



Measuring potential spatial access to primary health care physicians using a modified gravity model

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Ensuring equity of access to primary health care (PHC) across Canada is a continuing challenge, especially in rural and remote regions. Despite considerable attention recently by the World Health Organization, Health Canada and other health policy bodies, there has been no nation-wide study of potential (versus realized) spatial access to PHC. This knowledge gap is partly attributable to the difficulty of conducting the analysis required to accurately measure and represent spatial access to PHC. The traditional epidemiological method uses a simple ratio of PHC physicians to the denominator population to measure geographical access. We argue, however, that this measure fails to capture relative access. For instance, a person who lives 90 minutes from the nearest PHC physician is unlikely to be as well cared for as the individual who lives more proximate and potentially has a range of choice with respect to PHC providers. In this article, we discuss spatial analytical techniques to measure potential spatial access. We consider the relative merits of kernel density estimation and a gravity model. Ultimately, a modified version of the gravity model is developed for this article and used to

L'évaluation du potentiel d'accessibilité spatiale aux services de santé primaires à l'aide d'un modèle gravitationnel modifié

L'organisation de la prestation des services de santé primaires (SSP) partout au Canada sur une base équitable demeure un enjeu de taille, notamment dans les régions rurales et éloignées. Malgré l'importance accordée par l'Organisation mondiale de la santé, Santé Canada et d'autres instances chargées des politiques de santé, aucune étude n'a encore été menée à l'échelle nationale sur l'accessibilité spatiale potentielle (plutôt que réelle) aux SSP. Les défis et obstacles de la recherche visant à évaluer et à représenter avec exactitude l'accessibilité spatiale aux SSP pourraient expliquer en partie ce déficit de connaissances. En épidémiologie, l'approche traditionnelle utilisée pour évaluer l'accessibilité géographique repose sur un rapport simpliste entre le nombre de médecins prodiguant des SSP et la population totale. Nous défendons l'idée que les résultats qui en sont issus ne rendent pas compte de l'accès relatif. Par exemple, le niveau de soins qu'une personne qui vit à 90 minutes

calculate potential spatial access to PHC physicians in the Canadian province of Nova Scotia. This model incorporates a distance decay function that better represents relative spatial access to PHC. The results of the modified gravity model demonstrate greater nuance with respect to potential access scores. While variability in access to PHC physicians across the test province of Nova Scotia is evident, the gravity model better accounts for real access by assuming that people can travel across artificial census boundaries. We argue that this is an important innovation in measuring potential spatial access to PHC physicians in Canada. It contributes more broadly to assessing the success of policy mandates to enhance the equity of PHC provisioning in Canadian provinces.

Key words: primary health care, gravity model, kernel density estimation, spatial access, rural and remote health

d'un médecin en SSP peut s'attendre de recevoir est inférieur à celui d'une autre qui jouit d'une proximité et d'un plus vaste choix de SSP. Cet article porte sur les techniques d'analyse spatiale utilisées pour évaluer le potentiel d'accessibilité spatiale. Il est question d'examiner à la fois le bien-fondé relatif des méthodes d'estimation par noyau de densité ainsi que celui d'un modèle gravitationnel. Une modification a finalement été apportée au modèle gravitationnel utilisé pour le calcul du potentiel de l'accessibilité spatiale aux médecins prodiguant des SSP dans la province canadienne de la Nouvelle-Écosse. Ce modèle, qui utilise une fonction décroissante de la distance, permet de relativiser le niveau d'accessibilité spatiale aux SSP. Les résultats de l'application de ce modèle nuancent mieux le potentiel d'accessibilité. Il ressort de cette étude un portrait nuancé de l'accessibilité aux médecins en SSP en Nouvelle-Écosse. Partant du principe que les gens traversent les frontières arbitraires des unités de recensement, le modèle gravitationnel constitue un meilleur outil d'évaluation de l'accessibilité. Il constitue également un apport novateur dans l'évaluation du potentiel d'accessibilité aux médecins en SSP au Canada et fournit, de manière générale, une base sur laquelle évaluer si les politiques ont eu une incidence positive sur le caractère équitable de la prestation des SSP dans les provinces canadiennes.

Mots clés : Services de soins primaires, modèles gravitationnels, estimation par noyau de la densité, accessibilité spatiale, santé rurale et éloignée

Introduction

The problem of spatial access to primary health care (PHC) is especially Canadian given that ours is a largely rural and remote country from a geographical perspective—and one that is committed to health equity. Attention has recently been drawn to the mismatch between the spatial distribution of inhabitants and that of PHC providers (Pong and Pitblado 2005). Spatial analysis has an important role to play in understanding this phenomenon. Spatial measures of access to PHC are not well studied—despite some key studies in recent years (Gatrell *et al.* 1996). More importantly, they have not been well integrated into the health services literature (Pong and Pitblado 2005; Watson *et al.* 2005). Instead, such literature continues to focus on simple ratios

of physicians to denominator population as a means of measuring potential spatial access to PHC. By developing more nuanced measures of spatial access to PHC, spatial analysis can make a unique and important contribution to understanding equity of access to care in Canada.

This article begins by outlining the mandate for universal access to PHC in Canada and expectations fostered by international and national commitments to fair and equitable access. We then outline the two primary spatial analytical methods for calculating spatial access to physicians: kernel density estimation and the gravity model. We then move to create a modified gravity model to best determine potential spatial access to PHC physicians and demonstrate its use in the test province of Nova Scotia. Comparison between the modified gravity model and a

simple ratio of physicians to population demonstrate the role that spatial analytics can play with respect to modelling relative access to health services.

Primary Health Care and Expectations of Spatial Access in Canada

The basic tenants of PHC are that first-contact health and social care should be given in communities, by communities and for community members with the use of appropriate technology in ways that may advance social development (WHO 1978; Cueto 2004; Litsios 2004; Crooks and Andrews 2009a). In 1978, the World Health Organization (WHO) advanced PHC provision as a way to achieve 'health for all' at the global scale by the start of the twenty-first century. More specifically, the WHO released the *Declaration of Alma-Ata* following a conference held in the USSR in 1978 outlining its vision for providing PHC around the world (Cueto 2004). This Declaration is a landmark document as it establishes access to health care as a basic human right (Werner 1995). Although the goal of achieving health for all had not been reached by the start of the new millennium, PHC remains an important feature of health care systems across countries, and the WHO has renewed its interest in advancing such care provision (Pappas and Moss 2001).

