**Working title:** The impact of tobacco outlet density on smoking rate

**Introduction**

The detrimental effect of smoking on individual health is widely recognized.1 Smoking-related costs in the United States were estimated to exceed $300 billion since 2010,2 making the US among the most affected countries throughout the world.3 With various individual demographic, psychosocial, and behavioral risk factors being well-documented, there is a growing body of research that examines the influence of social determinants on smoking.

Evidence suggests that low socioeconomic status (SES) and geographical disparities are associated with higher smoking uptake.4,5 Previous studies at both the national and local levels have identified a strong correlation between tobacco retail outlet (TROs) density and disadvantageous socioeconomic status. At the national level, Lee and others found that tobacco outlet density was positively associated with the percentage of Black/African American residents but negatively related to the percentage of Asian and White residents.6 Regionally, while one study conducted in Iowa showed that there was a negative relationship between the percentage of African American residents and tobacco outlet density,7 studies conducted in other states such as New Jersey,8 New York,9 Maryland,10 and North Carolina11 showed that tobacco companies tended to promote tobacco products in geographic areas with lower socio-economic status, especially among Black/African American communities and areas with low median household income and high numbers of vacant houses.12 While it was shown that more tobacco outlets were found in low-income and/or minority communities,13,14 how geographical interdependence of outlets influence smoking rate is not well-studied and understood.

A recent systematic review suggested that the density of tobacco outlets was positively related to smoking prevalence regardless of the exposure measure used to explore tobacco outlet density.15 However, the conclusion was drawn from studies conducted in Canada,16-22 Scotland,23-25 New Zealand,26 or targeted at youth for the U.S.-based analyses.27,28 The cultural and contextual differences in these studies might not apply to the U.S. population or tobacco market in general. In the most recent study that focused on a U.S. county-level analysis, Golden and colleagues found that smoking prevalence was only 0.86 percentage points higher in the most outlet-dense counties as compared to the least and was only significant for metropolitan counties. However, the data was dated back to 2012 and potential spatial autocorrelation among counties was not accounted for in that study.29 Accounting for potential spatial autocorrelation is important in understanding the impact of outlet density on smoking in order to better inform future tobacco control policy.

The analysis of spatial data is challenging, as many traditional statistical techniques are not appropriate. The reason is that the interdependence (spatial autocorrelations) among the observations violates the assumption of independent residuals required for statistical conclusion validity.30 The main impact of such violations is the increased chance of committing a Type I error, i.e., claiming a significant effect exists when there is none.31 In our study, ignoring the spatial autocorrelation will undermine the validity of our conclusion on the relation between the smoking rate and tobacco outlet density.

Building models with spatial autocorrelation can also help control for omitted variable bias. More importantly, previous studies have urged the scientific community to disentangle the mechanism between tobacco outlet density and smoking in order to provide more actionable evidence to local, state, and federal regulators.15,29 In the present study, we aimed to (1) examine the impact of tobacco outlet density on adult smoking prevalence at the county level in Virginia, controlling for spatial autocorrelation, and (2) build models that disentangle the underlying mechanism of how outlet density is associated with smoking.

**Method**

**Data**

In this study, we pooled two data sets: the 2020 County Health Rankings and Counter Tools. The County Health Rankings provide data on the social determinants of health, using more than 30 measures to help understand how health is influenced by where people live. The County Health Rankings compile data from various sources including, but not limited to, the National Center for Health Statistics - Mortality Files, the Behavioral Risk Factor Surveillance System (BRFSS), and the American Community Survey.30 In total, 133 counties and cities in Virginia were analyzed in the present study and constitute our sample size for this study. Counter Tools was founded by Drs. Allison Myers and Kurt Ribisl, at the University of North Carolina, in 2011. Counter Tools provides the most recent geo-locations data on tobacco outlets in Virginia at the county and city levels.31

**Outcome**

The county-level adult smoking rate was the primary outcome measure. The smoking rate was obtained from BRFSS of year 2017, and defined as percentage of adults who are current smokers.

