NBER WORKING PAPER SERIES

GEOSPATIAL ANALYSIS OF THE SEPTEMBER 2020 CORONAVIRUS OUTBREAK AT THE UNIVERSITY OF WISCONSIN – MADISON: DID A CLUSTER OF LOCAL BARS PLAY A CRITICAL ROLE?

Jeffrey E. Harris

Working Paper 28132
http://www.nber.org/papers/w28132

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
November 2020

This study relies exclusively on publicly available data that contain no individual identifiers. The author has no competing interests and no funding sources to declare. This article represents the sole opinion of its author and does not necessarily represent the opinions of the Massachusetts Institute of Technology, Eisner Health, the National Bureau of Economic Research, the University of Wisconsin, the Wisconsin Department of Health Services, or any other organization.

Geospatial Analysis of the September 2020 Coronavirus Outbreak at the University of Wisconsin – Madison: Did a Cluster of Local Bars Play a Critical Role?
Jeffrey E. Harris
NBER Working Paper No. 28132
November 2020
JEL No. I1,I12,I38

ABSTRACT

We combined smartphone mobility data with census track-based reports of positive case counts to study a coronavirus outbreak at the University of Wisconsin-Madison campus, where nearly three thousand students had become infected by the end of September 2020. We identified a cluster of twenty bars located at the epicenter of the outbreak, in close proximity to on-campus residence halls and off-campus housing. Smartphones originating from the two hardest hit residence halls (Sellery and Witte), where about one in five students were infected, were 2.95 times more likely to visit the 20-bar cluster than smartphones originating in two more distant, less affected residence halls (Ogg and Smith). By contrast, smartphones from Sellery-Witte were only 1.55 times more likely than those from Ogg-Smith to visit a group of 68 restaurants in the same area. Physical proximity thus had a much stronger influence on bar visitation than on restaurant visitation (rate ratio 1.91, 95% CI 1.29-2.85, p = 0.0007). In a separate analysis, we determined the per-capita rates of visitation to the 20-bar cluster and to the 68-restaurant comparison group by smartphones originating in each of 19 census tracts in the university area, and related these visitation rates to the per-capita incidence of newly positive coronavirus tests in each census tract. In a multivariate regression, the visitation rate to the bar cluster was a significant determinant of infection rates (elasticity 0.90, 95% CI 0.26-1.54, p = 0.009), while the restaurant visitation rate showed no such relationship. Researchers and public health professionals need to think more about the potential super-spreader effects of clusters and networks of places, rather than individual sites.

Jeffrey E. Harris
Department of Economics, E52-422
MIT
50 Memorial Drive
Cambridge, MA 02142
and NBER
jeffrey@mit.edu

Introduction

Public health officials and researchers have made considerable efforts to pinpoint and understand super-spreader events during the ongoing COVID-19 pandemic (Adam et al. 2020, Wong and Collins 2020). Most of these efforts have focused on the identification of outbreaks at discrete sites with a high concentration of susceptible people, such as assisted living facilities, detention centers, sports arenas, reception halls, and food processing plants (Hamner et al. 2020, James et al. 2020, Mahale et al. 2020, Leclerc et al. 2020). Other studies have attempted to assess the spillover effects of identifiable mass gatherings, including political rallies (Dave et al. 2020, Bernheim et al. 2020). Still other recent work has used cellphone tracking data to identify potential super-spreader "points of interest" (Chang et al. 2020).

Here, we take a different tack. We focus not on discrete places, but instead on super-spreading *clusters* or *networks* of places. We think of infected individuals as moving easily and rapidly across multiple places within the cluster or network. The component places are linked together by close geographic proximity, or by an efficient transportation network.

This super-spreader model underlies our analysis of the possible role of a cluster of off-campus bars in a recent outbreak at the University of Wisconsin-Madison, where nearly three thousand students tested positive for SARS-CoV-2 during September 2020. To its credit, the university accomplished the extraordinary task of squelching the outbreak within a matter of weeks, rather than capitulating to a call by the Dane County board of supervisors to close its residence halls and send its 31,000 students back home. By October 1, in-person classes were being phased back in, and the rate of new infections on campus had dipped below that of the surrounding county. In a formal response to the county board, the university's Chancellor Rebecca Blank implored local officials to step up their own efforts at epidemic control. Stressing that the university had less authority over off-campus gatherings, Chancellor Blank added, "There is evidence that bars regulated by the city and county have been linked to the spread of COVID-19." (Blank 2020b)

From the methodological standpoint, our task here is to inquire: To what extent is Chancellor Blank's observation supported by geospatial data on the movements of smartphones with location-tracking software in combination with public health data on the geographic distribution of COVID-19 cases? With the arrival of the COVID-19 pandemic during the present era of big data, researchers have increasingly resorted to data-intensive geospatial techniques to address hard-to-tackle epidemiologic questions (Dickson et al. 2020, Franch-Pardo et al. 2020, Harris 2020b, c, e, i, Orea and Alvarez 2020).

Bars are widely cited as a potential locus of viral propagation. Numerous jurisdictions, seeking to curb the growth in local cases, have closed bars, constrained their capacity, or restricted them to take-out only. A retrospective study of infected persons yielded evidence of a contributing role for bar attendance (Fisher et al. 2020). One smartphone-based study tracked visits to local bars in order to shed light on differences in COVID-19 incidence between Dane and Milwaukee counties during the second wave of the epidemic in Wisconsin (Harris 2020b). As evidence supporting our model of a cluster of places, South Korean authorities last spring reported an outbreak of 34 cases after a 29-year-old patient visited five clubs and bars in Itaewon over the course of one night (Kwang-tae 2020, Kang et al. 2020).

College and university outbreaks have likewise received considerable attention (Walke, Honein, and Redfield 2020, Davidson College 2020). But detailed studies of the dynamics of these outbreaks are scarce. One study of a university campus in North Carolina identified multiple clusters of infection in residence halls, athletic teams, and fraternities and sororities (Wilson et al. 2020). In a preliminary look at 50 counties that contain four-year colleges, coronavirus cases tended to surge 4 to 12 days after students moved in (Diep 2020). Genomic sequencing of SARS-CoV-2 cases in a Wisconsin college outbreak has traced the paths of transmission from infected students to vulnerable individuals in the general population (Richmod et al. 2020).

Figure 1 below offers a preview of one of our empirical tests – a case-control study of two pairs of on-campus residence halls. Shown is a screenshot of a section of the university campus map, focusing on the eastern end of the campus. The superimposed solid, wine-colored lines mark the external boundaries between the census tracts, while the dashed lines mark the internal boundaries between the four census block groups within tract 16.06. The pair of green buildings within census block group 16.06-4 represent the two on-campus residence halls, Sellery and Witte, which were subject to a lockdown when approximately 20 percent of their residents became infected. The pair of red buildings further to the south within census block group 16.06-3 represent two other residence halls, Ogg and Smith, that were not overrun with infections and not subject to quarantine. The solid purple circles mark the locations of a cluster of 20 nearby off-campus bars, located mostly in census tracts 16.03 and 16.04. The yellow circles show a comparison group of 68 coffee houses, inexpensive and medium-priced restaurants located in the same area. These venues are closer to Sellery and Witte than to Ogg and Smith. The most remote bar was only a 13-minute walk from Sellery.

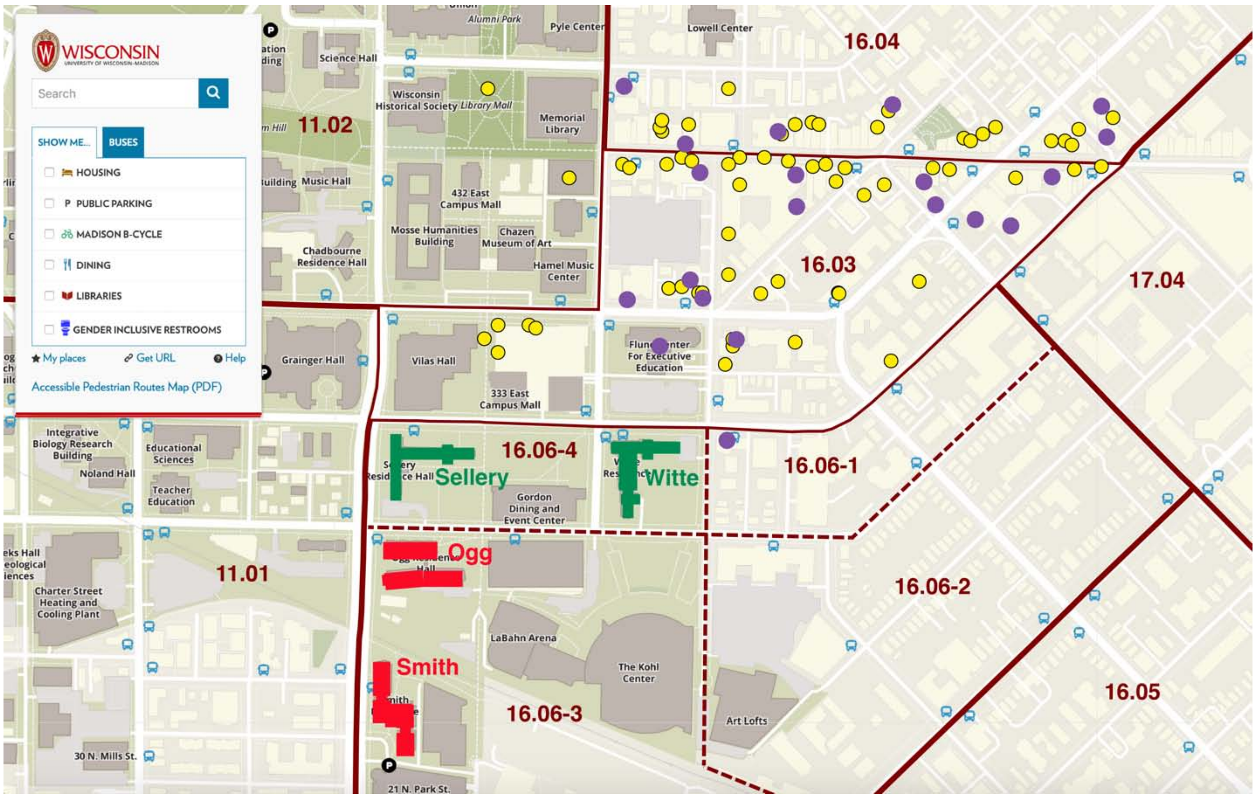

Figure 1. Section of U. Wisconsin-Madison Campus Map, with Census Tract and Census Block Group Boundaries, Locations of Four Key Residence Halls, a Cluster of Nearby Off-Campus Bars (Purple), and Comparison Restaurants (Yellow)

Smartphone tracking data, as we'll see below, permitted us to verify that during the university-imposed lockdown, there was a spike in the proportion of devices staying completely at home in census block group 16.06-4, but not in 16.06-3. This confirmed that 16.06-4 corresponded to Sellery and Witte residence halls, while 16.06-3 corresponded to Ogg and Smith. Moreover, the rate at which devices originating in census block group 16.06-4 (Sellery-Witte) visited at least one of the bars in the cluster was 2.95 times the rate at which devices homed in census block 16.06-3 (Ogg-Smith) did so. For the comparison group of cafés and restaurants in the same area, this visitation rate ratio was only 1.55. Physical proximity thus had a much stronger influence on the rate of bar visitation than on the rate of restaurant attendance.

Background

The Spike

Figure 2 below shows the daily counts of positive coronavirus tests among students at the University of Wisconsin–Madison from August 9 through October 4, 2020. The data come from the university's COVID-19 dashboard (University of Wisconsin-Madison 2020d). To construct the graphic, we combined positive tests among on-campus and off-campus students, but excluded a small number of positive tests among university employees.

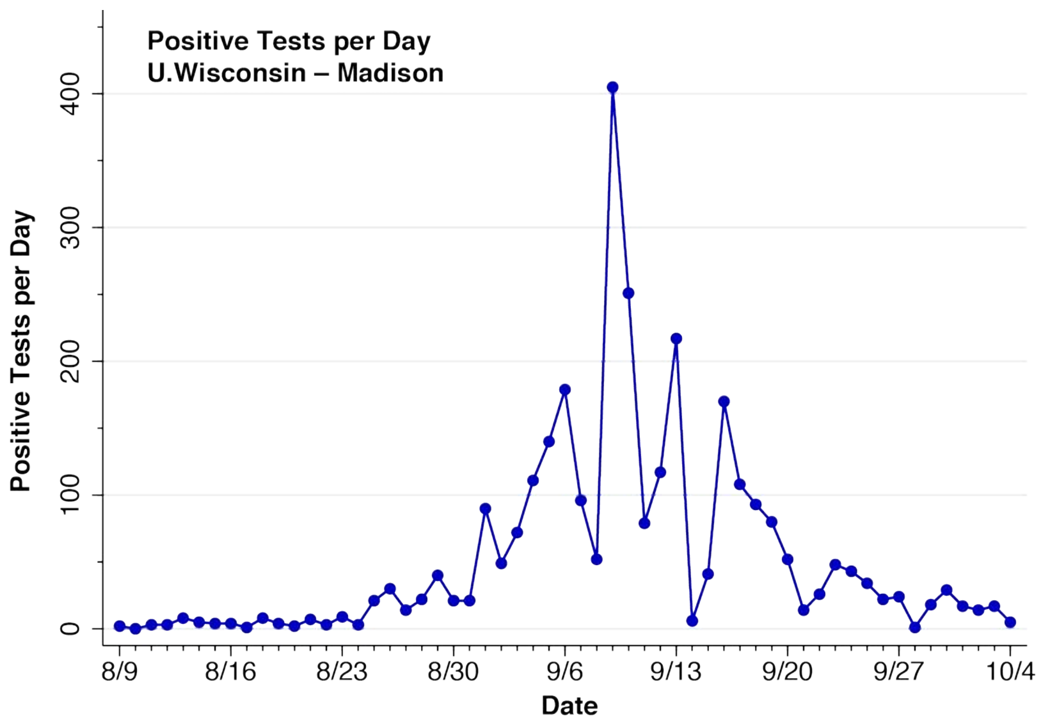

Figure 2. Reported Positive SARS-CoV-2 Tests per Day, University of Wisconsin–Madison Students, August 9 – October 4, 2020

The graphic shows a run-up in cases starting in the last week of August and culminating in a prominent spike of 656 cases during September 9-10, followed by a gradual run-off during the remainder of September, and ultimately winding down back to baseline by the beginning of October. In total, 2,955 students were documented to be positive during the interval covered by the figure.