PHC is understood to mean a number of different things depending on how it is interpreted. In developing nations, it has been frequently interpreted selectively (also known as selective PHC), whereby low-cost interventions to prevent the spread of disease are prioritized as the most important first-contact care that can be given (Wisner 1988; Cueto 2004). In developed nations with established care systems, health care decision makers have frequently translated the PHC mandate into a set of system priorities, namely that care be made affordable, universal, delivered equitably and comprehensive for all citizens (Hall and Taylor 2003). These priorities are often applied to primary care (i.e., the entry point in a system organized by care tiers) to facilitate the provision of comprehensive, coordinated and first-contact medical and preventative care (Schoen *et al.* 2004; Cardarelli and Chiapa 2007),

even though the PHC mandate clearly has relevance to other system tiers (Canadian Nurses Association 2005). The practice of family physicians and general practitioners is, in fact, central to both primary care and PHC (Agarwal 2009), and thus they are core providers of PHC across countries and systems.

Although PHC is defined and understood in a number of ways throughout Canada (see Crooks and Andrews 2009a), Health Canada (2006, n.p.) considers it to be both the 'direct provision of first-contact services (by providers such as family physicians...); and a coordination function to ensure continuity and ease of movement across the system...'. PHC is considered to be 'the single most important basis from which to renew the [Canadian] health care system' and forms the core of the country's health care system (Canadian Nurses Association 2003, 1). Enhancing Canadian PHC has been identified as a significant priority in a number of important and influential reports such as the 2003 *First Ministers' Accord on Health Care Renewal and the 10 Year Plan to Strengthen Health Care*, which was released in 2004. In fact, over one billion dollars have been spent since 2000 on enhancing PHC in Canada throughout the process of transitioning to a 'renewed' PHC system (Health Council of Canada 2005, 2008). A focus of this enhancement has been on implementing team-based care, creating after-hours care, using new care technologies and changing physician payment modes (Glazier 2008). Such enhancements are clearly designed to better facilitate Canadians' access to first-contact care, and particularly that provided by family physicians and general practitioners.

Access is a core geographic concept central to PHC that has been translated into system priorities across nations, along with community-based and equitable provisioning (Crooks and Andrews 2009b). For example, in the *Declaration of Alma-Ata*, mentioned above, the WHO calls for PHC to be 'universally accessible' (WHO 1978). The issue of equitable access is, however, complex. Talen (1998) argues that it includes a number of value judgments about which groups should benefit, what social justice looks like, and how to arrive at decisions about allocation of resources. Clearly, these issues are of concern to many as equitable access usually involves taxpayer funds

and spatial distribution of valued assets (Talen 1998). Access to health care in general can be thought of in a number of ways, including based on geographic location, wait-list times, availability of needed information (e.g., for system navigation) and service quality (Torgerson *et al.* 2006). According to Haggerty *et al.* (2007, 340), first-contact accessibility in PHC pertains to 'the ease with which a person can obtain needed care (including advice and support) from the practitioner of choice within a time frame appropriate to the urgency of the problem'. Certainly such accessibility is predicated upon having spatial access to practitioners. In fact, when care is spatially inaccessible this lessens the equitability of PHC provisioning (Bowen 2001; Crooks and Andrews 2009a; Wong and Regan 2009).

According to the results of the 2007 National Physician Survey (Question 1) there are just over 30,000 family physicians and general practitioners in Canada, 91.9 percent of who are involved in full- or part-time practice. Canadian family physicians base their practice on four main principles, that: (1) the family physician is a skilled clinician; (2) family medicine is a community-based discipline; (3) the family physician is a resource to a defined practice population; and (4) the patient-physician relationship is central to the role of the family physician (College of Family Physicians of Canada 2006). They, along with general practitioners, serve as gatekeepers for referrals to specialist providers and surgeons, provide generalized care for all body systems and also deliver preventative care, among other things. Thus, these physicians have an extremely important role in maintaining the health and well-being of Canadians through the delivery of care and enactment of their principles of practice. Clearly, then, having access—including spatial access—to their care is important. When asked to identify access issues affecting their patients, the distance patients must travel and related travel expenses was noted by Canadian family physicians and general practitioners as a barrier to care (National Physician Survey 2007, Question 25b). Interestingly, when specialist physicians were asked about their patients' access to family physicians (which likely also included general practitioners), of 3,197 survey respondents, 28.7 percent indicated it was poor, 26.5 percent indicated it was

fair, and only four percent indicated it was excellent (National Physician Survey 2007, Question 25a). It is clear, then, that there is concern about having access to family physician and general practitioner services, and given the focus of Canadian health care decision makers on renewing PHC, the analysis presented herein is needed in order to have an understanding of the current state of spatial access to general and family medicine care based on the best science possible. In this article, we thus focus our analysis on general practitioners and family physicians as they are core first-contact PHC providers in the Canadian system. We collectively refer to these two groups in the remainder of this article as 'PHC physicians'.

Spatial Access Calculations: Kernel Density Estimation versus the Gravity Model

Access to PHC is not a well-defined concept. This results in 'access' encompassing meanings that range from the capacity to pay (Wilkinson *et al.* 2001), clinic operation times (Macinko *et al.* 2004), culturally sensitive services (WHO 2008), feeling you have the right, ability or interest to access services (Bernard *et al.* 2004), to the physical siting of PHC service sites (Tanser 2006). Khan and Bhardwaj (1994) do, however, offer a particularly useful conceptualization of access, which is subdivided into four types: potential spatial, potential aspatial, realized spatial and realized aspatial (Khan and Bhardwaj 1994). Potential access refers to the availability of a service while realized access refers to actual usage (Aday and Andersen 1974). Spatial access is dependent on the geographic distribution of services and target populations while aspatial access depends on social factors such as income, education, race and age (Khan 1992). More specifically, potential spatial access to PHC depends on a patient's travel cost (time/distance) to the physician's office as well as the amount of demand for a physician's services by other clients (Joseph and Bantock 1982). Khan further clarifies that it 'refers to the *availability* of that service as moderated by space, or the distance variable... [and] stems from a proposed conceptualization of access to health care in terms of a series of

dichotomous dimensions' (1992, p. 275). Recent studies examining issues of potential spatial access have focused not only on health care services but also on issues of access to nutritious food (Sharkey and Horel 2008; Sharkey 2009), among others.

