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LETTER

Obesogenic environmental factors of adult obesity in China: a nationally representative cross-sectional study

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18 March 2020Xiao Zhang¹, Mei Zhang¹, Zhenping Zhao¹, Zhengjing Huang¹, Qian Deng¹, Yichong Li¹, An Pan², Chun Li¹, Zhihua Chen¹, Maigeng Zhou¹, Chao Yu³, Alfred Stein⁴, Peng Jia^{4,5,6,7,8}  and Limin Wang^{1,7,8}¹ National Center for Chronic and Noncommunicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing, People's Republic of China² School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, People's Republic of China³ State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, People's Republic of China⁴ Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands⁵ International Initiative on Spatial Lifecourse Epidemiology (ISLE), Hong Kong, People's Republic of China⁶ Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong, People's Republic of China⁷ These authors contributed equally to this work.⁸ Authors to whom any correspondence should be addressed.E-mail: jiapengff@hotmail.com and wanglimin@ncncd.chinacdc.cn**Keywords:** obesity, adult, physical environment, built environment, food environment, socioeconomic environmentSupplementary material for this article is available [online](#)**Abstract**

The prevalence of obesity is still rising among Chinese adults and may be attributed to environmental factors, which, however, has only been examined in western countries before. This study aimed to estimate associations between obesogenic environments and adult obesity in China, on the basis of the official 2013–4 nationally representative survey. General and abdominal obesity were defined by body mass index and waist circumference, respectively, according to both the Chinese and international criteria. The mean summer/winter temperature in provinces, the mean fine particulate matter (PM_{2.5}) concentration, gross domestic product *per capita*, and education level in districts/counties, and the densities of fast-food restaurants, full-service restaurants, grocery stores, and supermarkets in subdistricts/towns were calculated. Five-level logistic regression models were used to estimate their associations with obesity, also in urban and rural regions separately. Both general and abdominal obesity in men were associated with the highest PM_{2.5} concentration, summer temperature, and density of full-service restaurants and grocery stores, as well as the lowest winter temperature. These associations were also observed in women except for summer temperature and density of full-service restaurants with abdominal obesity. Some associations varied by urban-rural regions. Also, the higher regional education level was associated with general and abdominal obesity in men. Additionally, obesity was associated with the increasing number of coexisting obesogenic environmental factors. Our findings call for more attention to citizens living in certain environments in China, such as cold winters and with more full-service restaurants and grocery stores. This is the first national, comprehensive obesogenic environment study in China, which generated evidence-based hypotheses for future longitudinal research and interventions on obesogenic environments in China.

Introduction

Obesity prevalence has rapidly grown worldwide. According to the World Health Organization (WHO), the global prevalence of obesity has nearly doubled during 1980 and 2008. It is well established that obesity

contributes to many chronic diseases including cardiovascular diseases, diabetes, metabolic syndrome, and cancers [1]. A recent study on global burden of disease indicated that 4.0 million deaths and 4.9% of disability-adjusted life years have been attributed to overweight and obesity in 2015 [2].

While genetic and lifestyle factors can affect the likelihood to become obese [3, 4], clustering of obese people in specific regions/contexts may point to environmental and socioeconomic causes, or termed *obesogenic environments* [5]. Many existing efforts have focused on the roles of built environments in obesity epidemic, due to its intuitive influences on dietary and physical activity behaviors [6, 7]. The natural environment, although understudied [8], is also a contributor to obesity owing to its relation with individuals' energy expenditure [9]. In addition, existing evidence has revealed associations of both individual- and area-level socioeconomic status (SES) with obesity, which may vary by sex and country [10, 11]. Nevertheless, despite possible links to obesity, the associations of these environmental factors with obesity have been mostly investigated in western countries [12, 13] that dramatically differ from China in multi-dimensional environmental characteristics and exposure scenarios [6, 14]. An understanding of their associations with obesity in China is needed to develop studies examining causality and specific interventions targeting high-risk populations.

To fill this gap, we resorted to the 2013–4 China Chronic Disease and Risk Factors Surveillance (CCDRFS) for assessing associations with adult obesity of built, natural, and socioeconomic environments that have been commonly studied in obesogenic environmental research in western countries. To our knowledge, this is the first national, comprehensive obesogenic environment study in China, which will serve as a benchmark for future research, interventions, and policies in China [15] and further our understanding of worldwide obesity epidemic [16].

Methods

Study population

The CCDRFS is an official, successive nationally representative survey conducted every three years since 2004, aiming to monitor the epidemic of major chronic diseases and related risk factors in China. The most recent available CCDRFS wave conducted from August 2013 to April 2014 was used in this study. The sampling design has been described elsewhere [17]. In brief, eight strata were generated within each of 31 subnational administrative units (provinces) in mainland China based on three binary (high/low) variables (i.e. population size, proportion of urban population, and mortality rate). A total of 298 units (125 urban districts and 173 rural counties) were selected and designated as disease surveillance points (DSPs). Four subdistricts/towns chosen from each DSP and three neighborhoods/villages from each chosen subdistrict/town were further selected under a complex multistage sampling [18, 19]. A residential group with at least 50 households was randomly selected from

each chosen neighborhood/village, with one person randomly selected from each chosen household using a Kish grid method.

Ultimately, 179 347 participants were enrolled. The response rate was 93.40% and the replacement rate was 6.34%. The inclusion criteria included aged ≥ 18 and living at the current location for at least six months within the last year before survey. Participants living in communal residence or with severe diseases that might impede the progression of interview were excluded. Moreover, participants with incomplete data on weight, height, waist circumference (WC), or sociodemographic and behavioral characteristics were further excluded, resulting in 170 872 participants included in the analysis. The study protocol was approved by the ethical review committee of the Chinese Center for Disease Control and Prevention. Written informed consents were obtained from all participants.

