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Title: A Comparison of Methods for Measuring Spatial Access to Health Care

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ABSTRACT

Objective: To compare measures of spatial access to care commonly used by policymakers and researchers with the more comprehensive enhanced two-step floating catchment area (E2SFCA) method.

Study Setting: Fourteen southwestern Pennsylvania counties.

Study Design: We estimated spatial access to buprenorphine-waivered prescribers using three commonly used measures—Euclidean travel distance to the closest prescriber, travel time to the closest provider, and provider-to-population ratios—and the E2SFCA. Unlike other measures, the E2SFCA captures provider capacity, potential patient volume, and travel time to prescribers.

Data Collection/Extraction Methods: We measured provider capacity as the number of buprenorphine prescribers listed at a given address in the Drug Enforcement Agency's 2020 Controlled Substances Act Registrants Database, and we measured potential patient volume as the number of non-elderly adults in a given census tract as reported by the 2018 American Community Survey. We estimated travel times between potential patients and prescribers with Bing Maps and Mapbox application programming interfaces. We then calculated each spatial access measure using the R programming language. We used each measure of spatial access to identify census tracts in the lowest quintile of spatial access to prescribers.

Principal Findings: The Euclidean distance, travel time, and provider-to-population ratio measures identified 48.3%, 47.2%, and 69.9% of the census tracts that the E2SFCA measure identified as being in the lowest quintile of spatial access to care, meaning that these measures misclassify 30 to 52% of study area census tracts as having sufficient spatial access to buprenorphine prescribers.

Conclusions: Measures of spatial access commonly used by policymakers do not sufficiently accurately identify geographic areas with relatively low access to prescribers of buprenorphine. Using the E2SFCA in addition to the commonly used measures would allow policymakers to precisely target interventions to increase spatial access to opioid use disorder treatment and other types of health care services.

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Key Words: Geographic access, spatial access, geographic information systems, medical geography, buprenorphine, substance use disorder, opioid use disorder

What is known on this subject

- Despite the emergence of telehealth alternatives during the COVID-19 pandemic, there remains an urgent need to expand spatial access to opioid use disorder treatment.
- Commonly used measures of spatial access to health care, such as travel time to the nearest provider or provider-to-population ratios, do not adequately measure the availability and accessibility of health care.
- The enhanced two-step floating catchment area, a frequently used measure of spatial access in the geography literature, may overcome the limitations of the commonly used measures.

What this study adds

- Neglecting to use the enhanced two-step floating catchment area results in the misclassification of geographic areas as having or not having adequate spatial access to prescribers of buprenorphine, the most common medication for opioid use disorder.
- The two-step floating catchment area provides policymakers and researchers with an effective tool to identify geographic areas with relatively poor geographic access to buprenorphine prescribers and other types of health care providers.
- The demonstration of the overlap among identified geographical units with low spatial access by different measure methods in this study provide a helpful tool for policymakers and researchers to identify whether a standard method misclassifies areas regarding spatial access to care.

INTRODUCTION

Despite the emergence of telehealth alternatives for opioid use disorder (OUD) treatment during the COVID-19 pandemic,[1] many persons with OUD still require physical access to substance use disorder (SUD) treatment providers. As such, there remains an urgent need for more aggressive measures to expand spatial access to OUD treatment. Improved measures of spatial access can aid in strategic planning as policymakers seek to address this key barrier to OUD treatment.[2–4]

Potential patients have *spatial access* to health care when it is both available and accessible. *Availability* is the number of locations at which a patient may receive care. The availability of providers at a location to treat patients is determined both by providers' capacity to treat patients and the volume of nearby potential patients. *Accessibility* is the travel impedance between patients' locations and providers, measured in terms of distance or time.[5,6]

Commonly used measures of spatial access to health care do not adequately measure the availability and accessibility of SUD treatment providers, or health care providers in general.[6–8] Such measures typically fall into two categories: travel impedance to the nearest provider and provider-to-population ratios. Both are used to determine whether potential patients in a geographic area have sufficient spatial access to a given type of health care provider.

Travel impedance is typically measured as the travel distance or travel time to the nearest provider. Such measures only consider the accessibility of the nearest provider. They do not consider the accessibility of other providers, nor do they consider availability whatsoever. Travel impedance measures thus cannot distinguish between geographic areas where one or many providers are accessible to potential patients, nor can they account for the nearest provider not being available due to capacity constraints or a large quantity of other patients. Travel impedance measures are particularly limited when patients do not receive care from the nearest provider. A recent study of buprenorphine prescriber visits in the United States found that many OUD patients do not see the prescriber that is closest to their home,[4] possibly due to non-spatial barriers to access such as provider stigma towards OUDs. The use of travel impedance measures is therefore especially problematic in substance use disorder treatment.

Provider-to-population ratios are simply the number of providers over the population size in a government jurisdiction, typically counties. The intuitive appeal and simple computation of provider-to-population ratios have made them popular throughout the broader clinical and health services research literatures.[9,10] Although these measures can be useful for broad comparisons of health care capacity across large geographic areas, they have several limitations. First, they do not account for border crossing (e.g., patients receiving care outside their geographic area), which is more prone to occur in smaller geographies. Second, provider-to-population ratios cannot identify variation in accessibility within the chosen geographic area, which is especially problematic for larger geographies. Third, these measures implicitly assume that all providers are accessible to all patients within their geographic area. This is also problematic for larger geographies. Provider-to-population ratios can thus vary substantially depending on the size of geographic units that are studied.[11]

Travel impedance and provider-to-population ratio measures are widely used in developed and developing countries to measure spatial access to care for SUD[4,12,13] and non-SUD-related health care.[14–16] They are also used in the United States to determine the adequacy of health insurers' provider networks and to designate provider shortage areas to target for additional resources.[17] Standards for Medicaid, the US state-federal insurance program for low-income persons, and Medicare, which covers elderly and disabled Americans, impose regulatory standards for provider networks using travel time and distance and provider-to population ratios.[18,19]

Fortunately, widely used measures in the geography literature overcome the shortcomings of the travel impedance and provider-to-population measures. *Floating catchment area measures* consider the availability and accessibility of all providers within a given travel time,[6,20] and have been used in a small but growing literature to assess spatial access to primary care and oncology services.[21–26] With one exception,[27] these measures have not been used to study spatial access to SUD treatment. The most widely used floating catchment area measure is the *enhanced two-step floating catchment area* (E2SFCA).[20] The E2SFCA captures availability and accessibility using provider-to-population ratios weighted by provider capacity, potential patient volume, and travel impedance. As such, *the E2SFCA is a conceptually superior measure of spatial access because it captures both availability and accessibility*.[6,20] A limitation of the E2SFCA and similar methods is that it is a relative, not an absolute, measure of spatial access to care. **Table 1** compares the commonly used measures of spatial access to the E2SFCA.

The aim of this study was to compare the E2SFCA to travel impedance and provider-to-population ratio measures of spatial access to SUD treatment. Our results provide evidence on the differences between the measures by using each of them to examine spatial access to buprenorphine prescribers in southwestern Pennsylvania, an Appalachian region that has been disproportionately affected by the opioid epidemic in the United States.[28,29] While this study focuses on buprenorphine prescribers in the United States, the methods can be applied to any geographic area and are broadly applicable for measuring spatial access to health care. To our knowledge, no prior study has empirically examined the differences between these four measures in the health services research literature. In doing so, this study provides policymakers and researchers with an understanding of the trade-offs involved in using these four measures of spatial access to OUD treatment and clinic-based health care services in general.

METHODS

Data and Study Setting

We compared measures of spatial access to health care in the context of spatial access to buprenorphine prescribers in southwestern Pennsylvania, an area that has been adversely impacted by the opioid epidemic.[28,29] This Appalachian region contains Pennsylvania's second-largest city, Pittsburgh (population 300,286), and its eleventh-largest city, Altoona (population 43,364).[33]

We used four data sources to conduct this analysis. First, we obtained the addresses and buprenorphine waiver limits of health care providers from the 2020 Q1 version of the US Drug Enforcement Agency's (DEA) Controlled Substance Registrants Database.[30] These data list the addresses and waiver sizes of all health care providers—physicians, nurses, and physicians' assistants—waivered to prescribe buprenorphine in the US. A waiver allows office-based practitioners prescribing buprenorphine to treat persons with OUD, which is regulated by the Drug Addiction Treatment Act of 2000. Second, we obtained the demographic characteristics of census tract populations and census tract boundaries (i.e., TIGER/line shape files) from the US Census Bureau. Third and fourth, we obtained car-based travel times between census tracts and buprenorphine prescribers using Microsoft Bing Maps' and Mapbox application programming interfaces.[31,32]

We included all buprenorphine prescribers listed in the study area. Prescribers were identified at the street address level. Street addresses were geocoded (i.e., converted to longitude-latitude coordinates) using the OpenCage Geocoder.[34] We measured the census tract population using the number of adults aged 20 to 59, as this age range constitutes the vast majority of opioid-related overdose deaths in the United States.[28]

We chose to conduct our analysis at the census tract level because that is the lowest level at which researchers can typically obtain intercensal estimates of demographic characteristics beyond population totals. In some cases, however, researchers have sufficiently granular data to conduct more analyses at the census block or even address level. Such granularity is typically preferable in spatial analyses, conditional on computational burden. A third option is ZIP codes. While the most granular geographic unit in individual-level data is often the ZIP code, their use can be problematic. The United States Postal Service changes ZIP codes at irregular intervals, and their boundaries need not be continuous.