In this study, we examine potential spatial access to PHC, and specifically PHC physicians, using the Canadian province of Nova Scotia as an example. There are a number of traditional ways to measure spatial access, including the simple count of facilities within a defined unit, the average time to a facility, average travel distance and the opportunity versus impedance-to-travel models of access (Handy and Niemeier 1997; Talen and Anselin 1998). These methods were conceived in a more computationally limited era. Geographic information systems (GIS) methods now allow more facets of the environment to be included; measuring spatial access is made more complex by numerous variables including methods of geographical aggregation, how residential areas are defined, and distance measurements—all impact resultant measures of access (Apparicio and Séguin 2006; Apparicio *et al.* 2008). Ensuing approaches have sought to limit variation in the results of access analysis that are artefacts of the measurement technique rather than 'on-the-ground' reality. Kim and Kwan (2003) describe an enhanced space-time prism that attempts to account for the opportunities within a specified geographical area but also model the complexities of the spatial environment that ultimately affect access. Their model specifically incorporates the time of day that activities or services are offered (Kim and Kwan 2003). This dimensionality is further extended by Geurs and van Wee (2004), who argue that access models should ideally incorporate not only individual space-time constraints but also feedback amongst access, land-use and travel behaviour variables. They argue that these inter-relationships are necessary in order to fully understand transportation use decisions in different land-use scenarios. Moreover, they suggest that the perspective/perception of an individual regarding having access is more important than absolute measures (Geurs and van Wee 2004). These are important innovations in understanding and theorizing access.

In this article, we focus on potential spatial access strictly through the lens of road travel time as we are concerned especially with rural and remote access to an essential service (i.e., PHC physicians). Two leading potential spatial access modelling methods have emerged in the recent health services literature: kernel density estimation and the gravity model. We examine each in some detail below and ultimately argue that the gravity model is superior for the purpose of modelling potential spatial access to PHC in Canada.

Kernel density estimation

In general, kernel density estimation is used to estimate a smooth probability density function from univariate or multivariate data (Silverman 1986). For univariate data, it is the smooth equivalent of a histogram. To create a smooth density surface from a set of bivariate data points, a symmetrical hump, defined by a kernel function such as the Gaussian distribution function, is placed over each point. Each hump has a total density (volume) of 1.0. If a point has a population of 10, it counts as 10 points. The kernel density estimation process is illustrated in Figure 1.

One of the key attributes of this method that Figure 1 illustrates is that the choice of bandwidth greatly affects the resulting density surface. A large bandwidth will create a smoother surface and will mask local peaks or troughs. The choice of bandwidth depends on the data and the desired level of detail (like choosing a bin width for a histogram). According to the literature, choice of kernel function has little impact on the resulting surface. Bandwidth selection, on the other hand, greatly affects the results.

Initially, kernel density estimation was used in health GIS to model disease risk (Gatrell *et al.* 1996). It was applied on a set of points of disease occurrence to create a probability density surface of disease occurrence. This surface was divided by a population density surface to obtain a disease risk surface.

When using this model to create a potential spatial access surface for PHC, two kernel density surfaces are made: one for PHC

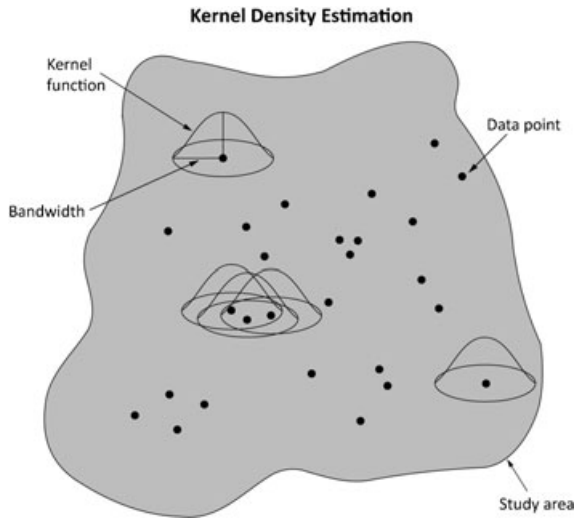


Figure 1

Kernel density estimation. The figure illustrates a set of points: $S_1 \dots S_n$. The circle around a point represents its sphere of influence and its radius is the bandwidth of the kernel function. The height of the hump (kernel function) models the influence of the data point S on its surroundings. This influence decreases with distance.

physician locations and one for population (or patient) centroids (Guagliardo 2004). The first raster is divided by the second in order to create a PHC physician-to-population ratio raster. The raster cell sizes and extents for the two surfaces should be the same. The raster cell values in each census polygon of choice can then be averaged to determine the PHC physician-to-population ratio for a census polygon.

One problem with using kernel density estimation to model the distribution of health care services, however, is that it uses straight-line distances (circles of a specified radius around a service point). These clearly do not correspond to road networks. Another problem is the bandwidth (radius) used for services is often large compared to the study area, which creates a service density layer consisting of one set of concentric rings (Guagliardo *et al.* 2004; Yang *et al.* 2006). This density distribution does not show much information about the distribution of services; it simply shows that services near the middle of an area are close to more services in the area than services near the periphery. The second problem with having large bandwidths

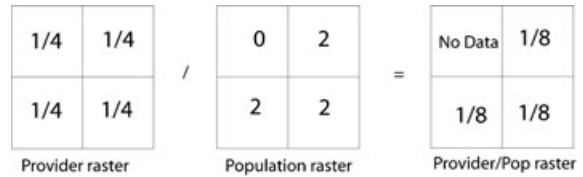


Figure 2

The problem with using the kernel density estimation method to estimate the ratio of provider to population is that unoccupied land distorts the ratio.

is that they increase the likelihood that some of the service supply will be lost to areas with no population, such as a large lake (Yang *et al.* 2006).

Many researchers use a larger bandwidth for physicians than for population points (Guagliardo *et al.* 2004; McLafferty and Grady 2004; Yang *et al.* 2006). This is because the bandwidth of the provider represents the distance from which patients are likely to come, while the population bandwidth is the radius of the circular area which the population of a centroid occupies. Thus, portions of PHC circles end up in lakes, airports, national parks and the like. This 'supply density' is lost. In the highly simplified raster division illustrated in Figure 2, 1/4 of a physician's potential supply is lost due to this problem.

Lastly, kernel density estimation is not a good model of population density. When modelling the kernel density of population centroids, one assumes that most of the population lives near the centroid and that population density decreases with distance from the centroid. This is absolutely false. In fact, it may be possible that no one lives near the centroid, it just happens to be the centre of the census block (the census block is a small unit for which no demographic information is given but for which full populations counts are available; it is approximately equivalent to a city block). The best we can assume from census population data is that a census block's population is evenly distributed within the census block polygon. Figure 3 below depicts a census block polygon, its centroid and the centroid's 'circle of influence'.

