Colorectal cancer screening participation: Exploring relationship heterogeneity and scale differences using multiscale geographically weighted regression

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Abstract

Scotland has an organised colorectal cancer screening programme; however, despite proactively offering screening opportunities free to the at-risk population, and also despite using a screening test which may be completed at home, screening participation levels are unequal. Understanding causal pathways linking participation with other population characteristics may be aided by identifying how relationships between the two patterns vary across different localities, and such knowledge may also inform decisions regarding geographical targeting of screening promotion efforts. In this analysis, models calibrated using multiscale geographically weighted regression enabled the assessment of spatial variations of determinants of screening participation levels. The models were calibrated for localities across west central Scotland (n=409), where participation levels were relatively low, using aggregated individual-level screening records within a two-year window (2009-2011). Area deprivation was found to have a strong negative impact on participation levels across the study area, and ethnic population concentration had a significant impact on male participation levels on localities within Glasgow city. Estimates of local intercepts pointed to a systemic difference in screening participation between the two health board regions in the study area. Overall the results suggest that work to increase screening participation was necessary. They also suggest that barriers to participation could be addressed locally, and that differences between health board regions required further investigation.

Introduction

It is now established that screening for early signs of colorectal cancer (CRC) has an important role to play in reducing the incidence of and mortality from the disease (Maida *et al.*, 2017; Rawla *et al.* 2019). However, while CRC screening programmes now operate in a number of countries, we are still some way from fully understanding the reasons why participation in these programmes is unequal across different demographic and social categories. Prior studies illustrate these inequalities in a number of ways, including by gender, age, socio-economic status, ethnic background and geography (Klabunde *et al.*, 2015; Honein-AbouHaidar *et al.*, 2016; Wools *et al.*, 2016), yet the use of explicitly spatial techniques for exploring them has been comparatively lacking. In consequence, we remain little further forward in better understanding whether or how location alters the processes influencing screening participation, or whether there may be any merit in geographically-tailored interventions aimed at increasing screening uptake in particular places.

Further research is required to address these knowledge gaps, and in this paper we consider one possible avenue, drawing on the local spatial modelling technique first developed as geographically weighted regression (GWR) (Brunsdon *et al.*, 1996; Fotheringham *et al.*, 2002), and subsequently refined as multiscale GWR (MGWR) (Fotheringham *et al.*, 2017; Oshan *et al.*, 2019; Yu *et al.*, 2020). GWR has been applied previously to several health topics, including cervical cancer incidence (Cheng *et al.*, 2011), coronary heart disease (Gebreab & Diez Roux, 2012), child immunisation (Marek *et al.*, 2020), elderly self-rated health (Yang & Matthews, 2012), longevity and quality of life (Tabb *et al.*, 2018), malaria (Ndiath *et al.*, 2015), and the human immunodeficiency virus (HIV) (Feldacker *et al.*, 2010). The number of health-focussed applications of MGWR is also increasing, including for examining obesity levels (Oshan *et al.*, 2020), general mortality rates (Cupido *et al.*, 2021), and the coronavirus disease 2019 (COVID-19) incidence (Mollalo *et al.*, 2020; Raymundo *et al.*, 2021), although to our knowledge, this is the first time it has been used in examining health-related behaviours (to the extent that

cancer screening participation can be considered as one such type of health-related behaviour). MGWR derives its name from its ability to calibrate the bandwidth separately for each individual dependent-independent relationship under study, where the bandwidth controls the number of data being used for local modelling-fitting purposes (Further details on GWR and MGWR available in the references cited above).

In the rest of this paper MGWR is drawn on for examining differentials in CRC screening participation levels in a study area covering west central Scotland, in and around the major city of Glasgow. Ordinary least squares (OLS) regression models are fitted as well, enabling comparisons between results from localised and conventional 'global' modelling approaches. From this analysis structure, the two fundamental research questions the paper addresses are as follows: i) Do relationships between local CRC screening participation levels and socio-demographic characteristics vary spatially within the given study area? ii) Is there evidence of scale differences in those relationships?

Materials and methods

Studying setting and participants

The organised CRC screening programme established in Scotland provides biennial screening opportunities for all at-risk persons free of charge on the National Health Service (NHS). The at-risk population includes all residents between 50 and 74 years old who are registered with the NHS in Scotland. The screening test involves searching for traces of blood in faecal samples, which, while unpleasant and potentially evoking disgust (O'Carroll *et al.*, 2015), also facilitates screening testing to be organised at a distance, without a need for visits to doctors or other medical facilities. The programme is instead organised around self-completion of 'home' screening test kits, which include sampling bottles and written instructions sent directly to invitees, enabling them to collect the required specimens themselves in their own time. Hygienic pre-paid return envelopes are also included with the kits, so that the completed sample sets can then be mailed onwards to the national screening laboratory for testing. Individuals with positive test results may be offered a colonoscopy appointment; however, this study concentrates on participation in the initial screening process as outlined.

