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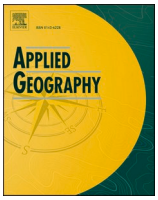

Social and spatial inequalities of contemporary food deserts: A compound of store and online access to food in the United Kingdom

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ABSTRACT

This research studies the social and spatial inequalities of contemporary food deserts in England and Wales. Two indices of the Store Food Desert Index and Online Food Desert Index are measured to examine store access and online access to food at the Lower Layer Super Output Areas geographical level. A detailed analysis is conducted to (i) identify "priority areas" where there is relatively lower store access and online access to food, (ii) synthesize population to understand the characteristics of "at-risk communities" that are disproportionately affected by food deserts, and (iii) examine the association between self-reported health conditions and a compound of store and online access to food. Three insights are provided. First, there is a clear urban-rural divide in which urban areas generally benefit from better provision of both store and online access to food. Second, about 23% of the population (13.8 million people) live in priority areas with limited access to both physical stores and online groceries. Within this group, 0.06% (8000 individuals) do not have cars, 2.17% (300,000 individuals) are Black, and 14.5% (2 million individuals) reside in deprived neighborhoods. This is an alarming picture. Third, people residing in areas with high store and online access to food reported better health conditions, and online access is as effective as store access in improving health conditions. The findings highlight the potential of combining online and store access to bridge geographical and economic gaps, thereby providing healthier food options to those in food deserts.

1. Introduction

Marked by socioeconomic deprivation and limited access to fresh, healthy food, over a million people in the United Kingdom (UK) reside in neighborhoods that suffer from a scarcity of nearby grocery stores and a dearth of easily accessible, nutritious food sources (Corfe, 2018). Much like an unforgiving desert landscape, they find themselves devoid of readily available, affordable, fresh produce, and other essential food items. Residents must contend with a significant absence of traditional supermarkets and grocery stores within a reasonable distance from their homes. Instead, they are left with a patchwork of convenience stores and small shops that often struggle to offer a diverse and wholesome range of food choices. Limited transport options, particularly for those with financial constraints, create significant hurdles in accessing supermarkets located outside the neighborhood. This scarcity of accessible, nutritious options combined with mobility barriers perpetuates a cycle of inadequate diets and compromised health outcomes within the community. The portrayal of these deprived neighborhoods epitomizes the pressing reality of the "food desert."

For over two decades, the notion of "food deserts" has evolved as a powerful metaphor, symbolizing the injustice that arises from limited access to nutritious food due to spatial disparities and social exclusion (Walker et al., 2010). Despite its initial resonance, it faces growing scrutiny from scholars and activists who argue that it perpetuates stigma, lacks accuracy, and falls short of capturing the complex web of structural inequities (De Master & Daniels, 2019). Critics argue that the food desert concept is stigmatizing, as it inadvertently places blame on the affected communities themselves by framing their circumstances as a result of their own choices or inherent deficiencies (Cummins & Macintyre, 2006). This framing overlooks the deeper structural inequities (e.g., poverty, systemic racism, discriminatory urban planning policies) that contribute to creating and perpetuating limited food access. The term "food desert" is insufficient to capture the multifaceted nature of spatialized food injustice. The sole focus on physical proximity to grocery stores neglects to address the intersecting dimensions of income inequality, transport limitations, and cultural barriers that impact

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access to healthy food. Criticisms urge a reevaluation of our understanding and call for address the multifaceted, spatialized aspects of food injustice.

The pursuit of equal access to food aims to establish equal or, at the very least, equitable availability of essential sustenance (Ermagun & Tilahun, 2020; Maharjan, Tilahun, & Ermagun, 2022). Ascertaining the degree of equality in food access has been challenging, however. Defining what qualifies as equitable access, particularly when it involves deviations from equal access, adds another layer of complexity. It may be tempting to assume that determining equal access is straightforward, akin to measuring income equality, and that equitable access consists of permissible or justifiable variations in access. It is clear that defining equal access and equitable access is far from simple. Particularly recently, with the emergence of online delivery and e-commerce, conceptualizing and measuring access to food has proven to be a more intricate task than initially apparent. This complexity arises partly due to the multifaceted nature of food, as it serves diverse purposes for individuals and disagreements regarding the nature of food as a social good. Some view it purely as a commodity, subject to market transactions like other goods, while others contend that it possesses unique significance as a pilar of survival that sets it apart from typical market commodities (Caraher & Coveney, 2016). To understand claims advocating for equal or at least equitable access to affordable and nutritious food, it is necessary to address barriers to access in order to ensure fairness.

With the well-founded criticisms surrounding store access to food, the overarching goal of this research is to adopt a compound of store and online access to food in the United Kingdom (UK). The UK makes an interesting focus for our analysis and enables us to draw on a recently released measure of contemporary food deserts, the E-food Desert Index (EFDI), introduced fully in our methodology (Newing, 2019). The UK has a longstanding policy interest in urban food deserts, with high-profile examples such as Seacroft (Leeds) gaining prominence in the academic and policy literature in the 1990s (Whelan et al., 2002; Wrigley, 2002). A trajectory of grocery retail development favoring larger format out-of-town stores left many urban neighborhoods devoid of grocery store provision in the UK. However, two decades of growth in convenience stores, discounters, and online groceries have provided new opportunities for grocery shopping and access to affordable and healthy food. Nevertheless, the Affordable Food for All campaign by the consumer group 'Which?' (Which?, 2022) highlights that many households still experience difficulties in accessing affordable and healthy food, set within the context of a "cost of living crisis." This makes it a topical and policy-relevant time to consider the presence of contemporary food deserts and the social and spatial inequalities in grocery provision in the UK.

We recognize and dismantle the underlying structural barriers that perpetuate unequal access to healthy food. This reframing necessitates broadening our scope to consider a comprehensive range of demographic and socioeconomic factors that contribute to social and economic inequalities, as well as the evolving landscape of online food access. The contribution of this study is threefold. First, we use indicators from the EFDI to generate measures of physical store and online access at the neighborhood level. We use these to identify "priority areas" with scarcity of store and online access to food in tandem, rather than in isolation. Second, we explore the spatial distribution of socioeconomic and demographic factors to diagnose "at-risk communities" that are disproportionately affected by food deserts. Third, we examine the association between store and online access to food and health outcomes to understand whether and to what extent access patterns are associated with community health. This research is conducted at a neighborhood level at a large scale, encompassing over 35,000 neighborhoods in England and Wales, providing insights into the broader context of food deserts in the region. The findings are then expected to contribute to the development of a more equitable and inclusive approach to addressing the multifaceted challenges surrounding access to nutritious food, particularly for marginalized communities. By recognizing the compounding effects of store and online access, as well as the influence of demographic and socioeconomic factors, we can foster awareness, understanding, and action to ensure that everyone has equitable opportunities to access healthy food.

The remainder of the paper begins with a review of the existing literature on the nexus between food deserts, equity, health, and e-commerce. It continues by outlining the data and methods as well as elaborating on the social and spatial disparities of scarcity of store and online access to food in England and Wales. The discussion concludes by illustrating the findings, discussing implications, and suggesting avenues for further research.

2. Review of literature

Food deserts captured the attention of academics and policymakers alike, conjuring up images of barren landscapes where communities are left isolated from essential resources needed for maintaining healthy diets (Bao et al., 2020; Chenarides et al., 2021; Wang et al., 2014). The metaphorical power of this term successfully highlighted the stark disparities that exist in accessing affordable and nutritious food options. However, understanding the complex factors contributing to the existence of food deserts requires delving deeper into the available studies.