We used R Version 3.5.1 for all analyses. This study was determined to be exempt by the University of Pittsburgh Office of Human Research Protection.

Standard Measures of Spatial Access

We constructed four measures of spatial access in the study area. The three standard measures include straight-line travel distance to the nearest buprenorphine prescriber; travel time by car to the nearest prescriber; and provider-to-population ratios. *Euclidean distance* is the "as the crow flies" distance in miles from the centroid (i.e., geographic center) of each census tract to the nearest buprenorphine prescriber. *Travel time* is the time in minutes from census tract centroids to the nearest prescriber. For computational reasons, this measure was calculated by first identifying the five closest prescribers by Euclidean distance, and then calculating the minimum of car-based travel times among these prescribers. These travel time calculations consider road structure, congestion, traffic lights and stops, etc. The *provider-to-population ratio* is the number of buprenorphine-waivered prescribers over the potential patient population (i.e., adults aged 20-59) in a census tract. The fourth measure, the E2SFCA, is discussed below.

The Enhanced Two-Step Floating Catchment Area Measure

The E2SFCA was developed by Luo and Qi in 2009.[20] While many variants of floating catchment area measures have since been developed, the E2SFCA measure is broadly used among health geographers due to its ability to parsimoniously incorporate availability and accessibility. E2SFCA measures are often constructed using ArcGIS, though they also can be constructed in statistical packages such as R and SAS. Code for implementing the E2FSCA in R is provided in the **Technical Appendix**.

Before constructing the E2SFCA, it is necessary to set the catchment area and subzones. The *catchment area* is the maximum travel time or distance that potential patients can be expected to travel to receive care. *Subzones* are travel time or distance intervals that distinguish between providers that are nearer and further away within the catchment area. Catchment areas and subzones can be set in response to survey responses or regulatory standards. For this study, we relied on typical Medicaid travel time requirements that a patient should be able to reach a behavioral health provider within 30 minutes to help define our catchment area and subzones.[35] We set the catchment area to twice this value, 60 minutes, and set the subzones to 0-15, 15-30, and 30-60 minutes. Intuitively, we identified providers within 15 minutes as easily accessible, those within 30 and 60 minutes as moderately and somewhat accessible, respectively, and those outside of 60 minutes as not accessible.

The *first step of the E2SFCA measures the availability of providers* in the study area by calculating weighted provider-to-population ratios. First, each provider is weighted by their capacity, which we assigned according to the mean patient census of buprenorphine prescribers as reported by Thomas et al.[36] Providers with buprenorphine waivers for 30 patients received a weight of 9.5; those with waivers for 100 or 275 patients received a weight of 32.6. While these weights likely provide us with a more accurate measure of provider capacity than waiver size, they still do not account for substantial variation in buprenorphine prescribing among providers with the same waiver size. For instance, Thomas et al. found that roughly a third of buprenorphine-waivered prescribers did not prescribe buprenorphine in any given month. This is a limitation of our analysis that, ideally, could be corrected with claims data. Second, each provider's capacity is divided by the sum of weighted patient populations within the provider's catchment area, 60 minutes this study. Patient populations are weighted by their size (i.e., number of 20-to-59-year-olds within the census tract) and their subzone with respect to the provider (e.g., a population within the 15-to-30-minute subzone is weighted less heavily than a population within the 0-to-15-minute subzone).

The *second step of the E2SFCA measures the accessibility of providers* for each potential patient population *and factors in their availability* as calculated in the first step. Spatial access is calculated as the sum of the provider-to-population ratios for all providers within a patient population's catchment area. Each provider is also given a travel time weight according to the subzone in which they are located relative to the given patient population. Holding the provider-to-population ratio constant, a provider in the 0-15-minute subzone is weighted more heavily than a provider within the 15-to-30-minute subzone. We discuss the assignment of subzone weights and provide a technical explanation of the calculation of the E2SFCA measure in the **Technical Appendix**.

Interpretation

The values produced by the E2SFCA are commonly referred to as *access scores* in the geography literature.[27,37] Access scores, as described above, are counts of providers adjusted for provider capacity, potential patient demand, and travel impedance. As such, researchers and policymakers can use the E2SFCA approach to identify where spatial access to care is relatively limited within a predefined geographic area. Access scores, however, are *relative* measures of spatial access. They therefore cannot be used to determine whether a given geographic area meets an absolute threshold for spatial access to care.

Comparing Standard Measures of Spatial Access and the E2SFCA

Unlike the standard measures of spatial access, the E2SFCA considers both availability and accessibility, the two components of spatial access. To examine how not considering availability and accessibility can lead to improper inference, we compared the census tracts identified as having low spatial access to buprenorphine prescribers by each of the four measures. Areas with low spatial access are referred to as *shortage areas*.

Comparing which census tracts are shortage areas across spatial access measures is complicated by the fact that the measures are based on different units. Discrepancies between census tracts identified as shortage areas may be a result of one threshold being stricter than another (e.g., is five miles a stricter standard than ten minutes?), or one measure being more precise than the other (i.e., car-based travel time is a more precise measure than Euclidean distance). To address this difficulty, we compared the percentage overlap between census tracts that are in the lowest quintile of spatial access for each commonly used measure to the E2SFCA. While being in the lowest quintile of spatial access does not necessarily mean that spatial access is poor, examining discrepancies between the lowest quintiles across measures allowed us to understand the limitations of standard spatial access measures relative to the E2SFCA measure.

RESULTS

The study sample included 879 census tracts in 14 counties, representing 1,281,618 potential patients aged 20-59 in southwestern Pennsylvania. This population was served by 997 buprenorphine prescribers. Approximately 21.7% of all prescribers had a waiver to prescribe to 100 patients; 21.3% had a waiver to prescribe to 275 patients. **Figure 1** shows the distribution of buprenorphine prescribers and the potential patient population throughout the study area.

Figure 2 presents the raw values of the four measures of spatial access. Euclidean distance and travel time to the closest prescriber range from 0-20 miles and 0-35 minutes, respectively. Mean (SD) Euclidean distance and time were 1.5 miles (SD = 1.9) and 6.79 minutes (SD = 5.3), respectively. Euclidean distance and time naturally increased the further a census tract was located from a prescriber. As such, these values are low near the metropolitan center of Pittsburgh (Allegheny County) where many prescribers are located (see **Figure 1**). The two measures were highly correlated (Pearson's correlation coefficient = 0.74, 95% CI = 0.71-0.77; P-value < 0.001). Prescriber-to-population ratios were zero in 596 census tracts without any prescribers and had a mean of 101.8 (SD = 1,923.5) prescribers per 10,000 population aged 20-59 among other census tracts. The E2SFCA, unlike the other measures, decreased in a continuous manner as a census tract was located further away from the population centers of Pittsburgh (Allegheny County) and Altoona (Blair County). The access scores of the E2SFCA measure range from 0.1 to 14.3. The minimum E2SFCA value being greater than zero indicates that at least one buprenorphine prescriber was available within a 60-minute drive of each census tract centroid.

Figure 3 shows the census tracts in the lowest quintile of spatial access according to the four measures. Note that the lowest quintiles of spatial access are those with the highest values of

Euclidean distance and travel time, and the lowest prescriber-to-population ratio and E2SFCA values. Also note that, for prescriber-to-population ratios, all 596 census tracts with ratios of zero are treated as belonging to the lowest quintile.

Figure 4 shows the overlap among census tracts in the lowest quintile of spatial access (i.e., shortage areas) between the E2SFCA measure and the other three measures. The Euclidean distance, travel time, and provider-to-population ratio measures identified 48.3%, 47.2%, and 69.9% of the census tracts the E2SFCA measure identified as being in the lowest quintile of spatial access to care, though the percentage for the ratio measure is inflated because all census tracts with a ratio of zero—596 of 879 census tracts—are regarded as belonging to the lowest quintile. These percentages provide a local estimate of the discordance between the three measures and the E2SFCA in identifying census tracts with relatively low spatial access to buprenorphine prescribers.