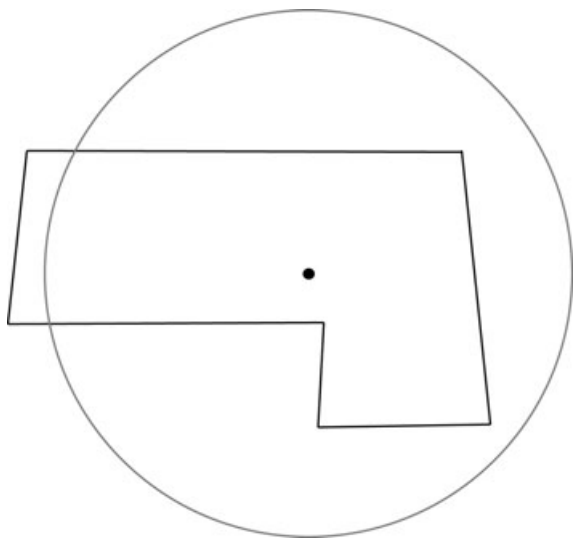


Figure 3
Census block polygon showing its centroid and the centroid's circle of influence.

Network kernel density estimation

The first two problems with two dimensional (2-D) kernel density estimation identified above can be fixed by using road network kernel density. This method distributes point densities over a road network instead of over 2-D space. Some advances have been made in this area in the last several years (Borruso 2005; Xie and Yan 2008; Okabe *et al.* 2009). Most notable is a toolbox for spatial analysis on a network: SANET (Okabe *et al.* 2006). These are upgraded regularly and can be installed on ArcGIS Desktop. However, the third problem remains. This is because 'PHC supply' is not well modelled by a continuous distribution over a 2-D landscape or a road network. It is distributed to discrete population pockets which can be separated by nonpopulated areas.

Gravity model

Although Guagliardo (2004) chose to use kernel density estimation in his study of access to PHC in Washington, DC, he argues that the gravity model is the most reliable measure of spatial access, whether potential or realized. He presents

the gravity equation developed by Joseph and Bantock to model potential spatial access to general practitioners in rural areas of Southern Ontario, Canada (Joseph and Bantock 1982). This equation is based on Newton's Law of Gravitation and is used in other studies of potential spatial access to health care (Luo and Wang 2003), as well as studies on access to employment (Wang 2001; Wang and Minor 2002).

$$A_i = \sum_j \frac{S_j}{D_j d_{ij}^\beta}$$

where:

A_i = access at population point i (census block centroid)

S_j = supply at physician location j (# of physicians at postal code centroid)

d_{ij} = distance/travel time between population point i and physician location j

β = distance decay coefficient

D_j = demand at physician location j

$$D_j = \sum_k \frac{P_k}{d_{kj}^\beta}$$

where:

P_k = population at population point k

d_{kj} = distance/travel time between population point k and physician location j

β = distance decay coefficient

In this model, a population block's access is equal to the sum of the supply and demand ratios, weighted based on distance/travel time from the population centroid at all physician locations (within a reasonable distance/travel time—we use two hours). Before calculating access, demand at each location must be determined. Physician demand is equal to the sum of all nearby populations weighted by distance/travel time.

The distance decay coefficient is the main drawback to using the gravity model. It measures the relationship between actual population-service interaction and distance, assuming other possible factors influencing interaction are constant (Fotheringham 1981). Theoretically, it should be calculated from actual physician

service utilization data using regression (Shen 1998; Wang 2001) but often these data are not available. The size of the exponent depends on how far people are willing to travel to access a service. A high exponent, which increases the rate at which the distance weight increases with increasing distance, means that people tend not to travel far for a service, while a low exponent means that people are willing to travel farther for a service (Black 1973). This suggests that different β values may need to be used to measure urban and rural access to PHC physicians. A low exponent results in a smoother 'access surface' while a high exponent produces sharper variation. Some authors have experimented with various exponents (Luo and Wang 2003) while others have chosen exponents based on published precedents (Joseph and Bantock 1982).

The impedance function, d_{ij}^β , can be replaced by an exponential function (Shen 1998) or a step function (Robitaille and Herjean 2008). The two-step floating catchment area method, designed by Luo and Wang (2003) and based on the spatial decomposition method by Radke and Mu (2000), is quite commonly employed in recent PHC access studies (Langford and Higgs 2006; Yang *et al.* 2006; McGrail and Humphreys 2009). This method, although developed from a different direction, is equivalent to the gravity model above with only two possible distance weights: 1 or ∞ (Luo and Wang 2003). If $d_{ij} \leq D$ then $d_{ij}^\beta = 1$ and if $d_{ij} > D$ then $d_{ij}^\beta = \infty$ (access = 0) for some cutoff distance/travel time D (such as 30 minutes). This cutoff value is a bit artificial, assigning the same travel impedance to all population centroids within a maximum travel time/distance, and complete lack of access to all populations outside this maximum value. McGrail and Humphreys (2009) begin their study of access to PHC in rural Australia with the regular 2-step floating catchment area method, later deciding to add a distance decay function (graduated between 15 and 60 minutes).

In the present study, we employ a two-hour cutoff when assessing potential spatial access as a means of accommodating the vast differences in population density and service distribution across Canada. It is premised on the understanding that in extremely remote areas, the perceived viable travel time to services will be longer than

in more compact urban areas that enjoy better PHC. Furthermore, we believe that two hours is a reasonable maximum one-way drive time for a day trip. This cutoff time is also supported—sometimes indirectly—by other research. For example, Luo and Wang (2003) tested various beta parameters for the gravity model to determine which one gave the preferred amount of variability for their study area (Luo and Wang 2003). They also tested various cutoff time parameters for the two-step floating catchment method (2SFCA). They found that larger cutoff times (2SFCA) and smaller beta values resulted in more gradual variations in access scores across a geographic region. Most PHC access studies, however, have been conducted on smaller areas such as counties and metropolitan areas (Joseph and Bantock 1982; Langford and Higgs 2006; Yang *et al.* 2006). These studies use cutoff times of 30 minutes or less. McGrail and Humphreys' (2009) study of access in rural southern Australia found that small cutoff times left too many regions with no access, so they preferred 60 minutes.

Luo and Wang (2003) tested various beta parameters ($\beta = 1$ to 2.2) for the gravity model to study access to primary care in the Chicago 10-county region. They found that the variances in the access scores were similar when using the gravity model with $\beta = 1.8$ and 2SFCA with a cutoff time of 50 minutes. Joseph and Bantock (1982) used $\beta = 2$ and were looking at access within a 15-mile radius in Wellington County, southern Ontario. McGrail and Humphreys (2009) used $\beta = 1.5$ when studying access to care in rural Australia within a 60-minute travel time (McGrail 2009, personal correspondence). In the present study, we are working with large distances and assuming car travel times and therefore need a smaller beta value than used in studies for smaller rural areas surrounding metropolitan areas where it may be financially feasible to have PHC services within 30 minutes of most residents. We chose to assume that travel time and PHC use were inversely proportional ($\beta = 1$): doubling travel time halves the willingness of people to visit a PHC physician. For our study area, this amount of variation in access works well.