The study area considered covers a large portion of west central Scotland, including two contiguous health board regions. Centred on the city of Glasgow, the area is already recognised for high levels of poor health (Walsh *et al.*, 2010), attributed to the combined effects of deindustrialisation, deprivation and damaging economic and social policies over recent decades (Walsh *et al.*, 2017). According to annual CRC screening programme performance reports, both of the health board regions in the study area also have persistently low levels of screening participation, lower than those attained in other health boards (ISD, 2011, 2018). Figure 1 illustrates the full study area, with the Greater Glasgow and Clyde health board region in the northerly part, and the Lanarkshire health board region in the south. Small area localities considered in the analysis, namely intermediate zones (IZs), are also shown.
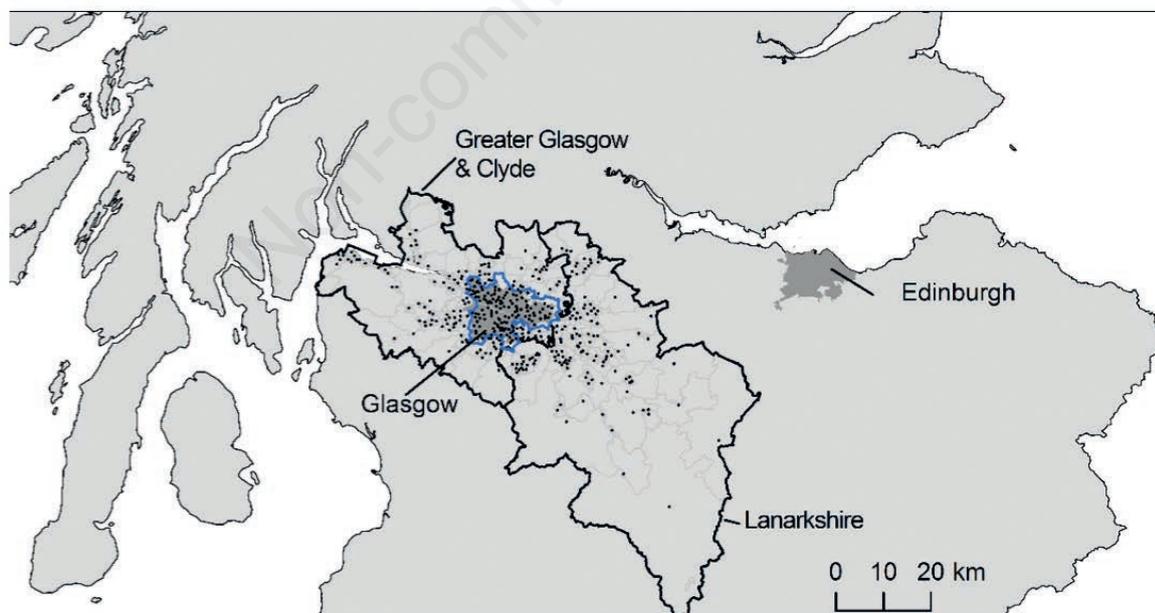
Figure 1. Location and extent of the study area in west central Scotland, including the two health board regions Greater Glasgow & Clyde; and Lanarkshire. Centroids of intermediate zones (IZs) are depicted by black dots while the faint outlines show the corresponding IZ boundaries. Also displayed are Glasgow and Edinburgh cities (the latter outside the study area). The blue polygon represents the extent of Glasgow city council area. *Boundary datasets attribution: Contains NRS data © Crown copyright and database right 2021. Contains OS data © Crown copyright (and database right) 2021. Centroids dataset attribution: Copyright Scottish Government, contains OS © Crown copyright and database right 2021.*

Data sources

A dataset including all residents in the study area invited for CRC screening between 1 January 2009 and 31 December 2011was provided by the NHS Scotland's Information Services Division (ISD). In the time period between these two dates, the national CRC programme was at an early stage, and consequently the invitations recorded in the study dataset were almost all first-time invitations. There is some evidence suggesting that successive screening invitations may themselves influence screening participation likelihood (Steele *et al*., 2010a), so to avoid this potential confounder, records for the small proportion of persons recorded as having had multiple invitations were excluded prior to the analysis. The ISD dataset also included the age and location of invitees at the time of their screening invitation, plus a flag variable indicating whether or not they returned their test kit for analysis within six months of receiving it. A positive response to this latter variable was taken to mean that the kit had been completed properly, as no further metadata were provided. To estimate local levels of CRC screening participation, the individual records in the ISD-supplied dataset were aggregated spatially, requiring use of a separate geographic look-up file, available from: https://www2.gov. scot/Topics/Statistics/sns/SNSRef/IZLookup201012. In addition, in order to create standardised measures, age and sex mid-year population estimates for 2010 produced by National Records of Scotland were sourced from: www.opendata.nhs.scot/dataset/population-estimates.