Outcome variables

Anthropometric parameters were measured on the day of the face-to-face interview. After removing heavy clothes and shoes, height, weight, and WC were measured by trained personnel with standardized techniques and protocols to nearest 0.1 cm, 0.1 kg, and 0.1 cm, respectively. The body mass index (BMI) was calculated by dividing weight (kg) by squared height (m). According to the Chinese criteria of obesity, *general obesity* was defined as BMI $\geq 28 \text{ kg m}^{-2}$ and *abdominal obesity* was defined as WC $\geq 90 \text{ cm}$ for men and $\geq 85 \text{ cm}$ for women [20, 21]. The concurrence of general obesity and abdominal obesity, written as *concurring obesity*, was also studied as an outcome, as the general obesity and abdominal obesity might have synergistic effects on health [22].

Environmental variables of interest

Built environment

The national points-of-interest commercial data set in 2013 was used to characterize the built environment within subdistricts/towns. According to the Chinese Industrial Classification codes, four categories of geocoded built environment features were extracted: western fast-food restaurant, full-service restaurant, small grocery (normally < 10 employees), and large supermarket. The *density of each category of features* (per km^2) was separately calculated within subdistricts/towns in which participants lived. Considering the degree of healthiness of food available in each type of food outlets and most findings in western countries, we hypothesized that higher density of western fast-food restaurants and groceries and lower density of full-service restaurants and supermarkets were associated with obesity [14].

Natural environment

The annual mean fine particulate matter (PM_{2.5}) concentration was produced at a 0.1° resolution from a two-stage spatial statistical model using satellite data and PM_{2.5} concentrations from the national ground monitoring network in China [23]. The daily temperature was obtained from the National Centers for Environmental Prediction Reanalysis at a 2.5° resolution [24]. Considering the weight transition from normal to obesity and the variation of natural environment across years, the mean PM_{2.5} concentration and temperature in summer and winter during 2011–2013 were separately calculated at the DSP and province levels. Given their impacts on physical activity, we hypothesized that higher PM_{2.5} concentration and summer temperature were associated with obesity, and lower winter temperature was associated with obesity [25, 26].

Socioeconomic environment

Two DSP-level measures of SES were used. The *gross domestic product (GDP) per capita* was obtained from the statistical communique of national economic and social development in 2012. The *percentage of residents with high school education or above*, referred as the *% of high education* afterwards, was obtained from the Chinese 2010 census data. We hypothesized that lower GDP *per capita* and lower % of higher education were associated with obesity [27].

Covariates

Five individual sociodemographic characteristics were included in the analysis: *age*, *ethnicity*, *educational level*, *living status*, and *annual household income per capita*. Five individual behavioral factors were also considered. *Current smoking* was answered as ‘No’, ‘Yes’, or ‘Cessation’. *Harmful drinking* was defined as average consumption of >60 g (40 g) alcohol per day for men (women). Using food frequency questionnaires, *regular excessive red meat intake* and *regular sufficient vegetable/fruit intake* were defined as average consumption of ≥100 g red meat and ≥400 g vegetable/fruit per day, respectively. *Regular physical activity* was categorized into three subgroups according to the time generally spent on moderate-intensity equivalent physical exercises in a week: ≤150, >150–300, and >300 min.

Statistical analyses

Five-level logistic regression model was used to examine the associations of environmental factors with obesity. The equation for regression analysis was:

$$\begin{aligned} \text{Logit}(P_{ijklm}) = & \beta_0 + b_m + b_{lm} + b_{klm} + b_{ijklm} \\ & + \sum_{h=1}^p (\beta_{1h} \text{FastFood}_{klm} + \beta_{2h} \text{FullService}_{klm} \\ & + \beta_{3h} \text{Grocery}_{klm} + \beta_{4h} \text{Supermarket}_{klm} \\ & + \beta_{5h} \text{SummerTemp}_{lm} + \beta_{6h} \text{WinterTemp}_{lm} \\ & + \beta_{7h} \text{PM}_{2.5lm} + \beta_{8h} \text{GDP}_{lm} + \beta_{9h} \text{Education}_{lm}) \\ & + \beta_{10} \text{Urbanicity}_{lm} + \sum_{n=11}^{10+q} \beta_n X_{nijklm} \end{aligned}$$

where P is the probability for obesity; i, j, k, l , and m denote individual, neighborhood/village, subdistrict/town, DSP, and province levels, respectively; b_m, b_{lm}, b_{klm} , and b_{ijklm} denote province-, DSP-, subdistrict/town-, and neighborhood/village-level random intercepts, respectively; p denotes the number of groups compared with the corresponding reference groups; and q denotes the number of individual-level covariates.

An empty model with random intercepts accounting for clustering of participants within units at each level was first fitted to investigate the variation of general and abdominal obesity at different geographic scales. The variation was translated into the median odds ratio (i.e. the median value of odds ratio of the areas with the highest and lowest risks) for better interpretability [28]. The associations between environmental factors and obesity were estimated with all individual-level covariates and urbanicity of DSPs (i.e. urban for districts or rural for counties) mutually adjusted. For more meaningful analyses and interpretation, individuals were categorized into tertiles based on each natural and socioeconomic environmental variable, and classified into three groups for each built environmental variable using the thresholds of zero and the median of non-zero values.

As sex may modify associations between environmental factors and obesity [29–31], all analyses were conducted in men and women separately. Models stratified further by urban-rural regions were also fitted with differences in statistical significance tested by z tests, because obesogenic environmental factors may play different roles in those two contexts in China. In addition, we examined whether or not coexistence of the obesogenic environment factors had cumulative effects on obesity. Finally, to test the robustness and increase international comparability of our findings, additional models were estimated with general and abdominal obesity defined as BMI ≥30 kg m⁻² (WHO criteria) and WC ≥102 cm (88 cm) for men (women) (National Heart, Lung, and Blood Institute criteria), respectively.