In the remainder of this article, we develop a variation of the distance/travel time decay

function, d_{ij}^β , identified in the literature review to accurately calculate potential spatial access to PHC physicians in the province of Nova Scotia.

Data

1) PHC physicians

Addresses of PHC physicians practicing in Nova Scotia were obtained from the MDSelect Canadian Medical Directory. We used only data for physicians with either a 'General Practice' or 'Family Medicine' designation in the directory listing. Since not all physicians had street addresses (some have PO Box addresses), postal codes were used to geo-code physicians. DMTI Platinum Suite 2008 postal codes were used. As the postal code file contains more than one point with the same postal code, the Single Link Indicator (SLI) field was used to select unique points for each postal code.

2) Population

Statistics Canada 2006 census block centroids were used as population points. 2006 census population values were obtained with Statistic Canada's Geosuite 2006 software. The dissemination block (DB) is the smallest unit of census geography covering all of Canada.

2) Roads

Road network analyses were run using DMTI 2008 CanMap RouteLogistics roads for BC, Nova Scotia and Ontario. These road data come with detailed spatial and nonspatial information: each road feature has a value for distance, speed limit and direction of travel.

Methods

Measuring potential spatial access to PHC: the gravity model

Potential spatial access to PHC depends on distance to nearby physicians as well as the availability of these physicians (i.e., the number of physicians [supply] relative to the demand on these physicians from surrounding populations). Because of this, the gravity model was chosen to determine potential PHC access in Nova Scotia. To do this, we used a slight variation of

the distance/travel time decay function, d_{ij}^β , presented in the literature review above. We denote this function as $f(t_{ij})$; we replace d_{ij} with t_{ij} since we use travel time, not distance. For travel times less than or equal to 10 minutes, we do not apply any decay; for 10 to 120 minutes we use a decay that is ($\beta = 1$) proportional to travel time. When travel times exceed 120 minutes, we consider these locations to be inaccessible.

Gravity model:

$$A_i = \sum_j \frac{S_j}{D_j f(t_{ij})}$$

where:

A_i = access at population point i (dissemination block centroid)

S_j = supply at physician location j (# of physicians at postal code centroid)

$f(t_{ij})$ = travel time impedance function

t_{ij} = travel time from population point i to physician location j

D_j = demand at physician location j

$$D_j = \sum_k \frac{P_k}{f(t_{kj})}$$

where:

P_k = population at population point k

$f(t_{kj})$ = travel time impedance function for travel from population point k to physician location j

The following travel time impedance function was used:

$$f(t_{ij}) = 1 \quad \text{for } t_{ij} \leq 10 \text{ minutes}$$

$$f(t_{ij}) = \frac{t_{ij}}{10} \quad \text{for } 10 < t_{ij} \leq 120 \text{ minutes}$$

$$f(t_{ij}) = \infty \quad \text{for } t_{ij} > 120 \text{ minutes (no access)}$$

We assigned no travel impedance, ($t_{ij}) = 1$, to any dissemination block within 10 minutes of a PHC physician. Dissemination block centroids farther than 120 minutes from a physician were considered to have no access. Between 10 and 120 minutes, impedance increased linearly (a dissemination block 40 minutes away from a PHC physician has four times the travel impedance of

a DB 10 minutes away). Actual PHC utilization data were not used to determine the relationship between travel time and utilization. However, since rural areas that are commonly located an hour or more from the nearest physician were included in the study, a linear relationship between travel time and impedance was assumed to be reasonable.

Figure 4 below illustrates our gravity model. Three scenarios are presented where access for the dissemination block i is calculated. Circles represent dissemination block centroids and squares represent postal code centroids. The numbers in each shape are the population count and physician count respectively. Travel times are indicated on the arrows. The first scenario is the simplest. Three PHC physician locations are within 120 minutes of DB i . Their facilities are all within 10 minutes so there is no distance decay. One hundred other people are also within 10 minutes of all three facilities. First, the demand at each facility is calculated: 150 for all. Access is then found by summing the supply over demand ratio for each facility. Note that in this case, the other population centroid has the

same access score. For the area covered by the two DBs, the access score is equal to the total supply, four physicians, divided by the total demand, 150 people. The second scenario shows the impact of competing populations on a DB's access. Here, the 'other' centroid theoretically does not have access to facility C. This decreases the demand at facility C and therefore increases access to care in the DB i . The third scenario shows the effect of the travel time impedance function. Facility C is now 20 minutes away from DB i . This decreases the demand at facility C, which is beneficial to the 'other' DB. However, it decreases the access of the DB i to facility C and also, its total access score.

Calculating travel times

Road travel times for each DB-PHC physician pair within 120 minutes drive time were calculated. ESRI's ArcMap 9.3 software and the Origin Destination Cost Matrix tool, which is part of the Network Analyst extension, were used. DB centroids within 2.5 kilometres of a road and with a

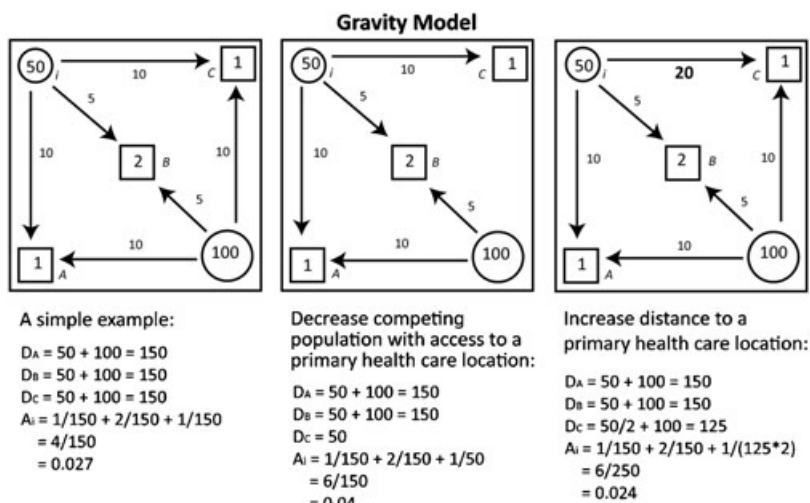


Figure 4

Three iterations of the modified gravity model. In the first example on the left, potential spatial access is determined by summing the supply over demand ratio for each facility. In the second example (middle), we illustrate the impact of a decrease in demand at one facility when it is inaccessible to a part of the population. The third scenario on the right illustrates the effect of travel time impedance on access to PHC.

