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Methods

An Ecological Approach for Mapping Socio-Economic Data in Support of Ecosystems Analysis: Examples in Mapping Canada's Forest Ecumene

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Abstract

Integrating socio-economic dimensions in ecosystems analysis and management is becoming increasingly important, particularly from a mapping standpoint. A key challenge with such integration is reconciling different geospatial representations based on census and administrative frameworks with natural ecosystems boundaries.This article presents one method for addressing this challenge by mapping an information rich 'ecumene'. In this approach, communities are mapped as human habitats using natural boundaries as opposed to administrative-type boundaries, integrated with authoritative socio-economic data. To illustrate the benefits of this approach, two example applications are provided that: 1) map and estimate the population of the 'forest ecumene' of Canada, and 2) map labour force distribution patterns associated with the forest sector and its relation to forest areas in Canada. Benefits and limitations of this approach are discussed, from which a number of priority areas for future research are identified.

Keywords

ecumene, ecosystems mapping, socio-economic, communities, geospatial analysis, economic geography

Introduction

Human dimensions are becoming increasingly important in regional ecosystems analysis and modelling due to the recognition that human activities are intrinsic to oveall ecosystem function. This is demonstrated in the many contexts in which coupled human and natural systems are considered in addressing human and environmental problems in an integrated manner. One of the main challenges with such integration involves reconciling how social and economic data are mapped and analyzed geographically in comparison to ecosystems data and frameworks (Liu et al. 2007, McKinnon and Webber 2005, Stevens et al. 2007). Social and economic variables are often mapped using census, political or administration-type boundaries that do not align well with geographically complex ecological boundaries. This presents many challenges in spatial data integration and analysis of coupled human-natural system relationships.

One approach for addressing this issue involves mapping human settlement patterns using natural boundaries of populated areas in a way that mimics a natural species distribution. The term most fitting for this approach is *Ecumene*, which is generally defined as the geographical pattern and extent of human settlement in relation to the biophysical environment (Maina Wambugu 2018, Weiss et al. 2008). It is derived from the Greek word "oecumene", and the root "oikos", implying 'house', 'dwelling' or 'habitat'. Given its common etymology with the root 'eco' in ecology, it is worthy of consideration as an alternative spatial framework for integrating and analyzing human dimensions in ecosystems analysis. By extension, the term can be applied to different types of human settlement patterns and subpopulations (e.g., indigenous, coastal, urban, or rural), or an industrial ecumene, such as forestry, mining, manufacturing, or agriculture (Weiss et al. 2008).

Herein, we present a method for mapping the ecumene for all of Canada for regional to national scale, or macro-scale ecosystems analysis. In addition to mapping the geographical character and extent of human settlement and infrastructure in relation to Canada's environmental setting, we also demonstrate how it can be used for spatial framework for integrating socio-economic data for ecosystems analysis. First, we discuss the requirements for such a method based on a number of common challenges identified in the literature. Second, we describe the methodology we used and how it differs from conventional methods for mapping socio-economic data. Third, we then present two applications as initial examples of the types of analyses that can be applied using an ecumene framework:

1. defining and mapping the physical character and extent of Canada’s *Forest Ecumene*, and
2. mapping regional labour force distribution associated with the forest sector.

We conclude the article with a discussion of benefits and limitations in relation to the identified requirements, and identify priority areas for further research and development.

Background

Problem Description

The recognition of the need for improved integration of human dimensions with biophysical dimensions in ecosystems analysis and management is not new (Brumell et al. 1990, Liu et al. 2007, Rindfuss et al. 2004). Ecosystems management has become more complex as it continues to adapt to broader questions and issues that are continuously changing and increasingly involve aspects of human-environment interaction (Szaro et al. 2005). Among many aspects that such integration entails, a core requirement pertains to the need for improved flexibility in spatial analysis and modelling of human interaction with ecosystems across multiple spatial and temporal scales. A number of themes discussed in the literature are identified as follows:

1. *Coupled human-natural systems:* The first is the recognition that there is a need for improved integration between human systems (socio-economic) and natural systems (ecological/biophysical) (Liu et al. 2007, McKinnon and Webber 2005, Rammel et al. 2007, Stevens et al. 2007). Such integration needs to consider how human and natural systems coevolve (Catton 1994, Stepp et al. 2003), and how new information can be obtained from an integrated analysis of their interaction that might not otherwise be determined individually within their respective domains (Christensen et al. 1996, Eddy et al. 2014).
2. *Defining of custom study areas:* Data and methods employed in studying particular human–environment relationships are highly contextual, depending on the spatial and temporal boundaries used to delineate a study area. There needs to be greater flexibility in working outside of pre-fixed geographical boundaries such as political, census, and other administrative-type spatial frameworks (Bachtler 2010, Bizikova and Waldick 2010, Marsden 2013, Marsden and Farioli 2015, McKinnon and Webber 2005, Morin et al. 2015, Reed et al. 2006, Stevens et al. 2007).
3. *Multiscalar focus in space and time:* Closely related to defining custom study areas, is the need to accommodate variables associated with human and natural systems that operate on different spatial and temporal scales (Holling 2001, Rindfuss et al. 2004, Satake et al. 2008, Stevens et al. 2007). Whereas many socio-economic analyses often focus on short-term timeframes (sometimes referred to as *fast* variables), there is a need to also support upscaling of the same type of data for longer term, regional-scale analyses and models that are synchronized with longer term ecosystems change (*slow* variables) (Holling 2004, Kangas and Kangas 2004).
4. *Multiperspective modelling:* Human–environment interaction is a complex system that inevitably involves having to work with incomplete data, knowledge, and related uncertainties (Hoogstra and Schanz 2008, Meitner et al. 2009). There is often no one correct answer to a particular question, but there are multiple ways of

exploring questions depending on the data, methods, and models available. This is best achieved by providing the flexibility needed to model scenarios that explore different assumptions and model criteria.

5. *Multiuser orientation:* The use of scientific information in evidence-based and consensus-based decision making is also an important factor. Scientific results need to be presented in terms that laypersons can readily understand (Eddy et al. 2014, Meitner et al. 2009), as well as make explicit all uncertainties and assumptions associated with any particular scenario or perspective (Hardi and Zdan 1997, Hoogstra and Schanz 2008).

