MULTI-SCALE ASSESSMENT OF POTENTIAL ENVIRONMENTAL PERFORMANCE OF CURRENT AND FUTURE URBAN SYSTEMS IN NEW ZEALAND

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ABSTRACT

Improving environmental performance and sustainability of urban systems requires understanding the opportunities and constraints associated with different types of forms and processes. Form determines the pattern of various urban features and thus the space for and relative proximity of required or desired services. Processes determine the types of services generated. Both operate and interact across a range of spatial and temporal scales and together determine the distribution of services relative to type, amount, location, and rate and length (i.e. sustainability) of generation. Changing either form, process or both can therefore change potential environmental performance by increasing or decreasing the generation and delivery of services across scales. For example dispersed urban forms may require additional energy and resources for transport of services or people. Conversely those same forms may accommodate processes on-site that generate some required services that more compact urban forms would not allow.

Ideally we want as much detail about form and process as possible to evaluate accurately the potential environmental performance of urban systems across a range of scales. Unfortunately detailed information is often limited, particularly at broader spatial and temporal scales. We must therefore rely on linking findings from fine-scale studies to data available at broader scales to try to assess potential performance.

Our study is evaluating methods to upscale measures of environmental performance derived from detailed studies at neighbourhood scales to broader scales (community, city) using commonly available statistical and spatial datasets in New Zealand. We focus on provision of four specific services: energy supply, water supply, carbon sequestration, and food supply. If successful, the method could be applied to many urban areas within New Zealand to evaluate potential environmental performance of existing or future urban forms and processes.

Keywords: environmental performance, multi-scale; New Zealand; urban sustainability

INTRODUCTION

Improving environmental performance and sustainability of urban systems requires understanding the opportunities and constraints associated with different types of forms and processes. Form determines the pattern of various urban features and thus the space for and relative proximity of required or desired services. Processes determine the types of services generated. Both operate and interact across a range of spatial and temporal scales and together determine the distribution of services relative to type, amount, location, and rate and length (i.e. sustainability) of generation. Changing form, process or both can change potential environmental performance by increasing or decreasing the generation and delivery of services across scales. For example dispersed urban forms may require additional electricity and resources for transport of services or people. Conversely those same forms may accommodate processes on-site that generate some required services that more compact urban forms would not allow.

Ghosh and Vale (2006a, submitted) undertook a study to evaluate the potential environment performance of urban systems at the neighborhood scale. Using high-resolution aerial photography and site visits, they compiled information on four different types of residential urban forms (Ghosh 2004) in Auckland New Zealand: low density-low rise, medium density-medium rise, and high density-medium rise. They then estimated the potential for the different forms to accommodate a number of environmental services. They also assessed and compared overall performance among the different forms using both ecological footprint methods and carbon sequestration as comparative frameworks. As might be expected, their results showed that the different residential forms had differing abilities to support different services. Unexpectedly, however, their results also suggested that low density low-rise residential areas, rather then more compact or dense forms, showed the potential to be most sustainable based services evaluated.

The power of Ghosh and Vale's study stemmed from their compilation and evaluation of detailed urban form characteristics that allowed them to quantify and compare specific aspects of environmental performance. Ideally we always want similar levels of detail about both urban form and process to evaluate accurately and comprehensively the environmental performance of urban systems across a range of scales. Unfortunately, detailed information is often limited, particularly as information needs typically increase exponentially as spatial and temporal scales increases. To assess environmental performance at broader scales such as entire cities or even regions, we must rely on linking findings from fine-scales studies with detailed data (e.g. Ghosh and Vale 2006) with coarser data available at broader scales.

Our current study attempts to build on the methods developed by Ghosh and Vale and tries to upscale them to measure potential environmental performance at broader scales such as communities or entire cities within New Zealand. Our approach involves using commonly available statistical and spatial datasets to estimate the potential for providing services across a range of scales. Thus far we have focused on four specific services: electricity supply, water supply, carbon sequestration, and food supply. If successful, the method could be applied to other urban areas to help evaluate potential environmental performance of existing or future urban forms and processes and inform debate on the future development of urban systems within New Zealand.

METHODS

We followed the same methods as Ghosh and Vale (2006) to estimate four aspects of potential environmental performance: electricity supply, water supply, food supply, and carbon sequestration. They calculated energy supply and water supply based on measured effective roof area from actual building footprints and detailed examinations of roof type (form, pitch) and food production and carbon sequestration based on measured amounts of suitable land.