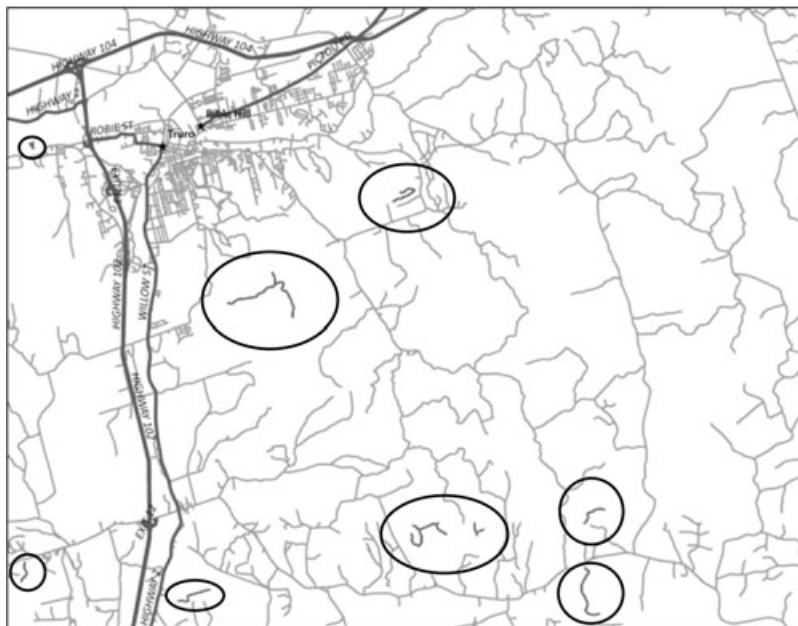


Figure 5

The problem of floating 'road bits' which are unconnected to the major road networks. Here we show a section of Nova Scotia in the Truro area with small floaters (circled).

population density greater than one person per five square kilometres were inputted as origins and physician postal codes within 2.5 kilometres of a road were inputted as destinations.

Initially, all roads for the province were used to create a road network data set and this network was used to generate an origin destination cost matrix (OD). However, it was found that some DBs with high population densities and close to other DBs with access were assigned potential spatial access values of 0. This is because the road file contains 'road bits': small sections of road which are not connected to the main road network. If a DB centroid is closer to a road bit than the main road network, its population is lost and thus not connected to a PHC physician. Road bits near Truro, Nova Scotia are shown in Figure 5 as disjointed purple strands to illustrate this problem.

In order to create a road network with no road bits, two-hour service area roads for PHC physician postal codes were generated using the Network Analyst extension New Service Area tool

(service area lines were generated for selected physician postal codes within about two hours of each other and not located near a road bit). These two-hour service area roads were used to create a new road network which was then employed to generate OD matrices. An earlier version of this method is described in detail in Schuurman *et al.* (2006).

Calculating access scores

The resulting OD matrix table contains fields for the DBUIDs (unique identifying number for a dissemination block) of the origin DBs, the postal codes of the destination PHC physicians and the respective travel times. The value of the travel time impedance function, (t_{ij}) , was calculated for each DB-PHC physician pair and added as a field. Before calculating the DB potential spatial access scores, a PHC physician demand table was created by querying the OD matrix. The OD matrix was joined to a table containing 2006 DB populations and another table containing the number of

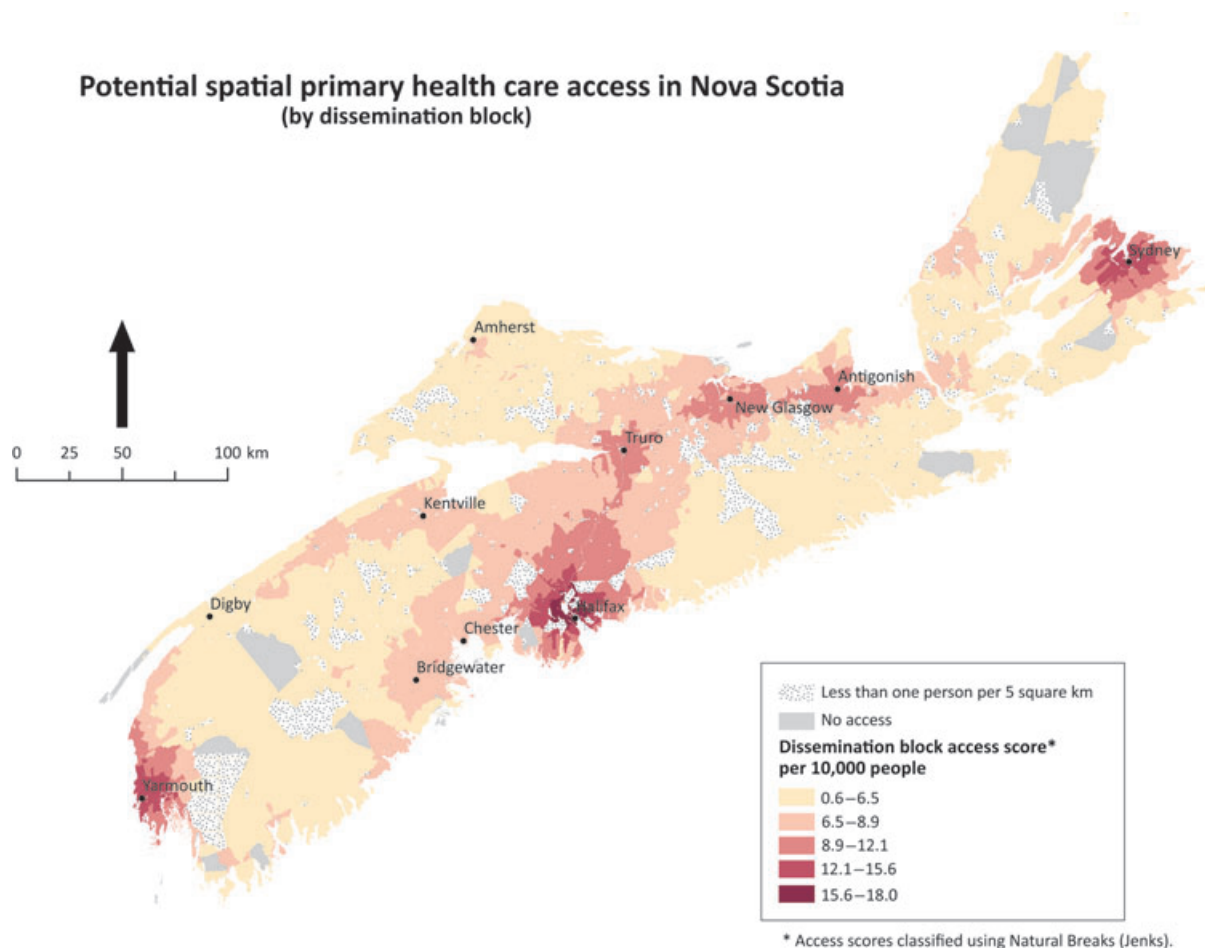


Figure 6
Modified gravity model results using dissemination blocks, a high resolution geographical unit. Note that rural areas have a relatively low access score.