Local socioeconomic conditions were measured in two ways, with reference to both area deprivation and ethnicity. For the former, the Carstairs index was selected, this being a key measure of deprivation used in health research in Scotland for some decades (Carstairs & Morris, 1989; 1991). Deprivation scores for this index are produced by combining standardised census measures of low social class, male unemployment, overcrowding in private households, and lack of car ownership. Data used to create this index for the present analysis were sourced from 2011 population census statistics available from: www.scotlandscensus.gov.uk. Data from the 2011 census were also used to create a variable describing the relative sizes of local ethnic populations, as described further below (and with the census being a rare source of quantitative demographic data on ethnicity).

The final data requirement for MGWR modelling was for coordinates of the locations where local models were to be fitted; this requirement was fulfilled by using population-weighted centroids for the above-mentioned IZs, with the centroids obtained from a Scottish Government dataset available via https://data. gov.uk/. In addition, to assist mapping of model results, boundary files were downloaded from the UK Data Service https://census. ukdataservice.ac.uk/get-data/boundary-data.

Variables

The response variables in the models consisted of age-standardised estimates of screening participation levels produced separately by sex for all IZs across the study area. These variables were created by first aggregating individual-level records to areas known as Data Zones, using the Data Zone of residence already captured by ISD. Subsequently, the Data Zone figures were aggregated to IZs using the look-up file noted earlier. Both Data Zones and IZs are important geographies in the overall national Scottish Neighbourhood Statistics framework, but IZs were the preferred choice in this case, in order to avoid potential difficulties with instability of estimates, as there were a number of Data Zones

where the numbers invited for screening were very small. IZs were designed with an average residential household population of 4000 with the study area completed divided into 409 IZs, roughly one-third the total across Scotland as a whole. The total number of invitees per IZ and the corresponding total recorded as returning their screening kits were used to calculate crude versions of local screening participation levels; this was done separately by sex. Age-standardised versions were then derived, due to other evidence indicating age-linked differences in screening participation (Steele *et al*., 2010b). Directly standardized estimates were obtained, which involved applying the crude values stratified by quinquennial age group (50-54 to 70-74) to corresponding mid-year population estimates.

The explanatory variables included the Carstairs index deprivation scores and ethnic population proportions for the set of study IZs. The required census variables were extracted at the Data Zone level as they are not published at the IZ level, and they were then aggregated using the same look-up file as above. The inclusion of ethnicity reflected findings from other studies, including from neighbouring England, where local levels of screening participation were shown to be significantly inversely associated with local minority ethnic population proportions, independent of area deprivation (von Wagner *et al*., 2011). However, as the actual pathways linking local ethnic populations with variations in local screening participation remain unclear, rather than focussing on any one or other specific minority ethnic group, a broad measure of the ethnic population was opted for in this instance. The measure derived for the present study included all residents who were not part of the two majority groupings of 'White Scottish' or 'White British'. Of the overall 1.78 million census-recorded residents within the study area, between 9 and 10 percent were part of the ethnic population defined on this basis, spanning Asian, African, Caribbean or Black, mixed, multi-ethnic or other unspecified groups, as well as other White groups. These groups were summed for each IZ then divided by the total residential population of the IZ.

Modelling methods and spatial analyses

All models were fitted using the MGWR 2.1 program downloaded from https://sgsup.asu.edu/sparc/multiscale-gwr. A variable standardisation option was selected, such that all modelling was performed using variables converted onto the same value scale (with mean =0, standard deviation =1). Variable standardisation enables relationship-specific bandwidths to be used as direct indicators of the spatial scale of those relationships (see also Fotheringham *et al*., 2017). For the MGWR models, the bandwidth size was specified based on the number of neighbouring IZs; this ensured that the number of data used for calibrating each local model could be held constant, irrespective of the actual irregular spatial distribution of IZs across the study area. Searches for the optimal bandwidth considered all possible bandwidth sizes between a minimum of 10 and maximum of 400 nearest-neighbour IZs, with a bi-square kernel function selected for weighting the data included within the bandwidth (with data beyond the bandwidth assigned zero weights and thus excluded from local model estimation). Maps and other visualisations were created in ArcGIS and R, with the latter used for computing both correlations and residual spatial autocorrelation measures. The locally-fitted coefficients from the MGWR models were also tested for significant differences from zero (the null hypothesis) using corresponding locally-calculated standard errors and *t*-values. Adjusted versions of the latter were used in line with guidance provided by da Silva and

Fotheringham (2016), to safeguard against risks of false positives arising due to multiple hypothesis tests, which are an inherent aspect of MGWR modelling based on overlapping local subsets of data. The required adjusted *t*-values for testing at the 95 percent confidence level were included in the MGWR model output files.