Ghosh and Vale (2006) measured potential performance values for several different urban forms at neighbourhood scales based on detailed mapping from high-resolution aerial photos supplemented by field visits. We extended those methods to evaluate similar aspects of potential environmental performance using a mesh block as our basic unit of measurement (Statistics New Zealand 2007). Mesh blocks represent the finest scale of spatial resolution in New Zealand for reporting census information. Meshblocks vary in spatial extent as a function of population because they attempt to include similar numbers of people and households. In towns and cities where populations are denser, meshblocks are generally smaller. In rural areas with low population density, meshblocks are generally larger. Meshblocks aggregate into area units, and area units aggregate into territorial authorities, which define the boundaries for district/city councils that comprise the lowest tier of government within New Zealand.

Because we lacked detailed data about building footprints and available (i.e. non-impermeable) land area, we used a combination of national spatial and census datasets to estimate values for environmental performance (Table 1). For building footprints we assigned a standard size for each separate dwelling based on the number of bedrooms. The sizes used reflected typical sizes for New Zealand houses built before 2001. To estimate available land area, we first estimated residential meshblock area by combining a number of GIS data layers to identify areas within meshblocks only used for residential purposes (Table 1). We then subtracted the estimated building footprints to obtain available land area as explained further below.

Ideally we wanted all input data to come from approximately the same time period. Therefore we used 2001 census information, even though new 2006 information is now available, for consistency with the spatial data sets that we used in our analyses.

Table 1: Parameters and calculation methods used to estimate potential environmental performance

Parameter	Symbol	Unit	Input Data	Method
Dwelling Area	DA	m^2	# Bedrooms per Dwelling	Estimated area for each separate dwelling (house): 1 Bedroom = 80 m^2 2 Bedrooms = 90 m^2 3 Bedrooms = 100 m^2 4 Bedrooms = 120 m^2 5+ Bedrooms = 140 m^2
Residential Meshblock Area	MA_R	m^2	Census Meshblocks Land Cover Database Topographic Map Features: Residential Areas, Residential Void Polygons, Non-Residential Building Footprints	Identify residential areas within Hamilton and subtract any non-residential uses/covers; overlay with meshblock layer to identify the effective meshblock area
Dwelling Density	DD	Dwellings/ hectare	Census # of dwellings Effective Meshblock Area	$\frac{\#\ of\ dwellings}{effective\ \ meshblock\ area}$

Study Area

The study area comprised the city of Hamilton, located in the North Island of New Zealand approximately 120 km south of Auckland. Hamilton is the 4th largest city in New Zealand, with an estimated population in 2006 of 129,000 (Statistics New Zealand 2007). The city is currently undergoing rapid growth in population and housing, concentrated primarily in the northern end of the city. City planners also encourage densification through targeted zoning throughout the city. This has resulted in the isolated replacement of single family housing with multi-unit housing, usually townhouses of 3-4 dwellings, throughout the city within neighborhoods with existing detached, single-family housing. Additional intensification has also commonly occurred through subdivision that splits lots into and back sections. The existing house is usually retained either in place or moved slightly to accommodate a second house.

Electricity Supply

Ideally we would want detailed information on the footprint, roof type and pitch, and orientation for each building to calculate the effective solar roof area available for solar panel installation (Ghosh and Vale 2006). While such information can be obtained from detailed analyses involving aerial photography and/or visitations, obtaining that information for the over 40,000 dwellings in Hamilton or the over 1,000,000 dwellings in New Zealand would be, while perhaps not theoretically impossible, certainly cost prohibitive at this time.

Instead for each meshblock we estimated the maximum potential electricity supply performance by assuming that the maximum solar roof area (SRA_{max}) equaled the estimated dwelling area and summed over all dwellings in each meshblock. We then transformed those estimates into values for annual electricity generation (*EG*) (Ghosh and Vale 2006).

$$SRA_{\max}\ (m^2) = \sum_{i=1}^{n} DA_i\ (m^2)$$

$$EG\ (Kilowatt - hrs/yr) = SRA_{\max}\ (m^2) \times 100\,(Kilowatt - hrs/m^2/yr)$$

Water Supply

We calculated the potential to replace non-potable water supplied through reticulation with water stored on site in rain tanks using a combination of census data and climate data (Leathwick et al. 2002). Hamilton City Council estimates daily per capita use at 230 litres, of which ~225 liters is for non-potable uses such as gardening, washing clothes, etc. Therefore a typical Hamiltonian uses 225 liters/day x 365 days = 82,125 liters per year of water. Rainfall in Hamilton averages approximately 1250 mm per year, which yields an average potential rainwater supply of 1,250 liters/m^2 of roof area. Therefore a common 100m^2 house in Hamilton could theoretically supply 125,000 liters of water per year or approximately 38% of the non-potable requirements of a 4-person household assuming 100% efficiency. We assumed 85% efficiency based on other studies of rain tank collection systems (Vale and Vale 2006).