The Preparation

The university made extensive preparations in advance of its planned Smart Restart. A testing program was already in place when the university opened its doors in late August to students returning for fall-semester classes (McGlone 2020). A total of 8,000 tests were to be performed during move-in week and an additional 6,000 tests were to be performed weekly thereafter (Blank 2020f). Infected students in campus residence halls were expected to self-isolate in designated quarantine spaces, while the families of off-campus students were expected to develop comparable isolation plans. Campus spaces were re-purposed during the summer to safely accommodate about 1,000 infected students and their close contacts – about 15 percent of the residence-hall population. In the event of an outbreak, contingency plans were already in place to close the affected parts of the campus and switch to virtual instruction.

Off-campus fraternity and sorority houses pledged to adhere to an order of the Dane County health officer prohibiting parties and other mass gatherings (Heinrich 2020). "For individuals who have intentionally behaved in ways that risk the health of our community," warned Dean of Students Christina Olstad, "we are pursuing actions that could result in discipline up to and including the revocation of Housing contracts and emergency suspension." (Olstad 2020a).

The Lockdown

By September 2, the day that fall semester classes officially began, 38 members of nine off-campus fraternities and sororities had tested positive. On September 4, Public Health Madison & Dane County (PHMDC), in coordination with the university, ordered all test-positive members of the nine off-campus houses to quarantine for 2 weeks (University of Wisconsin-Madison 2020i). In addition, the university would test all 1,500 live-in members of all 47 off-campus fraternities and sororities.

On September 7, with a growing number of cases detected off-campus, Chancellor Blank ordered all students to restrict themselves to essential activities for two weeks (Blank 2020d). "Unfortunately," noted the chancellor, "too many students have chosen to host or participate in social gatherings that seem to demonstrate a high disregard for the seriousness of this virus and the risk to our entire community. ... We've reached the point where we need to quickly flatten the curve of infection..." Still, in-persons classes were to remain open.

By September 8, the university's dashboard had tallied over 600 positive tests among students living in on-campus facilities. The following day, Chancellor Blank announced the quarantine of all residents of two on-campus residence halls, Sellery and Witte, which had experienced a "high number of positive test results." (University of Wisconsin-Madison 2020h).

An email sent to Sellery and Witte residents the following week by the university's housing division noted that about 20 percent of the dorms' residents had tested positive (University of Wisconsin-Madison 2020g).

By September 15, the university, working with PHMMC, had quarantined two dozen off-campus fraternities and sororities (Blank 2020e). As noted in Figure 3 below, the university had begun its transition to rapid surveillance testing, which would deliver results in about 30 minutes (Barncard 2020). Borrowing from the experience of other universities, UW-Madison deployed staff in student neighborhoods to "look for parties and encourage compliance." (Blank 2020e)

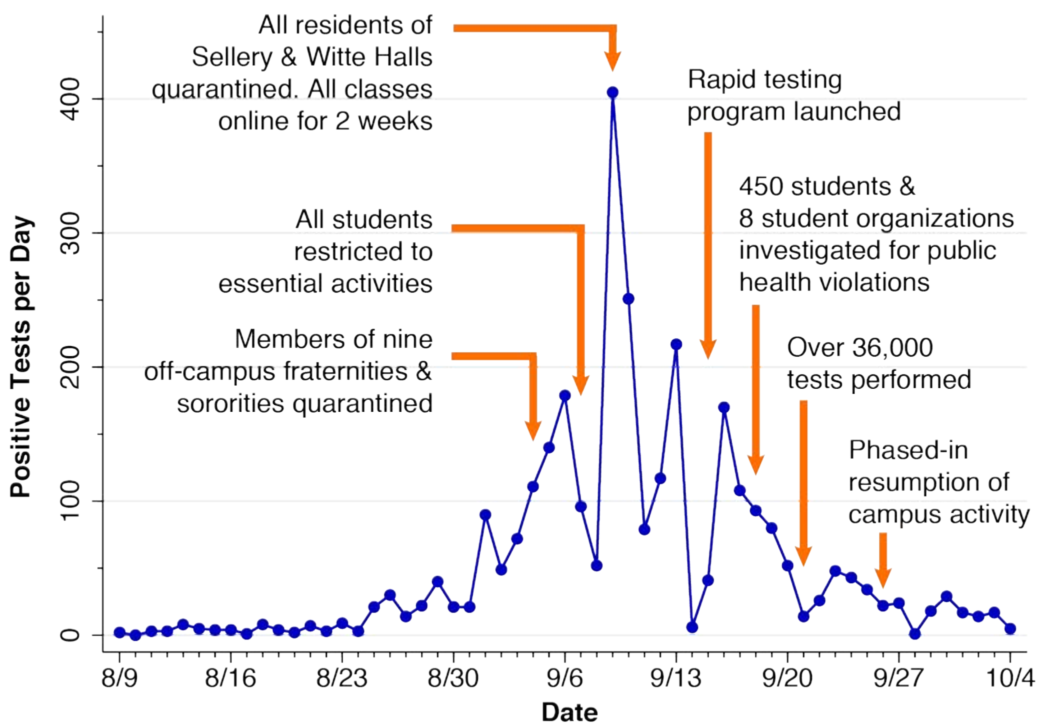

Figure 3. Annotated Version of Figure 2, Including Key Events During the Outbreak

The Recovery

On September 18, Dean Olstad warned, "Positive COVID-19 cases among students appear to be trending down, but the risk remains high ... intentionally contracting COVID to 'get it over with' is unsafe and irresponsible." (Olstad 2020b) Nearly 450 students and 8 student organizations had been investigated or were under investigation for public health violations. By September 21, the university had performed more than 36,000 tests on its campus population, a rate far greater than that of surrounding Dane County. "But you don't need to look hard on social media to find a photo of long lines outside downtown bars or parties in large apartment buildings," observed Chancellor Blank (Blank 2020c). She called on the county executive to enforce public health orders at off-campus locations beyond the university's jurisdiction.

September 26 saw the phased-in resumption of campus activity, including some in-person classes (Blank 2020a). Measures were taken to reduce the density of residence halls. More students were placed in single rooms. Guests were barred. Daily infection counts were down to a level last seen on August 25. While the university's dashboard had recorded some sporadic cases among faculty and staff, none had become infected in classrooms or lab settings.

Data

Geography

The screenshots of campus maps shown in Figure 1 above and in other figures below were derived from the university's website (University of Wisconsin-Madison 2020b). The overlaid census tract boundaries in Figure 1 and other figures were derived from the Census Bureau's TIGER shape files (U.S Census Bureau 2019). Supplementary information on the boundaries of census block groups, which represent the next level of geographic disaggregation, was derived from supplementary sources, including *statisticalatlas.com* (statisticalatlas.com 2018) and *landgrid.com* (landgrid.com 2020).

Housing

On-campus residence halls were identified from the university campus map. Data on the number of student residents and other characteristics of each residence hall were publicly posted by the university (University of Wisconsin-Madison 2020c).

Among all fraternity and sorority organizations referenced on the university's website (University of Wisconsin-Madison 2020f), we searched Google to find 43 organizations with identifiable addresses in the campus area, whether or not they had communal live-in facilities. The locations of off-campus housing in the vicinity of the university were derived from the university's off-campus housing marketplace as of October 25 (University of Wisconsin-Madison 2020a).

Population Denominators

The estimated 2018 populations of each census tract, used as the denominator to compute case incidence rates, were derived from *datacommons.org* (Data Commons Place Explorer 2020)

Bars and Restaurants

To identify bars, we first used Google and Yelp to compile a preliminary list of 69 candidate businesses in the University of Wisconsin-Madison area. The list included businesses described in Google as a bar, bar-grill, lounge, pub, tavern and in a few cases, a restaurant. From this preliminary list, we relied on descriptions in Google and on individual websites to identify only those entities whose principal offerings were alcoholic beverages. We excluded clubs and venues that may have served alcoholic beverages but opened only intermittently for scheduled events. We further excluded those entities that did not match any *point of interest* in the SafeGraph Patterns database, to be described below. This procedure left 51 business entities throughout the area. These bars are mapped in Appendix A. To define the cluster of bars shown in Figure 1 and other figures, we isolated the 20 bars located in census tracts 16.03, 16.04, and 16.06.

To construct a comparison group of restaurants in the same area as the cluster of bars, we again searched all points of interest in the SafeGraph Patterns database that were located in census tracts 16.03, 16.04, and 16.06, as well as the extreme eastern end of tract 11.02. Similarly relying on Google, Yelp and individual websites, we isolated a total of 68 entities, including 10 cafés, 37 restaurants rated as inexpensive (including burgers, pizza, and ramen), and 21 restaurants rated as moderately priced. We excluded expensive restaurants, wine/liquor stores, smoke and hookah shops, food markets and convenience stores, and ice cream parlors.

COVID-19 Cases

Data on the daily numbers of positive SARS-CoV-2 tests, as shown in Figures 1 and 2, were derived from the university's dashboard (University of Wisconsin-Madison 2020d). The daily counts in Figure 1 represent the sum of: positive tests among students living in on-campus residence halls; and positive tests, ascertained by Public Health Madison & Dane County, among persons living off-campus who were affiliated with the university (University of Wisconsin-Madison 2020e).

Data on the daily numbers of positive SARS-CoV-2 tests by census tract were downloaded from the website of the Wisconsin Department of Health Services (WDHS) (Wisconsin Department of Health Services 2020). Appendix B compares the total number of daily infections in the census tracts surrounding the campus, as computed from the WDHS data, with the university dashboard-derived daily counts in Figure 2. From about September 9 onward, the WDHS-reported case counts appear to lag behind the dashboard-derived counts by one day. The census tract distribution of cases reported by WDHS, however, implies a significantly higher proportion of off-campus cases than the proportion classified as off-campus on the university's dashboard. This apparent discrepancy remains unresolved.

SafeGraph Data

We relied upon two data sources provided by SafeGraph: the Patterns database (SafeGraph Inc. 2020a), and the Social Distancing database (SafeGraph Inc. 2020b). SafeGraph follows the movements of an anonymized panel of smartphones equipped with location-tracking software, where repeated pings from the devices are mapped into their geocoded locations.

The Patterns database provides information on the movements of smartphones equipped with location-tracking software to numerous *points of interest* throughout the United States. We previously relied upon this data source in studies of visitors to President Trump's rally at Tulsa's BOK Center on June 20, 2020 (Harris 2020h), restaurant attendance in San Antonio around the time of street protests during May 30 – June 11, 2020 (Harris 2020f), attendance at bars in a study of COVID-19 propagation in Milwaukee and Dane Counties in Wisconsin (Harris 2020b), and a study of the role of intrahousehold transmission in the COVID-19 epidemic in Los Angeles County (Harris 2020i).

A separate installment of the Patterns database is issued each calendar month. Within each monthly installment, each point of interest has its own record. Within each record, we used the variable *location_name* to identify specific bars and restaurants. We used the variable *visitor_home_cbgs* to identify the home census block groups of all visitors during September 2020, where a device's *home* is the location where it is regularly located overnight. This variable permitted us to compute the number of visitors during September from each census block group to the cluster of 20 bars and to the comparison group of 68 restaurants, where the same device visiting two different bars during September would be counted as two visitors. We further used the variable *visits_by_day* to compute the daily total number of visits to each point of interest for each calendar day in both August and September.

The Social Distancing database provides information on both the origin and destination census block groups of device holders. We previously relied upon this data source in a study of the movements of individuals with a *home* in the Queens-Elmhurst COVID-19 hot spot to subway stations in Queens and Manhattan during the earliest days of the epidemic in New York

City (Harris 2020e), and in the previously cited study of the role of intrahousehold transmission in the COVID-19 epidemic in Los Angeles County (Harris 2020i).

A separate installment of the Social Distancing database is issued each calendar day. Within a particular daily installment, each census block group has its own record. The variable *candidate_device_count* describes the number of devices known to have a home in the census block group, while the variable *completely_home_device_count* gives the numbers of such devices originating in each census block group that stayed completely at home during a particular day. These data allowed us to compute a daily series of the percentage of devices staying completely at home in each census block group. Since SafeGraph updates a device's home census block group at six-week intervals, the devices of many students who had only recently arrived on campus were not captured in the candidate device count. Still, there were sufficient numbers of device homes in the key census block groups in and around the university campus to detect the effects of a university-imposed lockdown.

Methods

Descriptive Geospatial Analysis

We begin by mapping the locations of on-campus residence halls, fraternities, sororities and other off-campus housing, along with off-campus bars and restaurants in relation to census tract. We then study the geographic distribution of newly diagnosed coronavirus tests by census tract. We further study the temporal evolution of the outbreak in relation to census tract.

Case Control Study

We compare a pair of on-campus residence halls, Sellery and Witte, which we designate as the cases, to another pair of on-campus residence halls, Ogg and Smith, which we designate as the controls. As noted in the Background above, Sellery-Witte pair, occupying census block group 16.06-4, was subject to a quarantine beginning September 9 as the prevalence of infection approached 1 in 5 residents. By contrast, in the Ogg-Smith pair, occupying census block group 16.06-3, no such lockdown was imposed.

We use data on the percentage of devices staying completely at home to check whether the division between census block groups 16.06-4 and 16.06-3 reliably captured the respective movements of devices originating in the case and control residence halls. As an additional reliability check, we examined whether the temporal evolution of visits to bars within a 10-

minute walk of Sellery Residence Hall was consistent with the subsequent evolution of newly positive coronavirus tests in census tract 16.06.

For both the cases and controls, we used the smartphone tracking data to compute the numbers of visitors during September 2020 to the previously identified cluster of 20 off-campus bars. We denote these counts by b_1 and b_0, respectively. We then computed the ratio $R_b = (b_1/N_1)/(b_0/N_0)$, where N_1 and N_0, respectively, are the known numbers of occupants of the case and control residence halls. The ratio R_b thus represents the relative bar visitation rate of an occupant of the Sellery-Witte case residence halls compared to an occupant of the Ogg-Smith control residence halls. Similarly, we determined r_1 and r_0, the respective numbers of visitors during September to the previously identified comparison group of 68 restaurants. We then computed the analogous ratio $R_r = (r_1/N_1)/(r_0/N_0)$, which represents the relative restaurant visitation rate of occupants of the case and control residence halls. Finally, we tested the null hypothesis that $R_b = R_r$ or, equivalently, $R_b/R_r = (b_1/b_0)/(r_1/r_0) = 1$.