2.1. Food deserts and equity

Scientific literature has discussed the association of food deserts with health outcomes, higher poverty rates, and demographic charactersitics. The findings remain mixed, regardless of the geographic area analyzed. Dutko et al. (2012) reported that food deserts are often found in less populated areas inhabited by low-income, less educated individuals who suffer from higher unemployment rates. They found that these areas have a higher concentration of ethnic and racial minority populations. Bower et al. (2014) elaborated on the racial disparities in supermarket access in a nationwide study in the US and found that African Americans were four times more likely than their Caucasian counterparts to reside in a neighborhood without a full-service supermarket. Even when comparing areas with similar poverty levels, predominantly African-American neighborhoods consistently exhibited the fewest supermarkets. Other researchers, however, found no discernible independent association between the availability of neighborhood food retail options and individual dietary patterns in the US (Dubowitz et al., 2015; Richardson et al., 2017). Dubowitz et al. (2015) investigated food access and purchasing practices in low-income, mostly African-American neighborhoods in Pittsburgh, PA, with limited access to healthy food. They found that while proximity to the nearest supermarket was important, most residents opted to shop at further distances where healthy foods were available. In another study, Richardson et al. (2017) examined the impact of a new supermarket on the economic status and health of residents in low-income Pittsburgh neighborhoods. They found that locating a new supermarket in such areas "may improve" residents' economic well-being and health.

A similar disparity is observed among the studies conducted in Canada. While a few studies have provided evidence supporting a significant association between food access and socioeconomic status in Canada (Joyce et al., 2017), others have found no or minimal socioeconomic differences in food access (Apparicio, Cloutier, & Shearmur, 2007; Bertrand et al., 2008; Smoyer-Tomic et al., 2006). Smoyer-Tomic et al. (2006) investigated supermarket access in inner-city neighborhoods and found that neighborhoods with high needs, as well as those within the smaller core of eight inner-city areas characterized by higher rates of low-income and carless households, had better access to supermarkets. Apparicio, Cloutier, & Shearmur (2007) utilized three access measures—proximity, diversity, and price variety—to identify food deserts in Montréal and found that food deserts were not a significant issue in the city, indicating that geographic accessibility to healthy food

was not a major concern. In a related study, Bertrand et al. (2008) examined disparities in access to healthy food in Montréal, specifically focusing on the availability of fresh fruits and vegetables as an indicator. Their findings revealed no correlation between median income in dissemination areas and food supply.

Research conducted in the United Kingdom presents mixed results as well. During the late 1980s and early 1990s studies highlighted demographic and socioeconomic inequalities, associating high prices and poor availability of food with disadvantaged areas experiencing deprivation (Cummins & Macintyre, 2006; Sooman et al., 1993). Later, however, observational studies in major urban centers across the UK presented a different perspective and yielded divergent conclusions. These studies have found no independent association between neighborhood food retail provision and individual dietary patterns (Giskes, Van Lenthe, Avendano-Pabon, Brug, & Health, 2010; Lake et al., 2010) with no identified significant differences in food prices, availability, and supermarket access between deprived and affluent areas (Pearce et al., 2009; Jiao et al., 2012; Cummins, Flint, & Matthews, 2014). The research surprisingly revealed the reasonable availability of a diverse range of "healthy" food options in urban areas (Lake et al., 2010; Pearce et al., 2009). Findings from these studies challenge the notion that low-income consumers in the UK encounter significant barriers when utilizing supermarkets or perceive limitations in terms of store choices and access to fruits and vegetables (Winkler et al., 2006; Cummins et al., 2014). Despite mobility challenges, few low-income consumers report encountering problems with using supermarkets, suggesting that access to larger retail establishments may not be a primary concern for them. Studies conducted in Northern Ireland also indicated that while consumers who rely on small local stores may face higher prices, there is limited evidence to suggest that consumers view traveling to edge-of-town supermarkets as a significant issue (Cummins, Flint, & Matthews, 2014). This suggests that individuals in the UK may navigate their food shopping patterns and adapt to the available options in their local areas. These findings present a perspective beyond the context of North America, shedding light on the more complex relationship between food access, affordability, and deprivation in the UK. They emphasize the importance of considering the local context and conducting rigorous, comprehensive research when addressing food inequalities and access to nutritious food options.

2.2. Food desert and health

Beneath the evocative appeal of the food desert concept lies a growing concern about the detrimental impact it has on the health of marginalized communities. Since the mid-1990s, there has been a surge of interest in examining the interplay between individual attributes and environmental factors in influencing health and health-related behaviors. Extensive scholarly discourse on area-based health disparities has scrutinized the conventional dichotomy of compositional and contextual explanations, with the former focusing on the socio-demographic characteristics of residents and the latter on the contextual attributes of the geographical area itself (Pickett & Pearl, 2001; Macintyre et al., 2002). Empirical analyses consistently suggest that individual determinant (e.g., age, gender, race, social class) are fundamental predictors of health outcomes and health-related behaviors. It is, however, a need to acknowledge that the physical and socio-political characteristics of one's residential environment also exert a discernible impact on health disparities and behavioral patterns (Pickett & Pearl, 2001). The limited presence of supermarkets offering affordable and nutritious food options is a pressing issue in many low-income and minority neighborhoods, exacerbating the health challenges faced by residents. It has been observed that neighborhoods inhabited by racial and ethnic minority groups bear a disproportionate burden of morbidity, mortality, and adverse health outcomes (Cubbin, LeClere, & Smith, 2000; Deaton & Lubotsky, 2003). The underlying factors contributing to these disparities (e.g., residential segregation, poverty, neighborhood deprivation) have significant implications for the health and well-being of individuals in these communities (Gee & Payne-Sturges, 2004). Environmental conditions create a complex web of health disparities that disproportionately affect marginalized communities. Rose and Richards (2004) argued that the concept of food access extends beyond physical availability and includes considerations of the built environment and individual characteristics. For instance, unsafe neighborhoods that discourage walking, time constraints resulting from work schedules or single parenthood, and the lack of time for meal preparation can all contribute to difficulties in accessing supermarkets (Rose & Richards, 2004). These multifaceted challenges highlight the necessity of new approaches that address the broader socio-environmental context and individual circumstances in addressing food access issues. To effectively promote equitable access to healthy foods, interventions should encompass more than just improving mobility options.

While food deserts focus on areas with limited access to healthy food options, food swamps are considered environments inundated with unhealthy food choices, often characterized by an overabundance of fast-food outlets, convenience stores offering processed foods, and limited access to nutritious options. Literature has also explored this as a potential avenue to examine the health impacts of food access. Smoyer-Tomic et al. (2008) in Edmonton, Canada, and Luo (2020) in Ontario explored the link between supermarket and fast-food exposure and neighborhood socioeconomic status. Higher odds of fast-food exposure were associated with areas with more Aboriginals, renters, lone parents, low-income households, and public transportation commuters. Low-wealth, renter-occupied, and lone-parent neighborhoods faced increased fast-food exposure without improved supermarket access, raising concerns about fast-food consumption, particularly among lone-parent families amid rising childhood obesity rates. Additionally, Block et al. (2004) in New Orleans highlighted a six-fold higher presence of fast-food restaurants in predominantly African-American neighborhoods, emphasizing food environment disparities. Further research by Block and Kouba (2006) revealed challenges in accessing healthier food options in predominantly African-American neighborhoods due to fewer supermarkets and more grocery stores with poorer product quality despite similar prices.