We estimated average water supply (WS_{avg}) for each meshblock as follows:

$$WS_{avg}\ (litres) = 0.85 \times \sum_{i=1}^{n} DA_i\,(m^2) \times 1{,}250\,(liters/m^2)$$

Food Supply & Carbon Sequestration

To estimate the maximum supply of productive area (PA_{max}) available for growing food for consumption or planting for carbon sequestration, we subtracted the total dwelling area from the residential meshblock area (Table 1)

$$PA_{\max}\ (m^2) = MA_R\,(m^2) - \sum_{i=1}^{n} DA_i\,(m^2)$$

As PA_{max} does not consider space allocated to sidewalks, driveways, garages, decks, patios, or other area not available for either food production or plantings, we further generated a high, medium, and low estimate for productive area (PA_{High}, PA_{Med}, PA_{Low}) assuming that 75%, 50%, and 25% of PA_{max} was actually suitable. Also we did not consider opportunities for collective or community gardening on public or private land. For carbon sequestration we did not include opportunities for carbon sequestration from plantings on public land, such as parks or gardens, although we did report on the total area of urban parkland and open space in Hamilton.

RESULTS

In the 2001 census Hamilton City comprised 924 meshblocks and 40 area units over a total area of 9,427 hectares. Meshblocks ranged in size from a minimum of 0.38 to a maximum of 414 ha.

Just over half of Hamilton was urban or built-up area, with high producing exotic grassland concentrated in both the northern and southern portions of the city accounting for one third total area (Table 2).

Table 2: Area (ha) of LCDB2 land cover in Hamilton City

Land Cover Class	Area	Land Cover Class	Area
Built-up Area	4,996	Major Shelterbelts	8
Afforestation	2	Manuka/Kanuka	11
Broadleaved Indigenous Hardwoods	94	Orchard & Perennial Crops	29
Deciduous Hardwoods	7	Other Exotic Forest	28
Forest Harvested	8	Pine Forest - Closed Canopy	1
Gorse & Broom	5	River	134
High Producing Exotic Grassland	2,934	Short-rotation Cropland	51
Indigenous Forest	123	Urban Parkland & Open Space	906
Lake and Pond	62		

Estimated Dwelling Area

The census reported on three dwelling types: private separate house, private other, and non-private other (Table 3). Due to random rounding to base 3 required by statute for reporting census data at the meshblock level, some low values for dwelling types may not be reported. Private Other and Non-private Other consisted of townhouses, apartment buildings, retirement villages, student housing, apartments above commercial buildings, or other multi-unit building types. From personal knowledge and an inspection of the data, primarily by comparing the ratio of Private Other to Total Dwellings and dwelling density, we could readily locate meshblocks containing either a mixture of houses and other dwellings or entirely other dwellings (i.e. no houses). However we lacked any methods to estimate dwelling area based solely on census information given the potential variability in building type. Therefore we concentrated our analysis only on private separate houses.

Table 3: Summary Statistics on Reported Dwellings by Meshblock

# of Dwellings	# of Meshblocks	Minimum	Maximum
Total = 0	48	-	-
Total ≥ 3	876	3	240
Private Separate House	840	0	216
Private Other	840	0	135
Non-private Other	840	0	6
Density*	876	0.02	32.37

*Dwellings/hectare

For meshblocks with mixed dwelling types, the number of dwellings reported with 1 or 2 bedrooms declined with a decreasing percentage of Private Other dwelling types. This indicated that dwellings other than Private Separate Houses tended to have fewer, typically 1 or 2, bedrooms. Therefore in meshblocks with both Private Separate Houses and Private Other (Non-private Other being very rare), we assigned the higher number of bedrooms to Private Separate Houses when calculating dwelling areas. For example, in a meshblock with 15 private dwellings consisting of 12 Private Separate Houses and 3 Private Others and a reported distribution of 3 2-bedrooms, 9 3-bedrooms, and 3 4-bedrooms, we assumed that the 12 Private Separate Houses comprised the 3- and 4-bedroom dwellings reported.