Taking all of these requirements into account, the manner in which both human and ecosystems data are represented geographically is fundamental to any scientific analysis of human-environment relationships. However, a fundamental barrier to addressing these requirements is the incompatibility between spatial data frameworks used for georeferencing socio-economic and ecosystems data. Ecosystems data are commonly portrayed using natural boundaries and complex spatial patterns, whereas socio-economic data commonly use more Euclidean-type administrative boundaries. When using GIS overlay processes to integrate data from these different spatial frameworks, a number of problems are encountered. Most fundamental are problems associated with scale mismatches and boundary alignment (Cumming et al. 2006, Huck et al. 2015), the most serious of which constrains our ability to spatially synchronize quantitative data variables for more advanced spatial analyses. The importance of this problem cannot be understated; socio-economic data systematically collected in many countries is referenced to administrative-type spatial frameworks that do not align with natural boundaries. Here, we examine the problem in more detail as experienced in Canada.

The Canadian Context

In Canada, the challenge in integrating socio-economic and ecosystems data is particularly challenging in this regard. Canadian census data is one of the most commonly used sources of socio-economic data, particularly at the level of census subdivisions (CSDs) which most closely serve as proxies for individual communities. However, CSD boundaries are delineated by geometric features derived from road networks and other administrative boundaries (e.g., municipal, county, or political jurisdictions), and therefore rarely follow natural features. For example, Fig. 1 shows a region in southern Manitoba in central Canada. It illustrates how an analysis that requires a spatial overlay of a socio-economic variable (e.g. population) with an ecosystems variable (e.g. forest cover) is confronted with a challenging overlay problem. If the aim is to estimate the human population associated with forested areas, one might be forced to split data values in individual census units to relate proportionally to corresponding areas of the forest pattern. Doing so not only risks falsifying data, but many other problems are encountered with using administrative frameworks in this manner.

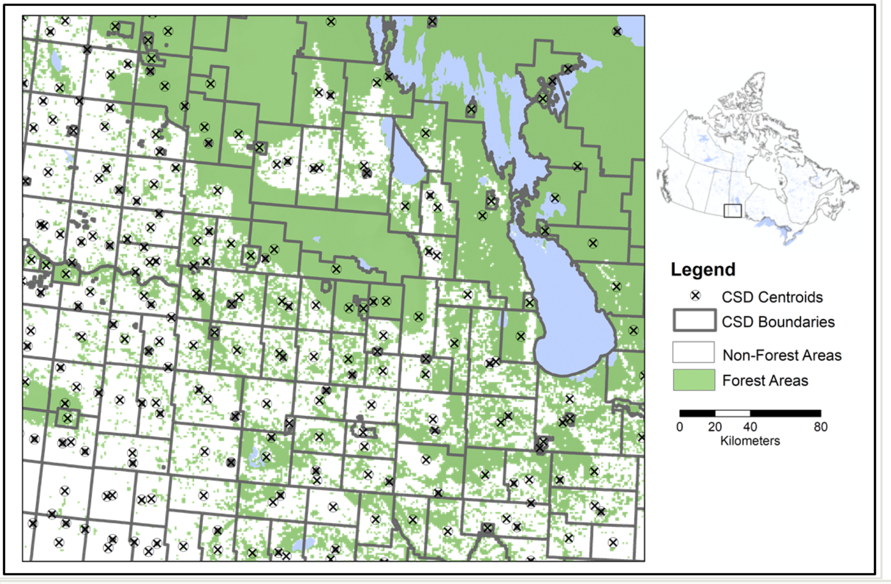

Figure 1.

Illustration of a spatial overlay problem between socio-economic and ecological data using census boundaries and forested areas. Example study area is located in southern Manitoba, Canada.

First, in the case of Canadian census data, CSDs are delineated on the basis of how municipalities are defined in each province, which results in a lack of normalization across provinces. As illustrated in Fig. 2, some provinces define municipalities at a fine scale for individual small towns and hamlets (e.g., Quebec, Saskatchewan), whereas other provinces define municipalities as regional clusters of communities (e.g., Ontario, Nova Scotia). Second, the geometries of CSD boundaries also vary from province to province in relation to the different frameworks used for delineating municipal boundaries. Some provinces use complex (irregular) boundary types that follow natural features or regions (e.g., Newfoundland and Labrador, British Columbia), whereas other provinces use more simplified (straight) administrative boundary geometries (e.g., Alberta, New Brunswick). The result is that municipalities are not only defined differently, but the shape and size of CSDs vary widely.

A third problem, of no lesser importance, relates to the identification and names of individual communities. The CSD framework is designed and structured primarily for the purpose of dissemination of census data to municipalities, and therefore the names of many CSDs do not always correspond with the names of communities where people live. This is an important issue in terms of considering sense of place and cultural identity (Sack 2003, Vodden et al. 2015), which is often the case for smaller communities that are grouped into larger regions. Data values for smaller communities are sometimes diluted in higher level aggregates at the CSD level. As a result, people who live in smaller communities do not find the higher level aggregated data meaningful because the data may incorporate trends happening in adjacent communities that contrast sharply with their own community (e.g. demographic, employment or labour force statistics).

