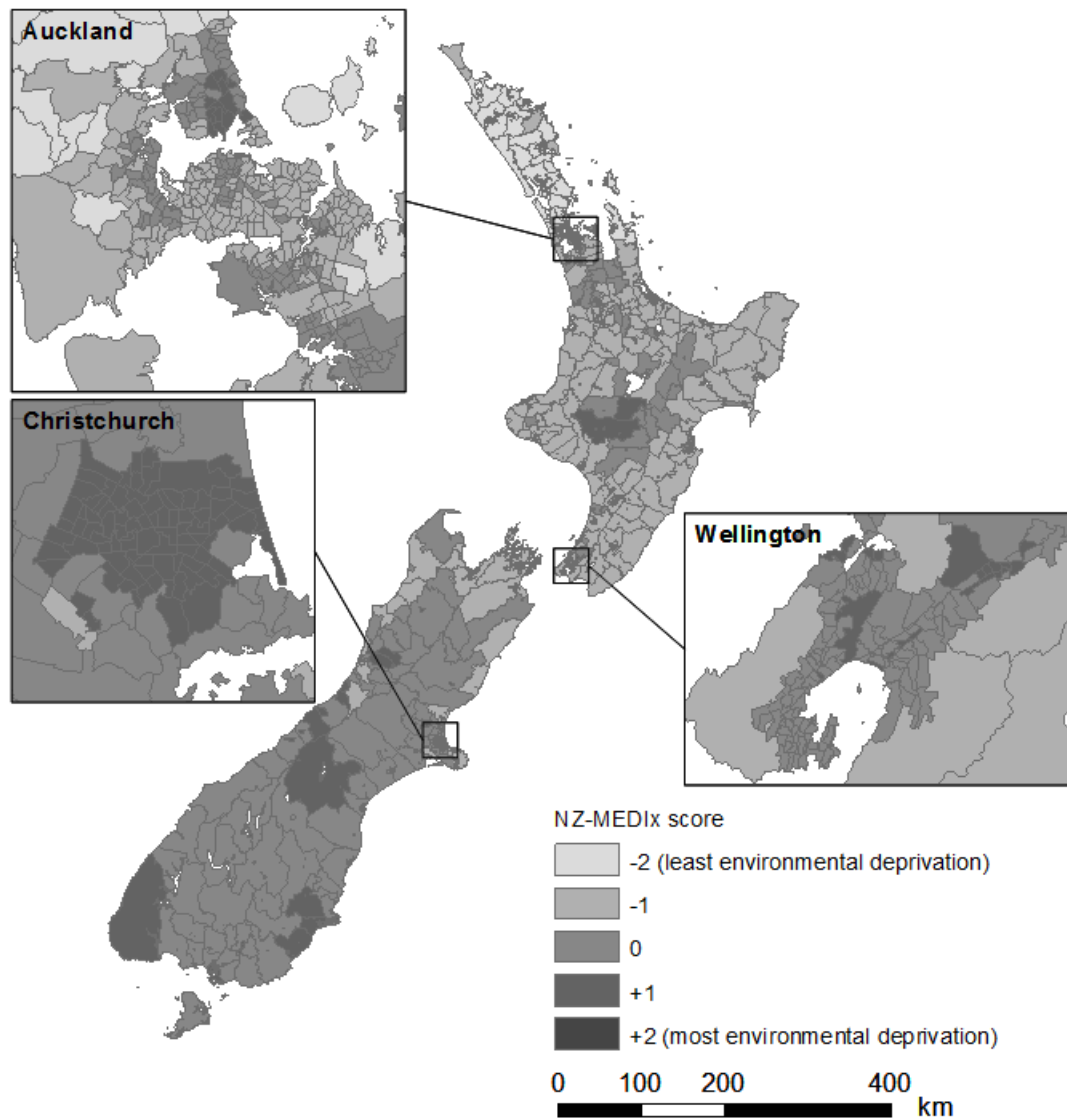
0   100   200   400
km

Figure 2. Mean NZDep2001 score for each NZ-MEDIx category (a measure of multiple environmental deprivation)