Regression Model

We formulated a regression model relating the per-capita incidence of newly positive coronavirus tests to the per-capita rates of visitation to bars and restaurants across 19 census tracts in the University of Wisconsin-Madison area. Let y_i denote the incidence of newly positive tests per 1,000 population reported by WDHS for census tract i during September 2020. Let x_{bi} and x_{ri}, respectively, denote the numbers of devices with a home in census tract i visiting the designated bars and restaurants during September, divided by the corresponding population of census tract i. We estimated the constant-elasticity regression model $\log y_i = \alpha + \beta \log x_{bi} + \gamma \log x_{ri} + \varepsilon_i$, where ε_i are assumed to be i.i.d. normally distributed errors, and tested the null hypotheses that $\beta = 0$ and $\gamma = 0$. To avoid giving too much leverage to census tracks farther from the epicenter of the outbreak, we also employed geographically weighted regression, where the weight was the logarithm of the incidence of COVID-19 infection (Nakaya et al. 2005). We also tested our regression model on visit rates in August and September combined.

Results

Descriptive Geospatial Analysis

We begin by mapping the spatial distribution of on-campus residence halls, off-campus housing including fraternities and sororities, and local bars and restaurants.

Figure 4 below shows a screenshot of campus map of the university. In the interactive legend at the left, we have selected the HOUSING option to highlight the on-campus residential facilities. In addition, we have superimposed the boundaries of the corresponding census tracts. The campus occupies all of tracts 32 and 11.02, and parts of tracts 11.01, 16.03 and 16.06. The residential halls are located principally in census tracts 32, 11.01, 11.02 and the west end of 16.06. To the east, we see the Capitol neighborhood of Madison, including tracts 16.03, 16.04, 16.05, 17.04, and 17.05.

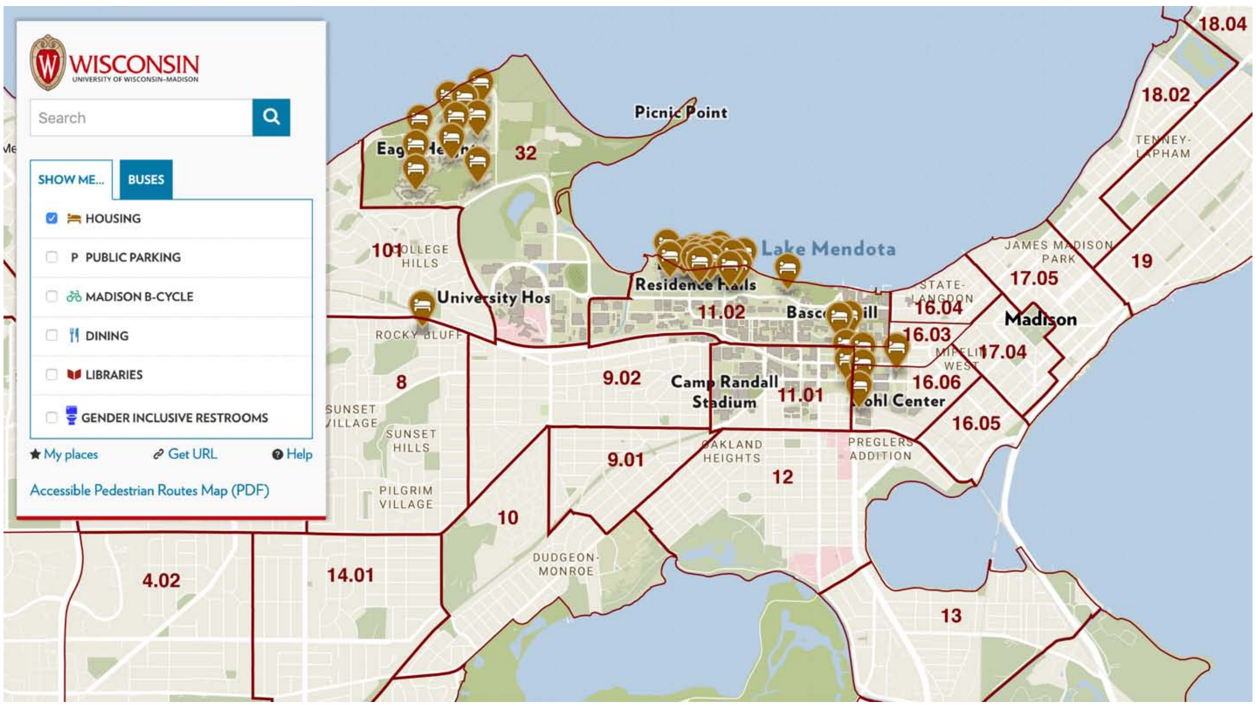

Figure 4. University of Wisconsin-Madison Campus Map with Locations of On-Campus Housing, with Overlaid Census Tract Boundaries

In Figure 5 below, we have zoomed down on the campus map to locate Sellery and Witte Residence Halls (green arrows), the two residence halls subject to quarantine during the peak of the outbreak. As indicated by the dashed lines separating the four census block groups within tract 16-06, Sellery and Witte are located in census block group 16.06-4. To the south, in census block group 16.06-3, we can also identify Ogg and Smith Residence Halls (red arrows).

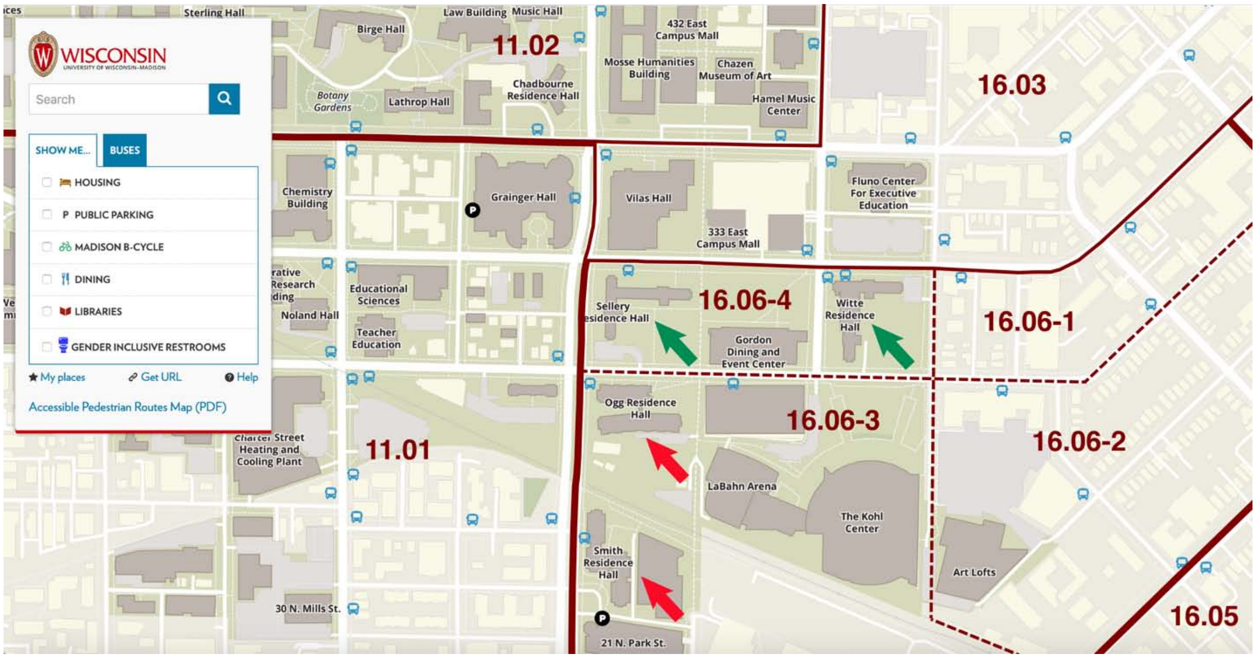

Figure 5. Details of U. Wisconsin-Madison Campus Map, Highlighting Sellery and Witte Residence Halls Within Census Block Group 16.06-4 and Ogg and Smith Residence Halls Within Census Block 16.06-3

Figure 6 below shows the locations of the off-campus fraternities and sororities in a screenshot from Google My Maps. Again, we have overlaid the boundaries of the census tracts on the map. As noted in the Data section above, among those fraternity and sorority organizations identified on the university's website (University of Wisconsin-Madison 2020f), we have mapped all organizations with identifiable addresses in the campus area, whether or not they had communal live-in facilities. The vast majority (36 out of 43) organizations located in the figure have addresses within in census tract 16.04.

Figure 7 below shows the locations of off-campus housing in the vicinity of the university. The figure is a screenshot of available housing opportunities taken from the university's off-campus housing marketplace as of October 25 (University of Wisconsin-Madison 2020a). The map shows the highest concentrations of off-campus housing in tracts 11.01, 12, 16.03, 16.04 and 17.05.

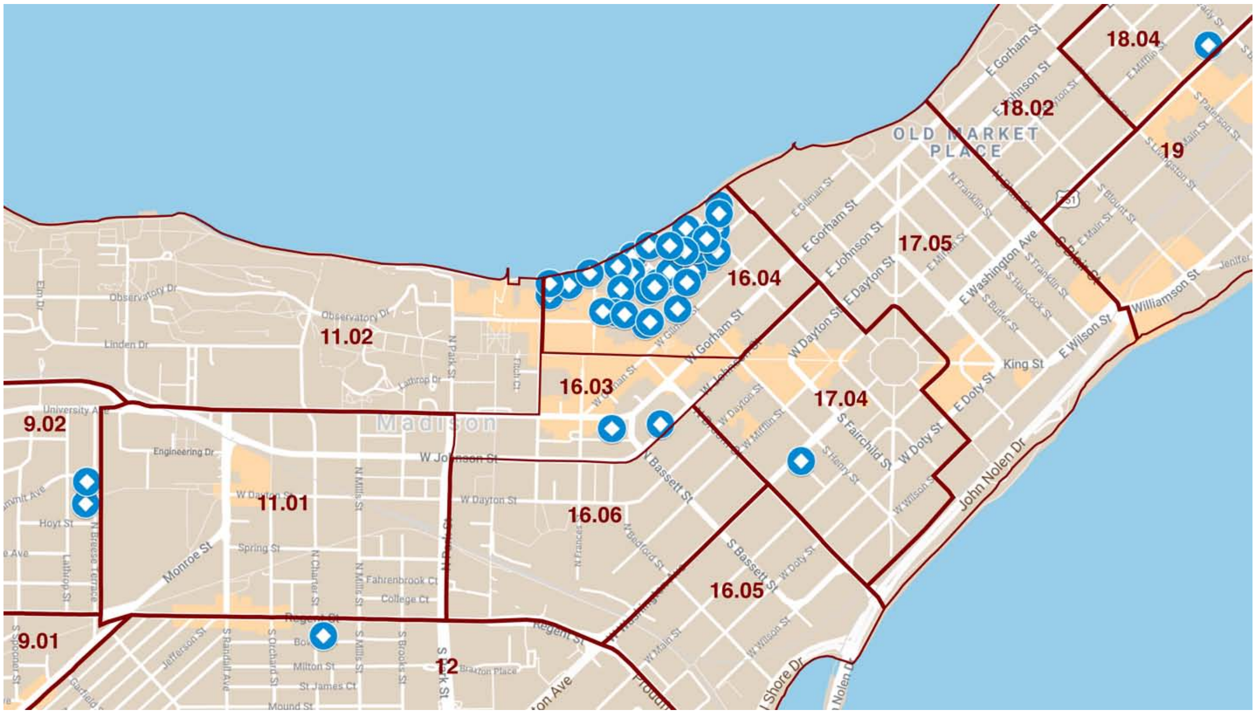

Figure 6. Google My Maps Screenshot of the Locations of Fraternities and Sororities in the University of Wisconsin-Madison Area, with Overlaid Census Tract Boundaries

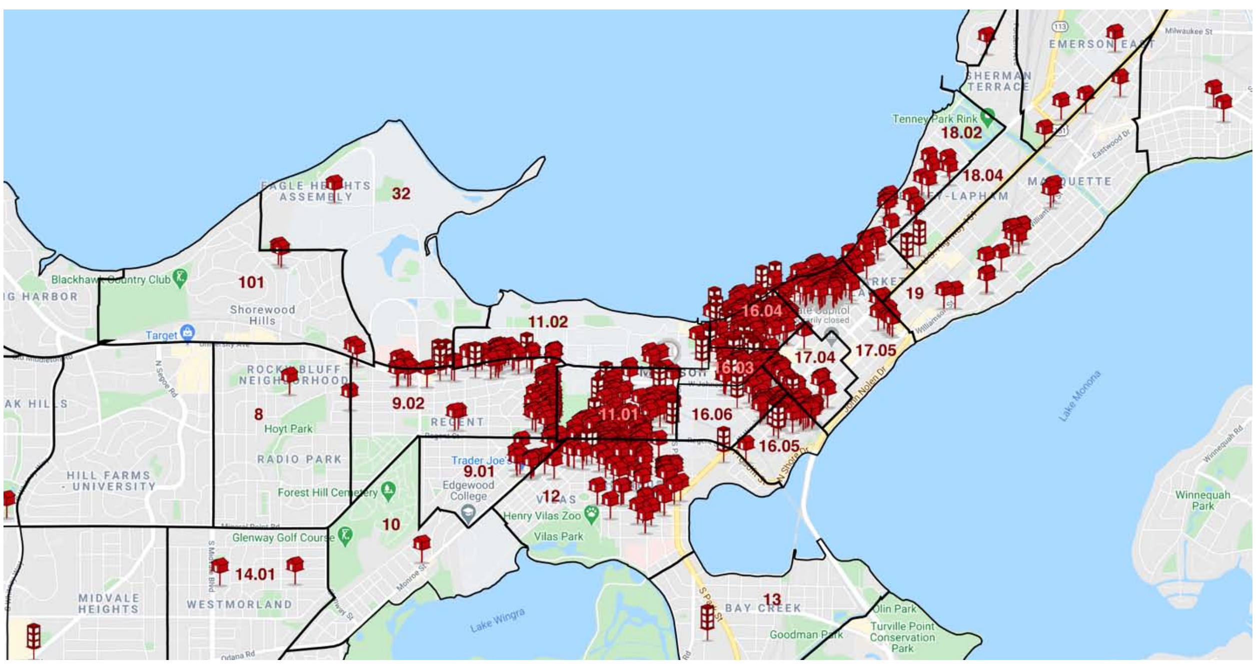

Figure 7. Screenshot of the Locations of Off-Campus Housing from U. Wisconsin-Madison Website, with Overlaid Census Tract Boundaries

Figure 8 below shows a screenshot of a Google My Maps rendering of the locations of the cluster of 20 bars and the comparison group of 68 restaurants in the U. Wisconsin-Madison area. Superimposed once again are the boundaries of the census tract. The two green squares mark the locations of Sellery to the west and Witte to the east within tract 16.06. The bars are indicated by purple icons . The cafés are identified by coffee cups , the inexpensive and medium-priced restaurants by the icons and , respectively. Comparison with Figures 4 through 7 shows that this cluster of bars and the comparison group of restaurants are in close proximity to nearly all fraternities and sororities, many on-campus residence halls, and the densest areas of off-campus housing.