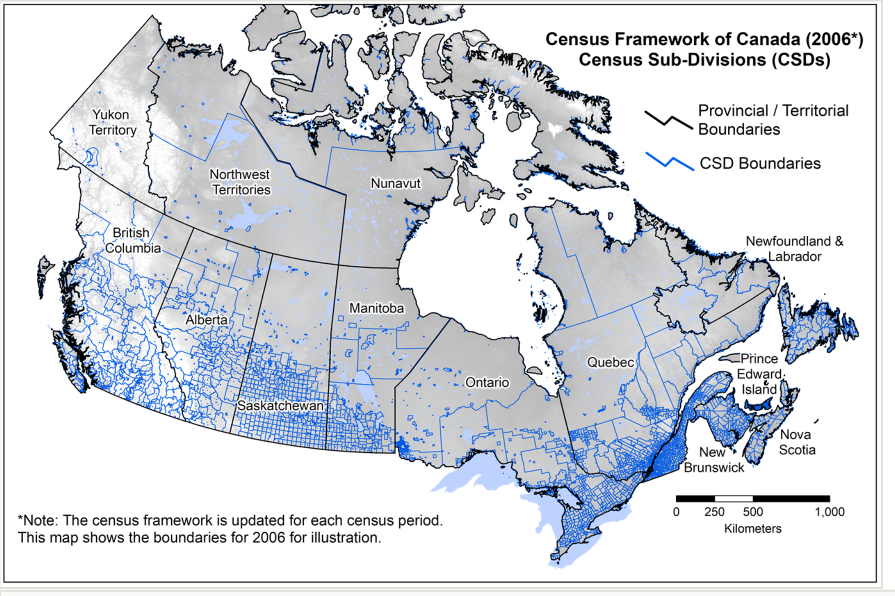

Figure 2.

Map showing the distribution of Census Sub-divisions (CSDs) for all of Canada. Note the differences in the shape and size of boundaries among different provinces.

Such limitations do not negate the important value that census data have to offer. The limitations identified here are associated more with the geospatial representation of communities than the quality of the data collected. Ideally, what is needed is a spatial representation of communities in which: 1) residents identify with on a local level, and 2) are delineated by boundaries that can be more naturally aligned and integrated with ecosystems data. A standardized approach would improve the normalization across provinces.

To address some of these problems, one method developed for this approach uses the concept of human habitats, wherein local community boundaries are mapped using natural boundaries delineated by the physical footprints, as opposed to using census or administrative boundaries (Eddy and Dort 2011). In that study, key socio-economic attributes that characterize each populated area as a human habitat are re-assigned to each community, and include physical size, population growth, physical development, demographic changes, education, employment, and income (ibid). When mapped collectively, the distribution of communities resembles a natural habitat map for the human species akin to habitat mapping for other animal species, and for which habitat characteristics can then be analysed. Building on this approach, the following section describes the data integration methodology used to map the whole ecumene of Canada in this manner.

Data integration methodology

Based on the limitations discussed above, three criteria are used to frame the data integration methodology:

1. boundaries of populated places are delineated on the basis of physical footprints of communities as opposed to census or administrative boundaries,
2. populated places are identified and differentiated individually as places that residents most commonly identify with, and
3. census, demographic, and other socio-economic variables can be integrated for mapping and analysis.

Our approach involved developing a triangulation method that addressed these criteria. Whereas details of this approach are provided in Eddy et al. 2020, here we provide a summary of the three corresponding processing steps involved as follows (Fig. 3):

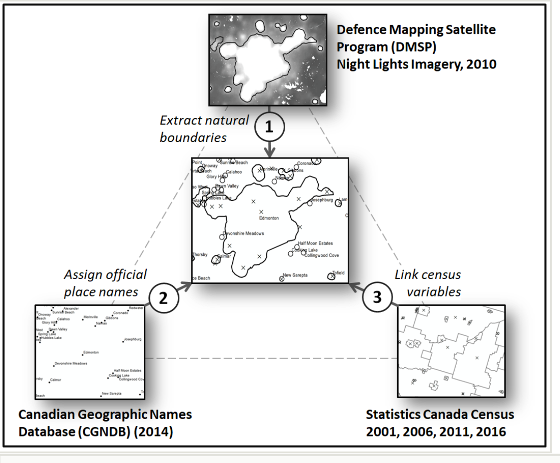

Figure 3.

Graphical illustration of the triangulation framework used in the ecumene data integration methodology.

Step 1. Delineating Populated Areas: Boundaries of populated areas were derived from Defense Meteorological Satellite Program (DMSP) Night Lights imagery for the year 2010 (NOAA 2010). The rationale for using night lights imagery is based on the requirement to identify distinct human settlement areas using a data source that is consistent for all of Canada, and is sufficiently detailed for application on regional to national mapping scales. With the DMSP night lights data, an "ecumene place" (or populated settlement area), is considered to be any distinctly identifiable lighted area that corresponds with a known location of a populated area that matches the other two data sources indicated in the triangulation framework shown in Fig. 3. In this approach, larger population centers are treated as one ecumene place (e.g., Greater Toronto or Greater Vancouver) in the same way as a smaller rural or remote community (e.g., Flin Flon, MB or Cochrane, ON). DMSP radiance values for Canada range from 1–63, and after comparison with settlement areas in Google Earth, it was determined that values equal to or larger than the value of 30 provided the most suitable delineation of populated areas, whereas values less than 30 were determined to be overshadows (halo effects). The image was reclassified into a binary raster for all values ≥ 30, and subsequently vectorized into individual polygons with unique identifiers.

Step 2. Assigning Official Place Names: Official place names from the Canadian Geographic Names Database (CGNDB) (NRCan 2014) were overlaid with the DMSP-derived polygons, and a spatial join was made for all locations where matches were found. In cases where more than one name corresponds with an individual polygon (e.g., larger urban centers), the most logical place name was assigned based on a detailed inspection and comparison with Atlas of Canada maps, topographic maps, and Google Earth. Although matches between the two sources were captured for the majority of locations, not all DMSP polygons correspond with official place names, nor did all place names have a corresponding DMSP polygon. In some locations DMSP polygons were identified as large industrial work areas or remote stations without any official population status, and were therefore excluded. Many official populated places that did not have a corresponding DMSP polygon were identified to be very small communities not large enough to register in the DMSP radiance image. In cases where such communities correspond with official CSD locations (the third data source), they were retained and assigned a circular buffer with a 3-km diameter. In total, 4288 polygons were mapped and identified covering approximately 15 million km^2. Of these, 824 (19%) are larger populated areas detectable in the DMSP imagery covering approximately 5.3 million km^2 (37%) of the total populated area, and 3464 are much smaller places covering approximately 9.2 million km^2 (63%).