2.3. Food deserts and E-commerce

With the advent of technological advancements, online food shopping has gained prominence. However, disparities in the availability of online food resources may hinder addressing the existing inequalities in food access; the presence of a digital divide and limited internet connectivity in underprivileged communities can further exacerbate these inequalities (Ploeg et al., 2014). E-commerce has been shown to be associated with socioeconomic and demographic factors. Luan et al. (2015) argued that it is important to acknowledge that low-income individuals face obstacles in online food delivery services. Meslin (2018) studied the potential of e-commerce to alleviate food deserts and indicated that current online grocery shopping practices do not substantially reduce barriers for low-income consumers in these underserved areas. Despite the convenience and accessibility of e-commerce platforms, the study suggested that it may not be the ultimate solution to address the complex challenges associated with food deserts, particularly for economically disadvantaged populations. The issue was further explored by Mishra et al. (2023), who identified factors (e.g., age, ethnicity, income) that influence residents' willingness to engage in online shopping. They found a positive correlation between youth, African American ethnicity, higher income, and increased participation in internet shopping. They highlighted the challenges faced by food desert communities in accessing an adequate food supply, mainly due to disparities between the demand for nutritious food and the minimum order quantities required for delivery. To address this issue, expedited and adaptable online delivery services are identified as potential solutions. While online food shopping offers convenience, several factors come

into play, such as digital literacy, internet availability, and the affordability of delivery services (Guy & David, 2004). Consumers' choices in online food shopping may also be influenced by their perceptions of the quality and freshness of food compared to physical stores.

E-commerce has also been shown to be associated with geographical and environmental factors (Kirby-Hawkins et al., 2018). A study by Li, Feng, et al. (2023) examined the spatial patterns and influencing factors distinguishing online-to-offline food delivery restaurants (O2O-FDR) from conventional ones. Their findings indicated that there is more restricted and dispersed access to O2O-FDR compared to conventional restaurants. This indicated a discernible regional economic orientation, which is, in part, impacted by regional economic factors. Li and Wang (2022) studied how the environment impacts the use of online delivery systems in Shanghai. They found that (i) home food environments are a greater driver of eating through online food delivery services than workplace food environments and (ii) healthy food availability and accessibility in residential neighborhoods reduce the probability of using online food delivery systems. Li, Ma, et al. (2023) investigated the influence of environmental concern on green consumption behavior. Their findings suggested that (i) heightened environmental concern can effectively drive green consumption behavior and (ii) fostering consumer concern for the environment positively contributes to improved green consumption behavior. In a related study, Zhang et al. (2023) examined the impact of online food ordering and delivery on the equity of food access. Their research found that (i) online food delivery generally improved the equity of food access, although it exacerbated existing spatial disparities between urban and rural communities and (ii) socially disadvantaged groups continued to face vulnerabilities in accessing food procurement opportunities.

3. Data and method

3.1. Study area

With a combined population of over 60 million people, England and Wales boast a vibrant mix of cosmopolitan cities (e.g., London, Birmingham, Manchester) alongside, suburban areas and rural villages and towns. There exists a diverse population with significant variations in socioeconomic status, health, and well-being. Existing neighborhood indicators of the English Indices of Deprivation (MHCLG, 2019) and the Welsh Index of Multiple Deprivation (Welsh Government, 2020) highlight small-area inequalities in income, health, and access to local services (e.g., grocery retail opportunities). The grocery market is dominated by four major grocers ("the big four"): Tesco, Sainsbury's, Asda, and Morrisons, with a combined market share of approximately 65% of the market. A further 18% is held by discounters Aldi and Lidl, with other grocers, including independent retailers and symbol groups accounting for less than 3.5% of the market (Kantar, 2023). The dominance of a small number of retailers means that the geographical patterns evident on the supply side are a result of the location-based decisions made by those firms, coupled with the impact of planning policy.

Within our study area, large format store provision is a legacy of a period of intense competition and growth in the supermarket sector, termed "store wars" (Wrigley, 1988). Tightened planning legislation and concern for town center vitality, coupled with an awareness of accessibility issues in relation to out of town retailing (Guy & David, 2004) has given rise to new forms of grocery retail development (Guy & Bennison, 2007; Wood et al., 2010). These include rapid growth in discount retailers who traditionally favored inner city locations (Thompson et al., 2012), the widespread growth of branded convenience stores (Hood et al., 2015), and the development of e-commerce services (both click-and-collect and home delivery) by the major players and pure-play operators (Kirby-Hawkins et al., 2018). In spite of the growth in both store-based grocery provision and online groceries, there remain inequalities in access to and affordability of groceries in both a store-based (Which?, 2022) and online (Newing et al., 2021) context.

3.2. Data collection

The analysis draws its data from two primary datasets. First, the UK Census 2021 data was used to determine the geographical boundaries, the composition of households, and the demographic and socioeconomic characteristics of the population across the study area. Lower Layer Super Output Areas (LSOA) geographical level was set as the geographical level of analysis. LSOAs in the UK are administrative geographies designed for statistical purposes. They are smaller than administrative districts or wards but larger than individual city blocks or streets. LSOAs are created to improve the reporting and analysis of small-area statistics. However, they are not necessarily equivalent to what is commonly considered a "neighborhood" in the everyday sense. Specifically, LSOAs, composed of four or five Output Areas (OAs), represent the smallest unit for census statistics. LSOAs encompass populations typically ranging from 1000 to 3000 individuals and include between 400 and 1200 households. Second, to measure access to food, data have been derived from the e-Food Desert Index (EFDI), a multivariate composite index capturing contemporary access to grocery retailing in England, Wales, and Scotland (Newing, 2019). The EFDI is freely available through the Consumer Data Research Centre (CDRC) and has been applied in research considering urban-rural inequalities in online grocery provision (Newing et al., 2021) alongside localized studies of grocery provision (Newing et al., 2023, pp. 1–24). It forms a key input to the "Affordable Food for All" (Which?, 2023) campaign by consumer group "Which?," as part of the Priority Places for Food Index (CDRC) (Priority Places, n.d.). Table 1 depicts both of the bespoke indices used within our analysis along with nine indicators contributing to their formation.

3.3. Food desert index calculation

Two indices of the Store Food Desert Index (SFDI) and Online Food Desert Index (OFDI) are measured to examine store access and online access to food at the Lower Layer Super Output Areas (LSOA) geographical level across England and Wales. The store food desert index centers around (i) proximity to and density of grocery retail facilities and (ii) transport and access characteristics, both domains drawn from the EFDI. A total of seven indicators that collectively represent the multi-dimensional aspects of grocery access at the neighborhood level are incorporated into the store food desert index. Proximity to and density of grocery retail facilities indicators calculate the distance to the nearest large grocery store (greater than 15,000 square feet), the average distance to the nearest three grocery stores, the number of stores within 1 km of each neighborhood, and a Hansen-style indicator of store access accounting for store size and brand attractiveness, derived from a Spatial Interaction Model (SIM) that was built for the EFDI (Newing & Videira, 2020). These indicators capture different aspects of store access, choice, and competition experienced by consumers and simulate grocery retail flows at the LSOA level across the study area. Transport and access indicators measure capture transit and automobile travel time to retail services as well as the average trip distance for grocery shopping, considering residents' store preferences, brand attractiveness, and store size. This represents the modeled trip distances to grocery stores used by residents in each LSOA, accounting for factors influencing store selection, drawn from the EFDI.

The online food desert index centers around e-commerce characteristics. This replicates the e-commerce domain from the EFDI. This includes two indicators that assess the availability of online grocery home delivery and the propensity of residents in each LSOA to shop online for groceries. The first indicator measures the number of retailers offering delivery services to each LSOA, as determined by Newing et al. (2021). The second indicator, derived from the Internet User Classification, evaluates the likelihood of residents in each LSOA to engage in

Table 1
Characteristic of indicators from the EFDI utilized in food desert index calculation.