physicians per postal code. It was then grouped by physician postal code and, for each postal code, the demand from each DB within two hours of that postal code, $P_i/f(t_{ij})$, was summed. To calculate DB access scores, the OD matrix was joined to the new physician demand table. The OD matrix was grouped by DBUID and, for each DB, the access values for all PHC physicians within two hours of that DB, $S_j/D_j f(t_{ij})$, were summed.

Results

The modified gravity model was used to calculate potential spatial access scores for PHC for the province of Nova Scotia using first DBs (the most granular unit of analysis possible). As illustrated in Figure 6, Nova Scotia DBs were mapped and coloured by an access score. Access scores were divided into five categories using the Jenks Natural Breaks method (score distribution did not

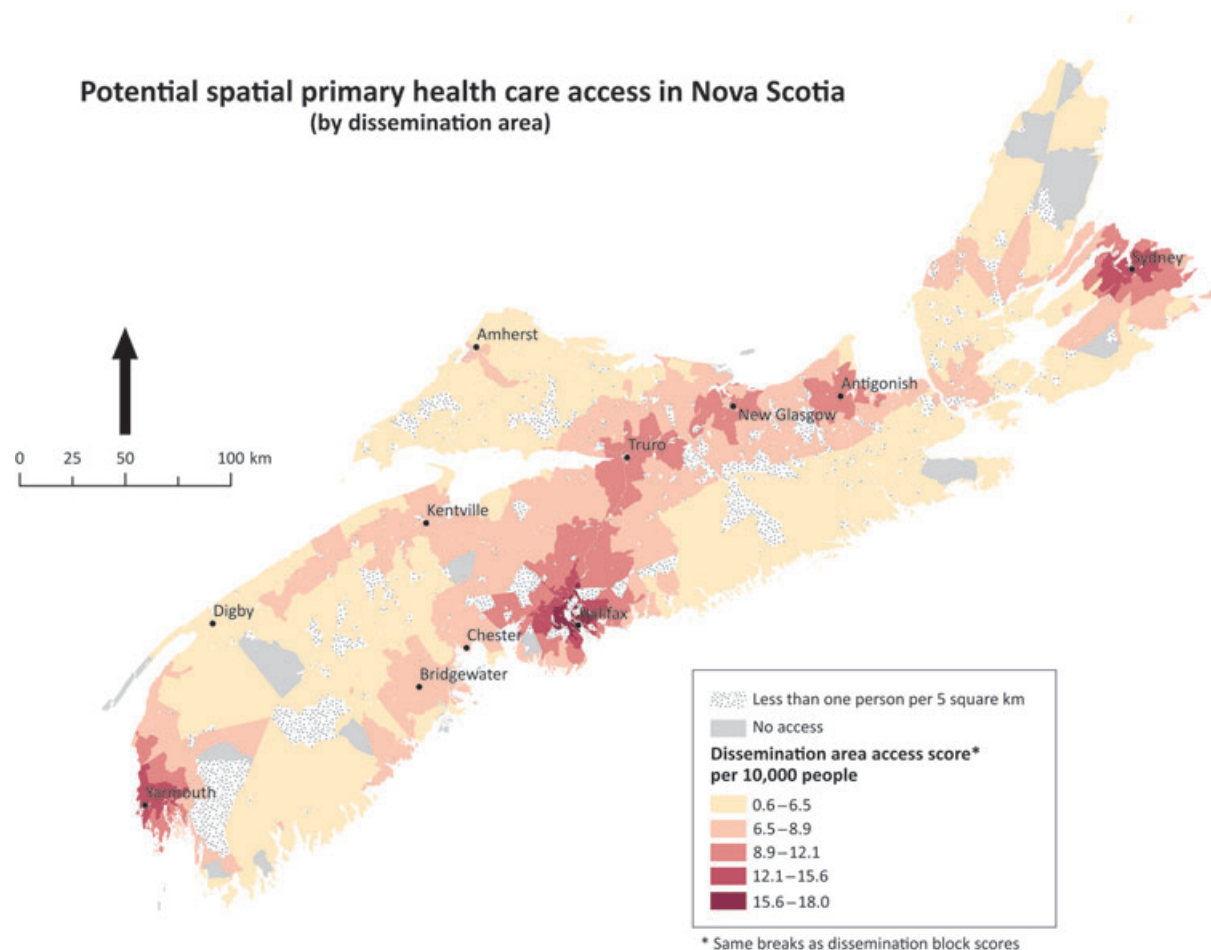


Figure 7

Modified gravity model results based on dissemination areas—the smallest census geography for which a full range of demographic data exist.

follow a normal distribution). Areas with no access (shown in grey) are either islands or DBs with areas larger than 5 km².¹ Otherwise, all DBs in Nova Scotia are within two hours of a PHC physician. Halifax has the highest access scores, followed by Yarmouth and Sydney. Popu-

¹ Limitation: DBs with areas larger than 5 km² were found to have no access since their centroids are usually farther than 2.5 km from a road. In the future, these centroids can be visually inspected and brought closer to an appropriate road segment before running the OD Cost Matrix tool. Doing so will depend on the location of a DB polygon with respect to the road network.

lations that live around Truro, New Glasgow and Antigonish have ‘average’ access scores. Other areas have relatively low potential spatial access to PHC physicians.