**Key exposures**

Tobacco outlet density, following the previous specification,32 was measured by the number of outlets/outlets existing per 1000 persons in a given county.

**Covariates**

In the present study, we categorized various social determinants into 6 classes based on social-ecological model: access to healthcare, demographics, socioeconomic status (SES), environmental factors, risk conditions or behaviors, and population health measures.33 Access to healthcare included the normalized (Z transformation) supply of primary care physicians and mental health providers; demographic factors consisted of the sex, race/ethnicity (Asian, Non-Hispanic White, Black/African American and Hispanic) measured in percentages; SES measures included the percentage of county residents not proficient in English, normalized income inequality and level of education, and county-level median household income; environmental factors included the percentage of people who owned their homes, those having severe housing problems, daily average traffic volume on county roads, and access to exercise opportunities. The risk condition or behaviors consisted of food insecurity (measured in percentages), normalized violent crime rate, and rate of excessive drinking. Finally, the population health measures included the percentage of the population experiencing frequent mental distress and physical inactivity.

**Statistical analysis**

To study the association between the adult smoking rate and tobacco outlet density, we conducted regression analyses controlling for various covariates and spatial autocorrelation. We first fit a univariate linear model using the tobacco outlet density as the sole covariate (referred to as Model [0]). The linear assumption of the regression model is satisfied based on the scatterplot of the non-transformed data shown in Appendix Figure S1. The common model assumptions, including normality and constant variance based on residuals, as well as potential outliers and leverage points were also checked (Figure S1). To examine the possible effects of model misspecifications, we conducted the Ramsey test to check for possible missing power terms and examined the potential influence of county-county correlation (spatial auto-correlation) by conducting Moran's I test.34 The test results confirmed the existence of spatial autocorrelation. To address this issue, we fitted the second univariate model (Model [1]) using a spatial autoregressive model, the form of which is decided by the results from the Lagrange multiplier diagnostics.35 In the diagnostics, we tested three different possible forms of spatial dependence structure: (1) a spatial error model (xxx), (2) a spatial lag model (dependence in the residuals is due to missing the spatial lag of the outcome variable), and (3) a spatial ARMA model (XXX). We also tried fitting a spatial Durbin model to the data. The result suggested that the spatial lag model (LMlag) is the most appropriate model to use to account for the spatial autocorrelation observed (shown in Table 1). The detailed model specification is documented in the Appendix. The estimation of parameters is based on the maximum likelihood method and is done by using the R package **Spatialreg**.36 We then expanded our model to include sets of covariates one at a time and compared models based on the Akaike information criterion (AIC), which is a common criterion to balance the model fit and the model complexity.37 For each model, we tested for the spatial autocorrelation based on the residuals. All analyses were conducted in R version 3.6.3. 38

**Results**

Figure 1a shows the number of tobacco outlets in Virginia at the county level. Three hot spots were noticeable from the map: Northern Virginia, Central Virginia and Southern East Virginia. In Northern Virginia, 498, 170, and 275 outlets were located in the counties of Fairfax, Loudoun, and Prince William, respectively. In Central Virginia, 263 tobacco outlets were located in the city of Richmond, 241 in Chesterfield County, and 270 in Henrico County. In Southeast Virginia, Virginia Beach had 350 outlets, 179 were in Chesapeake, 166 were in Newport News City, and 220 were found in Norfolk City.

Figure 1b shows the county-level smoking rate in Virginia. Smoking prevalence tended to increase when moving from XXX down to the southeastern part of Virginia. Fairfax County, which is only miles away from Washington, D.C., had the highest number of tobacco outlets across Virginia, although it had the lowest smoking rate (9.36%). Counties bordering West Virginia and North Carolina had smoking rates that were typically higher than 20%. Tobacco outlets tended to be located in the more populous areas, with the density of tobacco outlets on average in Virginia being less than 3 per 1000 persons. Only the cities of Emporia and Galax in the southern portion of the state showed a higher density (4 per 1000 persons or higher).