Statistical analyses were performed in MLwiN (Version 2.30), SAS (Version 9.4), and R (version 3.4.1). The two-sided $p < 0.05$ was considered as statistically significant.

Results

Descriptive statistics of the included participants

Our final sample of 170 872 adults comprised 72 884 men and 97 988 women (table 1). A comparison between participants included and excluded showed the similar distribution of most characteristics, but with more Han people, lower annual income, and more regular physical activity conducted among the included participants (table 1). The crude prevalences of general, abdominal, and concurring obesity, according to the Chinese criteria of obesity, were 15.0%, 36.2%, and 13.9%, respectively, and also, according to the international criteria, were 6.7%, 18.6%, and 5.4%, respectively.

Environmental determinants of obesity among all participants

The variation of general and abdominal obesity existed at all four levels above the individual (eTable 2). Compared with those who lived in subdistricts/towns without any full-service restaurant, people living in subdistricts/towns with the highest density of full-service restaurants showed higher odds of general (OR = 1.28 [95% CI, 1.07–1.53] and 1.19 [95% CI, 1.03–1.39] in men and women, respectively), abdominal (OR = 1.22 [95% CI, 1.01–1.47] in men), and concurring obesity (OR = 1.30 [95% CI, 1.08–1.57] and 1.19 [95% CI, 1.02–1.39] in men and women, respectively) (figures 1–3 and eTables 3–5). Similarly, compared to counterparts without any grocery store in their subdistricts/towns, people living in subdistricts/towns with relatively highest grocery store density had higher odds of general (OR = 1.20 [95% CI, 1.01–1.43] and 1.17 [95% CI, 1.01–1.35] in men and women, respectively), abdominal (OR = 1.24 [95% CI, 1.04–1.29] and 1.21 [95% CI, 1.03–1.42] in men and women, respectively), and concurring obesity (OR = 1.18 [95% CI, 1.02–1.37] in women). However, the impact of higher density of full-service restaurants on obesity became nonsignificant in both sexes after adopting international criteria for obesity definition (eTables 6–8).

People living in provinces with the highest summer mean temperature showed higher odds of general (OR = 1.30 [95% CI, 1.10–1.54] and 1.24 [95% CI, 1.04–1.46] in men and women, respectively) and concurring obesity (OR = 1.31 [95% CI, 1.11–1.55] and 1.22 [95% CI, 1.03–1.45] in men and women, respectively), with higher odds of abdominal obesity observed only in men (OR = 1.22 [95% CI, 1.05–1.43]) (figures 1–3 and eTables 3–5). The people who were exposed to higher winter mean temperature consistently had lower odds of general and abdominal obesity and their concurrence. Also, living in DSPs with the highest mean PM_{2.5} concentration were consistently associated with higher odds of general (OR = 1.25 [95% CI, 1.08–1.44] and 1.28 [95% CI,

1.11–1.46] in men and women, respectively), abdominal (OR = 1.32 [95% CI, 1.14–1.52] and 1.24 [95% CI, 1.05–1.47] in men and women, respectively), and concurring obesity (OR = 1.26 [95% CI, 1.09–1.45] and 1.28 [95% CI, 1.11–1.48] in men and women, respectively). All these associations remained regardless of the criteria for obesity (eTables 6–8).

Only the men living in DSPs with the highest % of high education, relative to the lowest tertile, had consistently higher odds of general (OR = 1.18 [95% CI, 1.00–1.39]), abdominal (OR = 1.17 [95% CI, 1.00–1.37]), and concurring obesity (OR = 1.23 [95% CI, 1.04–1.45]) (figures 1–3 and eTables 3–5). These associations became stronger when adopting international criteria for obesity (eTables 6–8). Associations between GDP *per capita* and obesity were not significant in both sexes.

Associations of the summer and winter temperature and density of full-service restaurants were generally stronger among rural participants, while the association between density of grocery stores and obesity was stronger among urban participants; however, only differences in ORs associated with the highest winter temperature and density of grocery stores reached statistical significance (figures 1–3 and eTables 9–11). The impact of PM_{2.5} also varied by urban-rural regions in women, with higher ORs among women living in rural regions.

The cumulative effects on obesity of the environment factors that were significantly associated with obesity from the above analyses were shown (figure 4 and eTable 12). Overall, the ORs for obesity showed a monotonic increase with the increasing number of coexisting obesogenic environment factors in men. For instance, the OR for general obesity associated with one obesogenic environment factor was 1.41 [95% CI, 1.22–1.63], but it elevated to 2.92 [95% CI, 1.65–5.17] when the number of coexisting obesogenic environment factors was six. This dose-response relationship also held true in women, but the increasing trend of ORs was less steep.

Discussion

The rise of obesity prevalence has been observed in China [32], which may be attributed to environmental factors. However, limited previous efforts have focused on environmental risk factors for obesity in China. On the basis of a nationally representative survey, we found that the higher summer temperature, PM_{2.5} concentration, and densities of full-service restaurants and grocery stores, as well as the lower winter temperature, were generally associated with increased risk of general and abdominal obesity and their concurrence in China. Some of these associations varied by urban/rural residence. Sex-specific association was also found, that is, only the men living in districts/counties with higher % of

Table 1. Individual and environmental characteristics (N, %) of the Chinese adults included in this study.