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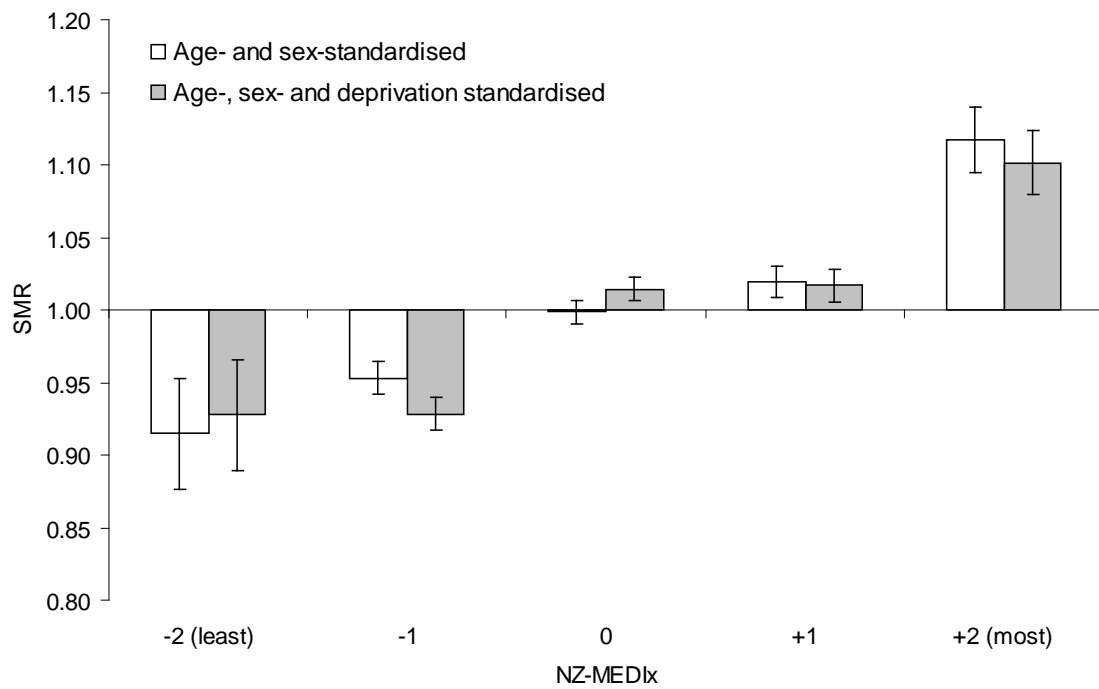
(a) All cause mortality

(b) Cardiovascular disease mortality

(c) Respiratory disease mortality

(d) Female breast cancer mortality

Table 1. Additional environmental factors identified to be of relevance in the New Zealand context, including a brief assessment of their relevance for population health.