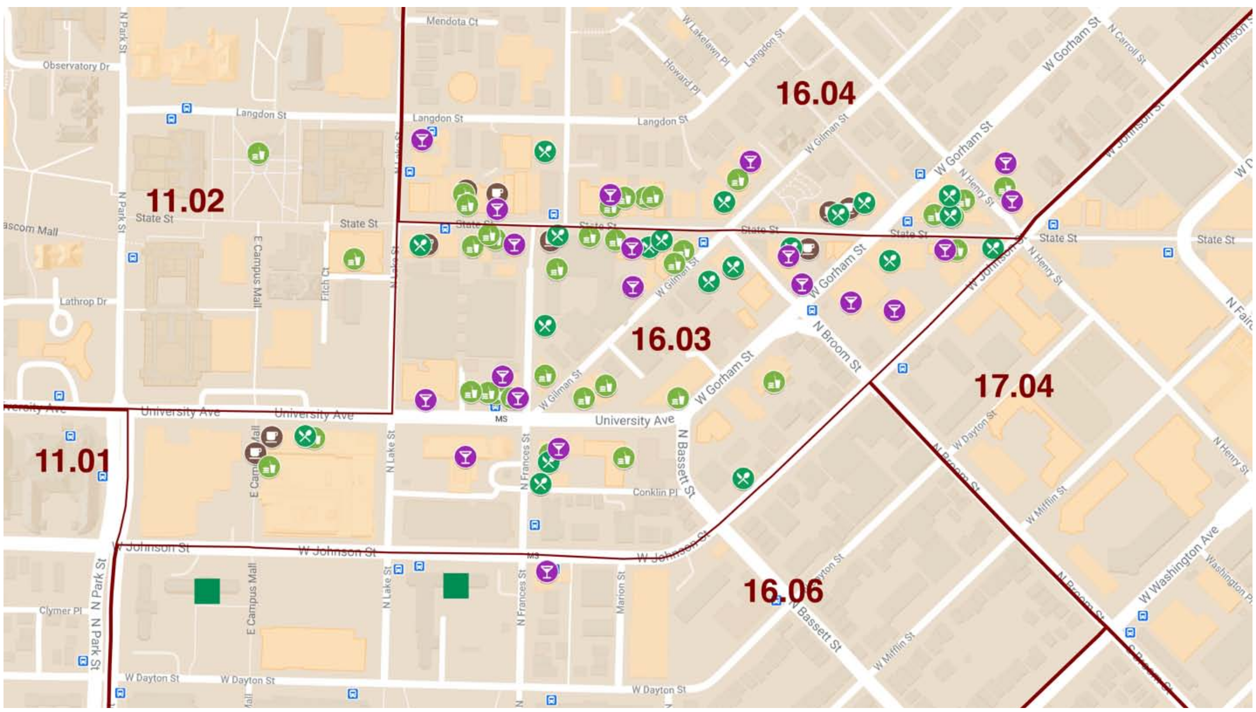

Figure 8. Google My Maps Screenshot of the Locations of a Cluster of 20 Bars and a Comparison Group of 68 Restaurants, with Overlaid Census Tract Boundaries

Having examined the locations of on- and off-campus housing as well as campus-area bars, we turn to the geospatial distribution of COVID-19 cases. Figure 9 maps the cumulative number of COVID-19 positive cases diagnosed during the two-month period from August 16 through October 16, 2020 in each of the census tracts surrounding the U. Wisconsin-Madison campus, as reported by the WDHS. The cumulative number of cases is proportional to the area (not the diameter) of each bubble. The four largest bubbles are: tract 16.04 (870 cases); tract

16.06 (726 cases); tract 16.03 (488 cases); and tract 11.01 (266 cases). For this 2-month observation interval, which is somewhat wider than that covered by the university's dashboard in Figure 2, these four census tracts comprised 76.7 percent of the 3,065 cases in campus-area census tracts compiled by the WDHS.

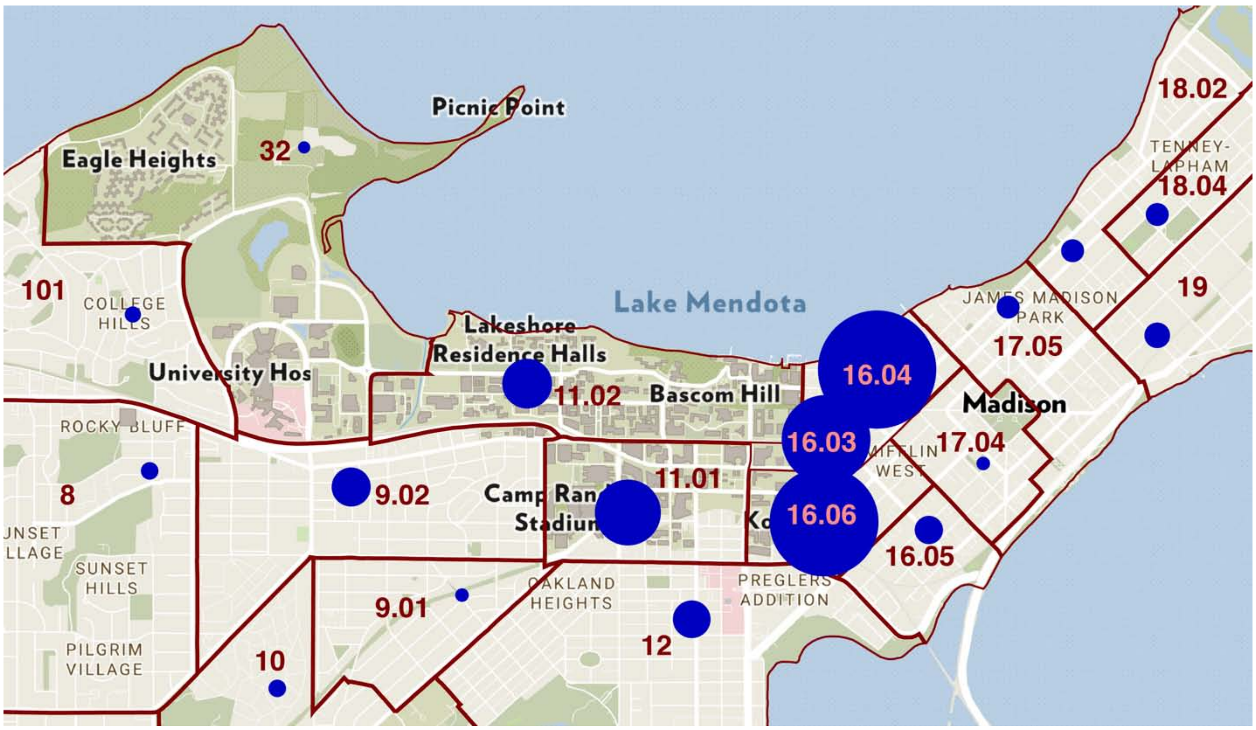

Figure 9. Map of Cumulative COVID-19 Positive Cases During August 16 – October 16 in Relation to Census Tract in the U. Wisconsin-Madison Area.

Figure 10 elucidates the dynamics of COVID-19 incidence in these four census tracts. Plotted are the daily incidence rates per 1,000 population from August 23 – October 4. In the graphic, we have colored the paths for tracts 16.03 and 11.01 in light gray to help elucidate the epidemic paths in the two principal tracts, 16.04 and 16.06. The incidence is measured on a logarithmic scale to show relative changes. As noted in Appendix B, the case counts ascertained by the WDHS were reported about one day after they appeared on the university's dashboard.

Figure 10 suggests that there were, in fact, two distinct waves to the outbreak. The first wave originated in tract 16.04, where we have identified a high concentration of fraternities and sororities (Figure 6) and off-campus housing generally (Figure 7). By the last week of August, daily incidence had already crossed to 1-per-1,000 threshold, about four times the daily rate in Dane County during the peak of the second epidemic wave in early July (Harris 2020b). By

September 2, as noted above, an outbreak had first been detected in nine off-campus fraternities. The incidence during this first wave peaked at 27 per 1,000 on September 10.

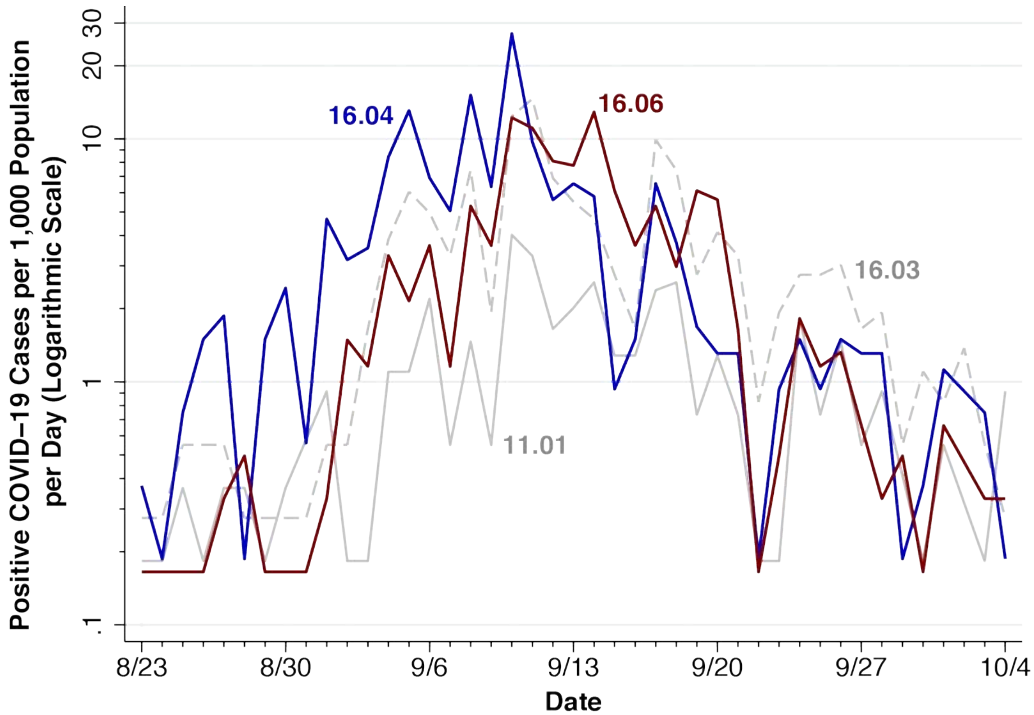

Figure 10. Positive COVID-19 Cases per 1,000 Population per Day in Four Key Census Tracts in Madison WI, August 23 – October 4, 2020

The second wave, concentrated in tract 16.06, lagged behind the first wave by about 4–5 days but grew more rapidly. The rise in incidence from 0.33 to 12.23 per 1,000 during September 1–10 implies a reproductive number of about $\mathcal{R} = 2.6$ (Harris 2020a). While tract 16.06 included on-campus residence halls and off-campus housing (Figures 5 and 7), Figure 10 is compatible with the September 9 lockdown of Sellery and Witte Residence Halls.

Case Control Study

Figure 11 below shows the proportion of devices staying completely at home among all devices whose *home* was identified as census block group 16.06-3 or 16.06-4. For census block group 16.06-4, which captures residents of Sellery and Witte, Figure 10 shows a spike in the proportion of devices staying completely at home on September 8, a finding compatible with voluntary self-quarantining as the proportion infected in these dorms neared 20 percent. There followed an abrupt drop on September 9, a finding consistent with a last-minute escape before the pending lockdown went into effect at Sellery and Witte at 11 p.m. The university-imposed quarantine at these two residence halls is captured by the second spike on September 10, followed by a sustained increase in stay-at-home devices during the next week. No such patterns were seen among residents of Ogg and Smith in census block group 16.06-3.

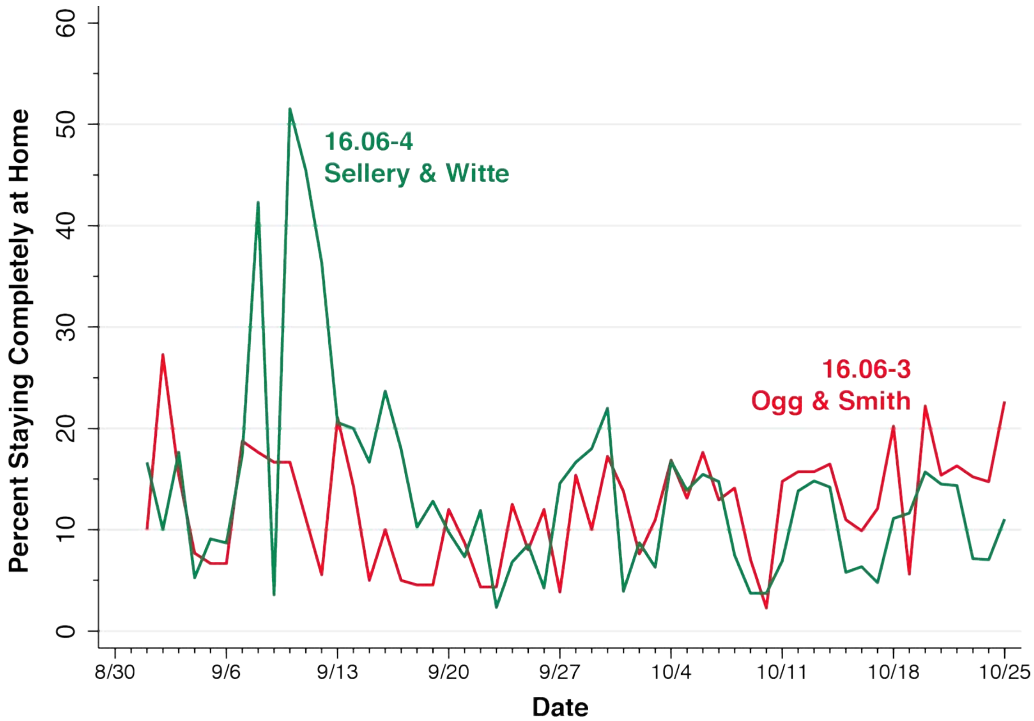

Figure 11. Percentage of Devices Staying Completely at Home in Census Block Groups 16.06-3 and 16.06-4

Figure 12 below locates eleven bars within a 10-minute walk of Sellery Residence Hall. They form a subset of the cluster of 20 bars identified in the map of Figure 8. Each bar is identified by a one- or two-colored bubble. The area of each lime-green bubble is proportional to the number of devices homed in census block group 16.06-4 that visited each bar during September, while the area of each pink bubble is proportional to the number of devices homed in census block group 16.06-3 that visited the same bar during September. When there is only a lime-green bubble and no pink bubble, there were no visitors from census block group 16.06-3. The figure also identifies the two residence halls (Sellery and Witte) in census block group 16.06-4 and the two residence halls (Ogg and Smith) in census block group 16.06-3. Next to each residence hall we have noted the number of residents (University of Wisconsin-Madison 2020c).