Step 3. Assigning Census Data Attributes: The third step involved assigning CSD identifiers to the populated places identified in Step 2. This task required detailed inspection at a local scale to determine which CSDs matched the ecumene populated places most appropriately. CSD polygon boundaries and centroids (StatsCan 2011a, StatsCan 2011b) were acquired for each of the 2001, 2006, 2011 and 2016 census years, and were overlaid on the ecumene places layer with the aim of performing a point-in-polygon analysis to match the ecumene ID with corresponding CSD IDs for each census year. In cases where two or more CSDs corresponded to an ecumene polygon, for example, in large urban areas, primary data values are aggregated for teh larger area. Whereas alignment between CSD centroids and ecumene places occurred for the vast majority of cases, there were some cases where centroids needed to be manually repositioned. A small portion of CSD centroids for which no matches were identified were treated as outliers due to their locations positioned at center of larger CSDs, and are not directly associated with any visibly identifiable populated place. Collectively these amount to only a small percentage of the overall statistical representation achieved (Table 1). The different number of CSDs in each census period resulted in a different number of matches with ecumene places for each period. Differences among the four periods are relatively small as a 98% representation of the total population was obtained for each census period. Additional details on this process are provided in Eddy et al. 2020.

Table 1.

Population data obtained with Ecumene data compared with CSD population data. See text for elaboration.

	2001		2006		2011		2016	
	Total Pop.	**Count**	**Total Pop.**	**Count**	**Total Pop.**	**Count**	**Total Pop.**	**Count**
CSDs	29,978,397	4,808	31,563,035	4,550	33,429,076	4,573	35,151,728	5,162
Ecumene Places	29,313,759	2,966	30,910,864	2,897	32,761,384	2,908	34,509,624	2,934
CSD Pop.: % Rep	97.8%	n/a	97.9%	n/a	98.0%	n/a	98.2%	n/a
SEDAC Pop	665,544	1,350	674,031	1,350	684,676	1,350	697,041	1,350
SEDAC Pop.: % Rep.	2.2%	n/a	2.1%	n/a	2.0%	n/a	2.0%	n/a
Total	29,979,303	4,316	31,584,895	4,247	33,446,060	4,258	35,206,665	4,284
Total % Rep.	100.0%	89.8%	100.1%	93.3%	100.1%	93.1%	100.2%	83.0%

As shown in Table 1, the 98% CSD representation by population was achieved by matching approximately 2900 of the approximate total of 4300 ecumene places. The remaining 2% of the population are dispersed among 1300 places, in rural and remote areas. Although CSD data variables could not be linked for these communities, supplemental population estimates were acquired from overlaying the ecumene polygons with the pixel values of NASA's Socio-Economic Data Analysis Center (SEDAC) population grids (CEISIN 2018). This data provided the needed complement to the CSD data to achieve a near 100% representation by population. Additional attributes were added to the ecumene polygons from several sources including:

1. ecological zones and regions,
2. ecunomic zones,
3. forest zones,
4. metropolitan influence zones, and
5. indigenous community indicators.

These additional reference variables were included to expand the analytical flexibility of the ecumene data.

The results of this work are published on-line as an ArcGIS database with the Government of Canada's Federal Geospatial Platform (Eddy et al. 2020). A map of the whole ecumene of Canada is provided in Fig. 4. In summary, boundaries of 4288 communities are mapped, identified and assigned population values and additional reference variables. Of these, approximately 2900 communities, comprising 98% of the total population of Canada, have assigned CSD identifiers for the 2001, 2006, 2011, and 2016 census periods. These linkages provide access to over 400 census data variables for each census period (StatsCan 2011c, StatsCan 2016) which can be extracted for mapping and spatial-temporal analyses.

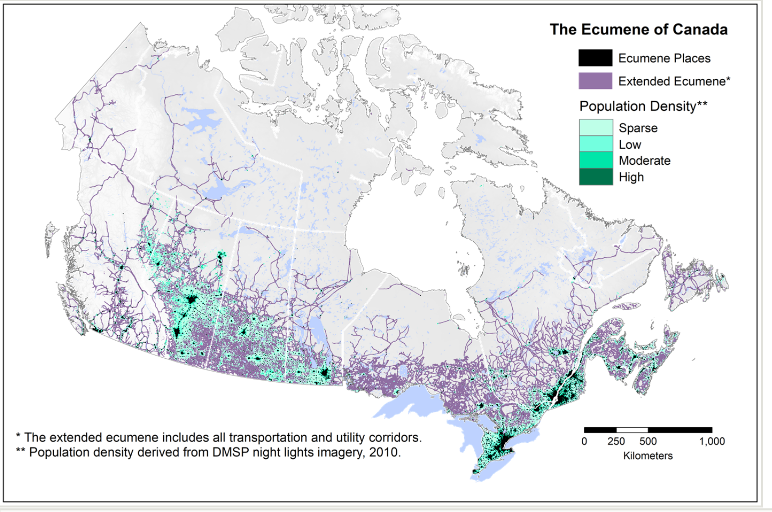

Figure 4.

Map showing the whole ecumene of Canada. Note the ecumene database contains both core areas (populated places) and extended areas (transportation and utilities). Generalized population density, derived from DMSP (NOAA 2010) night lights imagery, is added for reference.

Demonstrating the full range of ecological applications of this data is beyond the scope of this paper, however it is worth demonstrating how this approach can be applied for ecological analyses. To do this, the following section provides two examples for integrating socio-economic data through mapping Canada's forest ecumene. These include:

1. a spatial overlay analysis in estimating the human population of Canada's forest areas, and
2. a spatial interpolation of labour force employment and income data to map the labour force distribution associated with the forest industrial sector.