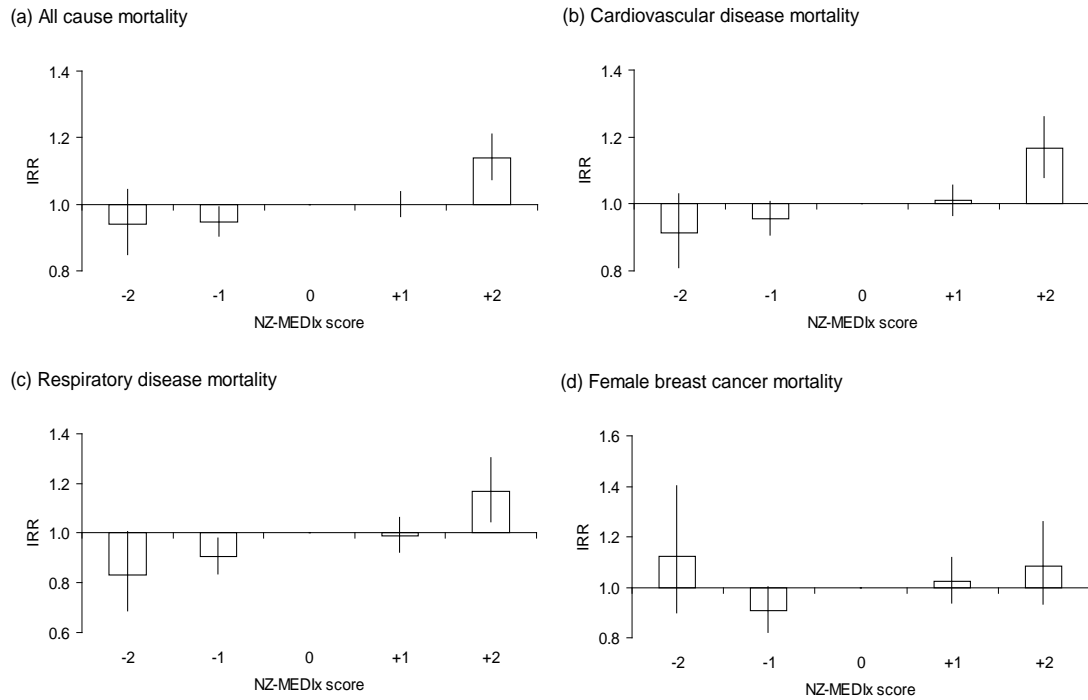| Environmental factor	Environmental exposure	Health	% exposure NZ population
Geothermal areas	Hydrogen sulphide and carbon dioxide emissions	Residents of geothermal areas have higher risks of respiratory and cardiovascular disease incidence (Bates, Garrett, & Shoemack, 2002; Durand & Wilson, 2006) and respiratory disease mortality (Bates, Garrett, Graham, & Read, 1997).	Population exposure to geothermal areas is low: the Census Area Units (CAUs) that overlap the fields contain less than 2% of the New Zealand population (our own GIS analysis).
Organic pollutants	Pesticides and herbicides contain components that are known to have significant human health impacts (e.g., furans and dioxins)	Studies of occupationally-exposed individuals have found little evidence for elevated health risks (Mannetje, McLean, Cheng, Boffetta, Colin, & Pearce, 2005; Smith, Fisher, Pearce, & Chapman, 1982).	The Ministry for the Environment (2008) concluded that health risks from the now-banned timber pesticide pentachlorophenol (PCP) are largely confined to those directly exposed to affected soil. Fewer than 10% of the New Zealand population are exposed to these organic pollutants at health-affecting levels
Microbial contamination	Large livestock populations across New Zealand lead to microbial contamination of water supplies and resulting water-borne enteric diseases such as campylobacteriosis, giardiasis and leptospirosis.	New Zealand has one of the highest incidences of giardiasis and campylobacteriosis in the developed world (Hearnden, Skelly, Eyles, & Weinstein, 2003; Hoque, Hope, & Scragg, 2002), but these acute short-term infections do not generally lead to death. As the effects of such exposures would not be reflected in the available health data (mortality) we excluded this environmental factor.	**Unknown**
Drinking water	Two-thirds of the New Zealand population use chlorinated water supplies and are therefore exposed to disinfection by-products (DBPs, specifically total tri-halo methanes, or TTHMs)	Cancers and birth defects (Malcolm, Weinstein, & Woodward, 1999)	An investigation for the Ministry of Health (Davies, Nokes, & Ritchie, 2001) found that less than 1% of the New Zealand population were exposed to water supplies that exceeded the Maximum Acceptable Values set for TTHMs.

Table 2. Assessment of whether health-relevant environmental factors identified for the UK are also relevant in the New Zealand context.

Environmental factor

Air pollution: Levels of particulate air pollution (PM_{10}) in New Zealand cities can exceed health guideline levels in winter, largely due to domestic heating systems (Krivácsy, Blazsó, & Shooter, 2006). In Christchurch particulate air pollution has been associated with increased risks of all-cause mortality, respiratory disease mortality, respiratory symptoms and hospital admissions (Epton, Dawson, Brooks, Kingham, Aberkane, Cavanagh et al., 2008; Hales, Salmond, Town, Kjellstrom, & Woodward, 2000; McGowan, Hider, Chacko, & Town, 2002). Potentially carcinogenic polyaromatic hydrocarbons (PAHs) are a by-product of fuel combustion and are a particular concern in New Zealand because domestic heating systems often require burning fuel in the home (Brown, Trought, Bailey, & Clemons, 2005).

Climate: Excess winter mortality in New Zealand is primarily due to circulatory and respiratory diseases, and is more substantial than in many European and Southern Hemisphere countries (Davie, Baker, Hales, & Carlin, 2007). In Auckland, daily respiratory illness hospitalisations increase with colder winter temperatures (Gosai, Salinger, & Dirks, 2009). In Christchurch, each 1°C increase in maximum temperature above 20.5°C has been associated with a 1% increase in all-cause and a 3% increase in respiratory disease mortality (Hales, Salmond, Town et al., 2000). Respiratory symptoms increase in prevalence with increasing annual temperature (Hales, Lewis, Slater, Crane, & Pearce, 1998).

Solar ultraviolet (UV) radiation: Skin cancer is the most common cancer in New Zealand, and rates are among the highest in the world (International Agency for Research on Cancer, 1992). Rates decrease from north to south (Martin & Robinson, 2004; Salmon, Chan, Griffin, McKenzie, & Rademaker, 2007), in line with solar UV levels. However, vitamin D deficiency, a symptom of insufficient exposure to solar radiation, is also a recognised health concern for New Zealanders (Livesey, Elder, Ellis, McKenzie, Liley, & Florkowski, 2007; Rockell, Skeaff, Williams, & Green, 2006). Vitamin D has a protective effect against many conditions including non-skin cancers (e.g., Holick 2004, van der Rhee et al. 2006).