Total dwelling area by meshblock ranged from 0 to 22,770 m^2 (22.8 ha) per meshblock (Figure 1). , As a percentage of total meshblock area, dwelling area varied from 0% to a maximum of 13.7% of the total meshblock area. Residential meshblock area varied from 0 to 97,819 m^2 (9.8 ha) per meshblock (Figure 1). Estimates for dwelling area and residential area generally agreed such that meshblocks with higher numbers of private separate houses had larger areas. However two particular cases showed high disagreement. Many meshblocks with no reported dwellings, either Private Separate House or Private Other, showed corresponding residential area. For example, Claudelands Park, a large public park and events centre in central Hamilton, has no reported dwellings but reported residential area. Conversely many meshblocks in the northern part of the city, where rapid growth has occurred over the past 10 years, had relatively little residential area. The slightly older (2000) topographic data characterising residential areas compared to the 2001 census data consistently underestimated such residential area because it had not "caught up" with the rapid urban expansion. This highlighted how quickly residential areas are expanding in that part of Hamilton.

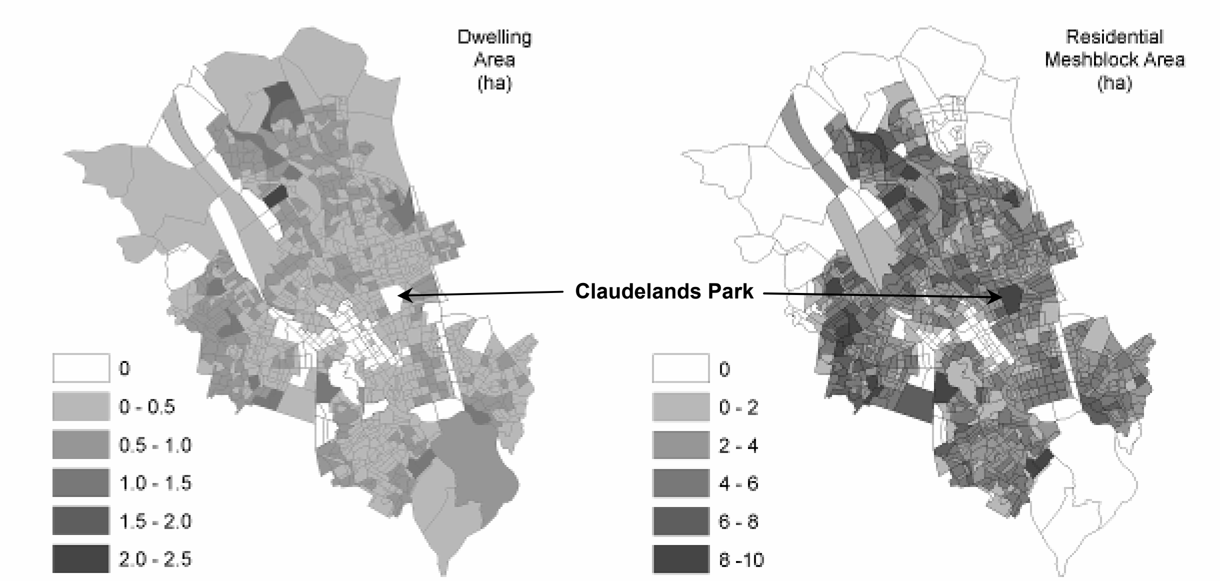

Figure 1: Estimated dwelling area for Private Separate Houses and residential area by meshblock.

Electricity Supply and Water Supply

Electricity supply and water supply were both functions of total dwelling area. Potential maximum electricity supply assuming entire roof coverage of solar panels ranged from 0 for no Separate Private Dwellings to 2,277 kilowatt-hours per year (Figure 2). The maximum supply for the city was estimated at 296,865,000 kilowatt-hours per year. As typically less than 20% of New Zealand roof areas is suitable for solar panels (Ghosh & Vale 2006, Vale and Vale 2006), estimated potential electricity supply should be reduced accordingly to approximately 59,373,000 kilowatt-hours per year. Water supply, assuming 85% efficiency varied from 0 to a maximum of 24,193 thousand-liters per year. Total potential city water supply from Separate Private Dwellings was 3,154,000 thousand-liters per year.