Table 2 presents the effect of social determinants on smoking prevalence in Virginia at the county level. Model [0] represents the univariate analysis without spatial dependence. The effect size of 1.268 indicates that every increase of one tobacco outlet per 1000 persons was associated with a smoking rate that was 1.268 percentage points higher at the county level (p < 0.01). After incorporating LMlag spatial dependence (Model [1]), the effect size was reduced to 1.16 (a 9% decrease), suggesting that the LMlag spatial dependence helped to explain 9% of the unobservable variation in the correlation between outlet density and adult smoking rate. We noticed that access to healthcare (measured by the supply of primary care physicians and mental health providers) was not related to the county’s smoking prevalence, with only 0.78% of the variation explained by these two variables (Model [2]). We next added demographic factors including sex and race/ethnicity (Model [3]). The effect of density on the smoking rate, although still significant, decreased to 0.665 (a 42% decrease). When adding socioeconomic status (SES) into the model (Model [4]), the effect of density was decreased by 76% and became non-significant ( 0.161, 95% CI: −0.151, 0.473). We noticed that the higher the percentage of females in a county was, the lower the smoking prevalence was ( −0.277, 95% CI: −0.534, −0.020). In addition, higher income inequality was associated with a higher smoking prevalence ( −0.326, 95%: CI 0.035, 0.617), while a higher median household income was negatively associated with smoking prevalence ( −1.702, 95%: CI −2.152, −1.251).

After adding risky conditions or behaviors (Model [5]), the effect of density on the smoking rate was decreased to 0.148. We found that every one percentage point increase in the rate of food insecurity was associated with an increase of 3.185 percentage points in smoking prevalence (95%: CI 2.181, 4.190). A higher rate of violent crime was also positively correlated with the smoking rate ( 0.33, 95%: 0.031, 0.629). Counties with more access to exercise opportunities showed a lower smoking rate ( −0.279, 95%: CI −0.527, −0.031). Intriguingly, in this model we noticed that the effect of income inequality, being positive at Model [4], became negatively associated with the smoking rate ( −0.418, 95%: CI −0.686, −0.151). Finally, we added indicators of population health (frequency of mental distress and physically inactive, Model [7]). The correlation between density and smoking prevalence decreased to 0.058 (a 61% reduction from Model [6]). In this final model, we found that population health indicators were associated with smoking prevalence. A one percentage point increase in the rate of mental distress at the county level was related to a 1.939 percentage point higher smoking rate (95% CI: 1.409, 2.468); one percentage point increase in the rate of physical inactivity was correlated with a 0.447 percentage point higher in the smoking rate (95% CI: 0.251, 0.642). Moreover, population health indicators helped to explain a great amount of the variation previously captured in SES, environmental, and risk behaviors. For instance, the impact of food insecurity, violent crime rate, and access to exercise opportunities became non-significant in the final Model [7]. While a higher percent female population was still related to lower smoking prevalence, we found that not being proficient in English was negatively correlated with the smoking rate ( −0.466, 95%: CI −0.861, −0.032).

Based on the AIC selection, model [7] was our preferred model. Although outlet density was positively associated with higher adult smoking rate, the correlation did not reach statistical significance ( 0.058, 95%: CI −0.159, 0.275). Higher rates of mental distress and physical inactivity were significantly associated with increased adult smoking prevalence.

**Discussion**

This study provides evidence that higher tobacco outlet outlets (TROs) density is associated with higher smoking prevalence at the county level in Virginia after controlling spatial dependence. But the impact of outlet density is largely explained by social determinants of health such as SES, risky conditions/behaviors, and environmental factors. We further noticed that the impact of social determinants of health are closely related and can be explained by indicators of population health (rates of mental distress and physical inactivity).

By calculating the global Moran’s I statistics, we concluded that there exists a positive spatial autocorrelation among the observations. To better handle the spatial autocorrelation, we choose to model the data by a spatial lag model, which assumes that the dependence can be explained by the spatial lag of the dependent variable. The residuals from the fitted models are no longer spatially correlated. Although the effect size is reduced by correcting for the spatial autocorrelation, the association remains significant.