There were many census tracts that were identified as being in the lowest quintile of spatial access according to the E2SFCA measure but not the commonly used measures: 91 census tracts compared with Euclidean distance to the nearest prescriber (adult population aged 20-59: 138,869), 93 tracts compared with travel time to the nearest prescriber (population aged 20-59: 141,439), and 53 tracts compared with prescriber-to-population ratios (population aged 20-59: 95,091). This low degree of overlap between the E2SFCA and the commonly used measures indicates that simply relying on the commonly used measures to identify geographic areas with low spatial access to care results in significant measurement error. Policy interventions based on the commonly used measures could thus be inefficient in targeting geographic areas most in need of additional resources.

DISCUSSION

We compared spatial access to prescribers of buprenorphine in southwestern Pennsylvania using three measures of spatial access commonly used by policymakers and a measure of spatial access commonly used in the geography literature, the E2SFCA. The E2SFCA is conceptually superior to the commonly used measures because it simultaneously considers the availability and accessibility of providers by measuring provider capacity, potential patient volume, and travel impedance. We tested whether these commonly used measures can accurately identify areas with the lowest levels of spatial access by examining the overlap of census tracts that were identified as being in the lowest quintile of spatial access according to the commonly used measures and the E2SFCA measure. The low overlap between the commonly used measures and the E2SFCA measure highlights the conceptual shortcomings of the commonly used measures and indicate that approaches like the E2SFCA are necessary for effective policymaking to improve spatial access to prescribers of buprenorphine. While improvements can be made to the commonly used measures (e.g., median travel time to the five closest prescribers, prescriber-to-population ratios that consider adjacent geographies), these improvements still do not overcome the conceptual limitations of the commonly used measures to the extent the E2SFCA does.

Our results suggest that policymakers will need to adopt floating catchment area measures like the E2SFCA if they want to accurately identify geographic areas with relatively limited spatial access to prescribers of buprenorphine and, perhaps, other forms of medical care. Without such an approach, commonly used measures of spatial access will fail to identify areas with limited spatial access to treatment and will mistakenly classify areas with sufficient access as lacking. Such misclassification of geographic areas with limited spatial access to buprenorphine will substantially diminish the effectiveness of interventions intended to eliminate geographic barriers to access, as any such intervention will be unable to properly target the correct geographic areas. This potential for misclassification is particularly concerning given large efforts around the world to increase access to SUD treatment providers.[38] To our knowledge, floating catchment area approaches have not been used to identify where increased prescriber capacity would be the most effective at increasing access to buprenorphine.

A regulatory shift towards an E2SFCA approach would not represent a difficult departure from existing regulatory practices based on provider-to-population ratios. The E2SFCA measure has become easier to implement in recent years due to the emergence of geography-based application programming interfaces from Google, Microsoft, Mapbox, Nokia, and OpenStreetMap. These interfaces have significantly decreased the complexity of creating E2SFA measures throughout most of the world. In light of these advances, policymakers can now easily use E2SFCA measures to create highly targeted, geography-based interventions to improve spatial access to care. For example, mobile clinics and non-emergency medical transportation services could be targeted towards areas with the lowest levels of spatial access to care. Efforts to expand the number and capacity of various types of providers could also focus on such areas.

Floating catchment area measures and particularly the E2SFCA measure also have large potential to improve the health services research literature's understanding of how spatial access to care affects clinical outcomes. First, the E2SFCA measure enables researchers to examine the relationship between spatial access and clinical outcomes at granular geographies such as census tracts or even street addresses. Second, the E2SFCA reduces measurement error and bias in models examining the relationship between clinical outcomes and spatial access to care. The limitations of commonly used spatial access measures may be thought of as a type of measurement error, which reduces both the magnitude and significance of spatial access to care parameters in regression models examining clinical outcomes. It is therefore possible that previous studies that examined the relationship between clinical outcomes and spatial access have underestimated the importance of spatial access to care. Third, the availability of a more precise measure of spatial access will enable researchers to study more complex, structural questions regarding policy interventions. For example, the E2SFCA measure could enable researchers to examine how initiatives to expand access to buprenorphine prescribers improved spatial access to buprenorphine, and in turn how that improved access may have resulted in increased uptake of OUD treatment and increased continuity of pharmacotherapy.

Limitations and Extensions of the E2SFCA

The E2SFCA, however, is not without its own limitations, which have led to the creation of numerous enhancements and alternatives to the E2SFCA in the geography literature. We elaborate on several of these limitations and extensions below:

- *Travel impedance is intuitively continuous, not discrete*: In the E2SFCA, travel impedance changes discretely at the borders of sub-zones and the catchment area. Yet, patients' demand for a provider that is a 14.9-minute drive from their home is likely only slightly higher than one that is 15.1-minute drive. To overcome this difficulty, Cao et al. merge an E2SFCA approach with a Huff model to measure travel impedance as a continuous function.[27,39] This approach, however, increases computational burden as it requires that travel times be calculated between each patient location-provider location dyad, whereas the E2SFCA simply requires the creation of isochrones.
- *Patients may use other modes of transit than cars*: Assuming car-based travel can be problematic when considering spatial access to medical care sought by patients without car access, as is often the case among persons with OUD in urban areas or more generally in areas with more robust public transit infrastructures.[40] In such cases, the creation of multi-

modal E2SFCA measures that consider multiple modes of transit may be necessary.[37] The E2SFCA can be calculated separately for cars and public transit. Public transit travel time calculation is supported by several application programming interfaces, including Google Maps and Bing Maps.

- *The edge effect can lead to measurement error at the border of the study area:* The "edge effect" refers to the fact that providers and potential patients beyond the boundaries of the study area are not considered, even though they may affect spatial access to care within the study area. This limitation can be minimized by selecting a study area whose adjacent areas are sparsely populated or a study area where access to providers outside the study area is limited for administrative reasons.
- *Willingness to travel and travel impedance may vary across patient populations*: Patients' willingness to travel may vary by rurality, other sociodemographic and health characteristics, or for different types of health care. Researchers can create an E2SFCA with variable catchment sizes in such cases.[41] They also may create an E2SFCA with varying travel impedance coefficients when patients have heterogeneous willingness to drive.[42]
- *The E2SFCA may overestimate demand when potential patients have access to several nearby provider locations*: This "overestimation problem" can be addressed through the use of a three-step floating catchment area model.[43] This approach addresses overestimation by assuming that patients' demand for any given provider decreases when more providers are located nearby.

Except for the edge effect, each of these limitations can thus be addressed through modifications to the E2SFCA approach. The researcher, however, is ultimately faced with trade-offs between complexity and increased computational burden on the one hand, and oversimplification and measurement error on the other. For a more detailed review of modifications to the E2SFCA method, see McGrail.[44]

A remaining limitation of the E2SFCA approach and its extensions is that they produce a unitless measure of spatial access to care. Access scores cannot be interpreted absolutely, only relatively. Access scores are useful for identifying geographic areas where spatial access to care is relatively low (e.g., spatial access to ICU beds is lower on the southside of Chicago[45]). However, one challenge for their use by policymakers and regulators is that clear thresholds cannot be used with the E2SFCA to set minimum standards (e.g., 32 more buprenorphine prescribers are needed in the North Shore neighborhood of Pittsburgh). For this reason, floating catchment area methods should not replace simpler measures of geographic access; rather, they should be used alongside simpler measures to overcome their limitations. In this way, policymakers can continue to use the commonly used measures of spatial access to establish absolute minimum standards for spatial access to care. Policymakers can use the E2SFCA to identify where the commonly used measures are overlooking geographic areas with limited spatial access to care, thereby enabling corrective action in those areas. As our findings indicate, the percentages of misclassified geographic areas are far from trivial, ranging from 30 to 52% of census tracts.

Floating catchment area methods are not the only type of approach to measuring spatial access that capture availability and accessibility. Optimization models, for example, allocate patient demand for health care to nearby locations to estimate spatial access.[46] Patients are probabilistically allocated to nearby providers, subject to providers' capacity. Remaining unmatched patients are matched to the next closest provider, if the next closest provider is within a given maximum travel time or distance. Optimization models have been used to study access to primary care in several states,[47–49] as well as inpatient care for common diseases.[50] Optimization models are more flexible than floating catchment area models in that they can use constrained optimization to determine whether provider capacity is sufficient to address patient demand, but they also can be more computationally burdensome.