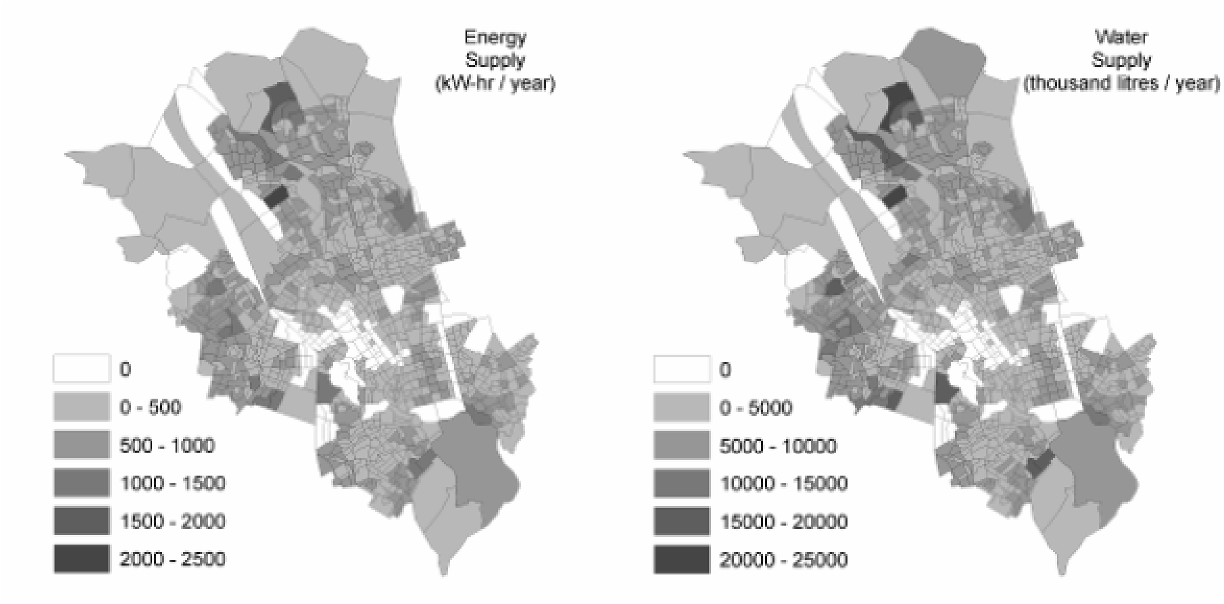

Figure 2: Estimated maximum electricity supply and water supply for Private Separate Houses by meshblock.

Productive Area

Potential productive area ranged from 0 to 8.6 ha across meshblocks (Figure 3). Total potential productive area was 2,517 ha for the maximum case and 1,888, 1,259, and 629 ha respectively for the high, medium and low cases. Because the analysis did not consider Private Other or Non-Private Other dwellings or account for other impervious surfaces (garages, decks, patios, sidewalks, etc.) other then roads, the medium and low cases likely provide the more realistic estimates of productive area. In fact, the low case assuming 25% of maximum area probably represents the most realistic estimate, as the total also do not include the ~3,000 ha remaining in non-urban areas based on land cover data as of 2001/2002. However those remaining areas have and will continue to experience rapid urbanisation as Hamilton continues to expand to the north and eventually to the south as well.

DISCUSSION

This paper provided estimates for four aspects of potential environmental performance for an entire city (Hamilton, New Zealand) based on methods developed at neighborhood scales and using census and spatial datasets that are either relatively inexpensive or free in the case of census data. Below we discuss the strengths and weaknesses of the approach, including discussing possible ways to improve the quality of the analysis and its results. Lastly we discuss the concept of potential performance in more detail and the possible implications for current and future urban systems within New Zealand.