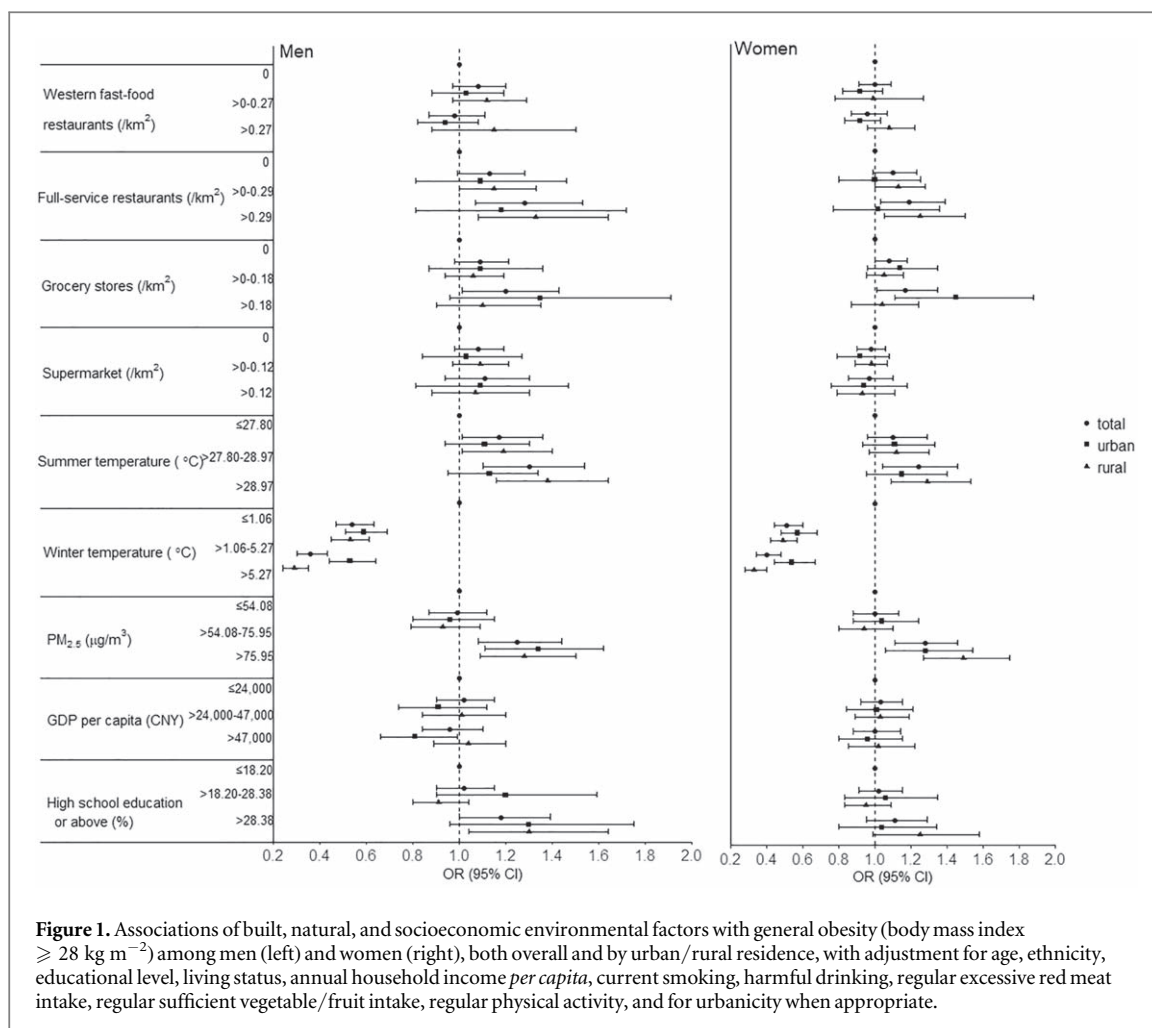
	All (n = 170 872)	Men (n = 72 884)	Women (n = 97 988)
<i>Individual sociodemographic characteristics</i>			
<i>Age (years)</i>			
18–29	13 746 (8.0)	6586 (9.0)	7160 (7.3)
30–39	22 141 (13.0)	9500 (13.0)	12 641 (12.9)
40–49	42 236 (24.7)	16 809 (23.1)	25 427 (25.9)
50–59	43 020 (25.2)	17 554 (24.1)	25 466 (26.0)
≥60	49 729 (29.1)	22 435 (30.8)	27 294 (27.9)
<i>Ethnicity</i>			
Han	151 303 (88.5)	64 160 (88.0)	87 143 (88.9)
Zhuang	2052 (1.2)	790 (1.1)	1262 (1.3)
Manchu	2136 (1.3)	907 (1.2)	1229 (1.3)
Muslim	2097 (1.2)	1002 (1.4)	1095 (1.1)
Uyghur	1919 (1.1)	1026 (1.4)	893 (0.9)
Tibetan	3070 (1.8)	1289 (1.8)	1781 (1.8)
Others	8295 (4.9)	3710 (5.1)	4585 (4.7)
<i>Educational level</i>			
Less than high school	135 587 (79.4)	55 360 (76.0)	80 227 (81.9)
High school	23 926 (14.0)	11 800 (16.2)	12 126 (12.4)
College or above	11 359 (6.6)	5724 (7.8)	5635 (5.7)
<i>Living status</i>			
Alone	24 183 (14.2)	10 001 (13.7)	14 182 (14.5)
Not alone	146 689 (85.8)	62 883 (86.3)	83 806 (85.5)
<i>Annual household income per capita (Chinese yuan)</i>			
≤12 000	59 381 (34.8)	26 112 (35.8)	33 269 (34.0)
>12 000–36 000	58 242 (34.1)	24 764 (34.0)	33 478 (34.1)
>36 000	13 174 (7.7)	5915 (8.1)	7259 (7.4)
Unknown	40 075 (23.4)	16 093 (22.1)	23 982 (24.5)
<i>Individual behavioral characteristics</i>			
<i>Current smoking</i>			
No	120 219 (70.4)	25 789 (35.4)	94 430 (96.4)
Yes	41 537 (24.3)	38 613 (53.0)	2924 (3.0)
Cessation	9116 (5.3)	8482 (11.6)	634 (0.6)
<i>Harmful drinking</i>			
No	165 269 (96.7)	67 645 (92.8)	97 624 (99.6)

Table 1. (Continued.)