Access scores are essentially physician-to-population ratios, except that they account for the fact that people are allowed to travel to nearby DBs. If people in a DB must travel far to reach a PHC physician, they are considered to have access to a partial physician. Only DB populations within 10 minutes of a physician have full access to the PHC physician. Like physician-to-population ratios, the population weighted

Primary health care physician to dissemination area population ratios in Nova Scotia

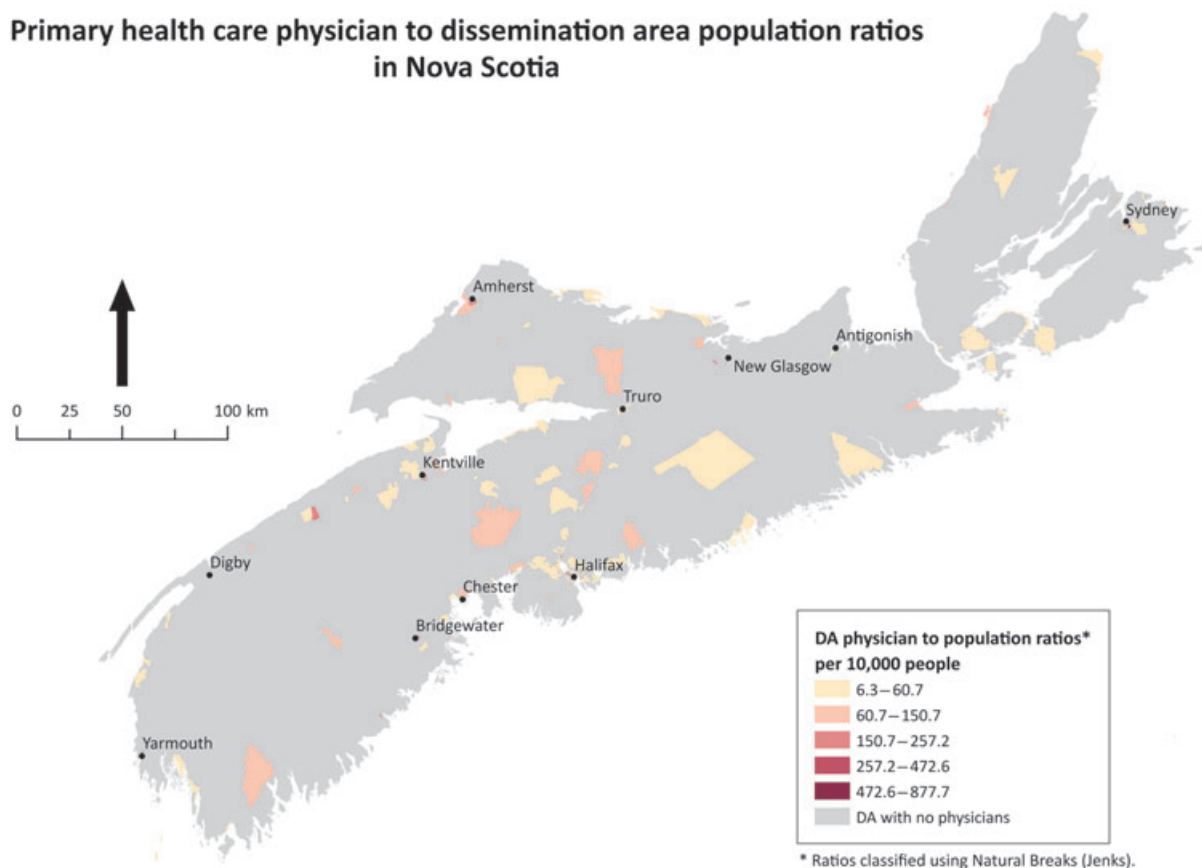


Figure 8

Conventional measure of physician-to-population ratios using census dissemination areas. Even if this measure is calculated based on the larger census geography unit of the census subdivision, the problem of fixed, impermeable geographic boundaries remains and confounds the metric. Note that even in large metropolitan areas (e.g., Halifax), the ratio is relatively low.

average of all the DB access scores is equal to the physician-to-population ratio for all of Nova Scotia. Calculated access scores were multiplied by 10,000 to show physician access per 10,000 people.

Figure 7 is similar to Figure 6 but is calculated based on the dissemination area (DA) unit. As a reminder, dissemination blocks (DB) are the smallest unit for which population counts are available. Dissemination areas (DA) are the smallest units for which complete demographic information is available for all variables. Typically DAs contain 400–700 people. DA access scores

were calculated as the population weighted average of DB scores. Comparing this map to Figure 8, which depicts the traditional epidemiological measure of physician-to-population ratios in Nova Scotia DAs, clearly shows the advantage of using the gravity model. The reader can quickly discern that the ratio does not do an adequate job of illustrating nuances of potential spatial access. For example, a person residing within 90 minutes of a PHC physician located in another DA or DB in rural Nova Scotia is still given an access score using the gravity model metric. Using the traditional ratio, this

person would appear to have no access whatsoever. The gravity model permits more accurate and nuanced relative measurement of access to PHC.

The regular ratio map (Figure 8) assumes that people cannot cross DA borders. Thus, only DAs with PHC physicians are considered to have potential spatial access. These DAs only contain 14 percent of Nova Scotia's population. All other DAs are considered to have no access—clearly a gross misrepresentation. In Figures 6 and 7, calculated using our modified gravity model, 440 people are considered to have no access and 18 are excluded for low population density. This is a much more realistic picture of potential spatial access to PHC.

Discussion and Conclusions

Though traditional epidemiology has relied upon using physician-to-population ratios to visualize and assess access, it is an insufficiently nuanced metric to appropriately describe spatial access in a large and highly rural country such as Canada. This article described a number of traditional accessibility models and specifically articulated the relative merits of kernel density estimation and the gravity model. Based on an assessment of the chief two candidates, we selected the gravity model as the preferable method and modified it to optimally describe spatial access to PHC. The results allow the reader to visualize relative geographical access to PHC—using the province of Nova Scotia as an example. Likewise, we demonstrated the relative paucity of description associated with the traditional ratio metric.

Spatial access to PHC is a pressing consideration for Canadians, and particularly those in rural and remote locations (Schoorman 2009). Focus group testing indicates that lack of timely access to PHC poses challenges to rural and remote residents and affects decisions about location of health services (Wong and Regan 2009). While ensuring access to PHC has long been recognized as an issue of creating health equity—clearly one that is especially resonant in rural regions—little attention has been paid to appropriate spatial analysis tools available to *most accurately* determine access. As practice patterns of physicians change over the next decade, measures of poten-

tial spatial access will become more important—and spatial analysis has an important role to play in providing the information needed to address these challenges. Even as the landscape of physicians and access shifts, the concept of optimal travel time distance will continue to be elusive. We suggest that optimal is perhaps a term best used when comparing methods rather than as a prescriptive modifier of spatial access.

Future research will use the modified gravity model to assess access to PHC across all provinces in Canada from a health services perspective. This article is an important first *methodological* step towards this end. The authors recognize, however, that the most important aspect of implementing gravity models is the process of interpretation and eventual implementation for decision making (Handy and Niemeier 1997). A key aspect of future research is thus the translation of potential spatial access models to policy and decision makers.

Acknowledgements

This research was funded by the Canadian Institutes of Health Research and the Michael Smith Foundation for Health Research.

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