Results

Global-level relationships between colorectal cancer screening participation and socio-economic characteristics

The screening dataset taken forward for analysis comprised almost 557,000 persons, 48.8% male and 51.2% female. Differentials in standardised local screening participation levels are summarised in Table 1. The median participation levels by deprivation quintile illustrated a wide gap between IZs in the most deprived and the least deprived quintiles (quintiles 1 and 5, respectively). Most of these median values were below 60%, this being the target minimum participation level defined for the Scottish CRC screening programme as a whole (Healthcare Improvement Scotland, 2015) Smaller differences were apparent across the quintiles based on ethnic population proportions. In that case, all the medians fell below the minimum target participation level.

The correlation between the covariates was relatively low (Pearson's *r*=0.30, 95% percent confidence interval =0.22-0.39), indicating that collinearity was unlikely to be problem for conventional global regression. Results for OLS regression models (Table 2) illustrate that local area deprivation was a statistically significant predictor of screening participation levels for both sexes, with the size of the coefficients reflecting the large differences noted above. In contrast, the relationships with local ethnic population proportions were not statistically significant, nor were they consistent, with an inverse relationship identified for male participation levels compared to a direct relationship with female participation levels. However, the models still accounted for over 70% and 66% of the variability in local female and male screening participation levels, respectively. On dropping the ethnic variable from the models, the adjusted R^2 values remained very similar, and the deprivation coefficient values changed only at the second decimal place (–0.815 for males and –0.864 for females).

The autocorrelation test indicated that the residuals from these models were spatially clustered to similar degrees (Moran's *I* of 0.57 and 0.58 for the male and female models, respectively, P<0.000 for both). Such evidence suggests that the assumption of independence of residuals was not met, possibly invalidating inferences drawn from the model results. Furthermore, it also pointed to the existence of potentially important spatial differences in the relationships under study.

Local modelling results

Table 3 provides model fit statistics for the MGWR calibrations. The overall adjusted R^2 values suggest improved fits compared to the OLS models, accounting for 86% of the variance in male participation levels and 90% of that in female participation levels. The reduction in values of the corrected Akaike Information Criterion (AIC$_c$) points to a similar conclusion (*cf.* Table 2). The local R^2 values provide an analogous measure of fit for the local

Table 1. Screening participation levels at intermediate zones (IZs) level by quintile of Carstairs deprivation score and ethnic population proportion.

Sex	Variable	Q1	Q2	Q3	Q4	Q5
Males	Deprivation	0.40	0.44	0.46	0.51	0.58
	Ethnic population proportions	0.44	0.47	0.46	0.49	0.48
Females	Deprivation	0.45	0.49	0.53	0.59	0.66
	Ethnic population proportions	0.50	0.53	0.52	0.55	0.54

Population-weighted quintiles, highest deprivation scores and ethnic proportions in Q1, lowest in Q5.

Table 2. Ordinary least squares regression models of local screening participation.

Sex	AIC$_c$	Adj. R^2	Parameter	Estimate	SE	*t*	P	Autocorrected Moran's *I*	P
Males	719.5	0.663	Intercept	0.00	0.03	0.00	1.00	0.57	0.000
			Deprivation	–0.80	0.03	–26.63	0.00		
			Ethnic population proportions	–0.04	0.03	–1.16	0.25		
Females	634.2	0.728	Intercept	0.00	0.03	0.00	1.00	0.58	0.000
			Deprivation	–0.86	0.03	–31.85	0.00		
			Ethnic population proportions	0.03	0.03	1.27	0.20		

AIC$_c$, corrected Akaike information criterion; Adj. R^2, adjusted Adj. R^2; SE, standard error.

Table 3. Overall and local model fit summaries for the multiscale geographically weighted regression models.

Sex	AIC$_c$	Adj. R^2	Local R^2		
			Min	Median	Max
Males	410.3	0.86	0.60	0.87	0.98
Females	318.5	0.90	0.77	0.91	0.98

AIC$_c$, corrected Akaike information criterion; Adj. R^2, adjusted Adj. R^2.

models of which each MGWR model is comprised, and for these models the median local R²s were very similar to the overall adjusted R². Mapping the local values illustrated similarities in spatial patterns between the two models (see Figure 2). Most local models with more moderate fit were concentrated among IZs in south Lanarkshire, in the more remote rural end of the study area. However, it should also be noted that the IZs in that portion of the study area exert disproportionate visual influence on the mapped patterns, due to their large territories. In numerical terms they constitute no more than about 5% of the total number of IZs –in other words, most study IZs in the other parts of the study area had local models with a higher degree of fit to the data. MGWR local residual values represent the difference between each of actual standardised local screening participation estimates and the corresponding local model estimate. No significant spatial clustering was apparent among these local residuals, with Moran's I of –0.03 (P=0.803), and –0.04 (P=0.860), for the male and female models, respectively.