CONCLUSION

Standard measures of spatial access to care do not adequately capture the availability and accessibility of buprenorphine prescribers. We found that these measures fail to identify geographic areas with limited spatial access to treatment. It is thus imperative that policymakers adopt more precise measures like the E2SFCA to determine where spatial access to SUD treatment is inadequate and to guide public investments in SUD provider treatment capacity.

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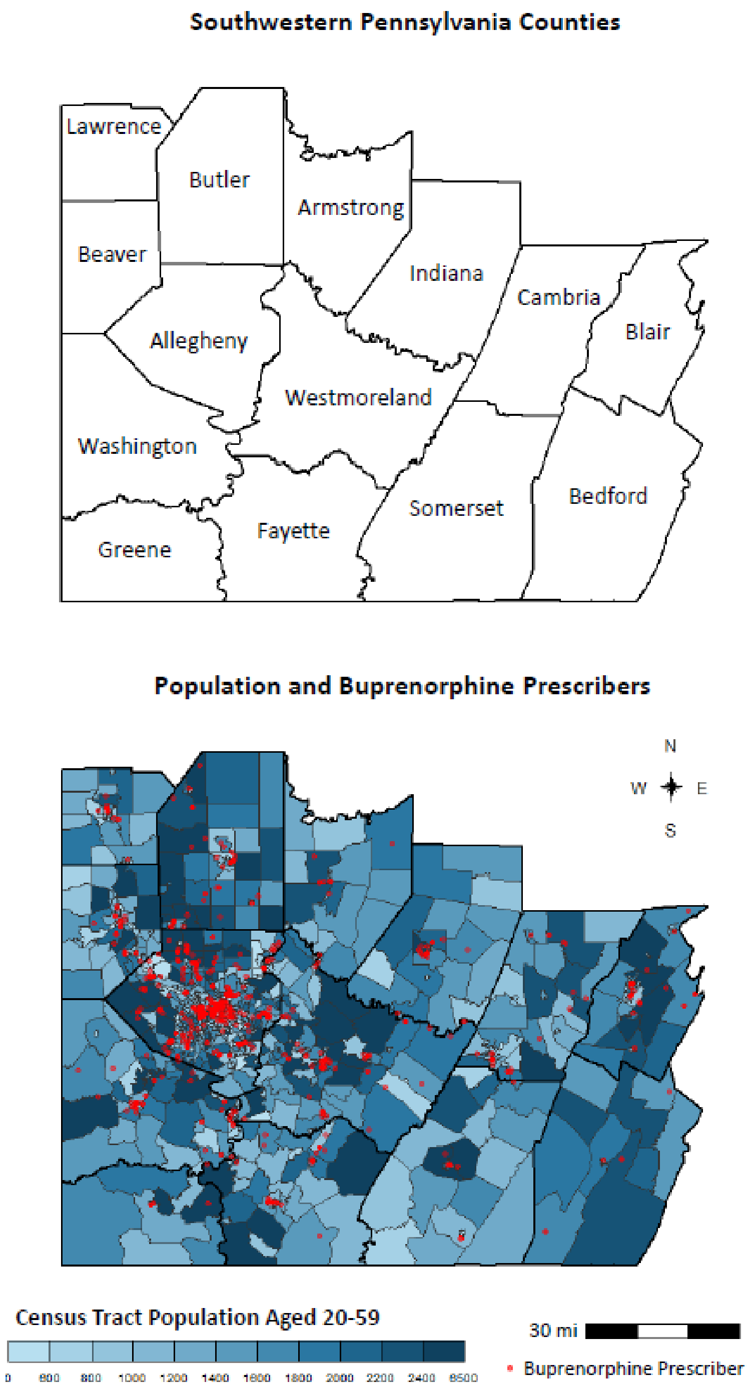
Table 1 Comparison of Properties of Spatial Access Measures

	Spatial Access Measure			
Property Addressed	*Shortest Euclidean Distance*	*Shortest Travel Time*	*Provider-to-Population Ratio*	*Enhanced Two-Step Floating Catchment Area (E2SFCA)*
Measures accessibility?	Only to nearest provider by Euclidean distance	Only to nearest provider by travel time	Yes, but treats all providers equally	Yes, weights providers by travel time
Measures availability?	No	No	Yes, within geopolitical unit	Yes, within catchment area
Considers road structure and built environment?	No	Yes	Yes	Yes
How to identify shortage areas?	Euclidean distance maximum	Travel time maximum	Provider-to-population minimum	Provider-to-population minimum

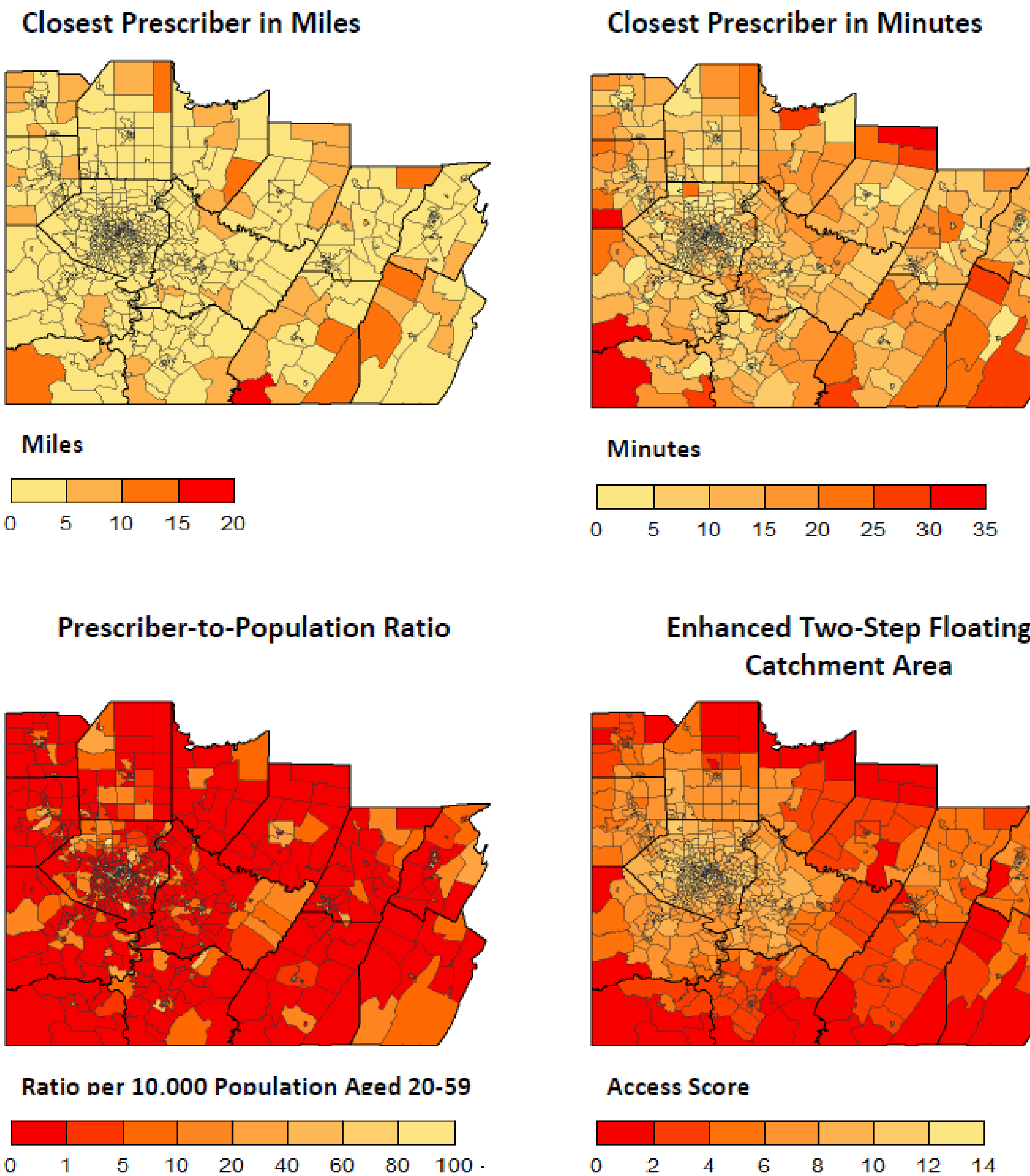
Availability is the number of locations at which a patient may receive care. Accessibility is the travel impedance, typically measured as distance or time, between patients' locations and providers.