Strengths and Limitations of the Approach

Clearly our approach has a number of limitations related to the data and the methods. The main limitation was our inability to assess the status of Private Other and Non-Private Other dwellings. Unlike Private Separate Houses where we could infer an area based on an observed relationship between total area and number of reported bedrooms, the census lacked information to estimate the configuration and therefore

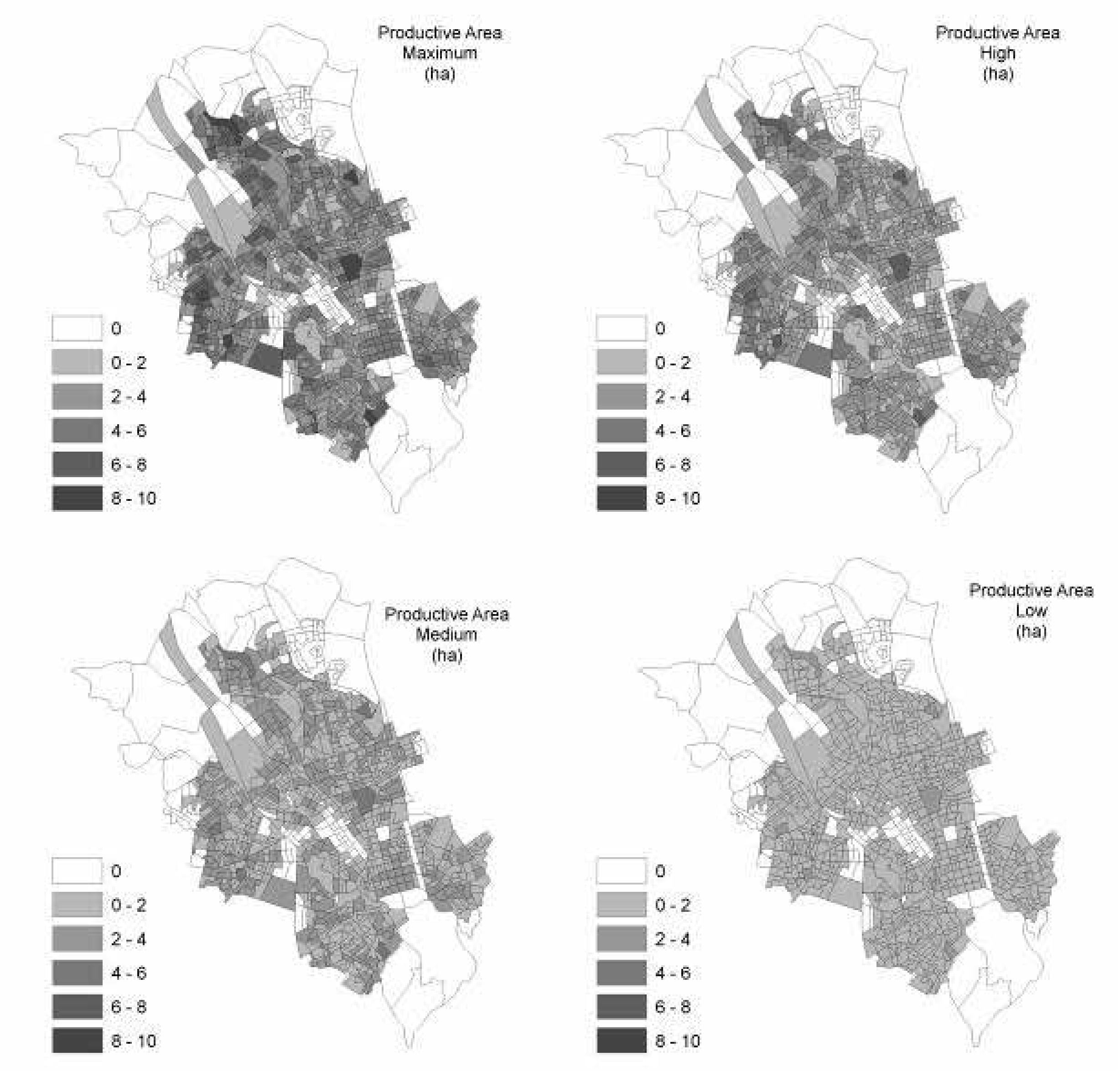

Figure 3: Estimated productive area supply by meshblock.

sizes of multi-unit dwellings like townhouses, apartments, etc. We also could not evaluate the potential performance of dwellings in predominantly commercial areas. At this stage, we see no other recourse but to obtain additional information to fill the gap. The lack of data on the two non-house dwelling types clearly affected our estimates of dwelling area (underestimate) and therefore electricity supply (underestimate), water supply (underestimate), and maximum productive land (overestimate). In the future we could explore using the total number of reported bedrooms by meshblock for both non-house dwelling types as an index of uncertainty or error, although obtaining dwelling area data from alternate sources will negate the need produce such an index.