Indicator	Description	Units	Original Source within the EFDI (Newing, 2019)
Proximity to and density of grocery retail facilities			
Nearest large store	Straight line distance to the nearest large store	km	Calculated using Geolytix Retail Points version 15
Count of stores within 1 km	Count of stores within 1 Km (straight line)	Count of stores	
Average distance to stores	Mean distance to the nearest 3 grocery stores	km	
Access Index	Hansen access index accounting for store size and brand	Relative measure	Custom-built SIM
Transport and access			
Drive time	Average minimum drive time to food store by car	Minutes	England: Journey Time Statistics 2017 (Table JTS0507) Wales: Welsh IMD 2019 Physical Access Domain
Accessibility via public transport	Average minimum travel time to food store by public transport	Minutes	England: Journey Time Statistics 2017 (Table JTS0507) Wales: Welsh IMD 2019 Physical Access Domain
Average trip distance	Average distance traveled to carry out food shop (simulating interrelated factors affecting store choice including size, brand, and proximity)	km	Calculated using a custom-built spatial interaction model capturing all interactions between residential neighborhoods and the physical grocery retail supply side
E-commerce			
Online groceries availability	Total number of retailers providing grocery delivery service	Count of retailers	Custom web-scraping from major UK retailers' delivery postcode checker
Propensity to shop online	The relative propensity for households to shop online –from IUC Cluster Centers	Mean attribute values (z-scores)	Internet User Classification 2018

online grocery shopping. The neighborhood socioeconomic and demographic domain from the EFDI is not included within our modified versions of the index to detach supply indicators (e.g., proximity to grocery retail facilities, the density of grocery retail facilities) from demand indicators (e.g., income deprivation, car ownership). This helps precisely identify the socioeconomic and demographic characteristics of "at-risk communities" who are disproportionately affected by the lack of accessibility to store and online groceries following the detection of "priority areas"

In common with the EFDI, and to ensure a standardized comparison and aggregation of indicators, we employed the min-max normalization approach, which rescaled the data to a common range between 0 and 1. This normalization process effectively eliminated any potential biases arising from varying measurement scales across the indicators. To enhance the sensitivity and relevance of these indices, we applied an exponential transformation to rank and normalize each domain. This transformation was strategically chosen to prevent one high-scoring domain from overshadowing or nullifying a low score in another domain. By doing so, the index prioritizes neighborhoods exhibiting food desert-like characteristics, ensuring that areas with inadequate food access receive appropriate attention and consideration. The use of exponential transformation aligns with the approach taken in the EFDI (Newing & Videira, 2020), which itself mirrors the best practice used by the Welsh Government in producing neighborhood-level deprivation indices (Welsh Government, 2020). It allows our indices to offer a balanced and nuanced assessment, highlighting areas with significant challenges in accessing groceries, thus providing valuable insights for policymakers and stakeholders in addressing food inequalities across Great Britain. A weighted average was then utilized to aggregate the normalized indicators into their respective domains. For this aggregation process, all indicators were given equal weight, except distance to the nearest large store and average distance to the nearest three stores. In common with the EFDI, each of these two indicators carried a half-weight to address the high correlation observed between them. This helps ensure that proximity to the nearest store was not double-counted and that the overall calculations accurately captured the nuances of grocery accessibility without redundancy. Fig. 1 depicts the spatial disparity of SFDI and OFDI across the study area.

3.4. Bivariate analysis: A spatial clustering approach

In the digital age, online food shopping has emerged as a potential remedy to mitigate the challenges posed by limited store access to food in certain regions. However, the scenario becomes considerably more daunting for areas grappling with both a scarcity of stores and online food access. We have devised a classification system that groups areas into four distinct categories based on their store food deserts and online food deserts rankings. The first region is HH in which residents benefit from a high level of store access to food through well-established grocery retail facilities and abundant online access, enabling them to conveniently procure groceries. The second region is HL including the population that enjoys relatively robust store access to food, with readily available grocery stores nearby. However, online access to food in these regions is limited, potentially reflecting barriers to e-commerce provision (see for example Newing et al. (2021)) or lower adoption rates of e-commerce services. The third region is LH where the population experience challenges in accessing grocery stores, but they have a higher level of online access to food. This may indicate that while traditional brick-and-mortar stores are scarce, residents in these areas are relying on online platforms to meet their food needs. The fourth region is LL which has a double burden of restricted store access to food and limited online options. This is the most concerning region as residents experience challenges in obtaining fresh, healthy, and affordable food, which can lead to adverse health outcomes and exacerbate existing inequalities.

3.5. Multinomial logit analysis

We employ the Multinomial Logit (MNL) model to explain the socioeconomic, demographic, and built environment characteristics associated with four alternatives (i.e., HH, HL, LH, LL). The unit of observation is LSOA with no repeated observations from LSOAs. This means each LSAO is a single observation and there is no sequence of outcomes for each LSOA in the dataset. Utility of alternative i is formulated as Equation (1), where x_i is a vector of observed variables and ε_i is the unobserved part of the utility.

$$u_i = \beta x_i + \varepsilon_i \tag{1}$$

Assuming ε_i is independently, identically distributed extreme value, the closed-form probability for choosing alternative i (P_i) is expressed by Equation (2).

$$P_i = \frac{exp\ (\beta x_i)}{\sum_j exp\ (\beta x_j)} \tag{2}$$

We tested the MNL model using the open-source Biogeme Python package version 3.2.12 (Bierlaire, 2023) with HH being selected as the

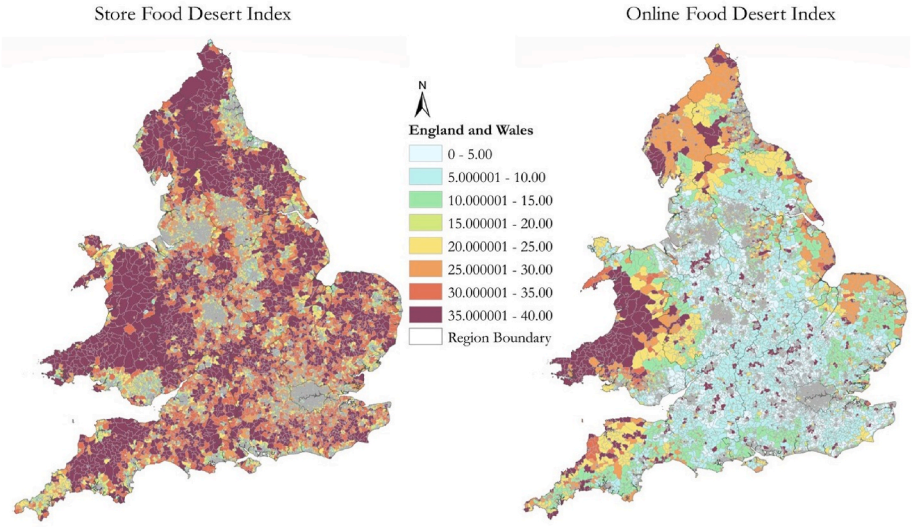

Fig. 1. Disparity of Store Food Desert Index (SFDI) and Online Food Desert Index (OFDI) across the study area.

baseline category. The package uses the maximum likelihood estimator to estimate the β coefficient of each explanatory variable. Table 2 summarizes explanatory variables that are used to model the choice situation. We measured Student's t-test to examine a statistically significant effect of each explanatory variable. We opted to include only statistically significant variables at the 99% confidence interval due to (i) a large number of observations and (ii) no established foundation in the relevant literature regarding the sign of omitted variables. We, however, included at least one variable from each category of explanatory variables summarized in Table 2. For instance, from the car ownership category, we included "carless," and from the deprivation category, we included "not deprived," when not all variables within these categories were found to be significant together. This mitigates, to an extent, the specification error in our hypothesis testing.

Table 2
Description of variables used in the study.