Green space: Witten et al. (2008) found that neighbourhood access to parks across New Zealand was not associated with BMI, sedentary behaviour or physical activity for participants in the New Zealand Health Survey (2002/3). There was some evidence that increased access to beaches was related to increased physical activity and decreased BMI. Richardson et al (2010) found that there were no significant associations between green space (usable or total) and mortality (after adjustment for potential confounders).

Industrial facilities: Waste management sites and metal production and processing plants are associated with health effects in the UK, but there is little evidence for this in New Zealand. A single study (Read, Wright, Weinstein, & Borman, 2007) reported significantly elevated cancer incidence around a herbicide manufacturing plant in the period 8 to 12 years after the plant began operating, but in no other later period. Proportion of New Zealand population exposed to industrial facilities is unknown.

Table 3. Details of the datasets acquired and CAU-level measures derived for the key environmental factors.

Key factor	Source of data	Year(s)	Processing	Specific measure derived
Air pollution	Kingham et al. (2008): developed and validated an empirical model that produced detailed estimates of PM_{10}[1] exposure for urban CAUs (necessary due to the absence of monitoring data for some areas).	2001	Urban areas: CAU level data provided. Rural areas: no measured or modelled data available. Following advice from S Kingham we assumed negligible contributions from vehicular, industrial and domestic sources, so all rural areas shared the background PM_{10} concentration of 2 $\mu g.m^{-3}$	CAU-level annual average PM_{10} ($\mu g.m^{-3}$)
Climate	Climate Surfaces of New Zealand database (Leathwick & Stephens, 1998): 1 km grid resolution, based on interpolation of weather data from > 300 stations. No missing data.	1951 to 1980	Each CAU was assigned the mean temperature occurring at its centroid (population weighted), as an indication of the climate that most of its population were exposed to.	CAU-level average annual temperature (°C)
UV radiation	National Institute of Water and Atmospheric Research (NIWA) UV Atlas: UV is monitored at 65 stations, and the UV Index[2] is calculated from these data. No missing data.	1960 to 2005	Average UVI was calculated for each station and then interpolated across New Zealand using a GIS technique.. Each CAU was assigned the UVI value occurring at its centroid (population weighted).	CAU-level average UVI value (unitless)
Green space	Green space classification work undertaken by some of the authors and reported elsewhere (Richardson, Pearce, Mitchell et al., 2010). Datasets from the Department of Conservation (DOC), Land Information New Zealand (LINZ) and Ministry for the Environment (MfE) were used. The data therefore reflect the completeness of these sources.	2001 to 2004	Total green space as a percentage of total area was calculated for each CAU, using GIS.	% total green space per CAU (by area)

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[1] Particulate matter with a median diameter less than or equal to 10 μm.
[2] UV Index (a unitless index of surface UV irradiance and sunburn risk (WHO, 2002))

Table 4. Distribution of the New Zealand population across socioeconomic and environmental deprivation categories (percentage of the total population).

Socioeconomic deprivation quintile (NZDep2001)	Physical environmental deprivation score (NZ-MEDIx)					
	-2 (lowest)	-1	0	+1	+2 (highest)	**Total**
1 (least deprived)	0.5	6.6	8.1	2.6	0.4	18.2
2	0.4	6.3	7.8	4.3	0.9	19.7
3	0.5	4.8	8.5	4.7	1.4	19.9
4	0.4	2.9	10.7	5.4	1.4	20.8
5 (most deprived)	0.5	4.8	11.7	3.7	0.4	21.1
Total	2.3	25.4	46.8	20.7	4.5	100

Table 5. Incidence Rate Ratios (IRRs) for the association between MEDIx and all-cause and cause-specific mortality with covariates