A second limitation stemmed from our simple relationship between bedrooms and dwelling area for Private Separate Houses. Thus estimates for individual meshblocks will vary from our estimates, in some cases significantly, although our sample size of 30,000+ houses in Hamilton helps the accuracy of the aggregated city estimates. To improve dwelling area estimates for Private Separate Houses, we could combine statistics on number of rooms per dwelling provided by the census with number of bedrooms to generate a more accurate distribution of house types (e.g., 4-6 room/2 bedroom, 3-7 room/3 bedroom). Also we know that New Zealand house sizes have increased over time, so we could investigate using historical census data to determine age classes for dwellings and adjust area upwards for newer houses.

A third limitation related to the spatial data sets used to estimate residential area and therefore productive area. Our basis for residential area consisted of several GIS layers from a digital topographic map dataset. This dataset included a base layer outlining residential areas, from which we subtracted areas in a "residential void" layer and commercial buildings layer. We relied on the interpretation of residential areas provided in those data layers, even though we identified several cases where land was non strictly residential, such as areas in Claudelands Park (Figure 1). Also the topographic map series came from 2000, and therefore was slightly out-of-date compared to the census information. This resulted in a significant underestimate for residential area for meshblocks experiencing recent urban growth. For further analyses we plan to use the most up-to-date spatial data available.

The key strength of our approach was its reliance on readily-available, national datasets versus the need to obtain (i.e. purchase) and analyze more detailed information at a specific location. Our reliance on these national datasets yields benefits in terms of consistency, comparability, and scalability. Our methods could be applied anywhere within New Zealand, allowing for rapid generation of consistent and comparable results. They could be aggregated or disaggregated as needed to support various planning or reporting purposes under a range of jurisdictions. Also the use of spatial data and the generation of associated maps generate a broader context that both provides a sense of place and helps explicitly connect the results of individual action to broader aggregate outcomes. Making such connections will be important for fostering improved environmental performance in the long term (Frame and Vale 2006).

The second strength (and also a weakness, see above) comes from the relatively straightforward methods used to estimate environmental performance. Our current methods use basic algorithms to calculate the values required to estimate performance. Therefore they should be relatively easy to describe, understand, and communicate, which is particularly important if they supported policy or planning. Similar to our data needs, we could develop more detailed models or methods for estimating the various aspects of environmental performance. For example, we possess fine-scaled maps of solar radiation by month, digital elevation models that we could use to develop a more sophisticated algorithm for electricity generation that considers both seasonal and diurnal variation in available solar radiation, incorporates aspects of shading and elevation/aspects, etc. Whether more sophisticated methods would improve the overall result or help achieve desired outcomes would require further investigation.

The third strength of the approach lies in the attempt to quantify potential performance. This has two important aspects. First the use of quantitative versus qualitative measures (e.g., energy star scheme) forces explicit consideration of scales and limits, which allows for more robust discussion and debate over what constitutes acceptable performance and what is/is not sustainable (Gabe and Vale 2008). Second the emphasis on potential performance conveys a positive message of what could be achieved rather than dwelling on how bad things may currently be.

Potential Performance and Implications for Current and Future Urban Systems

In urban systems, performance depends on patterns (i.e. urban form), processes, and behaviors operating together across many scales of interest. Potential performance defines the range or envelope of possible values that result from different combinations of form/pattern, process, and behavior. Evaluating potential performance requires stating the type and degree to which any of those three factors can change to alter performance. In urban areas the level of investment and long lifespan of most infrastructure means that urban form, once established, becomes relatively fixed barring major capital investments to change it. In cities undergoing substantial growth such as Hamilton, opportunities to change environmental performance result from a mixture of incremental changes in established areas with relatively fixed form and in greenfield or brownfield areas that offer more flexibility to change form. In the former, key opportunities for changing performance will result from changes in process and behavior rather than form.

In our study, we evaluated potential performance allowing for 1) no change to urban form, 2) potential change through the installation of particular building subsystems (i.e. solar panels, rain tanks) and 3) potential change to undertake food production or carbon sequestration on available land. Similar to Ghosh and Vale (2006), we wanted to explore the implications to environmental performance resulting from the accumulation of relatively modest individual process and behaviour changes, albeit at the broader city scale rather than the neighborhood scale, and evaluate the magnitude and implications of those potential changes for the broader city system.