Variable	Description	Average	SD
Population	Census 2021 estimates of population per LSOA	1670.70	354.18
Pop. Density	Number of usual residents per square kilometer	4403.48	4606.43
Households	Number of households per LSOA	694.75	144.02
One Car	Share of households with one car or van	0.41	0.06
Two Cars	Share of households with two cars or vans	0.26	0.11
Three Cars	Share of households with three cars or vans	0.09	0.06
Carless	Share of carless households	0.23	0.16
White	Share of English, Welsh, Scottish, Northern Irish, Gypsy, Roma, British or other Whites per LSOA	0.83	0.20
Asian	Share of Asian, Asian British, or Asian Welsh per LSOA	0.09	0.14
Black	Share of Black, Black British, Black Welsh, Caribbean, or African per LSOA	0.04	0.07
Mixed	Share of Mixed or Multiple ethnic groups per LSOA	0.03	0.02
Other	Share of the population belonging to any other ethnic group per LSOA	0.02	0.03
Not Employed	Share of population with no employment status or aged 15 years and under	0.53	0.07
Very Bad Health	Share of population with very bad health condition per LSOA	0.01	0.01
Bad Health	Share of population with bad health condition per LSOA	0.04	0.02
Fair Health	Share of population with fair health condition per LSOA	0.13	0.03
Good Health	Share of population with good health condition per LSOA	0.34	0.03
Very Good Health	Share of population with very good health condition per LSOA	0.48	0.06
Telework	Share of the population who works mainly from home per LSOA	0.15	0.07
D1 Deprived	Share of households that are deprived in one dimension	0.34	0.04
D2 Deprived	Share of households that are deprived in two dimensions	0.14	0.06
D3 Deprived	Share of households that are deprived in three dimensions	0.04	0.03
D4 Deprived	Share of households that are deprived in four dimensions	2.2×10^{-3}	3.2×10^{-3}
Not Deprived	Share of households that are not deprived in any dimension	0.48	0.11

A likelihood ratio test (McFadden ρ^2) is also used to examine the overall goodness-of-fit of the model. The McFadden ρ^2 ranges between 0 and 1, with values closer to 1 indicating better goodness-of-fit. McFadden (1977) discusses the interpretation of his ρ^2 and states: "Those unfamiliar with the ρ^2 index should be forewarned that its values tend to be considerably lower than those of the R^2 index and should not be judged by the standards for a 'good fit' in ordinary regression analysis. For example, values of 0.2–0.4 for ρ^2 represent an excellent fit."

4. Results and discussions

4.1. Priority areas identification

We visualize the spatial disparity of clusters across the regions of the study area in Fig. 2 using the HH, HL, LH, and LL classifications. Whilst we do not comment on all regions in detail, we observe that all regions exhibit the full range of categories, and therefore experience considerable inequality in both store-based and online access to groceries. Unsurprisingly given its high-density population, excellent transport links, diverse retail provision, and excellent coverage by online grocers (Newing et al., 2021), London has a predominance of neighborhoods falling into the HH category, with the dual advantage of very good physical store provision (proximity of large format stores, number of stores available locally, accessibility of those stores), alongside excellent provision and uptake of online groceries. In all other English regions, and in Wales, there is a clear urban-rural divide – urban areas generally benefit from better provision of both physical stores and online groceries (HH), with more accessible suburban and rural localities (those that are closer to major towns and cities) classified as either HH or LH. Even when these areas are more remote from physical store provision, they

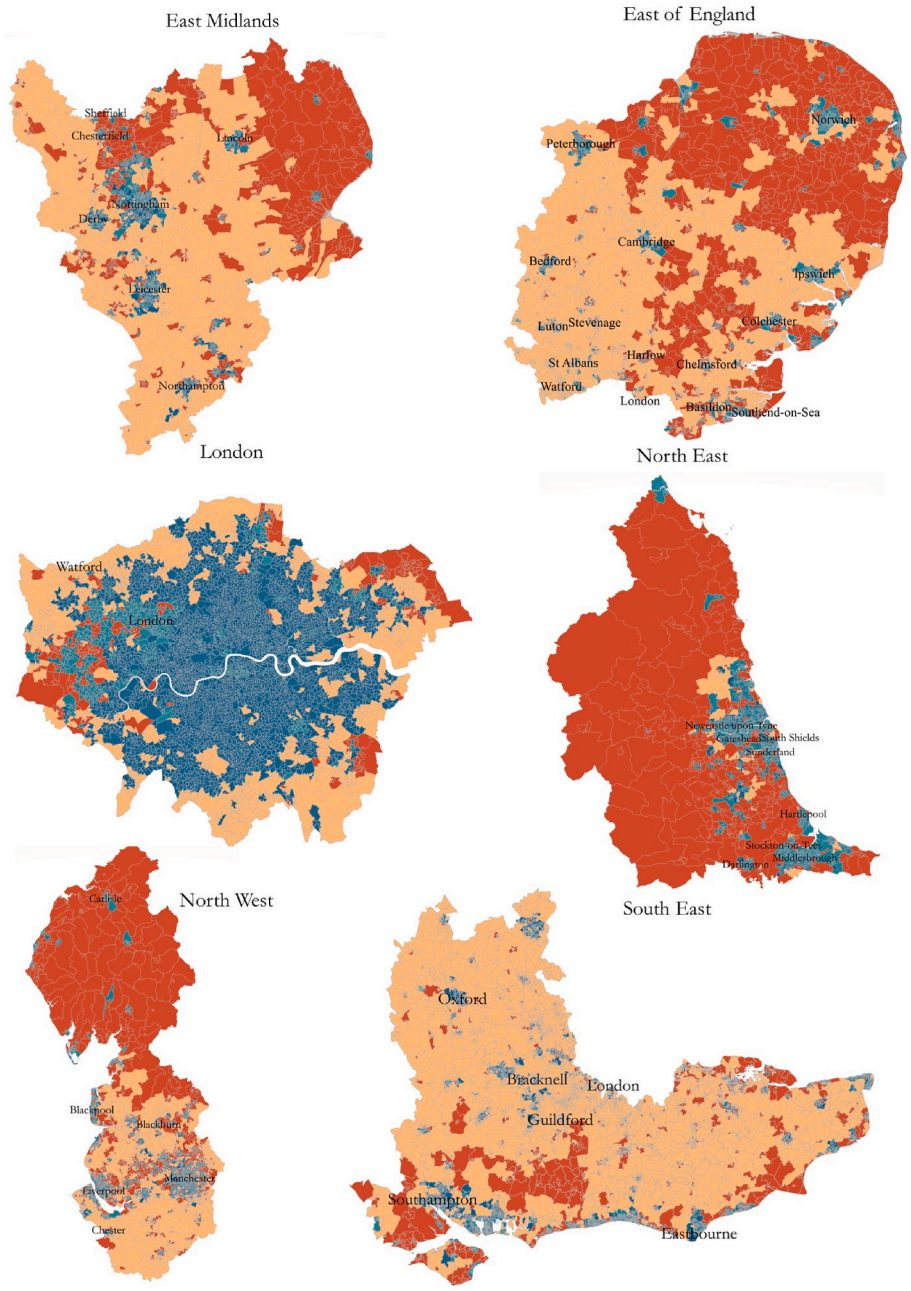

Fig. 2. Spatial distribution of clusters across LSOAs on 10 analyzed regions.

benefit from coverage of online groceries, supporting the "efficiency theory" which suggests that rural residents will use e-commerce to maintain access to goods and services for which physical access may be comparatively poor. Drawing on a large-scale survey of consumers, Hood et al. (2020) noted the complex inter-relationship between store provision, rurality, and online grocery uptake in a case study of Yorkshire and the Humber region.