Figure 1 Buprenorphine Prescriber Locations and Non-Elderly Adult Population in Southwestern Pennsylvania



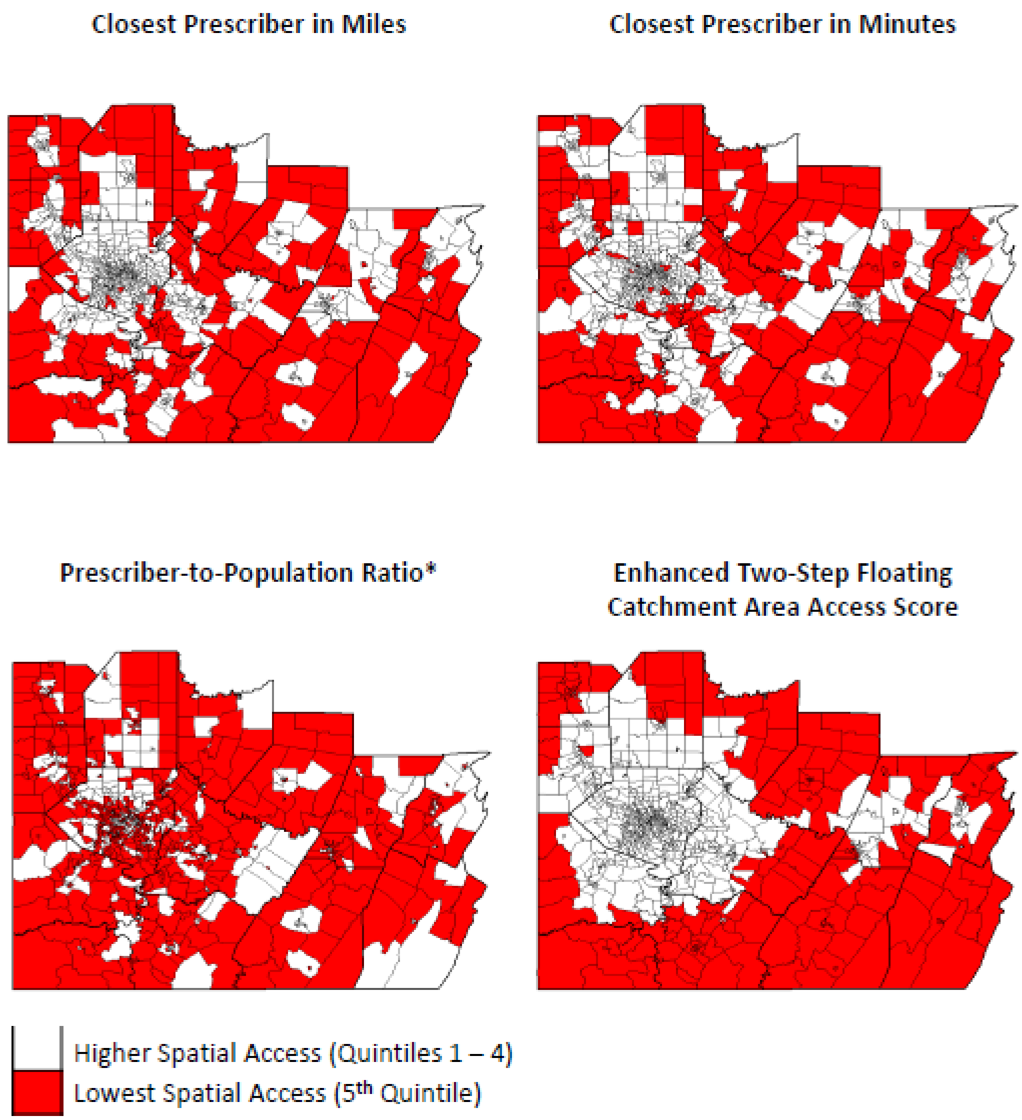
The study area includes 14 counties in southwestern Pennsylvania. This area includes Pittsburgh (Allegheny County) as well as a more densely populated area around Altoona (Blair County). Population aged 20-59 is shown in the lower panel by census tract. Buprenoprhine prescribers as reported in the Drug Enforcement's Agency Controlled Substance Registrants database are shown in the lower panel as well.

Figure 2 Spatial Access to Buprenorphine Prescribers in Southwestern Pennsylvania



Spatial access is calculated at the census tract level. A higher prescriber-to-population ratio suggests that the number of buprenorphine prescribers in a given ZIP code is sufficient to address the medical needs of the ZIP code's population. A relatively higher E2SFCA access score suggests that spatial access to buprenorphine prescribers in a given ZIP code is greater than spatial access to buprenorphine prescribers in ZIP codes with relatively lower E2SFCA access scores. The advantages and disadvantages of all four measures are discussed in the methods section, as well as Table 1.

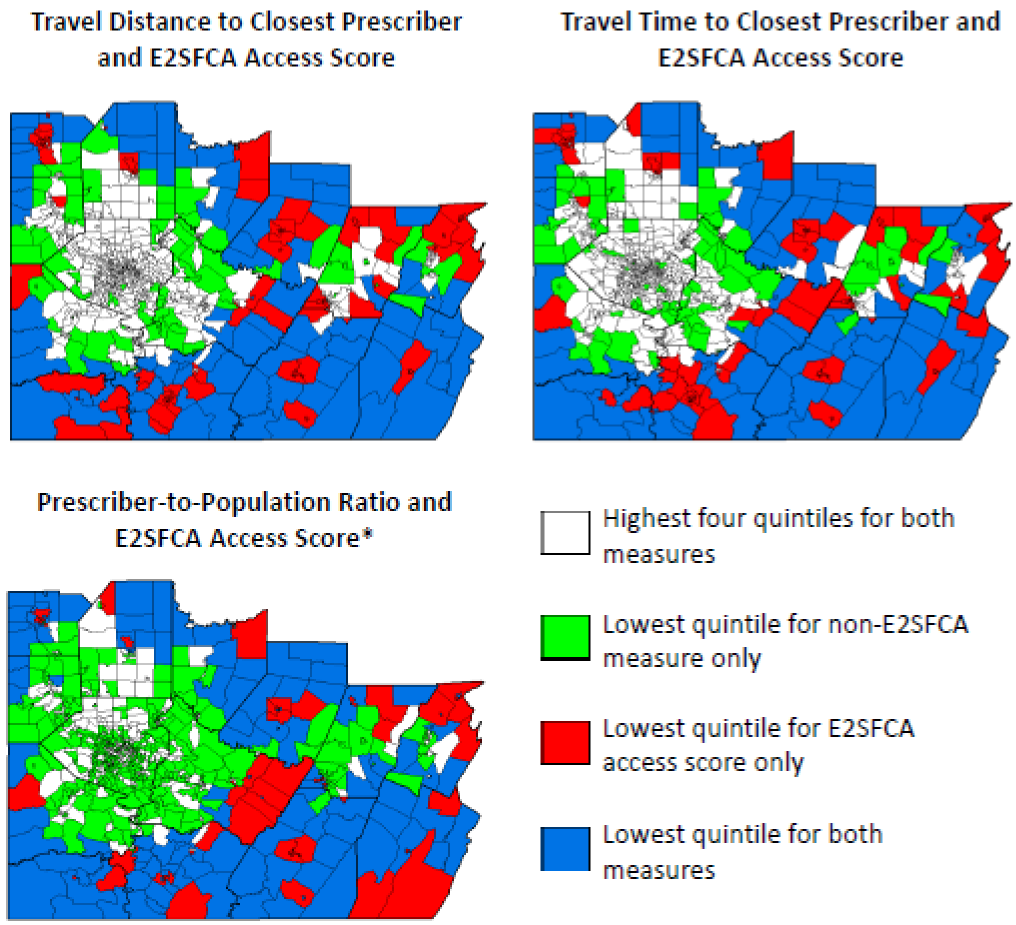
Figure 3 Lowest Quintiles of Spatial Access to Buprenorphine Prescribers across Four Measures of Spatial Access



The lowest spatial access quintile always corresponds to geographic areas with the lowest levels of spatial access to buprenoprhine prescribers. For closest prescriber in miles/minutes, the lowest spatial access quintile indicates that the census tract is in the quintile of census tracts with the highest travel distance/time. For the prescriber-to-population ratio and enhanced two-step catchment area (E2SFCA), the lowest spatial access indicates that the census tract is in the quintile of census tracts with the lowest score on the E2SFCA measure.

* For the prescriber-to-population ratio, the lowest spatial access "quintile" corresponds to census tracts with a ratio of zero. Such census tracts constitute roughly two-thirds of the sample (596 of 879 census tracts).

Figure 4 Overlap between Census Tracts in the Lowest Quintile of Spatial Access



The lowest quintiles of spatial access for each measure are shown in Figure 3. For the prescriber-to-population ratio, the lowest spatial access "quintile" corresponds to census tracts with a ratio of zero. Such census tracts constitute roughly two-thirds of the sample (596 of 879 census tracts).