	All (n = 170 872)	Men (n = 72 884)	Women (n = 97 988)
Yes	5603 (3.3)	5239 (7.2)	364 (0.4)
<i>Regular excessive red meat intake</i>			
No	118 000 (69.1)	46 095 (63.2)	71 905 (73.4)
Yes	52 872 (30.9)	26 789 (36.8)	26 083 (26.6)
<i>Regular insufficient vegetable/fruit intake</i>			
No	88 463 (51.8)	37 235 (51.1)	51 228 (52.3)
Yes	82 409 (48.2)	35 649 (48.9)	46 760 (47.7)
<i>Regular physical activity (min/week)</i>			
≤150	24 352 (14.2)	12 361 (17.0)	11 991 (12.2)
>150–300	15 017 (8.8)	6591 (9.0)	8426 (8.6)
>300	131 503 (77.0)	53 932 (74.0)	77 571 (79.2)
<i>Environmental factors</i>			
<i>Density of western fast-food restaurants (km⁻²)</i>			
0	109 945 (64.3)	48 190 (66.1)	61 755 (63.0)
>0–0.27	30 440 (17.8)	12 626 (17.3)	17 814 (18.2)
>0.27	30 487 (17.9)	12 068 (16.6)	18 419 (18.8)
<i>Density of full-service restaurants (km⁻²)</i>			
0	19 378 (11.3)	8650 (11.9)	10 728 (11.0)
>0–0.29	76 004 (44.5)	33 455 (45.9)	42 549 (43.4)
>0.29	75 490 (44.2)	30 779 (42.2)	44 711 (45.6)
<i>Density of grocery stores (km⁻²)</i>			
0	38 422 (22.5)	17 194 (23.6)	21 228 (21.7)
>0–0.18	66 370 (38.8)	29 033 (39.8)	37 337 (38.1)
>0.18	66 080 (38.7)	26 657 (36.6)	39 423 (40.2)
<i>Density of supermarkets (km⁻²)</i>			
0	38 968 (22.8)	17 637 (24.2)	21 331 (21.8)
>0–0.12	66 275 (38.8)	28 741 (39.4)	37 534 (38.3)
>0.12	65 629 (38.4)	26 506 (36.4)	39 123 (39.9)
<i>Mean summer temperature (°C)</i>			
≤27.80	63 017 (36.9)	27 549 (37.8)	35 468 (36.2)
>27.80–28.97	61 105 (35.8)	25 672 (35.2)	35 433 (36.2)
>28.97	46 750 (27.3)	19 663 (27.0)	27 087 (27.6)
<i>Mean winter temperature (°C)</i>			
≤1.06	53 696 (31.4)	23 523 (32.3)	30 173 (30.8)
>1.06–5.27	65 656 (38.4)	27 713 (38.0)	37 943 (38.7)

Table 1. (Continued.)

	All (<i>n</i> = 170 872)	Men (<i>n</i> = 72 884)	Women (<i>n</i> = 97 988)
>5.27	51 520 (30.2)	21 648 (29.7)	29 872 (30.5)
<i>Mean PM_{2.5} concentration (μg m⁻³)</i>			
≤54.08	56 017 (32.8)	24 764 (34.0)	31 253 (31.9)
>54.08–75.95	57 243 (33.5)	24 102 (33.1)	33 141 (33.8)
>75.95	57 612 (33.7)	24 018 (32.9)	33 594 (34.3)
<i>GDP per capita (Chinese yuan)</i>			
≤24 000	56 226 (32.9)	24 314 (33.4)	31 912 (32.6)
>24 000–47 000	57 364 (33.6)	24 642 (33.8)	32 722 (33.4)
>47 000	57 282 (33.5)	23 928 (32.8)	33 354 (34.0)
<i>% of residents with high school education or above</i>			
≤18.20	56 806 (33.2)	24 778 (34.0)	32 028 (32.7)
>18.20–28.38	56 466 (33.1)	24 867 (34.1)	31 599 (32.2)
>28.38	57 600 (33.7)	23 239 (31.9)	34 361 (35.1)
<i>Urban/rural residence</i>			
Urban	72 222 (42.3)	29 542 (40.5)	42 680 (43.6)
Rural	98 650 (57.7)	43 342 (59.5)	55 308 (56.4)