Table 4 gives the optimal bandwidths for the MGWR models. The majority of these bandwidths were substantially less than the upper search limit of 400 IZs, which had been set, suggesting that corresponding relationships exhibited some degree of spatial variability. The sole exception to this was the relationship between female participation screening levels and local ethnic population proportions, for which the bandwidth did in fact attain the maximum size, indicating a global-type relationship. For both MGWR models, the smallest bandwidths regarded the local intercept terms. The intercepts themselves indicate where screening participation levels were different than expected if conditions in every IZ were the same (*i.e.*, if they had average deprivation scores and average

ethnic population proportions). The localised nature of the intercepts indicated by these bandwidths suggests something intrinsically different about IZs in different parts of the study area (a point taken up again below).

Table 5 summarises the distributions of the local parameter estimates from the MGWR models. As the variables input to the models were standardised, these estimates may be compared directly in terms of their magnitude, to indicate strengths of associations. Similar to the OLS models, these parameter estimates suggest that local deprivation levels had a greater impact on screening participation levels than local ethnic population proportions. Area deprivation was inversely related to screening participation levels in all locations, and for both sexes, with median local coefficient values of around –0.8, close to the global OLS coefficient estimates, and with relatively tight ranges. In the model for males, local ethnic population proportions also tended to be inversely associated with screening participation levels, although around one-tenth of IZs had coefficients which were positively signed. However, in the model for females, the coefficient values for the relationship with ethnic population proportions were uniformly small, around just –0.07 (incidentally, a sign reversal compared to the corresponding global parameter estimate; *cf.* Table 2), indicating an only very small independent impact (if any) on screening participation levels among females, once deprivation was accounted for. For both models the estimates for the local intercepts ranged between positive and negative values, indicating respectively above and below-expected participation levels. The range of these intercept values was also relatively large, suggesting again (as with the bandwidths) a relatively strong, localised spatial variability.

Table 6 provides the parameter-specific adjusted critical t-values utilised for significance testing, with almost all of these values

Table 4. Optimal bandwidths for the multiscale geographically weighted regression models.

Sex	Intercept	Deprivation	Ethnic population proportions
Males	41	106	53
Females	27	50	400

Total intermediate zones (IZs) = 409.

Table 5. Summaries of local coefficients and intercept distributions from the multiscale geographically weighted regression models.

Sex	Parameter	Min	Median	Max
Males	Intercept	−0.82	0.17	0.58
	Deprivation	−0.96	−0.81	−0.61
	Ethnic population proportions	−0.58	−0.19	0.22
Females	Intercept	−0.84	0.03	0.49
	Deprivation	−1.03	−0.84	−0.52
	Ethnic population proportions	−0.07	−0.07	−0.06

Table 6. Adjusted critical t-values for the multiscale geographically weighted regression models, and the corresponding proportions of study intermediate zones with significant local parameters.

Sex	Parameter	Adj. t (95%)	Proportion of IZs > Adj. t
Males	Intercept	3.09	0.70
	Deprivation	2.79	1.00
	Ethnic population proportions	2.94	0.26
Females	Intercept	3.25	0.52
	Deprivation	3.04	1.00
	Ethnic population proportions	1.98	1.00

Total intermediate zones (IZs) = 409.

being higher (more conservative) than conventional *t*-values. Study IZs having significant estimates based on these critical values are mapped in Figure 3. The maps in Figure 3(a) are of the significant local intercepts, including about 70% of the entire set of study IZs for the model of male screening participation levels, and just over 50% for the model for females. These maps point to a clear contrast between the two health board regions comprising the study area. In the Greater Glasgow and Clyde region, almost all the IZs with significant local intercepts had above-expected local screening participation levels, whereas in the other health board region, Lanarkshire, IZs with significant local intercepts had below-expected participation levels. However, some marked internal variations are also seen within these two regions. In Greater Glasgow and Clyde, IZs with significant intercept values were predominantly located outside Glasgow, including in more affluent areas to the north and south-west of the city. In Lanarkshire, IZs with most negative intercepts were situated in the more urbanised and industrial northern part of the region.

For both models, *i.e.* males and females, all IZs had significant local deprivation coefficients, and the maps in Figure 3B show also that there was a high degree of consistency among the coefficient values, albeit with a somewhat weaker relationship observed among the Glasgow IZs compared to others. The median value among the Glasgow subset was –0.7 in the model of male participation levels and –0.74 in the model for female participation levels (*cf.* overall medians of –0.81 and –0.84, see Table 5).