TECHNICAL APPENDIX

Calculation of Enhanced Two-Step Floating Catchment Area Measure

The first step of the E2SFCA is to create weighted physician-to-population ratios, R_j, for each provider location j within the catchment area. These are calculated as follows:

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \in D_r\}} P_k W_r} = \frac{S_j}{\sum_{k \in \{d_{kj} \in D_1\}} P_k W_1 + \sum_{k \in \{d_{kj} \in D_2\}} P_k W_2 + \sum_{k \in \{d_{kj} \in D_3\}} P_k W_3}$$

where S_j is the number of providers at location j, P_k is the population of census tract centroid k, d_{kj} is the travel time between k and j, and D_r is the subzone $(r = 1 - 3)$ within the catchment. W_r is the travel time weight for the rth subzone, which captures the travel time decay of access to providers in subzone r. Travel time weights are typically calculated with a Gaussian function, which is explained below.

The second step of the E2SFCA is to calculate access scores for each population location i, A_i. Access scores measure spatial access to providers from location i. They may be used to compare *relative* spatial access to care within the study area. To calculate A_i, the researcher sums all of the weighted physician-to-population ratios from step 1 (R_j) with each population location's catchment area. Formally, this is calculated as

$$A_i = \sum_{j \in \{d_{ij} \in D_r\}} R_j W_r = \sum_{j \in \{d_{ij} \in D_1\}} R_j W_1 + \sum_{j \in \{d_{ij} \in D_2\}} R_j W_2 + \sum_{j \in \{d_{ij} \in D_3\}} R_j W_3$$

All notation is the same as in step 1.

Unlike gravity models that use continuous travel time, the E2SFCA discretizes travel time weights. This is purely for computational reasons. A continuous version of the E2SFCA would typically require millions of travel time calculations between population centroids and provider locations. This is problematic for users of standard mapping application programming interfaces such as Google, which limits free queries to 2,500 per day. The standard discretized version of the E2SFCA, however, simply requires the creation of three isochrones for each centroid. This can easily be accomplished in ArcGIS or with the R package purrr. For an application of the E2SFCA measure with continuous travel time, see Cao et al. (1).

Determining Impedance Coefficients

In measures of spatial access, β is known as a *gravity decay coefficient* or a *travel friction coefficient*. It represents the change in difficulty of travel as travel time increases (2). Actual travel time, d, is referred to as *travel impedance*. Determining an appropriate value for β requires a four-step process.

The *first step* is determining an appropriate geographic impedance function, $f(d)$. These correspond to various distributions. Typical examples include an inverse-power function ($d^{-\beta}$), an exponential function ($e^{-\beta d}$), or a Gaussian function ($e^{-d^2/\beta}$). The Gaussian function is preferred because it decays in an S-shaped manner rather than decreasing quickly and steeply, as the other two functions do (3,4). A refinement to the Gaussian function for floating catchment area measures is to specify it in a stepwise manner such that providers in the closest catchment area do not have their value decreased to nearby patients by geographic impedance (5,6). This is done by specifying the impedance function as

$$f(d_{ij}) = 1 \ if \ d_{ij} \leq d_{init}$$

$$f(d_{ij}) = e^{-(d_{ij}-d_{init})^2/\beta} \ if \ d_{init} < d_{ij} \leq d_{max}$$

$$f(d_{ij}) = 0 \ if \ d_{ij} > d_{max}$$

Here, we consider a 90-minute catchment are with subzones at 30 and 60 minutes. Accordingly, d_{init} is the travel time of the first catchment area, 30, and d_{max} is 90 minutes.

The *second step* is finding a value of β such that $A_i = 0.01$ for d_{max} (7). Here is an example:

$$0.01 = e^{-(90-30)^2/\beta}$$

$$\ln(0.01) = -60^2/\beta$$

$$-4.61\beta = -3600$$

$$\beta = 780.91$$

Per Kwan, it cannot be the case that $A_i < 0.01$. As such, we round up and set $\beta = 781$.

The *third step* is to determine Gaussian weights for each catchment area. Begin by taking the mean of the range of each catchment area (15, 45, and 75 minutes, respectively). Then, plug these values into the impedance function with $\beta = 781$. We have that

$$f(15) = 1$$

$$f(45) = e^{-(45-15)^2/781} = 0.32$$

$$f(75) = e^{-(75-15)^2/781} = 0.01$$

The *fourth step* is to test other values of β. The literature typically does this by increasing β in increments of 100. The result is always that the steepness of the S-shaped Gaussian function decreases with larger values of β, converging towards one. Consider the middle catchment area at $\beta = \{881,981\}$.

$$f(45|\beta = 881) = e^{-(45-15)^2/881} = 0.36$$

$$f(45|\beta = 981) = e^{-(45-15)^2/981} = 0.40$$

These values seem more realistic, though it is not obvious which one is objectively correct. Lou and Qi’s seminal paper on E2SFCA simply picked “high” and “low” values for β (8). Practically, the analyst should test different values of β and, *a priori*, select a set of values based on clinical expertise, regulatory guidelines, and prior literature. Relative to $\beta = 781$, we did not find meaningful differences in our results for $\beta = 881$ or $\beta = 981$.

Sample E2SFCA Code for the R Statistical Package

```
# Step 1: Create Weights Matrices and Calculate Provider-to-Population Ratios

# Gaussian Weights
Gweight <- function(traveltime, maxtime){
  beta <- -(maxtime^2)/log(0.01)
  weight <- exp(-traveltime^2/beta)
  weight <- round(weight, 2)
  return(weight)
}

# Weight for cells with no catchment area
wtNA <- 0
# Weight for 15, 30, and 60 minute catchment areas (traveltime = 1/2 catchment zone)
wt7.5 <- Gweight(traveltime = 7.5, maxtime = 60)
wt15 <- Gweight(traveltime = 15, maxtime = 60)
wt30 <- Gweight(traveltime = 30, maxtime = 60)

# 2SFCA Function
# outputmat = matrix that stores which catchment area each prescriber is in for each zip code
# provdf = spatialpoints data frame with all prescriber locations
# study_area.df = data frame with information about study area (one row for each polygon)


E2func <- function(outputmat, provdf){

  # Weights for provider ioschrones
  prov_scores <- t(outputmat)
  prov_scores[is.na(prov_scores)] <- wtNA
  prov_scores[prov_scores == "15 minutes"] <- wt7.5
  prov_scores[prov_scores == "30 minutes"] <- wt15
  prov_scores[prov_scores == "60 minutes"] <- wt30
  prov_scores2 <- apply(prov_scores, 2, as.numeric)
  rownames(prov_scores2) <- study_area.df$GEOID
  rm(prov_scores)

  # Total population matrix in study area ($Study_Pop = population for study)
  study_area_mat <- matrix(data = study_area.df$Study_Pop, nrow = 1, ncol =
nrow(study_area.df))
  colnames(study_area_mat) <- study_area.df$GEOID

  # Calculate weighted denominator for providers
  provmat <- study_area_mat %*% prov_scores2
  rm(prov_scores2)

  # Calculate physician-to-population ratio
```

```
  for (k in 1:ncol(provmat)) {
    if (provmat[1,k] != 0) {
      provmat[1,k] <- 10000/provmat[1,k]    # per 10,000 population
    }
  }

  # Step 2: Calculate spatial access index #

  # Weights for census tract ioschrones
  study_area_scores <- outputmat
  study_area_scores[is.na(study_area_scores)] <- wtNA
  study_area_scores[study_area_scores == "15 minutes"] <- wt7.5
  study_area_scores[study_area_scores == "30 minutes"] <- wt15
  study_area_scores[study_area_scores == "60 minutes"] <- wt30
  study_area_scores2 <- apply(study_area_scores, 2, as.numeric)
  rownames(study_area_scores2) <- provdf$id
  rm(study_area_scores)

  # Calculate SPAI
  SPAImat <- provmat %*% study_area_scores2
  rm(study_area_scores2)

  return(SPAImat)
}

# Create results matrix
SPAImat <- E2func(outputmat = output_tract, provdf = all_prov)
```

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2. (check at least 1 of 2 below)