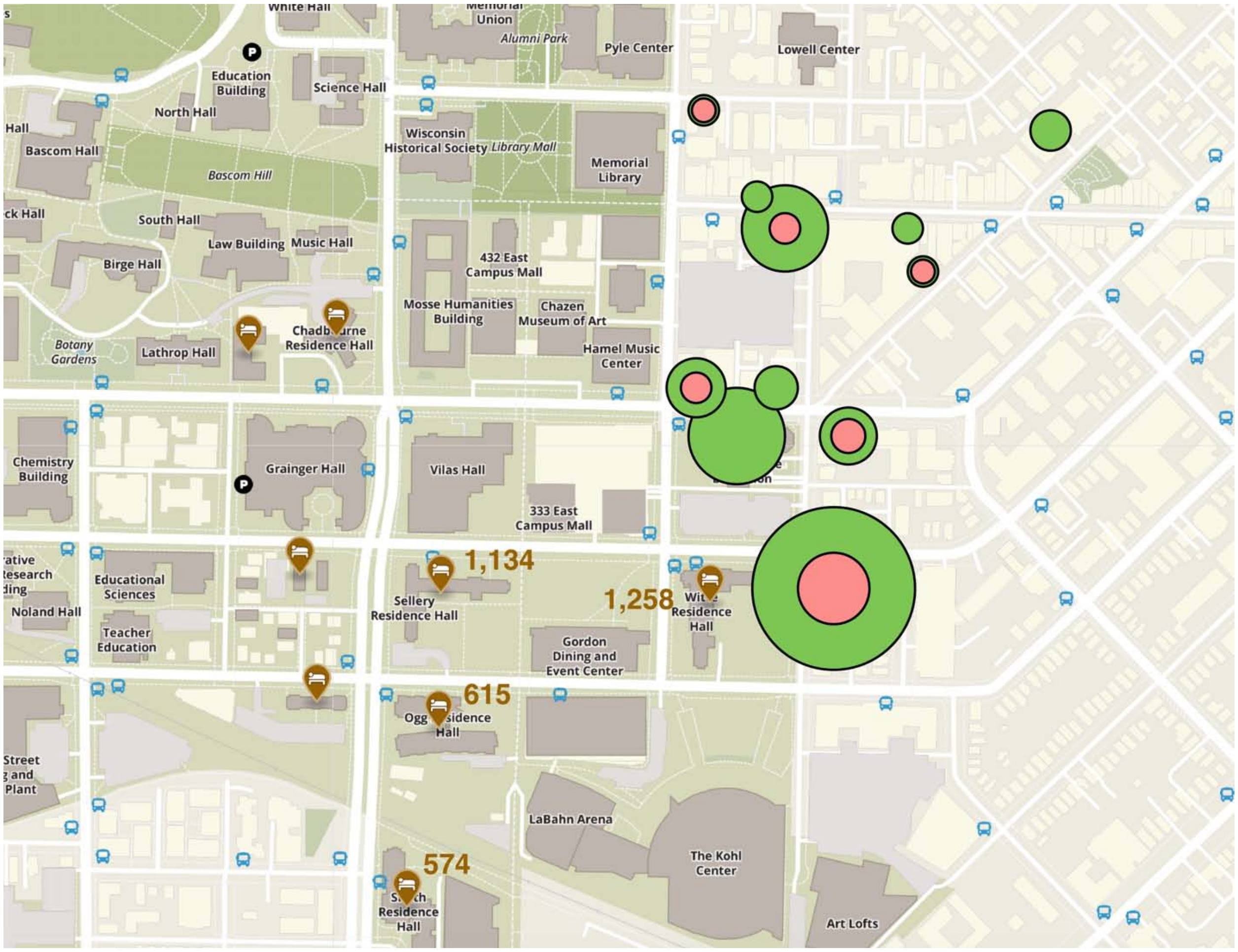

Figure 12. Number of Devices Visiting Eleven Bars Within a 10-Minute Walk of Sellery Residence Hall, September 2020: Visitors from Census Blocks Groups 16.06-3 in Pink and 16.06-4 in Lime

Table 1 below shows the data on the numbers of visitors from the two census block groups to all 20 bars and all 68 comparison restaurants in our analysis. The first row corresponds to the *case* residence halls in census block group 16.06-4, while the second row corresponds the *control* residence halls in census block group 16.06-3. The column labeled N shows the census of each residence hall pair, where N_1 = 2392 and N_0 = 1198. With N_1/N_0 = 2.01, we see that Sellery-Witte had twice as many residents and Ogg-Smith.

Table 3. Case Control Calculations

Census Block Group	*N*	*b*	*r*
16.06-4 (1)	2,392	255	426
16.06-3 (0)	1,198	43	137
R		2.95	1.55

The column labeled b shows the number of visitors to the cluster of 20 bars originating from the two census block groups in September. With b_1/b_0 = 5.93, we see that Sellery-Witte had nearly six times as many bar visitors as Ogg-Smith. Corrected for the difference in census, the ratio is $R_b = (b_1/N_1)/(b_0/N_0)$ = 2.95. The column labeled r shows the number of visitors to the comparison group of 68 restaurants in September. With r_1/r_0 = 3.11, we see that Sellery-Witte had about three times as many restaurant visitors as Ogg-Smith. Corrected for the difference in census, the ratio is $R_r = (r_1/N_1)/(r_0/N_0)$ = 1.55. Based on these data, we can then compute the overall ratio R_b/R_r = 1.91. This quantity is equivalent to an odds ratio in a classic epidemiologic study, with the bar visitors interpreted as the exposed subjects and the restaurant visitors interpreted as the unexposed subjects. The conditional likelihood estimate of the 95 percent confidence interval for this ratio (Rothman 1982) was 1.29 – 2.85. The null hypothesis that R_b/R_r = 1 was rejected at the significance level p = 0.0007.

Accordingly, the greater proximity of Sellery-Witte to the cluster of establishments shown in Figure 8 enhanced their residents' rates of both bar and restaurant visitation. But the fact of being just a few minutes' walk from these places was about twice as important in determining bar visits than restaurant visits. The higher rate of bar visits was, in turn, associated with a significantly higher prevalence of coronavirus infection.

We investigated whether an analogous case control design could be applied to the census block groups where fraternities and sororities were located within census tract 16.04 in Figure 6. Our results are shown in Appendix C. Based upon the proportion of devices staying completely at home, we could ascertain that organizations in census block groups 16.04-1 and 16.04-4 were subject to temporary quarantine. However, without more specific data on the accumulated incidence of coronavirus infections in individual fraternities and sororities, it was not possible to accurately isolate cases and controls.

Regression Model

Figure 13 below contains two concurrent plots covering each day from August 16 through October 11. The orange line, measured on the left vertical axis, shows the total number of daily visits by all devices, without restriction on origin, to any one of the eleven bars identified in Figure 12. As noted in the Data section above, this time series was derived from the Patterns database variable *visits_by_day*. Since the Patterns database tracks the GPS pings emitted from a limited panel of devices, only the relative changes in visit counts have significance. Thus, during the week of August 16, there was an average of 176 daily visits among device-holders in the SafeGraph panel to the eleven bars. During August 29-30, the number peaked at 471, a relative increase of 2.7-fold. By capturing all visits to the eleven bars, the *visits_by_day* variable includes those recently arrived device holders whose home location has not yet been updated.

The blue line, measured on the right vertical axis in Figure 13, shows the daily number positive COVID-19 cases reported by WDHS for census tract 16.06. This is a linearized (non-logarithmic) version of the data series labeled 16.06 in Figure 10, extended back into early August and forward into mid-October.

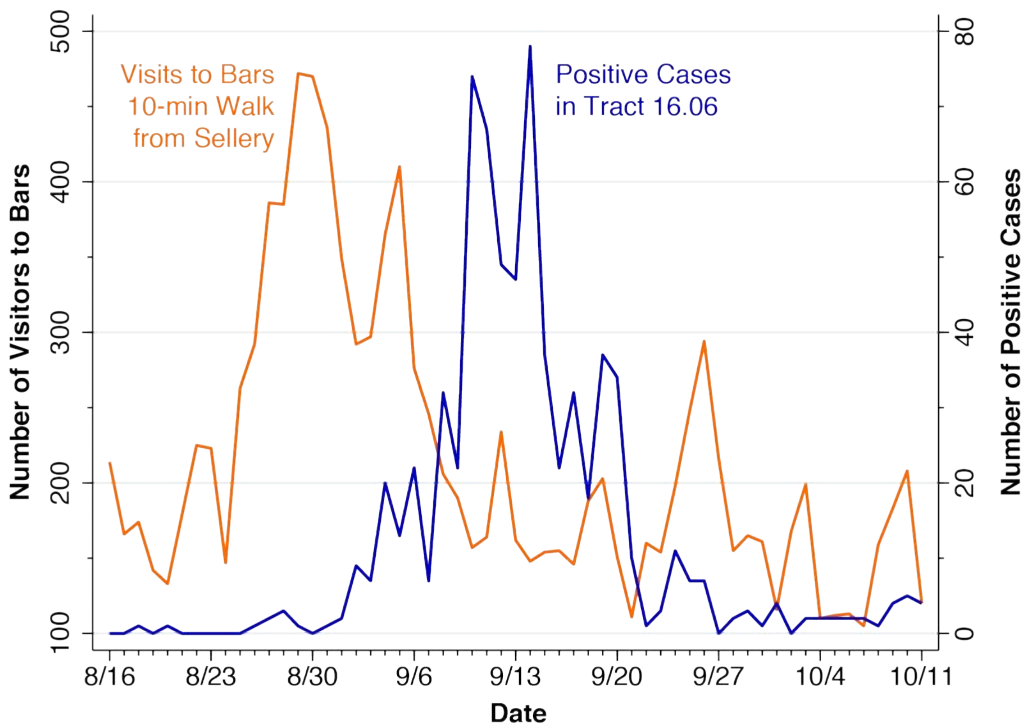

Figure 13. Left: Daily Visits by Device Holders in the SafeGraph Panel to Bars Within a 10-Minute Walk of Sellery and Witte Residence Halls. Right: Daily Positive COVID-19 Cases in Census Tract 16.06

Comparison of the two data series shows a double-peaked surge in the volume of bar attendance, with the first peak occurring on August 29-30 and the second on September 5. Soon thereafter, visits to the eleven bars began to fall as positive cases of COVID-19 began to grow. This observation is further consistent with the evidence on voluntary self-rationing by residents of Sellery and Witte seen in Figure 7.

The double-peaked surge in the volume of bar attendance was followed by a double-peaked surge in positive SARS-CoV-2 cases, with the first peak on September 10 and the second on September 14. With WDHS-reported cases lagging one day behind dashboard-reported cases (as noted in Appendix B), the data in Figure 13 would be consistent with an incubation period in the range of 3–6 days (Lauer et al. 2020).

Figure 14 shows a log-log bivariate plot of the incidence of newly diagnosed positive coronavirus tests per 1,000 population versus the number of visits to the cluster of 20 bars per 1,000 population during September 2020. The incidence data on positive tests are broken down by the census tract as reported by WDHS, while the numbers of bar visits per 1,000 population are broken down by the census tract of origin of the bar visitor. The slope of the linear relationship shown in the figure, estimated via geometrically weighted regression, was 0.87 (95% CI, 0.76 – 0.97). The slope of the unweighted regression was 0.92 (95% CI, 0.69 – 1.15). A bivariate comparison of September 2020 case incidence versus bar visits per capita in August and September combined gave virtually identical results (slope 0.91, 95% CI 0.79 – 1.03).

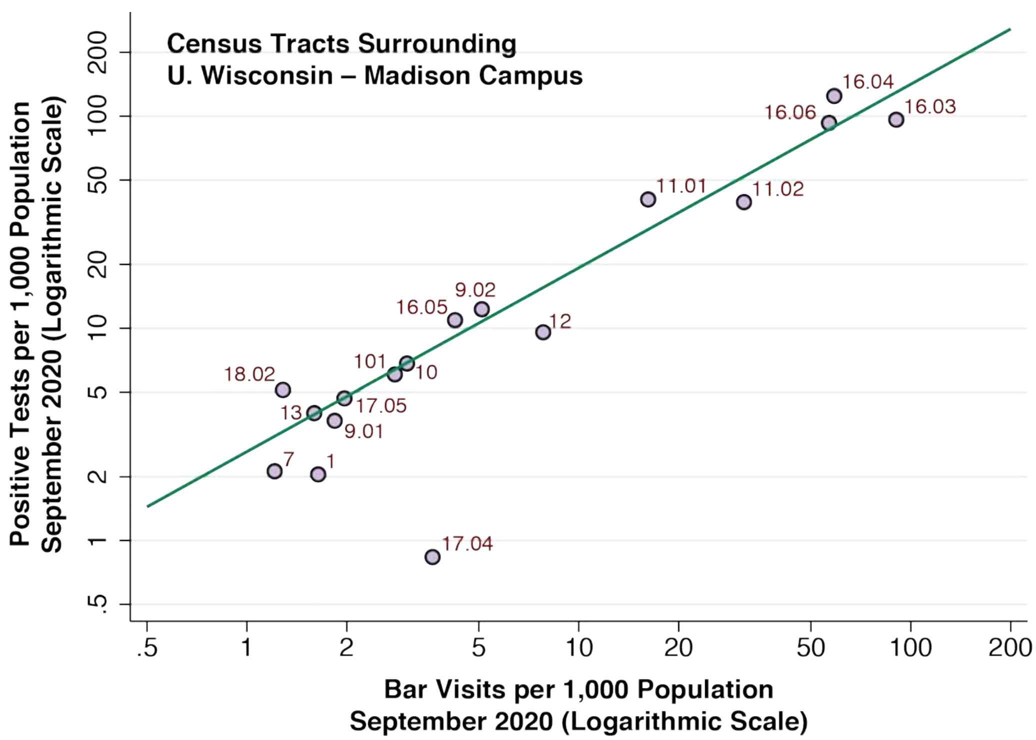

Figure 14. Incidence of Positive Coronavirus Test per 1,000 Population Versus Visits per 1,000 Population to the 20-Bar Cluster, September 2020.