There remain, however, a number of neighborhoods that face a dual disadvantage of comparatively low access and provision of both in-store and online grocery shopping opportunities. Whilst these are found in all English regions and in Wales, they are less pronounced in London and the South East, and notably present in much of mid-Wales, Northumberland and County Durham (North East), Cumbria (North West), North Yorkshire (Yorkshire and the Humber), Herefordshire and Shropshire (West Midlands) and East Anglia (East of England). These areas are typically associated with a higher degree of rurality and therefore comparatively poorer access to retail services, including the provision of online groceries than their urban counterparts. For example, Urquhart et al. (2022) highlighted the limited provision of online groceries across much of rural mid-Wales, based on a case study of a major retailer's online groceries provision. Whilst Wales presents one of our most extreme examples of comparatively poor access to physical and online grocery retail opportunities, the East of England may be more representative of the general trend. Here, excellent accessibility in the smaller cities of Cambridge and Ipswich and towns such as Colchester and Bury St Edmunds are interspersed with pockets of poorer accessibility in rural areas that are some distance from these principal settlements. Given that retail services cannot be provided uniformly across space, some of these inequalities in accessibility are possibly inevitable.

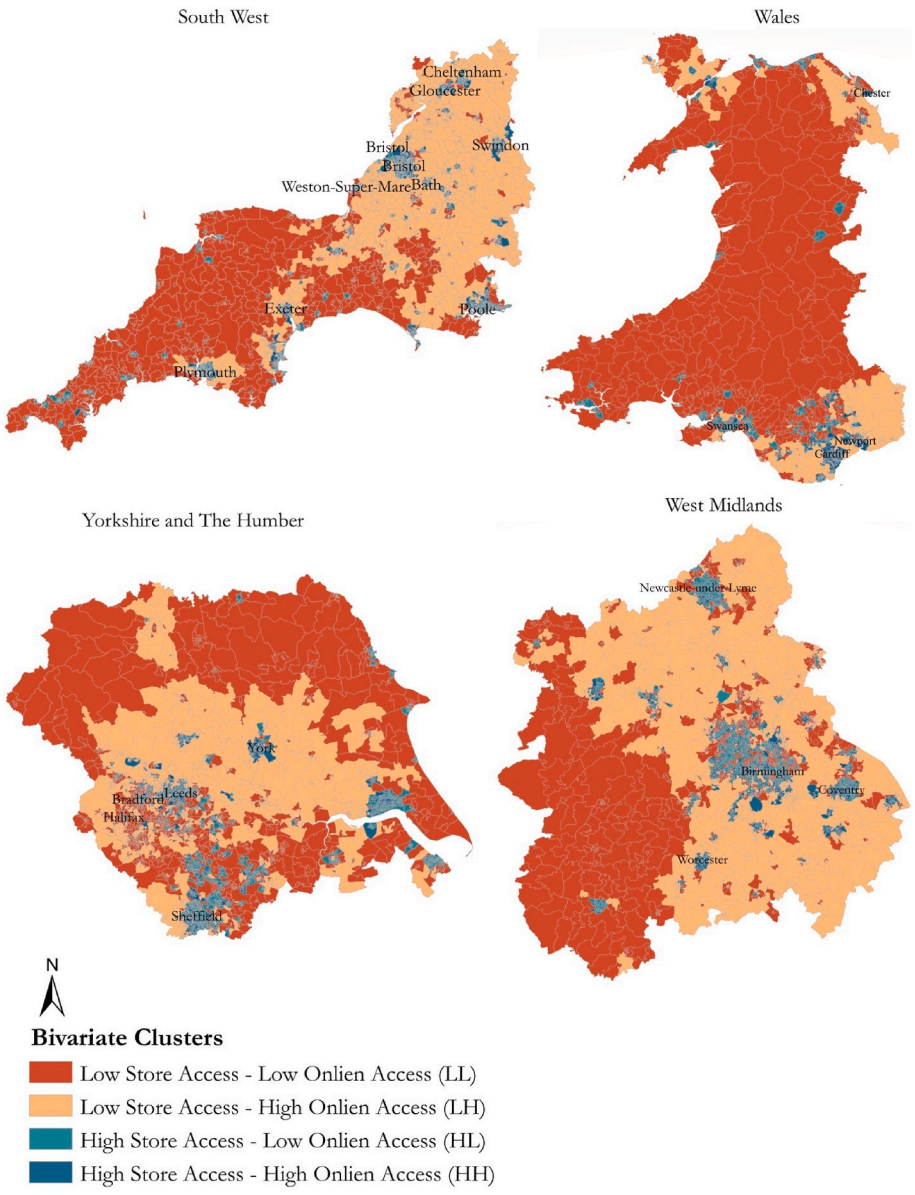

Fig. 2. (*continued*).

In the following sub-section, we draw on indicators of neighborhood and household type to consider the extent to which these differences in accessibility and provision are affecting different groups in society.

4.2. Descriptive analysis

We synthesize the demographic, socioeconomic, and health condition characteristics of residents in each HH, HL, LL, and LH cluster. Fig. 3 displays the disparity between clusters. We tested whether this disparity is statistically significant between clusters by conducting a chi-square test and found a p-value of 0.000 regardless of the characteristics of residents. Five observations are noticed.

First, a noticeable portion of the population, roughly 13.8 million (23%), resides in areas suffering from both low accessible stores and low online service coverage (LL cluster). Nearly 15.5 million (26%) have high access to grocery stores yet face barriers to accessing online food services. The significant share of the population challenged by low online access to healthy food signifies an untapped potential for online food delivery services that could lead to a more balanced distribution of food access and potentially improve overall food security and convenience for residents of LL and HL. Analyzing the geographical distribution of access clusters further adds to the complexity of the picture. In urban areas, despite higher population density, nearly 11,600 LSOAs (32%) exhibit low store access to food (i.e., LL and LH clusters), pointing to the persistence of urban food deserts, where residents in densely populated areas face barriers to accessing well-stocked grocery stores. In contrast, rural areas showcase a different pattern; with only 420 LSOAs (1.2%), a low share of rural areas have store access to food. This finding indicates that rural communities are disproportionately affected by low store access and online access to food.

Second, roughly 8000 carless households (19.8%) are subjected to limited store access and restricted e-commerce access to food (LL clusters). This demographic, despite needing accessible food options, is deprived of the convenience provided by online food services. In contrast, a positive correlation is evident between household car ownership and the likelihood of enjoying both high store and online food access. Single-car households represent the largest share, with approximately 2.5 million (24.2%) benefiting from elevated access to stores and online food services. Households with multiple cars possess the advantage of traveling greater distances to larger grocery stores,

