**Working title:** The association between tobacco outlet density and prevalence of cigarette smoking.

**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 inverse correlation between tobacco retail outlet (TRO) density and community 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 Black/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 lower SES Black/African American communities, areas with low median household income, and high numbers of vacant houses.12 While it was shown that more tobacco retail outlets were found in low-income and/or minority communities,13,14 the association between the concentration of tobacco retail outlets and smoking rate at county level is not well-studied or understood.

A recent systematic review suggested that the density of tobacco retail outlets was positively related to smoking prevalence regardless of the exposure measure used to explore tobacco retail outlet density.15 However, this conclusion was drawn from studies conducted in Canada,16-22 Scotland,23-25 New Zealand,26 or limited to youth smoking rates in the U.S.27,28 The cultural and contextual differences in these studies might not apply to the broader 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 outdated and potential spatial autocorrelation among counties was not accounted for in the study’s design.29

The analysis of spatial data is challenging, as many traditional statistical techniques may have poor statistical conclusion validity for several reasons. First, spatial autocorrelations or interdependence among the observations violates the assumption of independent residuals required to draw valid inferences in many statistical approaches.30 The main impact of such violations is the increased probability of committing a Type I error, i.e., claiming a significant effect of tobacco retail outlet density on smoking rates exists when there is none.31 Second, building models that account for spatial autocorrelation can also help control for omitted variable bias.

Previous studies have urged the scientific community to disentangle the mechanism between tobacco retail outlet density and smoking in order to provide more actionable evidence to local, state, and federal regulators.15,29 Accounting for potential spatial autocorrelation is important in such efforts in order to better inform future tobacco control policy. In the present study, we examine the association between tobacco retail outlet density and adult smoking prevalence at the county level in Virginia, controlling for spatial autocorrelation. We constructed regression models incrementally based empirical evidence and statistical model selection techniques to 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 (2019) on tobacco retail outlets in Virginia at the county and city levels.31 For more details of the Counter Tools data please see the *supplement*.

**Outcome**

The county-level adult smoking rate was the primary outcome measure. County smoking rates came from 2020 County Health Rankings (using 2017 BRFSS data to generate the prevalence estimates) and was defined as percentage of adults who are current cigarette smokers.

**Key exposure**

Tobacco retail outlet density was obtained from Counter Tools. The density, following the previous specification,32 was measured by the number of outlets per 1000 persons in a given county.

**Covariates**

In the present study, we categorized various social determinants of health that obtained from 2020 County Health Rankings into 6 classes based on the social-ecological model:33 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-transformed) 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 (Z-transformed) income inequality and population who had college 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 per meter on major county roads (numeric numbers), and percentage of population with adequate access to locations for physical activity. The risk conditions or risky 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 reporting physical inactivity.

**Statistical analysis**

To study the association between the adult smoking rate and tobacco retail outlet density, we conducted regression analyses that accounted for spatial autocorrelation and adjusted for county-level access to healthcare, demographics, SES, environmental factors, risk conditions or behaviors, and population health measures. We first fit a univariate linear model using the tobacco retail 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 assumptions of ordinary least squares models, 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 spatial autocorrelation by conducting Moran's I test.34 The test results confirmed the existence of spatial autocorrelation in our statistical approach. To address this issue, we fitted the second univariate model (Model [1]) using a spatial autoregressive model, the form of which is determined by the results from the Lagrange multiplier diagnostics.35 In these diagnostics, we tested three different possible forms for the structure of the spatial autocorrelation: (1) a spatial error model, where the observations are related due to unmeasured factors that are correlated across the distances among the observations (e.g., xxxxx), (2) a spatial lag model, where the dependence in the residuals is due to missing the spatial lag of the outcome variable, and (3) a spatial ARMA (SARMA) model, where the observations in space are related to neighboring values using spatial link matrices. We fit a spatial Durbin model to the data, a special case in combination of spatial lag model and spatial error model that accounts for the observable and unobservable spatial dependence.36 The Language Multiplier (LM) test suggested that the spatial lag model (LMlag), #2 above, is the most appropriate model to use to account for the form of spatial autocorrelation observed (shown in Table 1). The visualization of spatial autocorrelation was also shown in Figure S3. The estimation of parameters is based on the maximum likelihood method and is done by using the R package **Spatialreg**.37 We then expanded our model to include sets of covariates based on our 6 classes of socio-ecological model described above one at a time and compared these stacked models based on the Akaike information criterion (AIC), which is a common criterion to balance the model fit and the model complexity.38 For each model, we tested for the spatial autocorrelation based on the residuals. In addition, we also conducted sensitivity analysis using geographically weighted regression (GWR). The details of GWR can be found in the Appendix. All analyses were conducted in R version 3.6.3. 39