☑ a. drafting of the manuscript

☑ b. critical revision of the manuscript for important intellectual content

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Manuscript Number: 20-0633.R2	**Each author must check at least one blue box showing important contributions to:**			**& check contributions in at least one orange box:**	
Name of Each Author*	**Conception and design**	**Acquisition of data (arranging for or obtaining)**	**Analysis and interpretation of data**	**Drafting the manuscript**	**Critical revision for important intellectual content**
Coleman Drake	✔	✔	✔	✔	✔
Dylan Nagy	☐	☐	✔	☐	✔
Thuy Nguyen	✔	✔	✔	✔	✔
Kevin Kraemer	☐	☐	✔	☐	✔
Christina Mair	☐	☐	✔	☐	✔
David Wallace	✔	☐	✔	✔	✔
Julie Donohue	✔	☐	✔	✔	✔
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Research reported in this publication was supported by the National Institute on Drug Abuse, the National Center for Advancing Translational Sciences, and the National Heart, Lung, and Blood Institute of the National Institutes of Health under Award Numbers K01DA051761 (Drake), 5KL2TR001856 (Drake), and K08HL122478 (Wallace). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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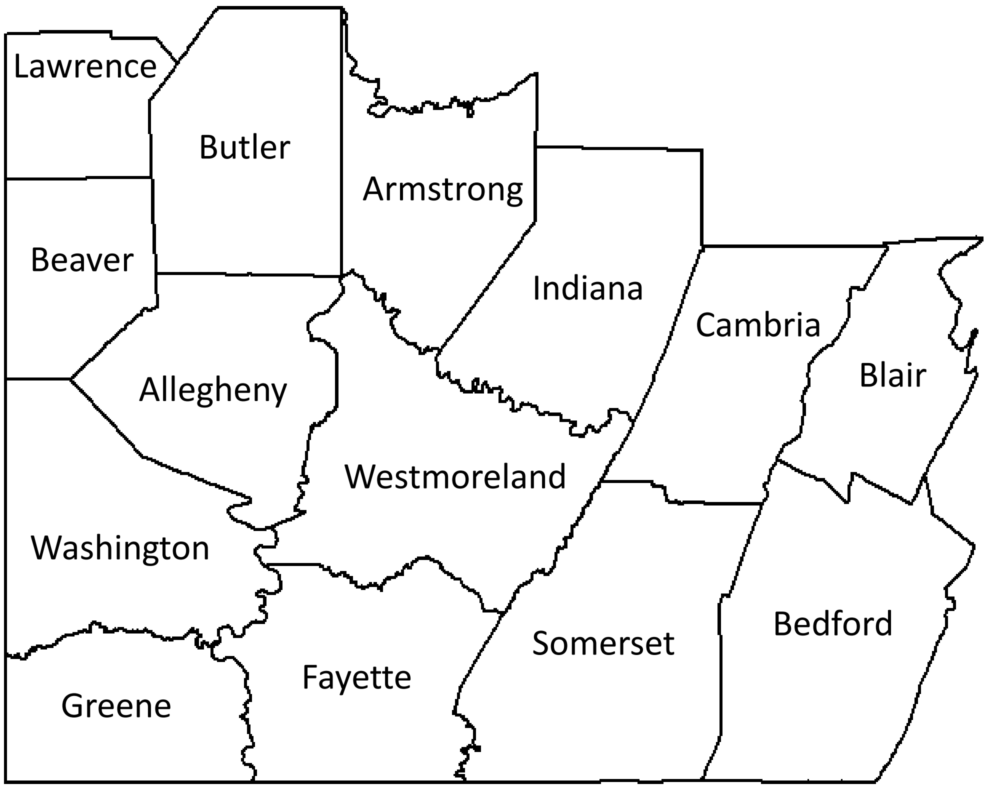
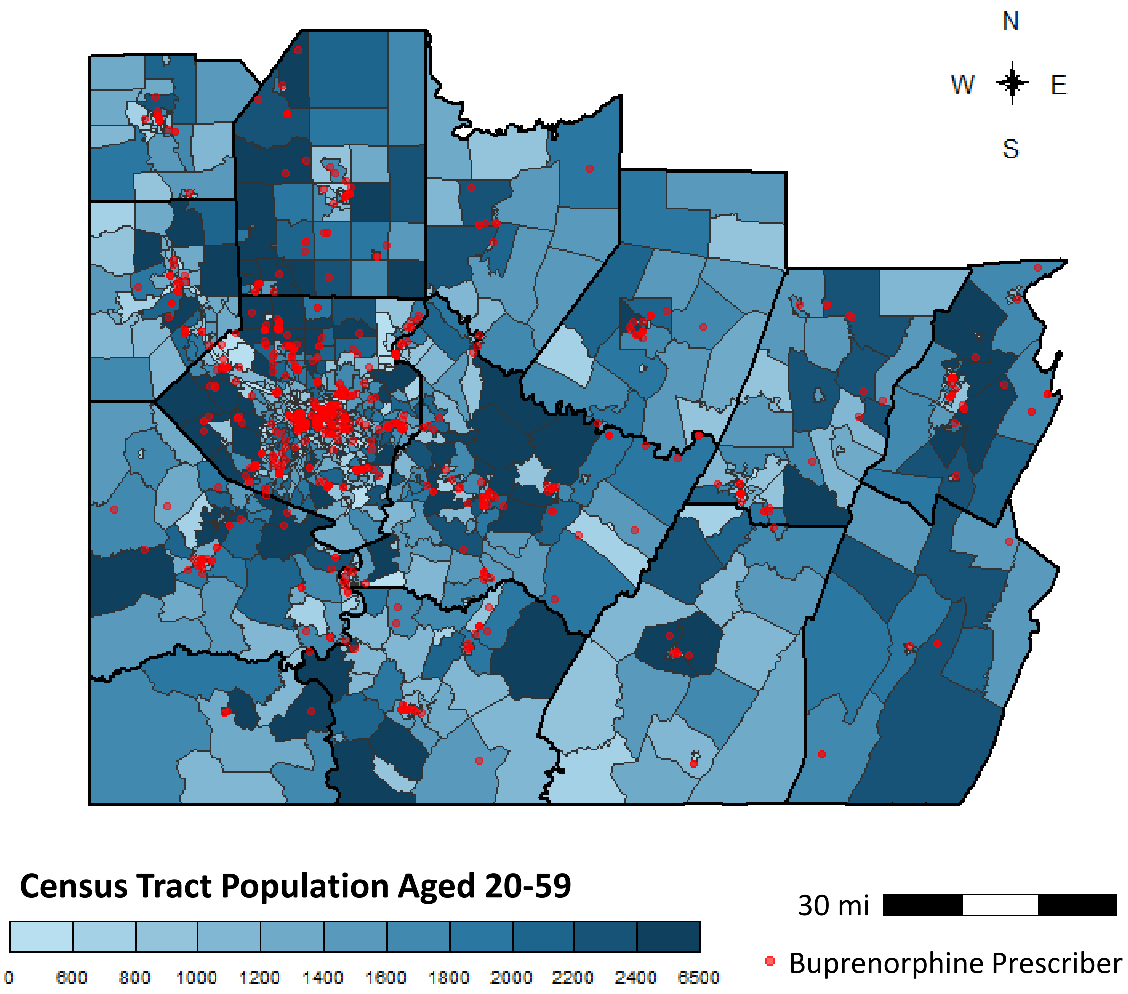
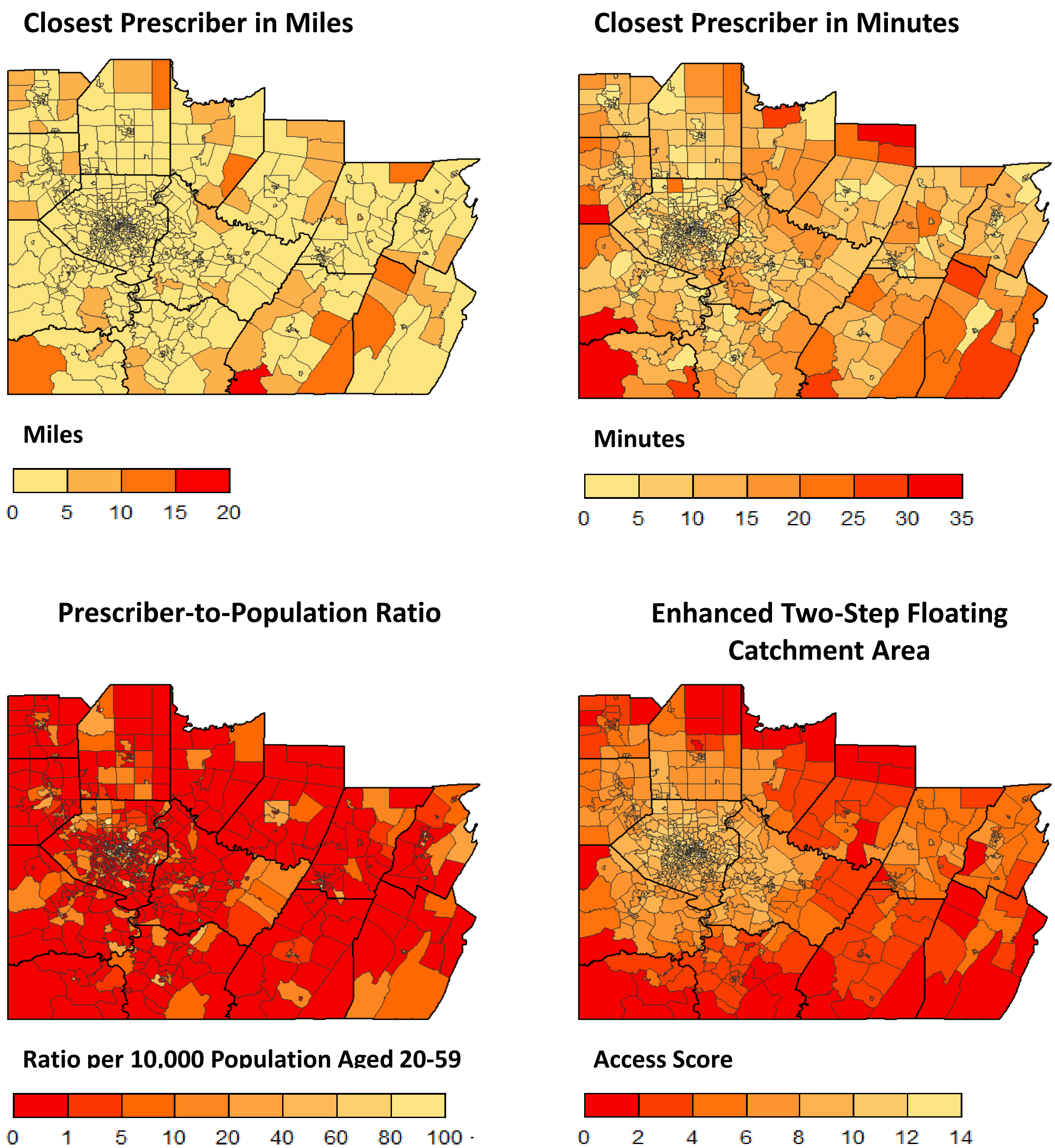
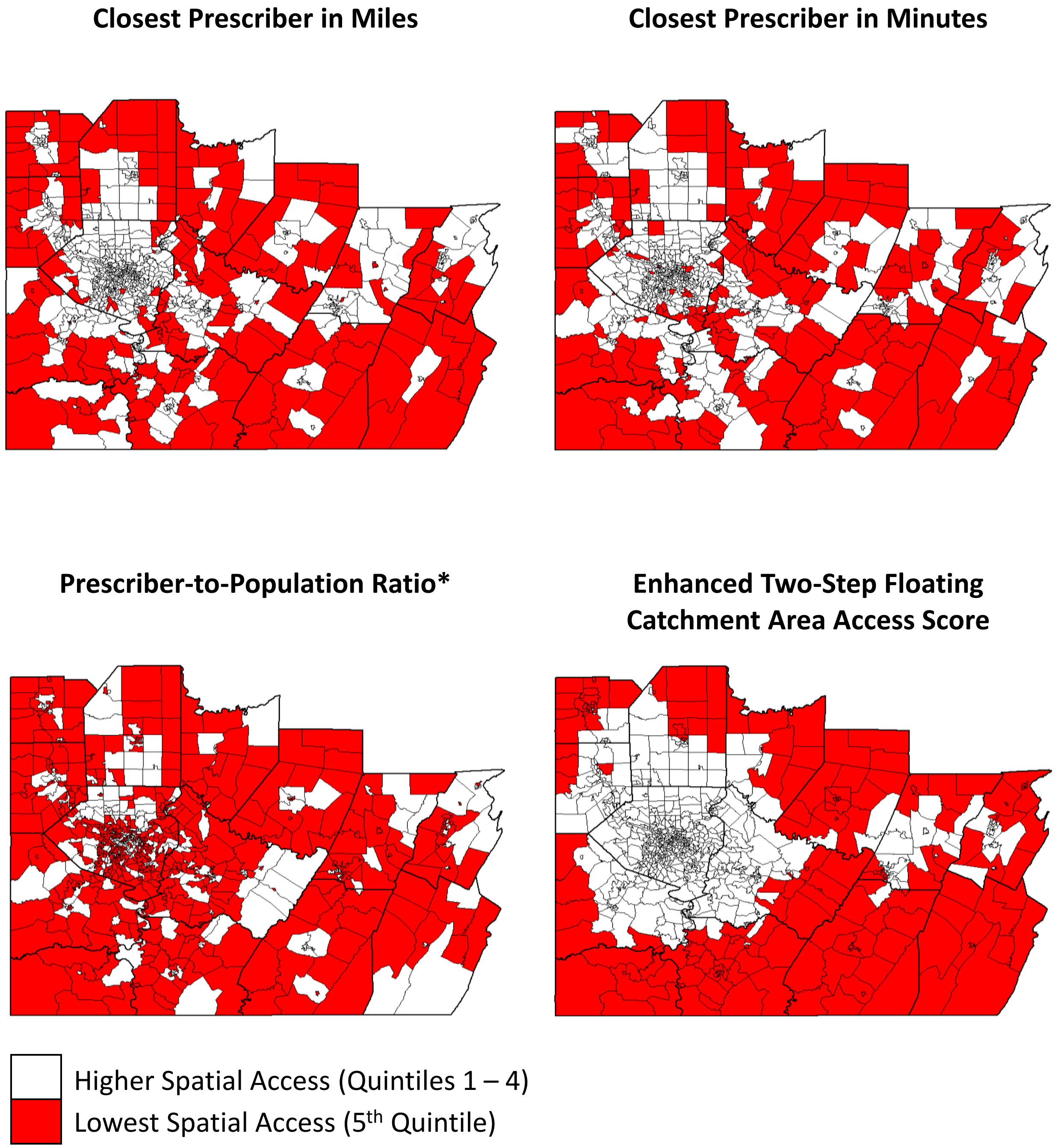
Southwestern Pennsylvania Counties