Appendix D shows the corresponding bivariate relationship between coronavirus incidence and per-capita visits to the comparison group of 68 restaurants. Although there was a positive relationship, the estimated elasticity was significantly lower (0.72, 95% CI 0.61–0.83). Moreover, the relation between incidence and visits was inconsistent among the census tracts at the epicenter of the outbreak.

We obtained the following multivariate relationship, estimated by unweighted ordinary least squares, between the coronavirus incidence and per-capita visits to the cluster of 20 bars and the comparison group of 68 restaurants. Standard errors are shown in parentheses.

$$\log \mathit{Incidence} = \underset{(0.302)}{0.903} \times \log \mathit{Bar\ Visits} - \underset{(0.281)}{0.074} \times \log \mathit{Restaurant\ Visits}$$

Thus, the multivariate elasticity of coronavirus incidence with respect to bar visits was 0.90 with a 95% confidence interval of 0.26 – 1.54 (p = 0.009), while the relation to restaurant visits was not statistically significant (elasticity –0.074, 95% CI -0.29 – 0.48). Geographically weighted regression also gave a significant relationship with bar visits (elasticity 0.70, 95% CI 0.29 – 1.11, p = 0.002), while the relation to restaurant visits was likewise statistically insignificant.

Discussion

Overview of Principal Results

We identified a cluster of 20 bars located within the epicenter of the September 2020 coronavirus outbreak at the University of Wisconsin-Madison (Figures 1, 8, and Appendix A). This cluster of bars was in close proximity to a significant portion of off-campus housing (Figure 7), most fraternities and sororities (Figure 6), and the two on-campus residence halls where cumulative infections approached 20 percent of occupants and a mandatory quarantine was imposed (Figure 5, 8, 12). This bar cluster occupied those census tracts with the highest per-capita incidence rates (Figure 9).

While the overall daily incidence of newly diagnosed infections peaked on September 9-10 (Figures 1, 2, and Appendix B), we found that the outbreak had actually had two successive waves. The first wave was dominated by cases from census tract 16.04, where nearly all off-campus fraternities and sororities were located. The second wave, which peaked about 4–5 days later, was dominated by cases from census tract 16.06, where the two on-campus residence halls with the highest infection rate were located. The upswing of this second wave had an estimated reproductive number of $\mathcal{R}$ = 2.6.

We conducted a case control study comparing the two quarantined, high-infection-rate residence halls (Sellery and Witte) with two other residence halls (Ogg and Smith) that had not been subject to quarantine. This comparison had the advantage that cases in Sellery and Witte were the only residents of census block group 16.06-4, while the controls in Ogg and Smith were confined to the separate census block group 16.06-3 (Figures 1 and 5). An analysis of temporal trends in the proportions of smartphone devices staying completely at home in these two census block groups was consistent with the fact that Sellery and Witte underwent lockdown, while Ogg and Smith did not (Figure 11).

As a further check on the validity of our case-control comparison, we focused on the 11 bars within a 10-minute walk of Sellery Residence Hall, which was farther to the west than Witte (Figure 12). We found that the time-path of visits to this subset of bars directly preceded the upsurge in the incidence of infection with a lag of 3–6 days, an interval consistent with the incubation period of the virus (Figure 13).

Our case control study revealed that a resident of Sellery-Witte had a 2.95-fold greater rate of visitation to the entire 20-bar cluster than a resident of Ogg-Smith, which was more distant from the cluster (Table 1). By contrast, a resident of Sellery-Witte had only a 1.55-fold greater rate of visitation to a comparison group of 68 restaurants located in the same off-campus area (Table 1, Figure 8). While geographic proximity was a significant determinant of restaurant visitation, it was an even more important determinant of bar visitation. These findings fit with the conclusion that the residents of Sellery and Witte suffered significantly more infections than the residents of Ogg and Smith because they were nearer to the 20-bar cluster, and not because they were also nearer to coffee houses, inexpensive and moderately priced restaurants.

We proceeded to a cross-sectional analysis of the incidence of newly diagnosed coronavirus infections among various census tracts in the area of the University of Wisconsin-Madison campus. We found a remarkably tight fit between the incidence of new infections in September and corresponding per-capita rate of bar visitation, with an estimated elasticity on the order of 0.9 (Figure 14). Multivariate analysis continued to show a significant relationship with bar visits, while there was no significant relation to restaurant visits. These findings reinforced the conclusion that bar attendance played a critical role in the outbreak.

Advantages and Advances

In contrast to studies of outbreaks that focus sharply on a single location, this study concentrates on a cluster of places, in this case a cluster of bars right in the geographic epicenter of the outbreak. The study does not attempt to pinpoint any particular bar, a task that is not feasible with currently available data. On the other hand, this study does decompose the University of Wisconsin-Madison outbreak into its critical components, distinguishing between an initial wave in a census tract where fraternities and sororities are situated and a subsequent wave in a census tract dominated by two key on-campus residence halls. This distinction allowed us to look separately at the potential effect of bar visitation on on-campus residents.

This study has the additional advantage of relying upon census tract-specific case counts provided by the Wisconsin Department of Health Services (Wisconsin Department of Health Services 2020). The availability of such fine detail avoids the need to use mathematical models to project census tract-level incidence from county-level data (Chang et al. 2020). Taking advantage of the fact that the two on-campus residence halls hit hardest by the outbreak were the only inhabitants of a particular census block group, our study was able to zoom further down below the census tract level.

Limitations

While we posit that a cluster or network of places can serve as a super-spreader, we did not have sufficient data in this study to map out the individual connections between places. We had some data on the movements of smartphone holders from one census block group to another, but we would need an even finer geographic grid to ascertain how the connections between bars within a census block group unfold. This hardly means that the task of identifying the connections is simply too daunting. In some cases, transportation networks can elucidate the connections between places (Harris 2020g, d, e, Hu et al. 2020, Du et al. 2020, Zheng et al. 2020). Still, it would be inappropriate to assume that, in absence of hard probative data, each establishment in the 20-bar cluster had no more than an independent effect on the risk of coronavirus propagation.

Central to our analytic strategy was the distinction between a bar and a restaurant. In our classification of business entities, we relied upon such descriptors as bar, bar-grill, pub, and tavern, but our main criterion was whether alcoholic beverages were the principal fare of the establishment. In some borderline cases, adherence to this criterion required us to reclassify a restaurant as a bar. However, in the large majority of cases, the distinction was clear. This was especially the case for bars that served only snacks and other bar food, and for cafés and fast-food restaurants that served no alcoholic beverages at all.

We identified two distinct waves of the outbreak: a fraternity-sorority-based outbreak localized in census tract 16.06 and an on-campus residence hall-based outbreak localized to census tract 16.04. This distinction alone does not inform us whether the first wave seeded the second or, alternatively, that the two waves resulted from multiple distinct importations. Distinguishing between these two hypotheses would ordinarily require phylogenetic analysis of viral samples (Gonzalez-Reiche et al. 2020, Harris 2020d, Richmod et al. 2020). Because SafeGraph updated the assigned *home* of many devices on September 1, many students arriving on campus at the end of August were not immediately reclassified as holders of devices originating in one of the key census block groups. This delay limited our ability to study the early movements of students between the dorms (census block groups 16.06-4 and 16.06-3) and fraternities and sororities (census block groups 16.04-1 and 16.04-4). In any event, it would be premature to conclude that the University of Wisconsin-Madison outbreak originated with a "student zero."

We did not have data on the specific fraternities and sororities that were initially hit by multiple COVID-19 cases and subsequently quarantined. As a result, we could not carry out the type of case control study for fraternities and sororities that we carried out for particular on-campus residence halls. While the data point for census tract 16.04 fit our regression model relating bar attendance to coronavirus incidence (Figure 14), we cannot rule out other contributing factors, such as parties in off-campus housing.

In our regression model relating the incidence of positive coronavirus tests to bar and restaurant visitation rates, census tract 17.04 was an outlier observation, with a much lower incidence of infection than expected (Figure 14 and Appendix D). Smartphones originating from this census tract went mostly to other bars surrounding the Capitol (Appendix A), while a small number of recorded visits to the 20-bar cluster may have had excessive leverage on the regression results. We need to investigate further why infection rates in this census tract were so much lower.

We do not have enough information at this juncture to resolve apparent discrepancies between the university's COVID-19 dashboard and the WDHS database. While the dashboard describes most cases as residing at on-campus locations, the WDHS data show most cases coming from off-campus census tracts. While the epidemic curves from the two sources show a striking concordance (Appendix B), it may still be the case that the WDHS database is picking up many cases unaffiliated with the university while the dashboard is picking up more students identified by rapid testing.

Perspectives

Our findings should not be interpreted broadly to mean that restaurants are entirely free of risk while bars are the sole source of contagion. The narrower interpretation is that a specific, centrally located cluster of bars appeared to be a significantly greater vehicle for propagation of the virus than restaurants in a particular university-based outbreak. Neither do our findings point the finger at all bars. Among the 51 bars throughout the campus area, we focused sharply on a cluster of 20 bars at the geographic epicenter of the outbreak (Appendix A). Nor should our findings be taken to absolve other high-density conditions that may enhance person-to-person transmission. In preparation for its Smart Restart and in its response to the outbreak, the university made efforts to reduce the density of its residence halls and assign more students to single rooms.

Future studies of college and university outbreaks need to concentrate harder on the dynamics of viral transmission, and not simply on how many cases ended up in dormitories, athletic teams, fraternities and sororities (Palin and Greer 2012). Retrospective case-tracking needs to expand its scope to ask an infected individual not just whether he went to a bar, but also whether he went bar-hopping, whether his roommates also went to bars, and if so, to what bars on what nights.

We need to think more about the ways that multiple places within a cluster may act synergistically to enhance viral propagation. The above-cited outbreak in South Korea (Kwang-tae 2020) points to a model where an index case moves from one place to another within the cluster. More generally, when there is high mobility between places, they may function effectively as one place. If an average of 20 patrons attended each of five interconnected bars on a single night, we would end up with an "event" with 100 attendees. When a student says to his friends, "Let's go to bar A and if we can't get in, we'll just go to bar B," we have a classic network externality where the mere availability of bar B enhances the demand for, and thus the transmission potential of, bar A.

Even more broadly, we need to think about systemic factors that influence viral propagation, and not simply the characteristics of individuals or the places they go to. The epidemic in Los Angeles County has been sustained in great part by intra-household transmission among multigenerational families (Harris 2020i). But the larger question is what public policies have enhanced or mitigated these housing conditions. The spread of coronavirus in New York City and other metropolises may have been enhanced by individuals of high mobility (Glaeser, Gorback, and Redding 2020). But the larger question is what transportation networks carried them from one place to another.

Appendix A: Map of Bars in the University of Wisconsin-Madison Area

Figure A1 shows a map of 51 bars in the U. Wisconsin-Madison area. The procedure for identifying these bars is described in the Data section above. In the map, constructed with the My Google Maps application, the purple markers locate the 20 bars belonging to the critical off-campus cluster within census tracts 16.03, 16.04 and 16.06. Among the remaining 31 bars identified by the blue markers, there is a cluster of 10 establishments surrounding the Capitol Square in tracts 17.04 and 17.05, and a separate array of five bars running along Regent Street, which bounds tracts 12, 11.01 and 16.06.

Figure A1. Map of Bars in the U. Wisconsin-Madison Area

Appendix B: Positive COVID-19 Case Counts from U. Wisconsin-Madison Dashboard and Wisconsin Department of Health Services

The data from the Wisconsin Department of Health Services include all positive tests reported from census tracts 10, 101, 11.01, 11.02, 12, 13, 14.01, 16.03, 16.04, 16.05, 16.06, 17.04, 17.05, 18.02, 18.04, 19, 32, 8, 9.01, and 9.02. Total positive tests reported by the UW-Madison dashboard were 2,955, while total tests from the WI Department of Health Services database were 2,934.