A contrasting picture was observed from the final pair of maps in Figure 3C, which include the significant coefficients for the relationship between screening participation levels and local ethnic population proportions. In the model of male participation levels, this included roughly a quarter of all IZs, the vast majority of which (92 IZs) were concentrated in Glasgow. The few other significant IZs outside this Glasgow cluster were divided roughly evenly between two groupings in the north-west and south of the study area. However, the local *t*-values for both the latter clusters exceeded the significance threshold only slightly, with medians of –3.08 and –3.03, respectively (*cf.* the critical value of 2.94 in Table 6), whereas *t*-values within the Glasgow cluster were higher, with a median of –4.04. Furthermore, the ethnic population proportions were also not high in the vicinity of either of these two additional clusters. To assess this, a subset of nearest-neighbour IZs was selected for an IZ located at the centre of each cluster, with 53 IZs selected per subset (*i.e.*, equivalent to the bandwidth size for the relationship). The median ethnic population proportions yielded from these selections were only 0.03 and 0.04, compared to a corresponding median of 0.15 for IZs within the Glasgow cluster. Consequently, it is possible that both of these clusters were spurious, even with using the more restrictive significance filtering process described above. In the model for females, the uniformly small coefficients for the relationship with local ethnic population proportions were all found to be significant.
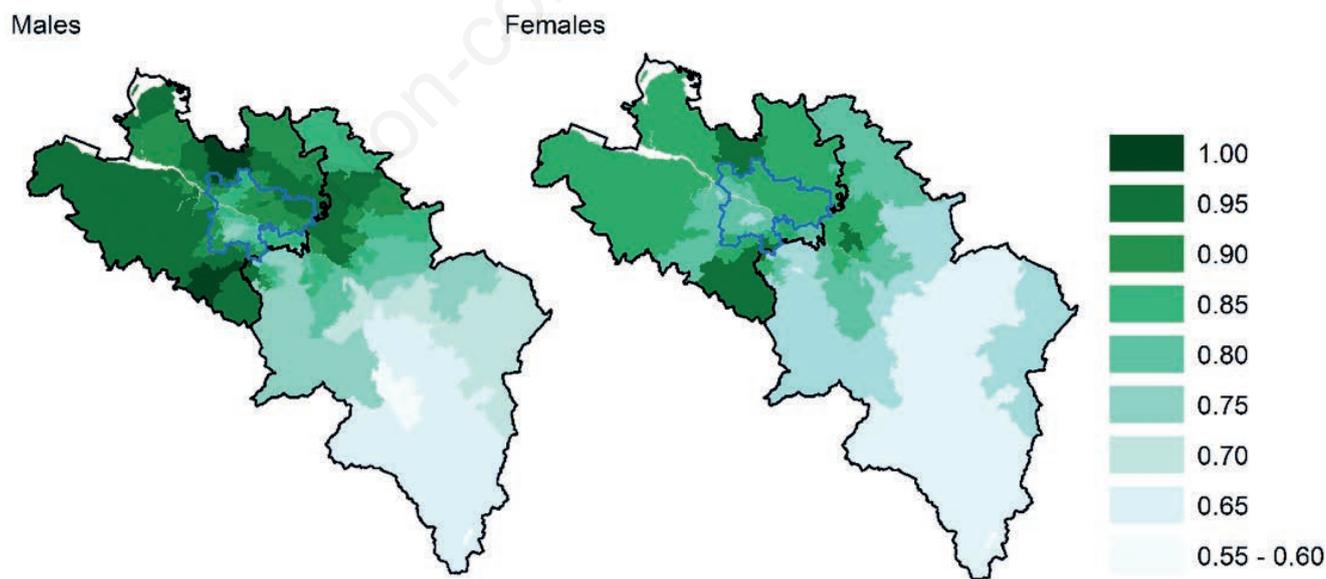

Figure 2. Local R2 maps from the multiscale geographically weighted regression models. The blue polygon represents the extent of Glasgow city council area. *Contains NRS data © Crown copyright and database right 2021. Contains OS data © Crown copyright (and database right) 2021.*

Discussion

This study found evidence of significant socioeconomic-related differences in local levels of participation in the organised CRC screening programme operating in a west central Scotland study area. Participation levels were generally higher for females than males, although for many locations within the study area, they were below the minimum target level set for the screening programme. There was a clear inverse relationship between local participation levels and area deprivation scores for both sexes. This relationship was similar across all locations, with only limited evidence of spatial variability, with local deprivation coefficient values being only a little smaller in the city area of Glasgow compared to the rest of the study area. This finding is somewhat surprising since Glasgow has both some of the most deprived areas in the study area (indeed nationally), as well as a high concentration of deprived areas. However, the inability of the Carstairs area depri-