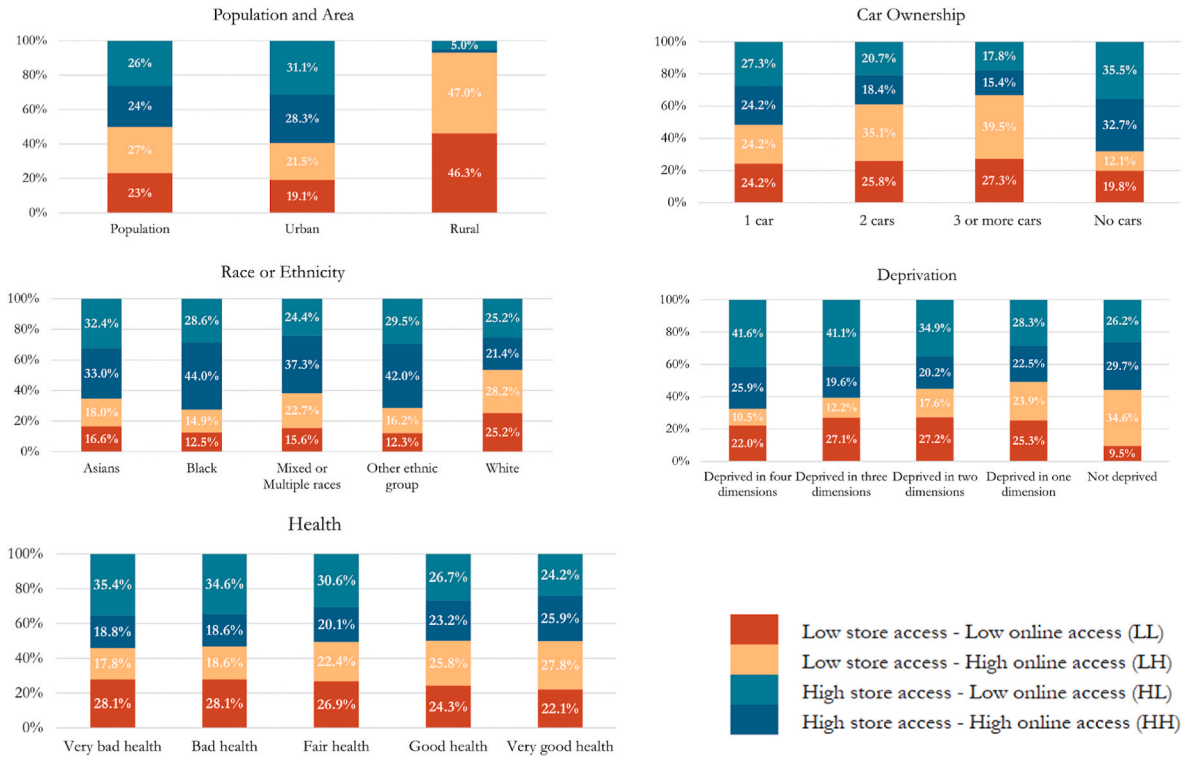

Fig. 3. Disparity of demographic, socioeconomic, and health conditions of the population across access clusters at the LSOA level.

offering a wider range of affordable food choices. Additionally, their increased mobility allows for greater flexibility in online shopping, further enhancing their overall food access. The observed correlation between car ownership and food access highlights the significant impact of transport infrastructure on food security.

Third, although the non-white population bears a disproportionate burden of online access, they relatively have better store access. Within the study area, the non-white population faces a greater likelihood of being exposed to the LL cluster in comparison to the white population. With the majority of the population being White, the numbers present a different perspective. Approximately 300,000 (12.5%) Black individuals live in neighborhoods that are associated with low store and online food access, followed by 250,000 (15.6%) individuals from mixed racial backgrounds and a higher number of Asians with 830,000 (16.6%). On the other hand, over 11.6 million White individuals are subjected to low store and online access. This disparity in numbers presents challenges in formulating an equitable response to address the deprivation of healthy food access. The observation highlights that despite their lower population, non-white communities are more likely to reside in geographical locations that lack equal access to essential services. The intersection of race and geographical disparities further emphasizes the importance of considering both store and online food access as integral components in efforts to achieve food justice and equality for all communities.

Fourth, deprived households are disproportionately affected by both low store access and online access to food. Households are categorized based on four deprivation dimensions: employment, education, health and disability, and household overcrowding. Approximately 10 million (9.5%) households that live in relatively more affluent neighborhoods are found to have lower access to both store and online food (LL cluster). This phenomenon may be attributed to a self-selection residential location, whereby these households find themselves situated in areas with limited food options. On the other hand, nearly 2 million (25.3%) households experiencing deprivation in only one dimension reside within the LL cluster. This number further breaks down to 840,000 (27.2%), 240,000 (27.1%), and 12,000 (22%) households experiencing two, three, and four dimensions of deprivation, respectively. The observed decline in store access among households facing multiple dimensions of deprivation is deeply concerning and may indicate the compounded barriers they encounter in reaching physical food retail outlets.

Fifth, there is a positive association between store and online access to food and health conditions. Among individuals with bad and very bad health conditions, roughly 550,000 have relatively higher access to online food services accompanied by a relatively low level of store access (LH cluster). This suggests that individuals with health challenges may prefer or inevitably be exposed to the convenience of online grocery shopping to meet their dietary needs. On the other hand, as health conditions improve, the reliance on online food access diminishes, and individuals tend to have better access to physical grocery stores. This observation underscores the significance of offering online food services to tackle the food desert problem, particularly for individuals facing health challenges. By doing so, local authorities can better address the needs of marginalized communities and ensure they have enhanced and lasting access to healthy food options. An example of such an approach in combating food access challenges can be traced back to the COVID-19 pandemic. In response to the growing need for food delivery services, some local authorities in the UK took proactive measures to address food insecurity among vulnerable and isolated populations. These authorities collaborated with online retailers and food delivery platforms to set up programs that catered specifically to those in need. These initiatives were especially crucial for individuals who were elderly, immunocompromised, or had limited mobility, as they were at a higher risk of severe illness from COVID-19 and faced greater challenges in venturing out to grocery stores. By partnering with online retailers, local authorities aimed to bridge the gap between vulnerable individuals and the food they required for their well-being. These partnerships allow for a more efficient and targeted distribution of food supplies, ensuring that essential items reach those who need them the most. The outcome of this effective targeted plan persists.

4.3. Statistical analysis

Table 3 depicts the results of the multinomial logit model. The model exhibits a good fit with the McFadden ρ^2 of 0.38. The final set of explanatory variables displays the expected signs, aligning with our hypotheses and the descriptive analysis. The results of statistical analysis, while confirming our descriptive analysis, offer an in-depth tangible discussion. Four associations are noticed.

First, population density is associated with store access and online access to food while store access shows a stronger association. It is inferred that the population density is higher in areas with high store access (i.e., HH, HL) than low store access (i.e., LL, LH). We speculate that it is because urban settings, characterized by higher population density, naturally attract a more extensive network of stores to cater to the needs of the concentrated populace. Online access is not ineffective, however. Comparing LH and LL areas, it is noticed that areas with high online access are more likely to be densely populated than areas with low online access. This might be explained in two ways. First, densely populated areas tend to exhibit higher technological adoption rates, meaning that residents in these areas are more likely to embrace online platforms as a convenient means of securing essential goods, especially when access to physical stores is limited. Second, the convenience of online platforms might be more appealing in densely populated areas, where residents often face time constraints and may, therefore, prioritize the efficiency offered by online food services. This preference suggests a dynamic adaptability of urban residents to diverse food access channels.

Second, car ownership is associated with the byproduct of store access and online access to food to the extent that carless households are less probable to reside in areas with low store access. The findings indicate that the likelihood of residing in high store access areas (i.e., HH, HL) is higher for carless households than residing in low store access areas (i.e., LH, LL). This might be explained by the urban-rural dynamic. Urban areas manifest convenient and accessible stores that respond to the needs of carless households. Urban residents may either choose to give up cars or reside in urban areas when they cannot afford one. The same might not hold true in rural areas, where store dispersion often necessitates car ownership. This need might be mitigated by community-based stores or mobile markets.

Third, households that are devoid of deprivation are associated with better access. Results indicate that those households without any deprivation are more likely to benefit from high store access (i.e., HH, HL). Even for households with limited store access, there exists a higher probability that they will choose to reside in areas where online food services are readily accessible (i.e., LH). Households not burdened by deprivation exhibit a significantly reduced likelihood of inhabiting areas characterized by constrained food access (i.e., LL). This suggests that individuals who are better positioned socioeconomically tend to avoid residing in neighborhoods where both store and online food access are limited. Households without deprivation, often having more economic resources, might prioritize convenience in their choice of residence. This preference could lead them to opt for areas with high store access (i.e., HH, HL), ensuring easy and immediate access to a variety of food options. Even in areas with limited store access (i.e., LH), households without deprivation may compensate by choosing locations with high online food service accessibility. Economic means allow them to leverage technology for convenient food procurement, mitigating the impact of limited physical store access. The reduced likelihood of households without deprivation inhabiting areas characterized by constrained food access (i.e., LL) suggests a conscious decision to avoid neighborhoods with limited food resources. Socioeconomically advantaged households may have the flexibility to choose residences based on a broader set of amenities, including food access. This observation highlights those socioeconomic disparities manifest spatially. Here, it implies that households without deprivation can strategically position themselves in areas with superior food access. Individuals with fewer economic constraints may prioritize their health and well-being. Opting for areas with high store access and, when necessary, high online food service accessibility aligns with a lifestyle that values convenient and diverse food options.