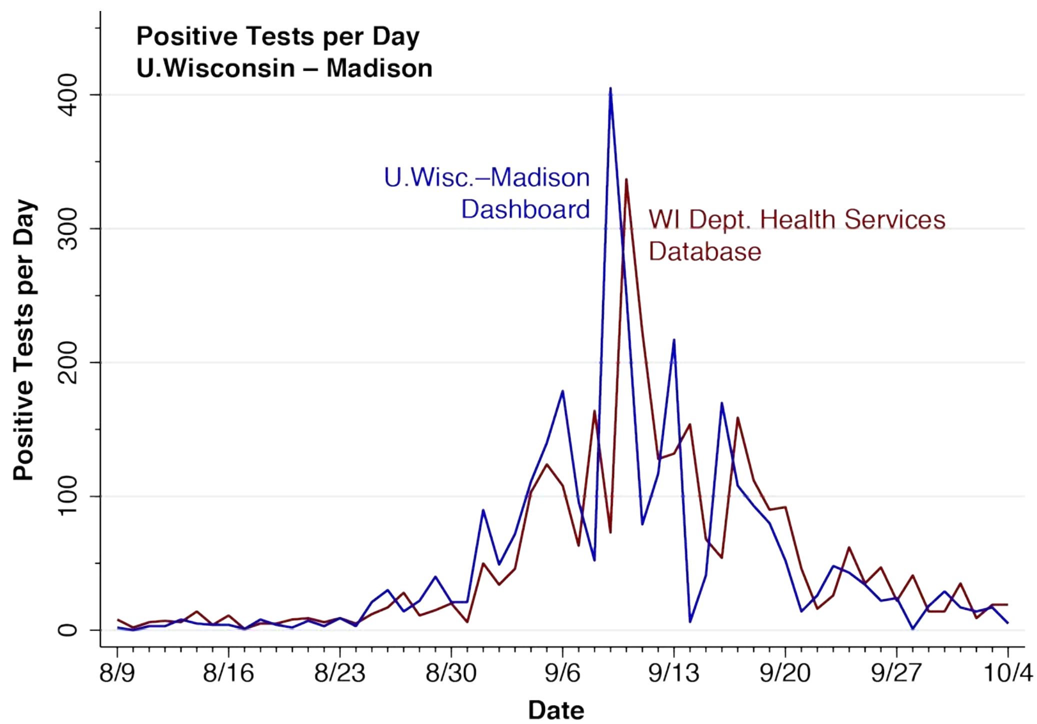

Figure B1. Comparison of Positive COVID-19 Tests per Day from Two Data Sources: University of Wisconsin-Madison Dashboard and Wisconsin Department of Health Services Database

Except for one-day differences presumably due to delays in reporting, the two series appear to be strikingly concordant. Nonetheless, there remained some unresolved discrepancies. In particular, the counts of cases attributable to off-campus census tracts 16.03 and 16.06 were larger than the numbers of off-campus cases in the dashboard. It is possible that the WDHS-reported data, which we relied upon for data analyses, are picking up more off-campus cases than the dashboard-based series.

Appendix C: Percentage of Devices Staying Completely at Home in Census Block Groups 16.04-1, 16.04-2, 16.04-3, 16.04-4

Figure C1 below depicts the census block groups of the fraternities and sororities located within census tract 16.04, as shown above in Figure 5. While most organizations are located within census block groups 16.04-1 and 16.04-4, some are also in 16.04-2 and 16.04-3. While the first wave of infections in census tract 16.04 occurred about 4–5 days before the second wave in tract 16.06 (Figure 10), there appear to be no publicly available data on the infection rates of specific organizations within the larger group.

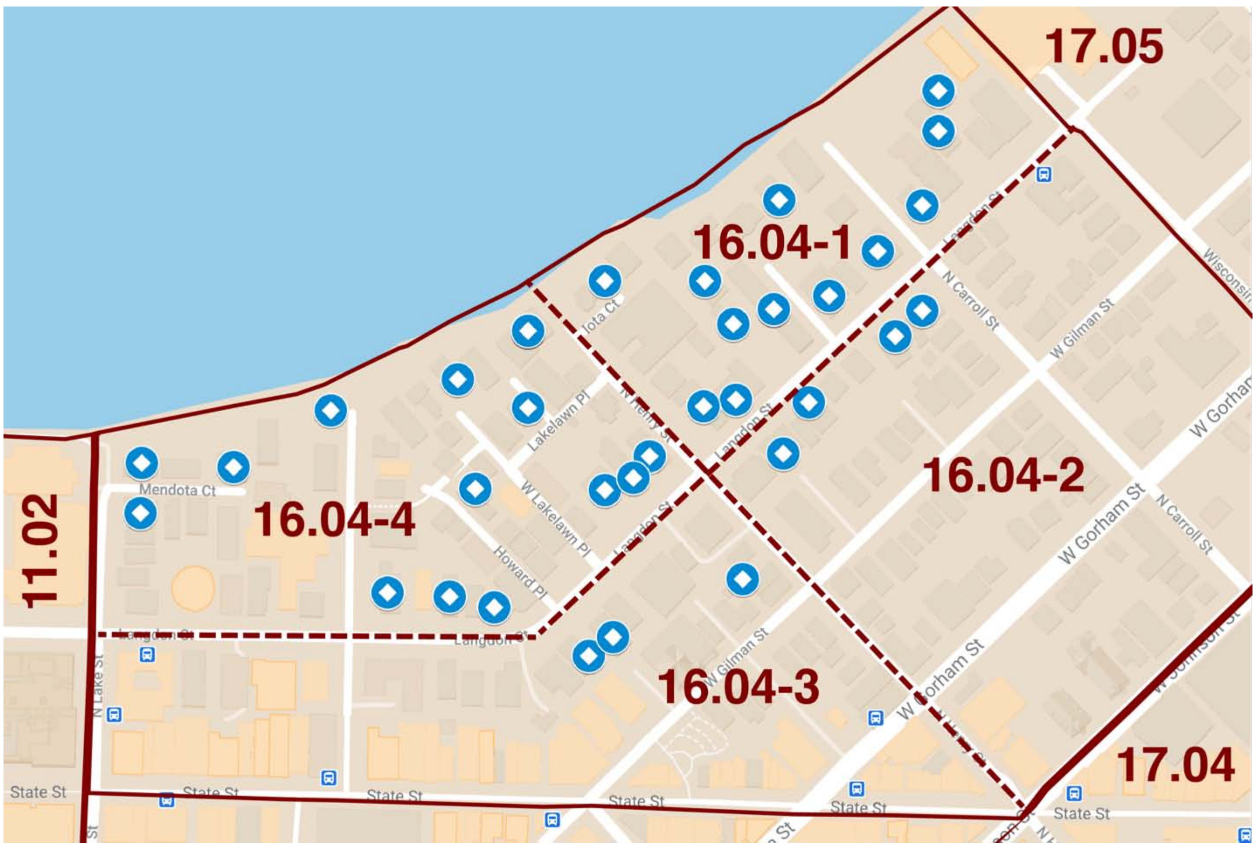

Figure C1. Census Block Group Locations of Fraternities and Sororities Within Census Tract 16.04

Figure C2 below shows the percentage of devices staying completely at home from September 1 – October 25 in each of the four census block groups of census tract 16.04. The single peak in census block group 16.04-1 and the double peak in 16.04-4 are quite similar to the pattern seen for census block 16.06-4 in Figure 11. These observations suggest that fraternities and sororities in blocks 16.04-1 and 16.04-4 were subject to quarantine. At this juncture, there appear to be no publicly available data on which organizations were subject to lockdown.

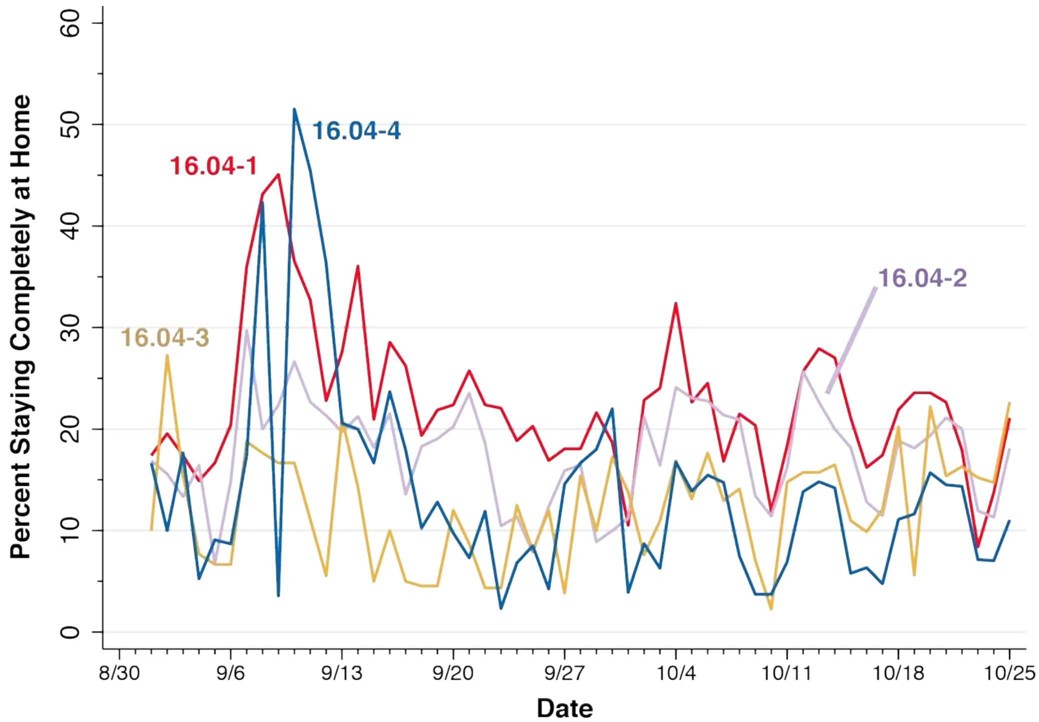

Figure C2. Percentage of Devices Staying Completely at Home in Census Block Groups 16.06-1 Through 16.04-4

Appendix D. Incidence of Positive Coronavirus Tests per 1,000 Population Versus Visits per 1,000 Population to the 68-Restaurant Comparison Group, September 2020.

Figure D1 below shows the bivariate relationship between the incidence of positive coronavirus tests per 1,000 population and the number of visits per 1,000 population to the 68 restaurants in the comparison group. As in the case of bar visits, there was an overall positive relationship. However, the estimated elasticity, based again on geometrically weighted regression, significantly lower (0.72, 95% CI 0.61–0.83).

Moreover, the explanatory power of the bivariate regression model was considerably lower. While the regression model for bar visits (Figure 14) yielded an R-squared statistic of 0.95, the corresponding model for restaurant visits (Figure D1) had an R-squared of 0.88. In particular, the relation between incidence and visits was inconsistent among the census tracts at the epicenter of the outbreak. The number of restaurant of visits per capita in census tract 16.06 (equal to 110 per 1,000) was lower than the corresponding per-capita restaurant visits in tract 11.02 (equal to 119 per 1,000), even though the incidence of newly diagnosed positive coronavirus tests was nearly three-fold greater (93 per 1,000 versus 39 per 1,000).

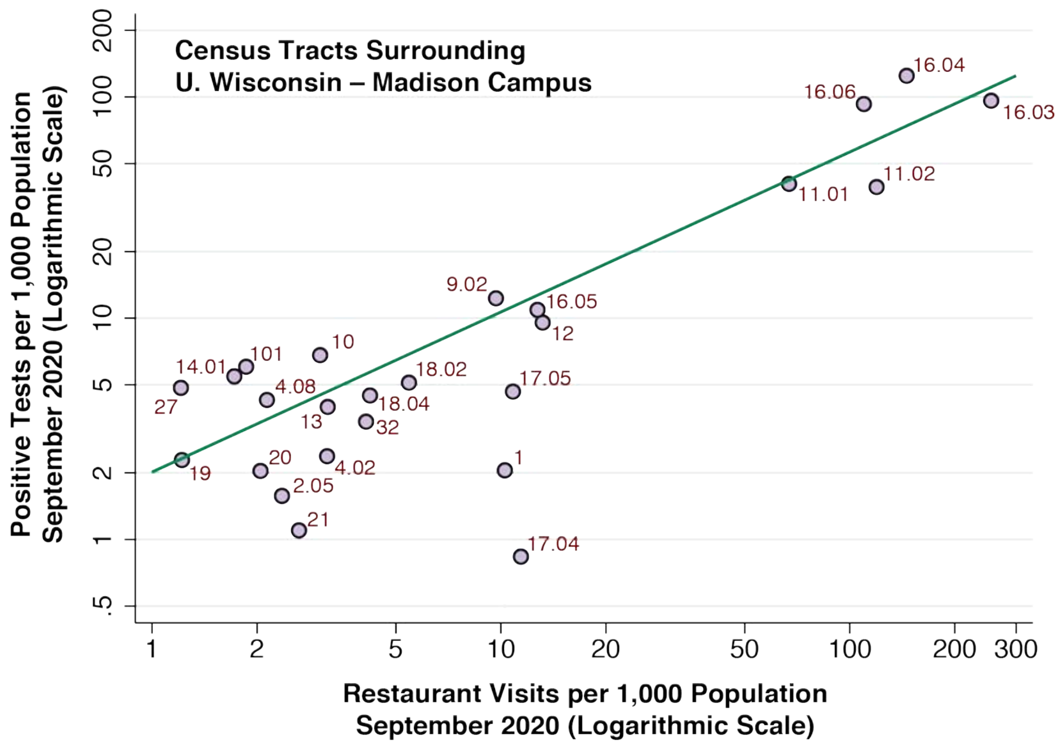

Figure D1. Incidence of Positive Coronavirus Test per 1,000 Population Versus Visits per 1,000 Population to the 20-Restaurant Comparison Group, September 2020

References

Adam, D. C., P. Wu, J. Y. Wong, E. H. Y. Lau, T. K. Tsang, S. Cauchemez, G. M. Leung, and B. J. Cowling. 2020. "Clustering and superspreading potential of SARS-CoV-2 infections in Hong Kong." *Nat Med*. doi: 10.1038/s41591-020-1092-0.

Barncard, Chris. 2020. *Simpler COVID-19 test could provide results in hours from saliva*. https://news.wisc.edu/simpler-covid-19-test-could-provide-results-in-hours-from-saliva/: University of Wisconsin-Madison, August 6.

Bernheim, B. Douglas, Nina Buchmann, Zach Freitas-Groff, and Sebastián Otero. 2020. *The Effects of Large Group Meetings on the Spread of COVID-19: The Case of Trump Rallies*. https://siepr.stanford.edu/research/publications/effects-large-group-meetings-spread-covid-19-case-trump-rallies: Stanford Institute for Economic Policy Research (SIEPR) Working Paper 20-043, October.

Blank, Rebecca. 2020a. *Campus to resume some in-person activities, maintain strict health measures*. https://covidresponse.wisc.edu/campus-to-resume-some-in-person-activities-maintain-strict-health-measures/: University of Wisconsin-Madison, September 26.

Blank, Rebecca. 2020b. *Chancellor Blank statement on Dane County Board of Supervisors*. https://news.wisc.edu/chancellor-blank-statement-on-dane-county-board-of-supervisors/: University of Wisconsin-Madison, October 1.

Blank, Rebecca. 2020c. *Chancellor Blank to County Executive: Partner with us in enforcing safe behavior off-campus*. https://news.wisc.edu/chancellor-blank-to-county-executive-partner-with-us-in-enforcing-safe-behavior-off-campus/: University of Wisconsin-Madison, September 21.

Blank, Rebecca. 2020d. *Chancellor directs 14-day student restrictions for health, safety*. https://news.wisc.edu/chancellor-directs-14-day-student-restrictions-for-health-safety/: University of Wisconsin-Madison, September 7.