vation index to capture all aspects of deprivation present in Glasgow may be one reason for this slight difference observed in the local model results. The screening participation levels also had a significant inverse relationship with local ethnic population proportions, although the impacts of the latter were considerably smaller in comparison to deprivation. The impact on male screening participation levels was confined to the Glasgow area, discounting two other potentially falsely significant clusters in other locations, whereas for females the impact was very minor, effectively zero, everywhere. Meanwhile, the local model intercepts points to a broad difference in screening participation levels between the two health board regions in the study area even after accounting for the explanatory variables. The reasons for this regional difference remain unclear: it may reflect differences in reporting, and/or promoting screening programme engagement, but this needs further investigation. What is clear is that this difference would be missed in the calibration of traditional non-spatial
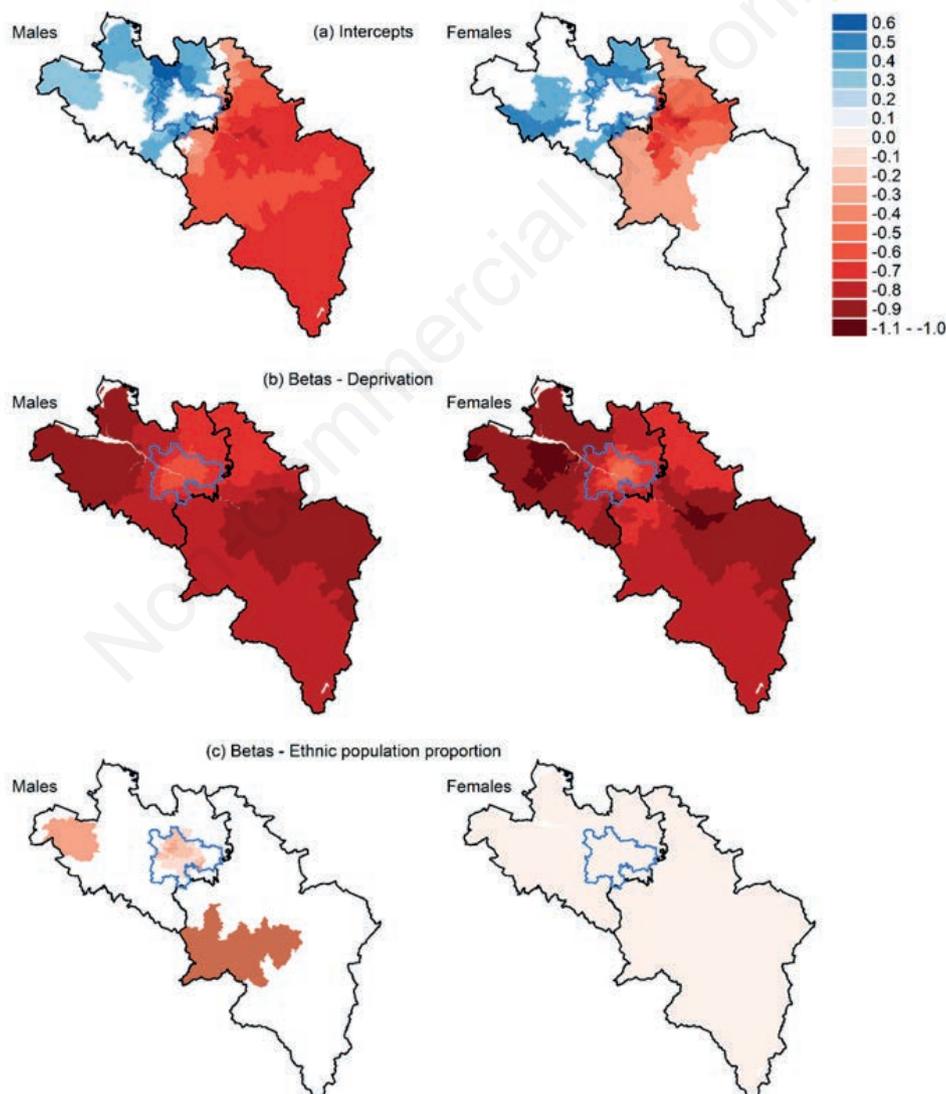

Figure 3. Local parameter maps from the multiscale geographically weighted regression models. *Contains NRS data © Crown copyright and database right 2021. Contains OS data © Crown copyright (and database right) 2021.*

global models. It is only through the application of local modelling that such differences can be identified.