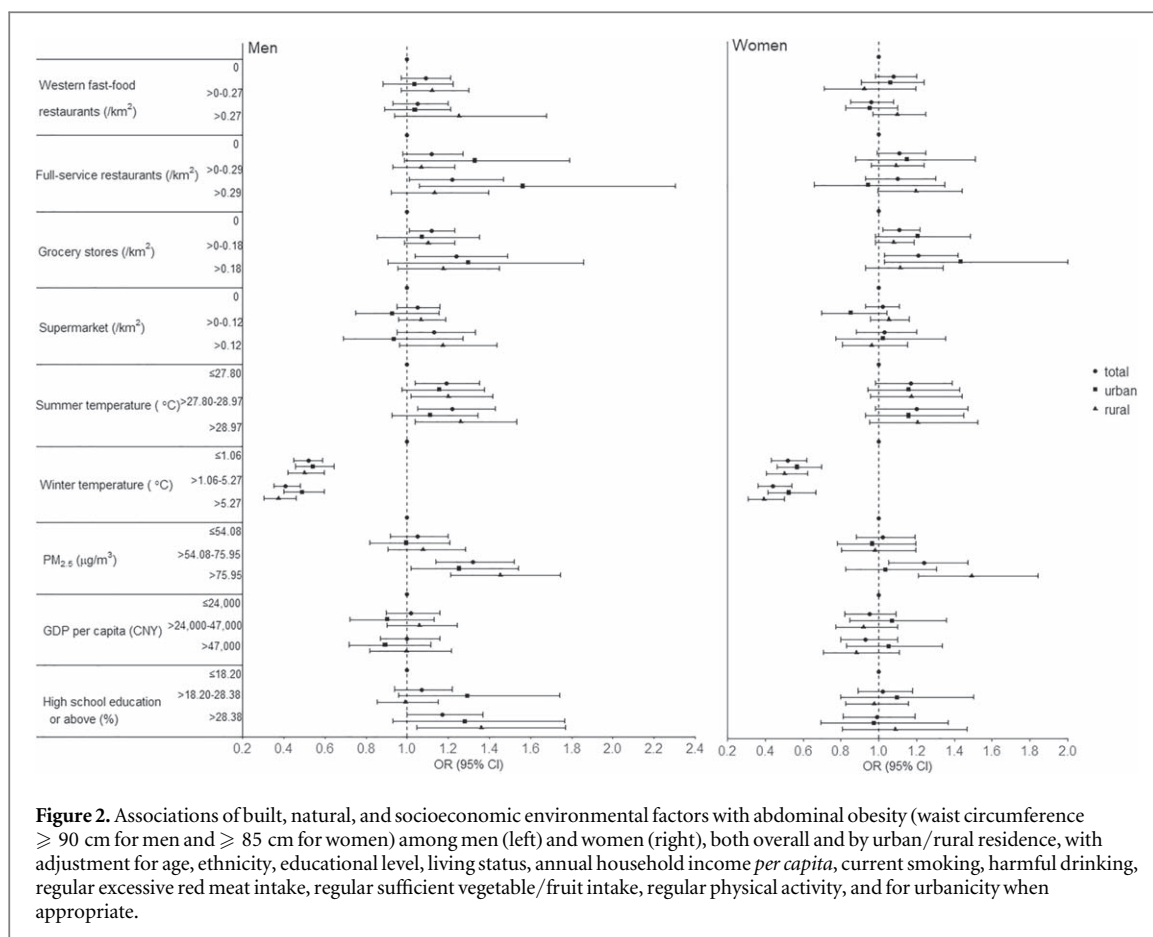


high education had higher odds of obesity. Additionally, coexistence of obesogenic environmental factors might have cumulative effects on obesity risk.

It is critical to investigate the associations between modifiable obesogenic environments and different measures of obesity in China, which has a different context from western countries where most hypotheses on the associations between obesogenic environments and obesity were established. The associations of $\text{PM}_{2.5}$ concentration, and temperature in summer and winter with obesity found in this study were consistent with our hypotheses. The higher PM concentration has been a well-known risk factor for many chronic diseases including cardiovascular disease and cancer, but its role in the development of obesity remains inconclusive. One reason may be different PM concentrations between studies [33–36]. For example, the mean $\text{PM}_{2.5}$ concentrations in two US studies were below the Air Quality Standard recommended by the US Environmental Protection Agency (i.e. $12 \mu\text{g m}^{-3}$) [33, 34], which were about seven times as low as those in two Chinese studies where a positive association between PM_{10} ($\text{PM} \leq 10 \mu\text{m}$) concentration with obesity risk among children and adults was found [35, 36]. Our study provided further evidence on the positive association between $\text{PM}_{2.5}$

concentration and obesity risk across the whole country. In addition, we revealed that both higher summer temperature and lower winter temperature were associated with increased obesity risk, which supported the notion that physical activity could be more discouraged by extreme temperatures at both ends and was consistent with the previous finding in the US [37]. Some other factors should be considered in future studies to identify mechanisms through which natural environments affect obesity risk. For example, cold weather could stimulate our appetite for energy-dense food and hot weather may tempt us to have more sugar-sweetened beverage and ice cream. The indoor climate control technologies (e.g. air conditioning and heating installation) may also influence the effect of temperature on obesity [38].