Fourth, there is a positive association between people suffering from very bad health conditions and low online access (i.e., HL, LL). However, they are more likely to benefit from store access than online access. Individuals with very good health conditions, on the other hand, are more likely to benefit from higher online access regardless of low store access (i.e., LH). This is inferred by the lower probability of healthy people residing in HL areas. Individuals suffering from very bad health conditions may face challenges in utilizing online platforms, preferring physical store access for immediate and tangible food procurement. The higher probability of such individuals residing in areas with store access (HL) could be linked to the practicality of physically visiting stores. On the other hand, individuals with very good health conditions may exhibit a health-conscious lifestyle, valuing the convenience offered by online food services. The lower probability of healthy people residing in areas with low store access (HL) suggests that, despite limited physical store options, they are more likely to opt for online access to meet their dietary needs. The observed association between health conditions and food access could be intertwined with the accessibility of health services in different areas as well. Individuals in poor health might choose residences with proximity to physical stores due to a higher reliance on immediate access to necessities. Lifestyle choices, routines, and habits might also influence the association between health conditions and food access. For instance, individuals accustomed to traditional shopping may continue this habit even when faced with health challenges.

Table 3
Results of the multinomial logit model with HH being the baseline category.

Variable	Coefficient	*t*-test	SE	Coefficient	*t*-test	SE	Coefficient	*t*-test	SE
Cluster	**HL**			**LH**			**LL**		
Pop. Density	-1.21×10^{-4}	−15.00	8.09×10^{-6}	-2.74×10^{-4}	−29.70	9.23×10^{-6}	-3.88×10^{-4}	−38.00	1.02×10^{-5}
White	4.19	15.20	0.275	–	–	–	13.60	12.90	1.05
Black	–	–	–	7.68	15.90	0.483	12.50	8.96	1.39
Asian	4.49	13.50	0.33	–	–	–	14.10	12.20	1.15
Carless	1.91	7.22	0.26	−15.40	−41.20	0.37	−7.79	−23.50	0.33
Telework	−18.80	−29.10	0.64	4.43	8.55	0.52	−12.10	−17.80	0.68
Not Deprived	−6.73	−12.80	0.52	−8.91	−17.40	0.51	−17.20	−32.60	0.53
Very Bad Health	36.60	8.46	4.32	–	–	–	27.50	6.37	4.32
Very Good Health	−9.44	−19.10	0.49	3.69	7.11	0.51	–	–	–
Not Employed	–	–	–	–	–	–	5.09	14.70	0.35
Constant	6.17	14.80	0.42	5.67	22.80	0.23	−2.92	−2.68	1.09
Sample size: 35,671									
McFadden ρ^2: 0.38									

Notes: SE means Standard Error; "-" means insignificant variable; All reported variables are statistically significant at the 99% confidence level.

The findings pertaining to different demographic and socioeconomic profiles highlight the significant influence of store access in shaping residential choices. This observation is further substantiated by the high likelihood of individuals not employed to reside in LSOAs falling within the LL cluster. This correlation signifies the interplay between social marginalization, economic circumstances, and access to physical grocery stores, indicating that individuals facing unemployment or socioeconomic hardships are more inclined to reside in areas with restricted access to both physical stores and online food services.

5. Final remarks

Apart from the longstanding financial barriers, the landscape of access to healthy food is marred by significant, and at times controversial, non-financial impediments. Inequalities in different forms (e.g., geographical constraints, cultural attitudes) act as formidable obstacles hindering individuals from attaining their preferred and nutritious food choices. This disparity, to some degree, permeates across all societies, posing a formidable roadblock on the path to a truly just society. Understanding the root cause of this disparity necessitates extensive research, delving into conscious and unconscious attitudes as well as the influence of racial stereotypes. Decades of rigorous investigation into food deserts have sought to address barriers and offer potential solutions, yet the problem remains stubbornly persistent.

The persistent challenge of food insecurity has given rise to multiple movements combatting this issue across the UK. In England, the National Food Strategy, spearheaded by the visionary Henry Dimbleby, has been commissioned to address the complexities within the food system, particularly concerning food poverty and equitable access to nutritious sustenance. This strategic endeavor intends to offer a healthier and more sustainable food ecosystem for the entire nation. At the grassroots level, diverse community-led initiatives and projects have emerged across the UK, demonstrating a localized and participatory approach to tackling food desert problems. By establishing community gardens, food cooperatives, and food banks, these projects strive to provide fresh and affordable produce to historically underserved communities, fostering a sense of empowerment and resilience. The advent of social supermarkets has garnered significant attention as a promising avenue for addressing food deserts. Such supermarkets proffer surplus food and discounted items to individuals and families on limited incomes, thereby enhancing access to healthful nourishment at a reduced cost. This innovative model strives to bridge the gap between the economically disadvantaged and vital food resources. In addition, local governments throughout the UK have taken up the mantle of combating food deserts by implementing diverse schemes and policies. Initiatives range from supporting local farmers' markets to championing healthy eating campaigns in schools, with a shared goal of augmenting food access and education.

Despite the spirited movements and dedicated efforts, the issue of food desert persists, standing as a testament to the multifaceted and deeply entrenched nature of this challenge. This perhaps stems from the intricate interplay of economic, political, and social frameworks within each society, such as its laws, institutions, and policies. These societal structures determine the distribution of services and burdens among people, shaping access to healthy food and perpetuating disparities. These societal structures are the products of human political processes, continuously evolving across societies and within them over time. Their structures are of great importance, as they directly impact the distribution of benefits and discrimination in access to healthy food. To holistically address food desert challenges, a profound understanding of these complex frameworks is essential, yet challenging. Identifying such structures is beyond the scope of our study. Our study did not extinguish the issue. It, however, brought to the fore a fresh perspective by tailoring the non-spatially dependent concept of e-commerce with supermarket access to tackle the challenges of food deserts.

Our exploration of potential solutions to the food desert problem reveals two components that must be explored before practicing any potential solution. On the one hand, there is a comparative component, identifying priority areas where online and supermarket access to healthy food is low. Through this comparative component, we discerned the areas that demand urgent attention and intervention to ensure equitable access to nutritious food. On the other hand, there is a descriptive component, uncovering the characteristics of potentially vulnerable populations living in these priority areas. This in-depth analysis aids in further prioritization, enabling us to develop targeted strategies and plans that transcend mere demographic and socioeconomic factors. When equity goals come into play, understanding the specific needs and challenges of communities within these priority areas becomes paramount (Janatabadi & Ermagun, 2023). In the realm of food desert challenges, our study emphasizes the importance of innovative solutions that challenge the status quo and transcend conventional boundaries. By empowering local communities and forging partnerships, initiatives like community gardens, food co-ops, and social supermarkets hold promise in breaking the cycle of economic deprivation and uplifting underserved populations. Our research also highlighted the potential of combining e-commerce with traditional supermarket access to bridge geographical, and potentially economic to provide healthier food options to those in food deserts.

CRediT authorship contribution statement

Fatemeh Janatabadi: Formal analysis, Methodology, Software, Writing – original draft, Visualization. **Andy Newing:** Data curation, Writing – original draft. **Alireza Ermagun:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declarations of competing interest

None.

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