The design of screening including a proactive invitation system and use of home screening kits suggests that the programme under consideration here should be free of certain kinds of physical and supply-side barriers, which have been shown to affect screening participation in other locations, such as density of physicians providing screening (Vogt *et al.*, 2014) or issues with transportation to screening facilities (Honein-AbouHaidar *et al.*, 2016). Safer comparisons may be drawn with the earlier pilot programme in north-east Scotland and with the counterpart organised screening programme in England, which operates on a similar basis to the Scottish programme. Analysis of these programmes has similarly found differences in participation levels by sex and by area deprivation (Nnoahm *et al.*, 2010; Steele *et al.*, 2010b; Von Wagner *et al.*, 2011). Moreover, in the last of the studies cited, the global relationship gradient with area deprivation levels was found to be steeper for females, and this was further hypothesised to reflect the influences of stronger socio-spatial networks among women compared to men. Results from the present study weigh in support of this hypothesis, as the local deprivation coefficients from the MGWR models were also somewhat larger on average in the model for females than in the model for males, plus the bandwidth size for the participation-deprivation relationship was also smaller, suggesting a more localised scale of relationship. Having said this, the local deprivation coefficients also show that the dampening influences of deprivation are widely experienced, in turn suggesting that a broad-scale approach to tackling barriers is needed, rather than one where attention becomes fixed only on the most deprived communities. Additionally, the results underscore an urgent need to improve understanding of impediments to and facilitators of screening across the socio-economic spectrum, among males in particular.

Most recent monitoring reports for the screening programme in Scotland suggest that inequalities in participation persist, despite a change having been made to the screening test, which reduces the number of samples required for the home screening kits from three down to one (ISD, 2019; Clark *et al.*, 2020). It is also possible that some kits do not reach their intended recipients, and that factors such as working patterns, organisation of living spaces and access to the postal system also pose constraints on screening participation. However, review evidence suggests that poor awareness of cancer screening, and emotional factors as well as cultural beliefs influencing negative attitudes towards cancer and screening are generally more substantial types of hurdle to overcome (Chapple *et al.*, 2008; Honein-AbouHaidar *et al.*, 2016; Wools *et al.*, 2016). Translating evidence of such factors into practical and effective programme changes, at scale, is also challenging. For example, O'Carroll *et al.* (2015) scored only modest success with trialling an 'anticipated regret' questionnaire, which was enclosed with invitation letters distributed to CRC screening programme invitees across Scotland. Among those who responded to this questionnaire, the intention to return the screening kit was strengthened, yet responses were only received from around one-third of those who were sent the questionnaire. In a similar vein, with the previous pilot screening programme mentioned above, repeat invitations were found to have only a modest impact on participation in terms of increasing odds of participation (Steele *et al.*, 2010b).

The relationship between CRC screening participation and local ethnic populations had not been examined previously in Scotland, perhaps because this part of the United Kingdom has not

been considered ethnically diverse. However, in recent decades ethnicity has in fact been growing, and ethnic diversity increasing, although many local areas in Glasgow continue to have high ethnic populations and diversity compared to other locations (Simpson, 2014). The results for males in this study suggests that it may be especially important in Glasgow to find ways to build an 'as one' mentality towards screening participation; in other words emphasising the general betterment of health and welfare for all families and communities that may follow from higher levels of screening engagement. Additionally, the influences of residential mixing/segregation on screening participation should be investigated further, starting with Glasgow. The benefit of local modelling is again demonstrated here, as the 'Glasgow effect' referred to here was only shown by MGWR, rather than using the standard global modelling approach. Moreover, the MGWR model of female participation levels shows the benefit of calibrating bandwidths separately for different modelled relationships. Had standard GWR been used, then the large bandwidth for the participation-ethnicity relationship in the model for females would have been forced to decrease towards a 'model average size', potentially giving misleading local parameter estimates.

The measures of the explanatory variables used in this study have their limitations, but so do alternatives which were considered. For example, the official small-area index of multiple deprivation is not designed for use with IZs, and while some data on income deprivation from that index could be aggregated to the IZ level, there was no clear rationale to do so, given the free, no-charge basis of CRC screening in Scotland. Also, it is possible that the model results could alter if the size and/or configuration of spatial units were changed; however, this issue is a perennial consideration when working with geographically-aggregated data, and not specific to the present study. Finally, while MGWR enables bandwidth optimisation for individual relationships, the 'single figure' bandwidth found for each relationships provides a limited basis for judging scale differences in the spatial variability of relationships, given uncertainty affecting parameter estimates. Bandwidth confidence intervals have been incorporated within the newest release of MGWR (Li *et al.*, 2020), and constitute an important step in representing such uncertainty more explicitly.

Conclusions

A key goal for organised CRC screening programmes is to ensure equal access to screening opportunities. However, from this study, it appears that such programmes are unable to remove all barriers on screening participation, even in situations where screening is free and universally available and can be completed at home. Multiple actions to increase participation to higher, more uniform levels may be considered. Investigating spatial variations in influences on screening participation is shown here to have potential to contribute knowledge regarding future areas of research and appropriate interventions and strategies to develop towards increasing screening uptake and tackling participation inequalities.

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