Blank, Rebecca. 2020e. *Update on COVID-19 Response*. https://chancellor.wisc.edu/blog/update-on-covid-19-response/: University of Wisconsin-Madison, September 15.

Blank, Rebecca. 2020f. *UW in a Semester of COVID*. https://chancellor.wisc.edu/blog/uw-in-a-semester-of-covid/: University of Wisconsin-Madison, Office of the Chancellor, August 26.

Chang, S., E. Pierson, P. W. Koh, J. Gerardin, B. Redbird, D. Grusky, and J. Leskovec. 2020. "Mobility network models of COVID-19 explain inequities and inform reopening." *Nature*. doi: 10.1038/s41586-020-2923-3.

Data Commons Place Explorer. 2020. *Census Tract 16.06, Dane County, Wisconsin*. https://datacommons.org/place/geoId/55025001606: Accessed November 1.

Dave, Dhaval, Andrew I. Friedson, D. McNichols, and Joseph J. Sabia. 2020. *The Contagion Externality of a Superspreading Event:The Sturgis Motorcycle Rally and COVID-19*. http://ftp.iza.org/dp13670.pdf: IZA Institute of Labor Economics, Discussion Paper 1360, September 2020.

Davidson College. 2020. *The College Crisis Initiative (C2I) Dashboard,*. https://collegecrisis.shinyapps.io/dashboard/: Accessed November 14.

Dickson, M. M., G. Espa, D. Giuliani, F. Santi, and L. Savadori. 2020. "Assessing the effect of containment measures on the spatio-temporal dynamic of COVID-19 in Italy." *Nonlinear Dyn*:1-14. doi: 10.1007/s11071-020-05853-7.

Diep, Francie. 2020. *'Our Biggest Fear': What Outbreaks on 3 Campuses Say About the Pandemic This Fall*. https://www.chronicle.com/article/our-biggest-fear-what-outbreaks-on-3-campuses-say-about-the-pandemic-this-fall: Chronical of Higher Education, September 3.

Du, Z., L. Wang, S. Cauchemez, X. Xu, X. Wang, B. J. Cowling, and L. A. Meyers. 2020. "Risk for Transportation of Coronavirus Disease from Wuhan to Other Cities in China." *Emerg Infect Dis* 26 (5):1049-1052. doi: 10.3201/eid2605.200146.

Fisher, K. A., M. W. Tenforde, L. R. Feldstein, C. J. Lindsell, and others. 2020. "Community and Close Contact Exposures Associated with COVID-19 Among Symptomatic Adults >/=18 Years in 11 Outpatient Health Care Facilities - United States, July 2020." *MMWR Morb Mortal Wkly Rep* 69 (36):1258-1264. doi: 10.15585/mmwr.mm6936a5.

Franch-Pardo, I., B. M. Napoletano, F. Rosete-Verges, and L. Billa. 2020. "Spatial analysis and GIS in the study of COVID-19. A review." *Sci Total Environ* 739:140033. doi: 10.1016/j.scitotenv.2020.140033.

Glaeser, Edward L., Caitlin Gorback, and Stephen J. Redding. 2020. *How Much Does COVID-19 Increase with Mobility? Evidence from New York and Other Cities*. https://www.nber.org/papers/w27519: National Bureau of Economic Research Working Paper No. 27519, Revised October 2020.

Gonzalez-Reiche, A. S., M. M. Hernandez, M. J. Sullivan, B. Ciferri, and others. 2020. "Introductions and early spread of SARS-CoV-2 in the New York City area." *Science* 369 (6501):297-301. doi: 10.1126/science.abc1917.

Hamner, L., P. Dubbel, I. Capron, A. Ross, A. Jordan, J. Lee, J. Lynn, A. Ball, S. Narwal, S. Russell, D. Patrick, and H. Leibrand. 2020. "High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice - Skagit County, Washington, March 2020." *MMWR Morb Mortal Wkly Rep* 69 (19):606-610. doi: 10.15585/mmwr.mm6919e6.

Harris, Jeffrey E. 2020a. *The Coronavirus Epidemic Curve is Already Flattening in New York City*. https://www.nber.org/papers/w26917: National Bureau of Economic Research Working Paper No. 26917, Updated April 6, 2020.

Harris, Jeffrey E. 2020b. "COVID-19, bar crowding, and the Wisconsin Supreme Court: A non-linear tale of two counties." *Research in International Business and Finance* 54:101310. doi: doi.org/10.1016/j.ribaf.2020.101310.

Harris, Jeffrey E. 2020c. "Data from the COVID-19 epidemic in Florida suggest that younger cohorts have been transmitting their infections to less socially mobile older adults." *Review of Economics of the Household* (August 11, 2020). doi: doi.org/10.1007/s11150-020-09496-w.

Harris, Jeffrey E. 2020d. *The Earliest Days of the Coronavirus Outbreak in New York City: Part 1*. https://lifeunderquarantine.blog/2020/08/13/the-earliest-days-of-the-coronavirus-outbreak-in-new-york-city-part-1/: Life Under Quarantine, August 13.

Harris, Jeffrey E. 2020e. *The Earliest Days of the Coronavirus Outbreak in New York City: Part 2*. https://lifeunderquarantine.blog/2020/08/30/the-earliest-days-of-the-coronavirus-outbreak-in-new-york-city-part-2/: Life Under Quarantine, August 30, 2020.

Harris, Jeffrey E. 2020f. *San Antonio Conundrum*. https://lifeunderquarantine.blog/2020/07/15/san-antonio-conundrum/: Life Under Quarantine, July 15, 2020.

Harris, Jeffrey E. 2020g. *The Subways Seeded the Massive Coronavirus Epidemic in New York City*. http://web.mit.edu/jeffrey/harris/HarrisJE_WP2_COVID19_NYC_24-Apr-2020.pdf: National Bureau of Economic Research Working Paper No. 27021, Updated April 24, 2020.

Harris, Jeffrey E. 2020h. *TETRIS For Tulsa*. https://lifeunderquarantine.blog/2020/07/12/tetris-for-tulsa/: Life Under Quarantine, July 12, 2020.

Harris, Jeffrey E. 2020i. *Understanding the Los Angeles County Coronavirus Epidemic: The Critical Role of Intrahousehold Transmission*. https://www.medrxiv.org/content/10.1101/2020.10.11.20211045v2: medRxIv, updated October 23.

Heinrich, Janel. 2020. *Order of Public Health Madison & Dane County, Emergency Order #8*. https://publichealthmdc.com/documents/2020-07-07_Order_8.pdf: July 7, 2020.

Hu, M., H. Lin, J. Wang, C. Xu, A. J. Tatem, B. Meng, X. Zhang, Y. Liu, P. Wang, G. Wu, H. Xie, and S. Lai. 2020. "The risk of COVID-19 transmission in train passengers: an epidemiological and modelling study." *Clin Infect Dis*. doi: 10.1093/cid/ciaa1057.

James, A., L. Eagle, C. Phillips, D. S. Hedges, C. Bodenhamer, R. Brown, J. G. Wheeler, and H. Kirking. 2020. "High COVID-19 Attack Rate Among Attendees at Events at a Church -

Arkansas, March 2020." *MMWR Morb Mortal Wkly Rep* 69 (20):632-635. doi: 10.15585/mmwr.mm6920e2.

Kang, C. R., J. Y. Lee, Y. Park, I. S. Huh, H. J. Ham, J. K. Han, J. I. Kim, B. J. Na, and Covid-Rapid Response Team Seoul Metropolitan Government. 2020. "Coronavirus Disease Exposure and Spread from Nightclubs, South Korea." *Emerg Infect Dis* 26 (10):2499-2501. doi: 10.3201/eid2610.202573.

Kwang-tae, Kim. 2020. *S. Korea reports 34 new virus cases, biggest single-day jump in one month*. https://en.yna.co.kr/view/AEN20200510001251320?fbclid=IwAR0pjbudgGNngf91Vr9KwhkEVyg0VXP1Qi99XqlK9QnJ-nNjfq-PxJ1F-zc: Yonhap News Agency, May 10.

landgrid.com. 2020. *Census Tract 16.06*. https://landgrid.com/us/tracts/55025001606#b=tracts: Accessed November 1.

Lauer, S. A., K. H. Grantz, Q. Bi, F. K. Jones, Q. Zheng, H. R. Meredith, A. S. Azman, N. G. Reich, and J. Lessler. 2020. "The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application." *Ann Intern Med* 172 (9):577-582. doi: 10.7326/M20-0504.

Leclerc, Quentin J., Naomi M. Fuller, Lisa E. Knight, and others. 2020. *What settings have been linked to SARS-CoV-2 transmission clusters?* https://wellcomeopenresearch.org/articles/5-83/v2: Wellcome Open Research, June 5, 2020.

Mahale, P., C. Rothfuss, S. Bly, M. Kelley, and et al. 2020. "Multiple COVID-19 Outbreaks Linked to a Wedding Reception in Rural Maine - August 7-September 14, 2020." *MMWR Morb Mortal Wkly Rep* 69 (45):1686-1690. doi: 10.15585/mmwr.mm6945a5.

McGlone, Meredith. 2020. *UW–Madison launches campus COVID-19 dashboard*. https://news.wisc.edu/uw-madison-launches-campus-covid-19-dashboard/: UW-Madison Press Release, August 28,.

Nakaya, T., A. S. Fotheringham, C. Brunsdon, and M. Charlton. 2005. "Geographically weighted Poisson regression for disease association mapping." *Stat Med* 24 (17):2695-717. doi: 10.1002/sim.2129.

Olstad, Christina. 2020a. *Message from Dean of Students Christina Olstad*. https://news.wisc.edu/message-from-dean-of-students-christina-olstad/: University of Wisconsin-Madison, September 2.

Olstad, Christina. 2020b. *Message to students: COVID-19 clarifications and reminders*. https://news.wisc.edu/message-to-students-covid-19-clarifications-and-reminders/: University of Wisconsin-Madison, September 18.

Orea, Luis, and Imaculada C. Alvarez. 2020. *How effective has the Spanish lockdown been to battle COVID-19? A spatial analysis of the coronavirus propagation across provinces* https://documentos.fedea.net/pubs/dt/2020/dt2020-03.pdf: FEDEA, April 13, 2020.

Palin, K., and M. L. Greer. 2012. "The effect of mixing events on the dynamics of pH1N1 outbreaks at small residential colleges." *J Am Coll Health* 60 (6):485-9. doi: 10.1080/07448481.2012.696294.

Richmod, Craig S., Arick P. Sabin, Steven D. Lovich, and Paraid A. Kenny. 2020. *SARS-CoV-2 sequencing reveals rapid transmission from college student clusters resulting in morbidity and deaths in vulnerable populations*. https://www.medrxiv.org/content/10.1101/2020.10.12.20210294v1: medRxiv, posted October 14.

Rothman, K. J. 1982. "Spermicide use and Down's syndrome." *Am J Public Health* 72 (4):399-401. doi: 10.2105/ajph.72.4.399.

SafeGraph Inc. 2020a. *Places Schema*. https://docs.safegraph.com/docs/places-schema: Data accessed July 30-31, September 24-26, 2020.

SafeGraph Inc. 2020b. *Social Distancing Metrics*. https://docs.safegraph.com/docs/social-distancing-metrics: Accessed September 24, 2020.

statisticalatlas.com. 2018. *Overview of Tract 001705, Dane County, Wisconsin*. https://statisticalatlas.com/tract/Wisconsin/Dane-County/001705/Overview#nav-map/block-group: Cedar Lake Ventures, Inc., Last Accessed November 5.

U.S Census Bureau. 2019. *TIGER Shape Files: U.S. Census Tracts*. https://www2.census.gov/geo/tiger/TIGER2019/TRACT/.

University of Wisconsin-Madison. 2020a. *Campus Area Housing: Off-Campus Housing Marketplace*. https://campusareahousing.wisc.edu/listing: Accessed October 25.

University of Wisconsin-Madison. 2020b. *Campus Map*. https://map.wisc.edu/.

University of Wisconsin-Madison. 2020c. *Compare Our Residence Halls*. https://www.housing.wisc.edu/residence-halls/halls/compare/: Accessed October 31.

University of Wisconsin-Madison. 2020d. *COVID-19 Response: Dashboard*. https://covidresponse.wisc.edu/dashboard/: Accessed October 27, 2020.

University of Wisconsin-Madison. 2020e. *Data Notes*. https://covidresponse.wisc.edu/dashboard/#data-notes: Accessed October 27.

University of Wisconsin-Madison. 2020f. *Fraternity & Sorority Life: Councils*. https://fsl.wisc.edu/councils/: Last accessed November 6.

University of Wisconsin-Madison. 2020g. *Sellery & Witte Requirements*. https://www.housing.wisc.edu/2020/09/sellery-witte-requirements/: September 15.

University of Wisconsin-Madison. 2020h. *University shifts to two weeks of remote instruction, quarantines two residence halls*. https://news.wisc.edu/university-shifts-to-two-weeks-remote-instruction/: Press Release, September 9.

University of Wisconsin-Madison. 2020i. *UW, Public Health act to stop COVID-19 spread in fraternity, sorority houses*. https://news.wisc.edu/uw-public-health-act-to-stop-covid-19-spread-in-fraternity-sorority-houses/: Press Release, September 4.

Walke, H. T., M. A. Honein, and R. R. Redfield. 2020. "Preventing and Responding to COVID-19 on College Campuses." *JAMA*. doi: 10.1001/jama.2020.20027.

Wilson, E., C. V. Donovan, M. Campbell, T. Chai, and others. 2020. "Multiple COVID-19 Clusters on a University Campus - North Carolina, August 2020." *MMWR Morb Mortal Wkly Rep* 69 (39):1416-1418. doi: 10.15585/mmwr.mm6939e3.

Wisconsin Department of Health Services. 2020. *COVID-19 Data by Census Tract*. https://data.dhsgis.wi.gov/datasets/40a25761793c4501a291852b7d39432b_9: Accessed October 16.

Wong, F., and J. J. Collins. 2020. "Evidence that coronavirus superspreading is fat-tailed." *Proc Natl Acad Sci U S A*. doi: 10.1073/pnas.2018490117.

Zheng, R., Y. Xu, W. Wang, G. Ning, and Y. Bi. 2020. "Spatial transmission of COVID-19 via public and private transportation in China." *Travel Med Infect Dis* 34:101626. doi: 10.1016/j.tmaid.2020.101626.