**Results**

Figure 1a shows the number of tobacco retail 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 Southeastern Virginia, Virginia Beach had 350 outlets, 179 were in Chesapeake, 166 were in Newport News City, and 220 were found in Norfolk City (the detail location of each outlet was presented in supplementary Figure S4).

Figure 1b shows the county-level smoking rate in Virginia. Smoking prevalence tended to increase when moving from Northern Virginia 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 of health on smoking prevalence in Virginia at the county level. Model [0] represents the univariate analysis without spatial dependence. The point estimate of 1.268 indicates that every increase of one tobacco retail 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 point estimate was reduced to 1.16 (a 9% decrease, where AIC also decreased from 589.478 to 583.732), suggesting that the LMlag spatial dependence helped to improve the model-fit.

We noticed that access to healthcare (measured by the supply of primary care physicians and mental health providers) does not improve the model-fit and was not related to the county’s smoking prevalence, with AIC valued of 585.72 (Model [2]) in comparison with 583.732 of model [1]. 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 (percent of county reporting mental distress and physical inactivity, Model [7]). The association between density and smoking prevalence decreased to 0.058 (a 61% reduction from Model [6]). In the 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) and a one percentage point increase in the rate of physical inactivity was correlated with a 0.447 percentage point higher smoking rate (95% CI: 0.251, 0.642). Moreover, population health indicators helped to explain a substantial amount of the variation previously captured in SES, environmental, and risk conditions or 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 a county’s smoking rate ( −0.466, 95%: CI −0.861, −0.032).

Based on the AIC, model [7] was our preferred model. Although tobacco retail outlet density was positively associated with higher adult smoking rate, the association did not reach statistical significance ( 0.058, 95%: CI −0.159, 0.275). As mentioned earlier, higher percentages of females, limited English proficiency, and income inequality in a county were inversely associated with smoking rates, while percentages of those in mental distress or physically inactive were significantly associated with increased adult smoking prevalence.

**Sensitivity analysis**

Using GWR as the sensitivity analysis, we fitted the same model as model [7] and reported the median, minimum and maximum weighted coefficients. The conclusion remains the same that tobacco outlet density had positive but insignificant correlation with adult smoking rate (median = 0.245, min = -0.085, max = 0.398).

**Discussion**

This study provides evidence that higher tobacco retail (TRO) density is associated with higher smoking prevalence at the county level in Virginia after controlling spatial autocorrelation. But the impact of outlet density is largely explained by social determinants of health such as SES, risky conditions or 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 were then no longer spatially correlated. Although the point estimate was reduced by correcting for the spatial autocorrelation, the association remained significant prior to including additional county-level covariates.

TROs are the main source for most people to access tobacco products.40 People living in areas with more tobacco retail 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 the association between TRO density and youth smoking rates.41 One meta-analysis concluded that the density of TROs near a school is not statistically associated with adolescents’ smoking behavior.42 Evidence in young adults is also unclear. 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.43When 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.

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 higher underrepresented racail geopolitivcal areas and income inequality were associated with a higher concentration of TROs.13,14 In this study, although we found the percent of Black/African American residents of a county was positively correlated with smoking, no statistical significance was established; such effects further became negative, though still nonsignificant, after controlling other SES and environmental factors. On the other hand, consistent with evidence examining national data,44 we found counties in Virginia 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 point estimate 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, median household income at the county level had a more direct effect on smoking rates. It has also been demonstrated that lower income counties are more likely to experience an increase in food insecurity and violent crime.45,46 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 county-level household income and were more closely associated with county-level smoking prevalence.

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.47 It has been shown that smoking is used as a tool in coping with anxiety and distress,48 and often mental distress was interconnected with physical inactivity.49 And, a person who has no leisure-time physical activity has been documented to be more likely to smoke over the life course.50 Indeed, we also found county-level mental distress and physical inactivity were positively correlated with smoking rates. 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.51

**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 thus coefficients are prone to concerns about reverse casualty and other forms of 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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