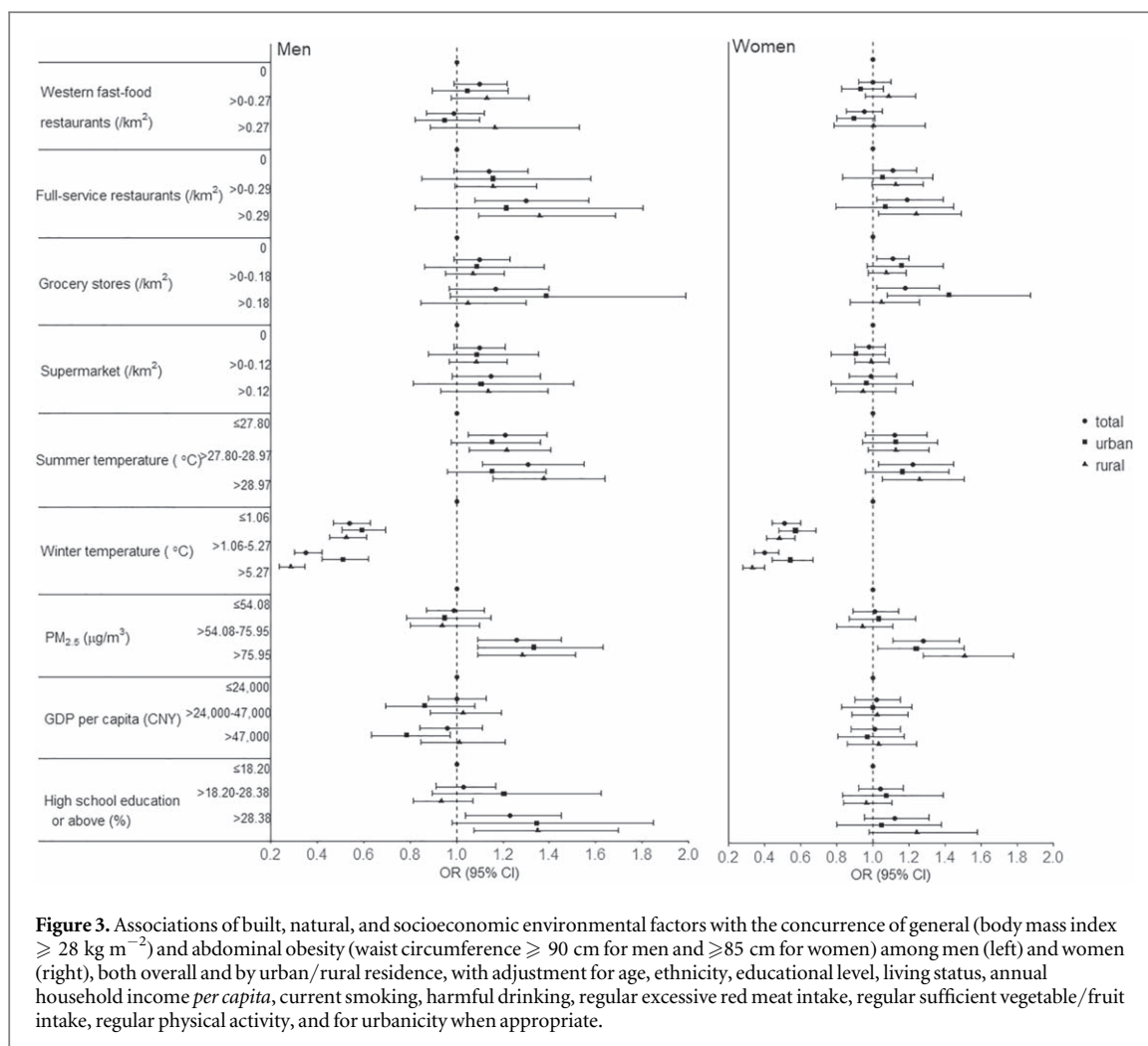
There have been mixed associations between full-service restaurants and obesity in western countries [31, 39–41] and we found a positive association in China. In addition to the fact that the food made in restaurants often contains excessive cooking oil which make the appearance and taste of the food more attractive, the higher density of full-service restaurants could increase opportunities of eating out [42]. The main purposes of eating out in China are socializing and entertaining in groups, thus the degree of



healthiness of eating out (e.g. the balance of meat and vegetable) is likely to deviate from recommendation. However, the influence of full-service restaurants on obesity may be limited, as their association became non-significant when using a higher cutoff of BMI to define obesity (i.e. the international criteria). The positive association of grocery stores with obesity found in this study was consistent with our hypothesized direction observed in many studies [14, 39, 43], although some other study found no association [44]. These variations could be partly attributed to complex routine activity space of individuals and different definitions and classification schemes of grocery stores in various countries [14], which further emphasized the importance of investigating individuals' time-activity patterns and food purchasing (behaviors). In addition, the positive association between regional education level and obesity found only among men in our study seemed contrary to many findings in western countries, although education level has always been adjusted as a covariate at the individual level. In China, food availability is spatially more homogeneous than, for example, the US. A higher regional education level may mean more access to food (e.g. more food purchasing and consumption, more eating out); on the other hand, in the environment populated with highly educated people, eating and sleeping rhythms are more likely to be disturbed by the fast pace of life,

which may predispose people to become obese through, for example, more exposure to psychological stress and less community engagement [45, 46]. Future research is warranted to use innovative approaches (e.g. ecological momentary assessment) to examine how individuals may perceive and interact with their surrounding food environments, in not only residential but work/school neighborhoods, and those frequently visited places.

Understanding the modifiers of the associations between environmental factors and obesity is informative, because it can help to identify subregions and/or subpopulations at higher risk that deserve more attention and tailored interventions. With different living environments, urban-rural residence has potential to modify the roles in obesity of factors such as climate and food environments. We found that the impacts of $PM_{2.5}$ concentration and summer and winter temperature were more pronounced among rural residents. The most likely explanation for these consistent differences is that physical activities of rural residents are more affected by extreme meteorological conditions and air pollution than those of urban residents. Indeed, the outdoor working environment and more flexible working time make rural residents prefer staying at home, when they encounter uncomfortably hot and cold temperature and high $PM_{2.5}$ concentration outdoors. In addition, urban residents can do