Applications

Population Estimation of Canada's Forest Ecumene

Forest communities are an integral component of forest management in Canada, and in the development of Canada's forest sector. Given that the forest industry is one of the most geographically distributed economic sectors in the country, it should be no surprise that forest communities made a significant contribution to the development of Canada's human settlement pattern over the past 200 years. The close relationship Canadians have with the forest has resulted in complex patterns of human activity within and adjacent to Canada's forest ecosystems. The interaction can have both positive and negative effects to varying degrees, which makes consideration of multiple human factors critically important in forest science, policy, and management. Identifying and estimating the population of forest communities in Canada is therefore an important scientific policy input, and requires an unambiguous definition of what constitutes a 'forest community'. Criteria used may vary depending on the application. Factors such as economic dependency, population characteristics, and physical proximity in relation to forest areas are key considerations. The approach taken here first begins by considering all communities in Canada (the whole ecumene) to which different criteria may be applied depending on the definition used. For comparison, whereas the map in Fig. 4 shows the whole ecumene of Canada, the map in Fig. 5 shows one rendering of the forest ecumene by where populated places, transportation and utility lines intersect forest-dominated ecozones. Quantitative estimates, however, of the number of communities and corresponding population can vary widely depending on the definition of forest community used.

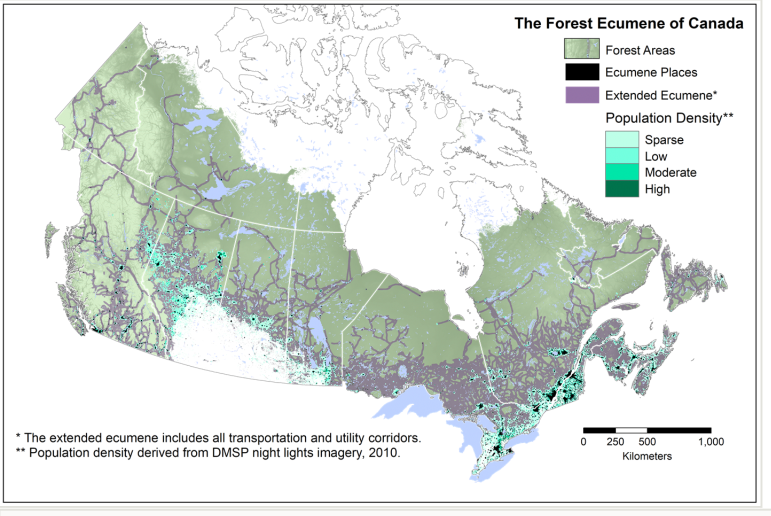

Figure 5.

Map of Canada's "Forest Ecumene", as a sub-set of the whole ecumene of Canada (see Fig. 4). In this rendering, the forest ecumene is shown as the portions of the whole ecumene of Canada that intersect with forest dominated ecosystem zones.

In our analysis, we examine three definitions combined with two ways of representing forested areas. First, a 'forest zones' layer was created by combining physical forest areas with major ecological zones. The forested areas layer was derived from a 250 m MODIS kNN land cover analysis (Beaudoin et al. 2014) by reclassifying each land cover type into a binary raster of 'forest' and 'non-forest'. This layer was then combined with a derivative of the national ecological zones layer (CCEA 2014) which was classified into 'Forest-dominated' and 'Non-forest dominated' ecological zones. The resulting forest zones map contains four classes: 1 – Non-forest/Non-forest Ecozones (NF/NFE), 2 – Forested/Non-forest Ecozones (F/NFE), 3 – Non-forest/Forest Dominated Ecozones (NF/FDE), and 4 – Forested/Forest Dominated Ecozones (F/FDE). By using a zonal analysis overlay method in ArcGIS, each ecumene polygon was assigned the highest intersecting forest zone class value. Population values were then aggregated for each forest zone category for each census year. The map in Fig. 6 shows examples of communities that correspond to each definition, and technical details on the overlay GIS process used to generate these results are provided in Supplement A (Suppl. material 1). Table 2 presents resulting population estimates and percentages for each forest zone (2a, 2b), and additional aggregation estimates using three definitions (D1, D2, and D3) of a forest community (2c, 2d).

Table 2.

Population estimates for forest communities under different definitions. a) Population and community counts according to forest zone, b) Percent change by census period according to forest zone, c) Population and community counts according to three definitions (D1-D3) by census period, and d) Percent of total population for each definition (D1-D3) according to census period.

a. Population Estimates by Forest Zone and Census Year						
Forest Zone	**1996**	**2001**	**2006**	**2011**	**2016**	**Total Count**
1 - NF/NFE	11,866,748	12,661,186	13,629,699	14,697,054	15,709,298	859
2 - F/NFE	2,601,608	2,691,766	2,859,346	3,089,827	3,243,090	374
3 - NF/FDE	6,686,999	6,949,034	7,256,532	7,701,881	7,992,714	495
4 - F/FDE	7,607,464	7,634,687	7,782,746	8,063,700	8,274,496	2560
Grand Total	**28,762,819**	**29,936,673**	**31,528,323**	**33,552,462**	**35,219,598**	**4288**

b. Population Change by Forest Zone (% change from previous period)						
Forest Zone	**1996**	**2001**	**2006**	**2011**	**2016**	**20 Yr. Change**
1 - NF/NFE	-	6.7%	7.6%	7.8%	6.9%	32%
2 - F/NFE	-	3.5%	6.2%	8.1%	5.0%	25%
3 - NF/FDE	-	3.9%	4.4%	6.1%	3.8%	20%
4 - F/FDE	-	0.4%	1.9%	3.6%	2.6%	9%
Grand Total	-	4.1%	5.3%	6.4%	5.0%	22%

c. Population Estimates of Forest Ecumene by Definitions D1-D3 plus Communities (Count)						
Definition	**1996**	**2001**	**2006**	**2011**	**2016**	**Count**
D1	7,607,464	7,634,687	7,782,746	8,063,700	8,274,496	2,560
D2	14,294,463	14,583,721	15,039,278	15,765,581	16,267,210	3,052
D3	16,896,071	17,275,487	17,898,624	18,855,408	19,510,300	3,426

d. Population Estimates of Forest Ecumene as a Percent (%) of the Total Population and Total Number of Communities (Count)						
Definition	**1996**	**2001**	**2006**	**2011**	**2016**	**% Count**
D1	26%	26%	25%	24%	23%	60%
D2	50%	49%	48%	47%	46%	71%
D3	59%	58%	57%	56%	55%	80%