TROs are the main source for ordinary people to access tobacco products.39 People living in areas with more tobacco outlets are theoretically more likely to smoke because of greater accessibility. Empirically, however, the evidence is mixed. A number of research studies focusing on youth found that while there is some positive support for this theory, the current literature does not provide consistent evidence regarding youth smoking rates.40 Our meta-analysis concluded that the density of TROs near a school is not statistically associated with adolescents’ smoking behavior.41 Evidence in young adults is also unclear, as Cantrell et al. suggested that adults aged 25–34 living in areas with greater TROs density were more likely to have tried cigarettes for the first time in the past 6 months, while there was a positive but nonsignificant trend for initiation among those 18–24 years old.42When controlling various social determinants of health, our results were aligned with the current literature showing that outlet density was not significantly correlated with smoking prevalence. Such findings could reflect a fact that TROs density is dependent upon other social determinants of health.

One possible explanation for why outlet density is not associated with smoking rates is that the effect of TROs density is captured by other, more influential factors. Previous studies documented that racial disparity and income inequality were associated with a higher concentration of TROs.13,14 In this study, although we found race/ethnicity was positively correlated with smoking, no statistical significance was established; such effects further became negative after controlling other SES and environmental factors. On the other hand, consistent with the national trend,43 we found counties with a higher number of female residents showed lower smoking prevalence. Our findings shed a light on current literature showing that the race/ethnicity composition within a county in Virginia was not a significant determinant of smoking in 2020. Other determinants of health played a more important role at the county level.

We found that SES helped to explain a great amount of the variation in the effect of TRO density on smoking. The effect size shrank by 76% and became non-significant after controlling for SES. In line with evidence showing that TROs were more concentrated in low-income communities,12 our findings suggest that, rather than affecting TRO density, low household median income at the county level had a more direct effect on smoking uptake. Areas with a higher low-income rate were more likely to experience an increase in food insecurity and violent crime.44,45 We confirmed these associations and showed that risky environmental conditions related to low-income such as food insecurity and violent crime diluted the impact of low-income and were more closely associated with county-level smoking prevalence. The correlation between the living conditions of a geographic area and the smoking rate suggests that tobacco-control can focus not solely on smoking reduction tactics but more on improving living standards.

Increasing living standards has a broader implication and is closely related to an individual’s well-being. In the present study, we showed that rates of mental distress and physical inactivity are the most important determinants of smoking at the population level. The national trend in smoking showed that between 2011 and 2014, the decline in smoking among individuals with mental illness was less than those who did not have a mental illness.46 It has been shown that smoking was used as a tool in coping with anxiety and distress,47 and often mental distress was interconnected with physical inactivity.48 We found being physically inactive was correlated with an increase in smoking rate. A person who has no leisure-time physical activity has been documented to be more likely to smoke over the life course.49 Although we noticed that having a higher rate of mental health providers was negatively associated with smoking in Model [3], such effect was offset by mental distress prevalence and other social determinants of health. Our finding echoes previous research and provides insights to help inform future tobacco-control policies. As we illustrated before, a new direction for tobacco control policies is to increase regional living standards. Increasing living standards by focusing on economic growth might not be sufficient; promoting work-life balance in the workforce and improving overall well-being could be a promising strategy.50

**Limitations**

This study has several limitations. First, the information regarding the TROs might not be the most up-to-date (i.e., there could be some TROs opened or closed before the year 2020). Second, the data were analyzed at the aggregate level; we were not able to control for the individual factors that might affect cigarette purchasing behaviors from TROs. Third, a cross-sectional study design was used and coefficients are prone to reverse casualty and endogeneity.

**Conclusions**

Although higher tobacco outlet density is associated with an increase in county-level smoking prevalence, the impact of outlet density is largely explained by social determinants of health and population mental illness. Improving well-being at the community level could be a promising strategy in future tobacco control policies.

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