Based on the results of our study, we estimated that approximately 25% and 30% of the annual electricity and water demands, respectively, of private dwellings could be supplied from on-site generation processes. On average 195m^2 of land was available for either food production, which also reduces carbon emissions compared to off-site food production, or plantings for carbon sequestration (Table 4). What do these results mean for the city of Hamilton both now and for future growth? That is a complex question that depends on a number of factors. Below we briefly discuss those factors for each aspect of performance considered within the broader context of sustainable urban systems.

Table 4: Estimated supply and demand of electricity, water, and land for private houses in Hamilton (n = 32,268 houses[1])

		Hamilton	Per House		
	Units	Estimated Annual Supply	Estimated Annual Supply	Estimated Annual Demand	% Demand Met
Electricity	kilowatt-hrs	59,373,000	1,840	7,245[2]	25
Water	thousand litres	3,154,000	97,700	328,500[3]	30
Land	ha	629	0.0195 or 195m^2	Varies	Varies
Land - Food	tonnes CO$_2$	8,152[4]	0.253	Varies	Varies
Land - Planting	tonnes CO$_2$	1,019[5]	0.032	Varies	Varies

[1] Only 32,088 houses were used to generate the estimates due to methodological constraints
[2] 10,500 kilowatt-hrs per year per house * 0.69 electricity share (http:www.level.org.nz/energy)
[3] Assumes 4 persons per house
[4] 629 ha x 12.96 tonnes /ha/ yr (Ghosh 2004)
[5] 629 ha x 1.63 tonnes/ha/yr (Ghosh 2004)

Regarding electricity, New Zealand is fortunate by global standards in that ~60% of its electricity comes from renewable sources (i.e. hydropower, geothermal, wind). A sustainable energy strategy would aim to reduce overall demand by 40% to match renewable supply levels and then only allow increases at the same rate as renewable levels increased. Our calculations estimated that potential on-site supply could reduce off-site demand by 25%, which represents 62% of the overall reduction target. Considering we assumed a very low (20%) ratio of solar efficient roof area, increasing those areas would further reduce demand, at least for private houses. More likely a combined strategy of on-site supply via solar panels and energy efficiency improvements via renovations (e.g., Vale and Vale 2006) would be the most realistic in established areas. New developments or subdivisions could clearly take advantage of substantial knowledge in sustainable building and low-impact design (e.g., passive design, proper building orientation, etc). to minimise demand for off-site electricity or even reduce it to zero.

Regarding water, Hamilton city takes its water supply from the Waikato River. In addition to supplying water for domestic uses, the river also supplies agricultural users, supplies electricity through a series of hydroelectric dams, and supports many recreational uses. Irrigation demand for water is expected to double by 2010 and domestic and community demand will continue to increase due to continuing population growth (Environment Waikato 2006). Our calculations estimated that on-site supply could meet 30% of demand in established areas. On-site supply could increase further if other roof areas (i.e., garages, carports) also supported water collection. Additional reductions could also clearly come from behaviour changes or other process changes, such as greywater recycling, which we did not explicitly consider in our analysis. Similar to electricity, new developments could take advantage low-impact urban design principles to generate, store, and treat water on site as much as possible. Regardless how the environmental performance of water supply is improved, a sustainable strategy clearly requires maintaining or reducing demand in the face of static supply.

Regarding the land, the options are the most numerous. Our calculations estimated a potential productive area of 195m^2 per house. On site food production would meet a portion of human nutrition requirements, although exactly what level depends on what is grown. Gerbens-Leenes et al. estimated that 3,420 m^2 of land was required in the Netherlands to feed an average household of 2.41 persons a varied diet including meat for a year. Assuming the same applies in New Zealand, estimated potential productive area would meet 5% of annual nutrition needs. Even assuming much greater efficiency or yield, on-site food production would be unlikely to ever contribute more than 10 or 20% of dietary needs. Producing food on-site would have the co-benefit of reducing carbon emissions compared to off-site production (Ghosh 2004), while plantings could be undertaken for direct carbon sequestration (Table 4).

The discussions above highlight the potentially large environmental performance gains that could be achieved through the collective action of many individuals or households at very local scales, i.e. the house scale. Such changes represent relatively minor alterations to urban systems when compared to the full range of options available to improve environmental performance. When coupled with changes to processes and urban form at broader scales, they could yield even greater benefits. Nonetheless the changes also are not trivial. They require financial and personal commitments by individuals to achieve and in some cases represent substantial hurdles to change. Somehow we must learn how to overcome or remove those hurdles and modify our urban systems to make them more sustainable.

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