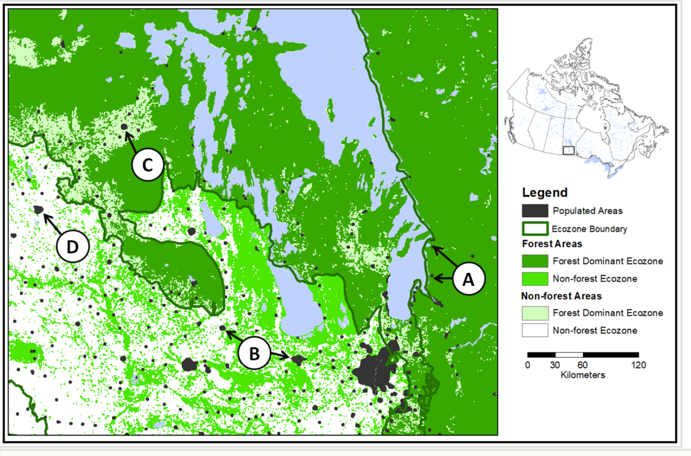

Figure 6.

Map showing the spatial relationships of communities to forest areas and forest-dominated ecosystem zones for different definitions of a forest community. See text for elaboration.

Each definition in Table 2 is successively more inclusive of communities in terms of the spatial relationship to forests and forest-dominated ecosystems. The first definition (D1) is limited to communities that are located exclusively within forested areas and within forest-dominated ecozones (location A in Fig. 6). The second definition (D2) includes all communities in D1 plus communities outside of the forest-dominated ecosystems but located either within or are in close proximity to forested areas (location B in Fig. 6). There are also many communities within forest-dominated ecozones that are not located within or in close proximity to forested areas (location C in Fig. 6). Such communities may be considered for inclusion in the forest ecumene by virtue of being surrounded by forest-dominated ecosystems (D3), with the rationale that they may be subject to hazards from forest areas (e.g., smoke from wildfire) or have greater economic, social, or cultural dependence than similar nonforest communities in nonforest-dominated ecozones. The only communities that are not considered to be forest communities are those that are not located within or in close proximity to forest areas, nor within forest-dominated ecosystems (location D in Fig. 6).

In terms of the results of this analysis, for comparison, Natural Resources Canada used CSD level data to estimate the total population of forest communities to be approximately

11 million people, or approximately 31% of Canada's total population for 2016 (NRCan 2019). By contrast, quantitative differences shown in Table 2c in terms of both population estimates and number of communities illustrate the sensitivity in choice of definition and the analysis method used. In our analysis, population estimates range from approximately 8.2 million (D1) to nearly 19.5 million (D3), or a range of 23% to 55% of Canada's total population for 2016. The total number of forest communities range from around 2500 under D1 (60%) to as many as over 3400 (or 80%) communities under the D3 definition.

A number of trends and relationships among community categories can be observed from this analysis, starting with the relative increase in the nonforest population (Forest Zone 1 – NF/NFE) (Table 2b). A continuation of the rural–urban population shift is evident in comparing changes in these values with the values of forest communities under either of the D1-D3 definitions, particularly in terms of percentages of total population (Table 2d), and in considering that many of the major urban areas do not qualify as forest communities. A trend worth noting is how the population of the forest ecumene has also increased during the same time period, despite the economic downturn that has affected many forest communities over the past twenty years. It illustrates that although the rural–urban population shift continues, the population of forest communities also continues to increase, but at a comparatively slower rate. The overall 20 year % change for the Forest Zone categories 2, 3, and 4 in Table 2b range from 9% to 25% increase, in comparison to a 32% increase for the strictly non-forest (and urban dominant) communities.

Information extracted from this type of analysis provides an important input for integrating regional economic development, and other socio-economic considerations in ecosystems management and planning. Whereas the use of spatial overlay analysis in mapping the forest ecumene and deriving quantitative measures on population captures the *extensiveness* of human interaction with forest ecosystems of Canada, it is also possible to use ecumene data to model spatially *intensive* socio-economic patterns that relate to the proximity of ecosystems resources and services. To demonstrate such an approach, our second example application focuses on mapping labour force distribution as an indicator of economic dependency on the forest industry within the forest ecumene.

Mapping Labour Force Distribution

Mapping labour force data can be useful for identifying regions that are economically reliant on natural resources by virtue of their physical proximity to the resource base. It is one means of including an economic dimension in ecosystems management, and by extension, associated social, demographic and cultural factors. As is the case with population data described above, in Canada, labour force data and other social, demographic and economic variables are also collected and aggregated according to census and administrative boundaries. In the Canadian forest sector, for example, economic dependency of forest communities has been a topic of interest for many years (Korber et al. 1998, Parkins et al. 2001, Stedman et al. 2004, Stedman et al. 2005, Stedman et al. 2012, Stedman et al. 2007). In such studies, economic dependency measures use labour force data linked with CSDs to identify and rank forest-dependent communities (FDCs). FDCs are measured on the basis of a proportional contribution of the forest industry to the overall structure of a local economy. The outputs of such studies are tabular lists of communities with corresponding dependency values. This approach has been useful for general tracking purposes; however, there are limitations with mapping such data using CSD boundaries for ecological applications.

In cartography, mapping data variables using homogeneous units, such as census or other administrative boundaries, is known as choropleth mapping (Slocum et al. 2005). Choropleth maps are intended for mapping numerical or categorical data only in cases where it is known that the value of the data being mapped is homogeneous throughout the geographical area covered by the choropleth unit, and when the size and shape of the units are similar (ibid., 286). The lack of similarity in size and shape of CSDs in Canada is therefore a challenge in this regard (see Fig. 2). Mapping ratio or proportional data values is not considered to be cartographically valid unless it is known for certain that the data values are relatively similar for all communities within an administrative unit. In spite of these limitations, choropleth mapping has been a common practice due to the convenience in linking data to the administrative or census units in which the data was collected and/or distributed.