	All cause mortality	Cardiovascular disease	Respiratory disease	Female breast cancer
NZ-MEDIx				
-2	0.94 (0.85 to 1.04)	0.91 (0.81 to 1.03)	0.83 (0.69 to 1.01)	1.12 (0.90 to 1.40)
-1	0.95 (0.90 to 0.99)*	0.96 (0.91 to 1.01)	0.91 (0.84 to 0.98)*	0.91 (0.82 to 1.00)
0	1.00	1.00	1.00	1.00
+1	1.00 (0.96 to 1.04)	1.01 (0.97 to 1.06)	0.99 (0.92 to 1.06)	1.02 (0.94 to 1.12)
+2	1.14 (1.07 to 1.21)***	1.17 (1.08 to 1.26)***	1.17 (1.05 to 1.30)**	1.09 (0.93 to 1.26)
Age group				
0 to 14	0.06 (0.06 to 0.06)***	0.00 (0.00 to 0.01)***	0.03 (0.02 to 0.04)***	0.00 (0.00 to 0.00)***
15 to 24	0.03 (0.02 to 0.03)***	0.01 (0.01 to 0.01)***	0.02 (0.01 to 0.03)***	0.00 (0.00 to 0.01)***
25 to 34	0.05 (0.04 to 0.05)***	0.03 (0.03 to 0.04)***	0.03 (0.02 to 0.04)***	0.06 (0.05 to 0.08)***
35 to 44	0.12 (0.11 to 0.12)***	0.11 (0.10 to 0.12)***	0.08 (0.06 to 0.09)***	0.24 (0.21 to 0.28)***
45 to 54	0.35 (0.34 to 0.36)***	0.35 (0.33 to 0.37)***	0.20 (0.17 to 0.23)***	0.62 (0.55 to 0.69)***
55 to 64	1.00	1.00	1.00	1.00
65 to 74	2.68 (2.62 to 2.75)***	3.11 (2.99 to 3.23)***	3.89 (3.59 to 4.21)***	1.25 (1.11 to 1.40)***
75 to 84	7.11 (6.91 to 7.31)***	10.62 (10.19 to 11.07)***	11.48 (10.60 to 12.42)***	1.83 (1.64 to 2.05)***
85+	19.71 (19.06 to 20.38)***	35.25 (33.67 to 36.91)***	33.37 (30.64 to 36.34)***	3.02 (2.65 to 3.45)***
Gender				
Male	1.00	1.00	1.00	
Female	0.70 (0.69 to 0.71)***	0.63 (0.61 to 0.64)***	0.65 (0.62 to 0.68)***	
NZDep01 quintile				
1 (least deprived)	1.00	1.00	1.00	1.00
2	1.06 (0.99 to 1.14)	1.07 (0.99 to 1.16)	1.04 (0.92 to 1.17)	0.92 (0.81 to 1.04)
3	1.20 (1.12 to 1.27)***	1.20 (1.12 to 1.30)***	1.25 (1.12 to 1.40)***	0.99 (0.88 to 1.12)
4	1.32 (1.24 to 1.40)***	1.31 (1.22 to 1.41)***	1.40 (1.26 to 1.55)***	1.03 (0.92 to 1.16)
5 (most deprived)	1.72 (1.61 to 1.83)***	1.73 (1.61 to 1.86)***	1.84 (1.65 to 2.05)***	1.03 (0.91 to 1.17)

* $0.01 < p < 0.05$; ** $0.001 < p < 0.01$; *** $p < 0.00$

Table 6. Incidence Rate Ratios (IRRs) for the association between MEDIx and all-cause and cause-specific mortality adjusted for covariates (with the addition of smoking).

	All cause mortality	Cardiovascular disease	Respiratory disease	Female breast cancer
NZ-MEDIx				
-2	0.96 (0.86 to 1.06)	0.93 (0.83 to 1.04)	0.84 (0.70 to 1.01)	1.13 (0.91 to 1.41)
-1	0.96 (0.91 to 1.00)	0.97 (0.92 to 1.02)	0.92 (0.85 to 1.00)*	0.91 (0.83 to 1.01)
0	1.00	1.00	1.00	1.00
+1	1.00 (0.96 to 1.04)	1.01 (0.96 to 1.06)	0.99 (0.92 to 1.06)	1.02 (0.93 to 1.11)
+2	1.13 (1.07 to 1.20)***	1.16 (1.07 to 1.25)***	1.16 (1.04 to 1.29)*	1.08 (0.93 to 1.26)
Smoking rate (quintiles)				
1 (lowest)	1.00	1.00	1.00	1.00
2	1.01 (0.94 to 1.08)	1.01 (0.94 to 1.10)	1.05 (0.94 to 1.17)	0.98 (0.86 to 1.11)
3	1.02 (0.95 to 1.09)	1.04 (0.96 to 1.12)	1.10 (0.98 to 1.24)	0.97 (0.85 to 1.11)
4	1.06 (0.99 to 1.13)	1.06 (0.98 to 1.15)	1.10 (0.97 to 1.25)	1.01 (0.86 to 1.17)
5 (highest)	1.20 (1.11 to 1.30)***	1.23 (1.13 to 1.35)***	1.24 (1.08 to 1.43)**	1.06 (0.88 to 1.27)

* $0.01 < p < 0.05$; ** $0.001 < p < 0.01$; *** $p < 0.00$