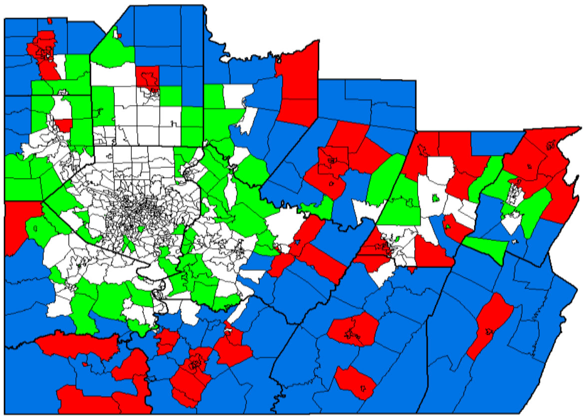
Population and Buprenorphine Prescribers



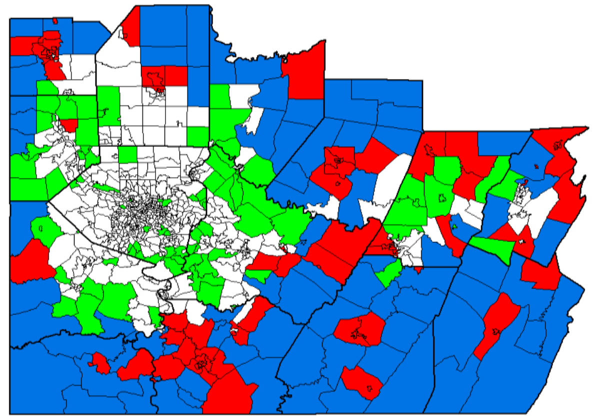

Closest Prescriber in Miles
Miles
0
5
10
15
20
Closest Prescriber in Minutes
Minutes
0
5
10
15
20
25
30
35
Prescriber-to-Population Ratio
Ratio per 10,000 Population Aged 20-59
0
1
5
10
20
40
60
80
100
Enhanced Two-Step Floating Catchment Area
Access Score
0
2
4
6
8
10
12
14


Closest Prescriber in Miles
Closest Prescriber in Minutes
Prescriber-to-Population Ratio*
Enhanced Two-Step Floating Catchment Area Access Score
Higher Spatial Access (Quintiles 1 – 4)
Lowest Spatial Access (5th Quintile)

Travel Distance to Closest Prescriber and E2SFCA Access Score



Travel Time to Closest Prescriber and E2SFCA Access Score



Prescriber-to-Population Ratio and E2SFCA Access Score*