Using an ecumene as an alternative spatial framework addresses some of these limitations. For comparison, Fig. 7 and Fig. 8 show maps of the labour force distribution for the forestry sector using the CSD boundaries and ecumene, respectively for the year 2006. The method used for the CSD map is straightforward choropleth mapping. Labour force ratios are calculated for each CSD, then mapped using a standardized legend showing a range of threshold intervals with a monochromatic colour ramp. Custom tabulations of the labour force data were provided by StatsCan (2018). As an alternative to the approach used in the calculation of FDCs, which is specific for the forest sector only, the approach taken here uses a standardized calculation of 'Labour Force Distribution (LFD)' which can be applied for the forestry sector or any other sector or sub-sector for direct comparison. In this approach, labour force ratio values are calculated as the total income for the forestry sector as a proportion of the total income for all base economic sectors, where the base sectors include the natural resource, utilities and construction, and manufacturing sectors.

The resulting map in Fig. 7 shows a wide variation of class values associated with the different sizes and shapes of the CSD boundaries. As an area-based representation of the data, it is prone to misinterpretation as the larger CSDs in the northern areas have lower population values and smaller communities, whereas the smaller CSDs in the southern areas have higher numbers of communities with higher population values. The resulting map pattern gives the impression that very large areas of northern Canada are highly dependent on the forest sector, yet in reality, there are very few communities in these large areas. There is also no clear spatial relationship between the labour force distribution within the limit of the managed forest area and the location of mill facilities.

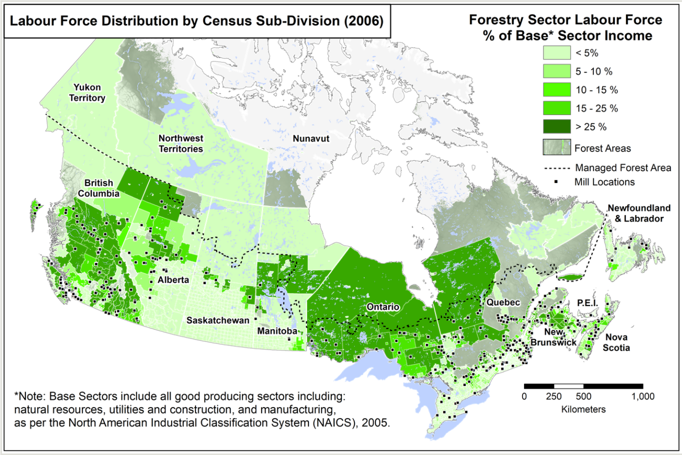

Figure 7.

Choropleth map showing labour force distribution for the forestry sector using census sub-division (CSD) boundaries for the year 2006. Locations of forest product mills and the northern limit of the managed forest area is shown for additional reference. Compare with Fig. 8.

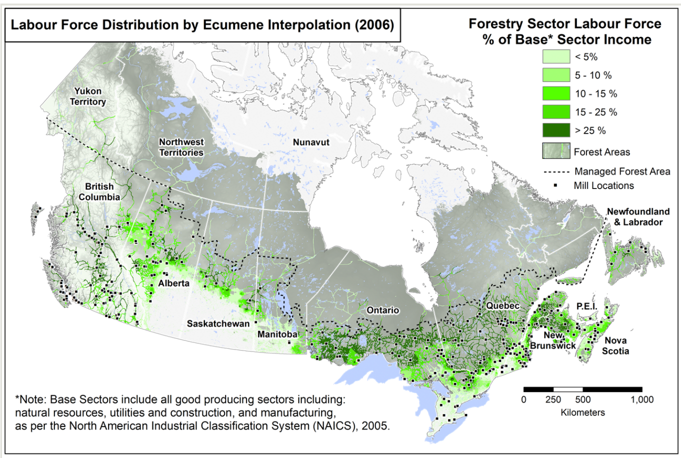

Figure 8.

A spatial interpolation map showing the labour force distribution for the forestry sector using the ecumene framework for the year 2006. Locations of forest product mills and the northern limit of the managed forest area are shown for reference. Compare with Fig. 7.

By comparison, the same data mapped using the ecumene framework in Fig. 8 shows labour force distribution as a more realistic geographical representation. The same labour force data aggregated to forest ecumene communities (as opposed to CSDs) also provides a means for normalization. In this approach, labour force ratios are first calculated for individual ecumene communities, from which a spatial interpolation is applied to map clusters of forest dependency on a regional level. Technical details on the method used for this map are provided in Supplement B (Suppl. material 2). In terms of the result, one pattern worth noting is how the higher dependency values tend to cluster in some regions more than others, notably the southern and central interior of BC, the north-central areas of the prairie provinces, northern Ontario, through Quebec, northern New Brunswick, and western-central Newfoundland. The higher values in these areas are not surprising given these regions follow the southern edge of Canada's forested areas. Although these regions are already well known to be highly dependent on the forest industry, this map makes this knowledge spatially explicit. It reveals relative economic importance of the forest industry in many regions of Canada, and how much regional variation there is in the labour force distribution. An earlier version of this map was used in a national integrated assessment of potential impacts of climate change on Canada's forest sector (NRCan 2016, Ste-Marie et al. 2015) where it is observed that regions with the highest level of forest industry dependency correspond with transitional areas along the southern limit of the boreal forest that are potentially vulnerable to the impacts of climate change (Boulanger et al. 2016).

It is also worth noting that because the ecumene allows for spatial normalization (among provinces) and temporal normalization (across census periods), a series of maps may be generated for each census period, or combined for time-series analysis. In addition, because the formula used is a simple calculation of the labour force income for the forestry sector as a proportion of the total base economic sectors, the same method can be used as a standardized approach for mapping other natural resource sectors such as fisheries, agriculture, mining, and petroleum industries. A series of these maps are provided in Supplement C (Suppl. material 3) for illustration.