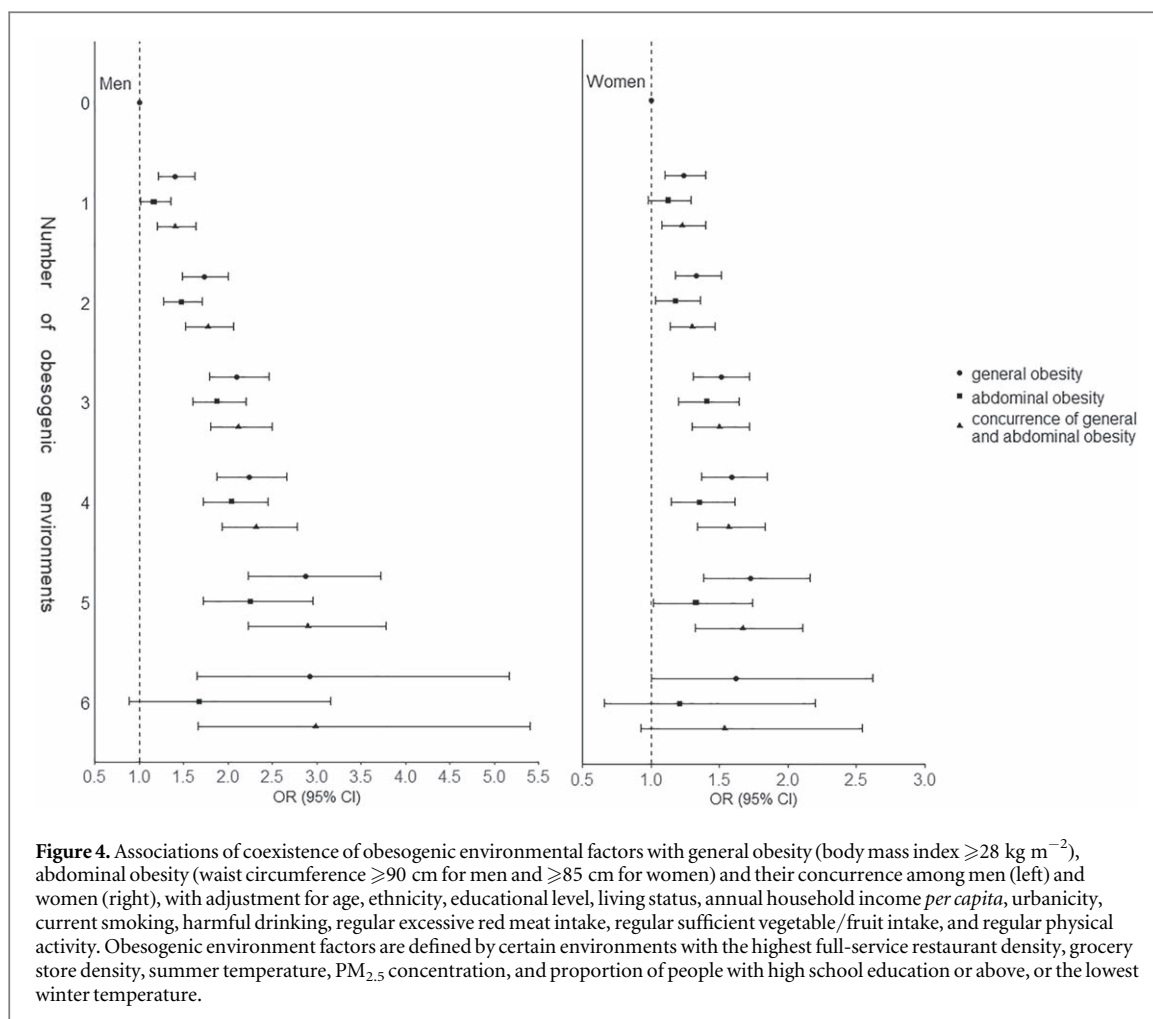


exercise in gyms when climate is less pleasant, while this is less possible for rural residents who live in areas with little to no gyms. It is noteworthy that a stronger impact of $\text{PM}_{2.5}$ concentration on obesity in rural regions is limited to women, suggesting that physical activities of rural women may be more sensitive to air pollution than rural men. The interaction of urban-rural residence with built environments in affecting obesity are more complex. We observed that the associations between the density of grocery stores and obesity were stronger among urban residents. It is expected as the transition of two or three meals toward meals combined with snacks is much faster in urban areas. Besides, more advertising and a larger variety of snack food in urban areas may also contribute to this result. In contrast, the associations between the density of full-service restaurants and obesity were stronger among rural residents, possibly because rural people generally have more spare time and higher engagement with local residents. These findings have certain public health implications as health interventions to be implemented at an administrative unit level seem more efficient than at the individual level.

In fact, obesogenic environments are not independent but rather tend to coexist in the same area, thus

they may work in combination to promote obesity. We observed the cumulative effects of multiple environmental factors, as evidenced by the dose-response relationships between the number of obesogenic environmental factors and obesity. In particular, these cumulative effects were relatively weaker among women. Based on these results, policies for obesity prevention that focus on multiple environmental factors and consider gender vulnerability to their cumulative effects should be highlighted.

This study has several limitations. First, we only examined associations with obesity of those commonly studied obesogenic environmental factors in western countries, without intention to be inclusive with all potential factors added in. Our results may be affected by other environmental factors, such as density of and proximity to street vendors and wet markets, which, however, are at present difficult to be accurately measured in China due to a large area and the limited data infrastructure. The classification of supermarkets and grocery stores should also be refined in future studies [41]. Second, individuals' exposure to built environments were estimated within subdistricts or towns where they lived instead of within buffer zones centered on their residence. Also,



individuals' activity space (or movement patterns) and environmental exposures around workplaces and along commuting routes were not considered [47]. Third, the average temperature used in our study was in a narrower range than raw monthly values, which may hide a non-linear (e.g. parabolic) relationship between temperature and obesity. More temporally frequent measurements of temperature will be matched to regional cohorts to scrutinize the association between temperature and obesity [48, 49]. Fourth, due to lack of previous obesogenic environmental research and consequently limited knowledge of determinants of obesity in China, some associations might be driven by different mechanisms than what were explained above, such as the positive association between regional education level and obesity. The improved study design and more and better data are needed to further investigate these associations. Lastly, the excluded 8475 participants (4.7% of the total sample) were somewhat different from the included ones in terms of ethnicity and income, which might introduce selection bias in this study. However, our large sample size and adjustment for characteristics that affect the probability of the inclusion enable us to assume that the potential impact of selection bias on our estimates is limited [50].

Conclusion

This study, for the first time, generated evidence-based hypotheses on the associations between obesity and obesogenic environmental factors in China, where we found different or even opposite associations of some environmental factors with obesity from those reported in western countries, e.g. the density of full-service restaurants. Our findings called for more attention to citizens living in certain environments in China, such as cold winters, hot summers, with severe air pollution, and with more full-service restaurants and grocery stores. Also, the variation of the associations between the obesogenic environment and obesity in urban and rural regions may imply different practices and policies to mitigate obesity risk in different contexts. This study holds potential to facilitate more in-depth research, as well as region- and sex-specific interventions, in order to attenuate health inequalities in future China.

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Competing interests

The authors declare no competing financial interests.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Peng Jia  <https://orcid.org/0000-0003-0110-3637>

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