Discussion

This paper presents an alternative approach for mapping socio-economic data for ecological applications by using an ecumene as an alternative spatial framework for socio-economic data integration, analysis and mapping. It can be considered an ecological approach due to the manner in which it naturalizes the geospatial representation of human dimensions in ways that mimic mapping characteristics of a natural species distribution, thus extending an ecosystems approach to be more inclusive of human ecology, and vice versa. Whereas both the method and the applications presented in this paper have direct application, we also see this development as a cornerstone for substantive further research. There remain a number of limitations with the specific method presented here, particularly in the Canadian context, that will need to be addressed in future iterations. However, as a general approach, in principle it may be worth consideration for application in other jurisdictions. Some of the benefits and limitations of this approach are summarized in relation to the five requirements outlined in the beginning of this article, and enable identification of several priority areas for further research (discussed in the following section):

1. *Coupled human-natural systems*: using the natural boundaries approach improves the ability to spatially align and integrate socio-economic data for ecological applications. As demonstrated by the two applications above, the ecumene approach improves the flexibility required to identify particular human-environment

relationships. Although the types of human-environment relationships that can be modelled may be limited depending on the scale of application, the ability to spatially visualize and analyse relationships is significantly improved over the use of administrative-type spatial representations. Using the ecumene approach offers the potential to reveal socio-economic patterns that are either directly or indirectly related to characteristics of the surrounding ecosystem in ways that are not attainable through the use of conventional administrative-type frameworks.

2. *Defining of custom study areas*: segmenting and selecting socio-economic data from administrative or census frameworks for irregularly defined study areas is a difficult task and prone to error. As demonstrated in the population analysis in mapping Canada's forest ecumene, re-integrating socio-economic data to individual populated places defined by their natural boundaries and locations allows customized spatial selection of data according to particular application requirements. One limitation with the current version of the database is the scale of the boundaries used to represent individual populated places. Whereas it is currently suitable for regional-national scale applications, some users may find the data limited for more local area applications. A potential solution to this limitation is discussed below as an area for further research.
3. *Multiscalar focus in space and time*: in the case of Canada's census framework, socio-economic data is structurally confined both spatially, due to the rigidity of the spatial framework, and temporally, due to changes in CSDs across census periods. The ecumene approach addresses these constraints by normalizing the data across provinces and census periods. Combined with the ability to define custom study areas (the horizontal dimension), ecumene data can be used to aggregate data to more general scales, or analyzed at different spatial resolutions (the vertical dimension) through interpolation and other spatial statistical analysis methods. However, as with the scale limitations with defining custom study areas, there remain some limitations for local area applications.
4. *Multiperspective modelling*: there are many factors that contribute to different perspectives on human-environment relationships. Most important is setting an appropriate context in terms of the spatial and temporal scale of analysis, and having the ability to upscale and downscale data as needed. There is also some degree of subjectivity involved in defining the context of analysis, and in the terms used. The example applications provided above (e.g. defining 'forest community' or 'economic dependency') illustrate how differences in definitions and viewpoints may be better accommodated.
5. *Multiuser orientation*: closely related to the need for multiperspective modelling, stakeholders with different interests and levels of technical and scientific expertise may need different ways of analyzing and visualizing data, and to transparently examine the effects of associated assumptions and uncertainties in an analysis. To this end, because the ecumene approach naturalizes socio-economic patterns and improves the flexibility in spatial and temporal scaling of data, it provides the potential to enhance learning, communication and understanding among diverse stakeholders.

Further research

The methodology and example applications presented above represent an initial stage of research that provides a cornerstone for further research and development. Given the identified benefits and limitations, priority areas for further research and development include the following:

1. *Mapping local-scale boundaries*: as mentioned above, the current version of the ecumene framework may be limited for use on more local scales depending on the study area of interest. Although the geospatial representation of communities is improved in comparison to the use of CSDs, there remain some differences among provinces due to the inherent lack of normalization among CSDs. Ensuring complete normalization would require compiling more detailed census data and boundaries for ecumene communities based on the level of Dissemination Areas (DAs), which correspond with very local-level boundaries of neighborhoods within the census framework.

2. *Regional Socio-Economic Profiling*: the labour force distribution maps presented in Fig. 8 and in Supplement C provide a basis for a more comprehensive analysis of socio-economic dimensions for each of the five major natural resource sectors in Canada. Further examination of the inter-relationships among sectors in conjunction with relevant ecosystems management issues in different regions could prove to be beneficial.

3. *Advanced Spatial Analysis*: the ecumene approach provides an alternative spatial framework for more advanced spatial analysis research in areas such as hotspot and cluster analysis, exploring spatial auto-correlation among socio-economic variables, and geographic weighted regression. Advancing research in this area offers the potential to yield new insights on the geographical dimension of inter-relationships among socio-economic factors in relation to locational and environmental settings.

4. *Applications Development*: there are a variety of pertinent application areas that may benefit from adopting the ecumene approach including vulnerability assessment, ecosystems services mapping, climate change impact and adaptations, cumulative effects modelling, ecological risk analysis, and sustainable resource management, to name a few. Implementing applications in these areas would provide a useful testing ground for further development and opportunities to support the other priority areas for further research and development.

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Ethics and security

No ethics clearance was required for this research

Conflicts of interest

The authors report no conflicts of interest

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Supplementary materials

Suppl. material 1: Supplement A - GIS Procedure for Population Estimation doi

Authors: Eddy, BG, LeBlanc, R
Data type: Document
Brief description: This file describes the GIS processing procedures for the calculation of population estimates of communities in relation to forest zones.
Download file (465.20 kb)

Suppl. material 2: Supplement B - GIS Procedure for Mapping Labour Force Distribution doi

Authors: Eddy BG, Osmond J, Kean C., Boyd, E
Data type: Document
Brief description: This document describes the GIS processing procedures for mapping labour force distribution maps using the ecumene framework. It applies to the Map shown in Figure 8, and the maps contained in Supplement C.
Download file (808.86 kb)

Suppl. material 3: Supplement C - Labour Force Distribution Maps of Natural Resource Sectors in Canada doi

Authors: Eddy BG, Muggridge M, LeBlanc R, Osmond J, Kean C, Boyd E
Data type: Document
Brief description: This document includes individual labour force distribution maps for the natural resource sectors in Canada. The sectors include Agriculture, Fisheries, Forestry, Minerals, and Petroleum and Coal. Each map shows the average labour force distribution as a proportion of base sector income for the census pereiods 2001-2016.
Download file (2.54 MB)