EXPANSION AND DENSIFICATION OF CITIES: LINKING URBAN FORM TO URBAN ECOLOGY

Nahid Mohajeri[1*], Agust Gudmundsson[2], Jean-Louis Scartezzini[1]

[1]Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland, e-mails: nahid.mohajeri@epfl.ch; jean-louis.scartezzini@epfl.ch

[2]Department of Earth Sciences, Queen's Building, Royal Holloway University of London, Egham TW 20 0EX, UK. E-mail: a.gudmundsson@es.rhul.ac.uk

**Corresponding author. E-mail: nahid.mohajeri@epfl.ch*

ABSTRACT

Despite much research on the ecological impacts of urbanization, we still do not know what development patterns are most effective in supporting ecological function. In particular, it is as yet unclear if compact urban forms are ecologically more favourable than dispersed forms. Using historical data from the city of Geneva in Switzerland, we present results on its growth from 1841 to 2005, or for 165 years. We first show that the main street orientations have been maintained since the initiation of the city, which implies that the Shannon-Gibbs orientation entropy has been essentially constant during this period. We also show that the length-size distributions of the streets follow power laws and that the length entropy has, in contrast to the orientation entropy, gradually increased during the 165-year evolution of the city. This means that the maximum length and the average length of the street network has increased as the network has expanded. This study suggests that the city of Geneva has grown through two processes: expansion and densification. In Geneva, expansion has dominated during the entire period, but there has also been densification, particularly in the second half of the period. City expansion means that the land used for human activities increases over time. The urban area covered by Geneva increased from about 0.6 km^2 in 1841 to about 16 km^2 today, so that the area covered by fields and woodlands and available to plants and animals has reduced by more than 15 km^2 during this period. Similarly, densification normally (but not always) implies that the green areas available for plants and animal inside the city reduce in size. Densification results in less average human-travel distances, less fuel consumption for transportation, and less land being urbanized; it is also favourable to certain aspects of the ecosystem. Densification may thus be a viable planning scenario for the future growth of many cities, in Switzerland and elsewhere. However, expansion appears to favour other aspects of the ecosystem, and further studies are needed to assess ecologically the overall pros and cons of city densification versus expansion.

Keywords: Urban Ecology, Size, Scaling, Spatial distribution, Urban growth

INTRODUCTION

Rapid urban expansion and associated land cover changes have strong impact on the ecosystem (e.g., biodiversity). In Switzerland, urban growth has been rapid. In 1930, less than 36% of its population was urban (the majority being rural), whereas by 2011 74% of the population was living in urban areas. The forecast is that by 2050 more than 83% of the Switzerland population will be urban [1].

Given the current high rate of growth of cities worldwide, it is of great importance to minimise the negative ecological effects of the growth. This means that we should design city growth so as to make efficient use of land and aim at sustaining the ecosystem and promote biodiversity. To accommodate increasing urban population, cities can grow primarily through two processes or mechanisms: densification and expansion. Densification means adding build-up areas, primarily streets but also houses, within the existing boundaries of the city. By contrast, expansion means adding new urban areas at the margin, that is, at the present boundary, of the city.

These two different mechanisms of growth have different urban and ecological implications which are here explored with reference to the evolution of the city of Geneva, Switzerland, during the past 165 years. In particular, we show that both mechanisms have operated during this period, but one has been the more dominating. We put the results from Geneva into a wider context of city growth and discuss the implication of the results for further growth of cities in general, and those in Switzerland in particular.

The purpose of this paper is to present new data on how cities grow, with a particular focus on the evolution of the street network of the city of Geneva over the past 165 years. The results as to the street network are then related to the general population growth during the same period, as well as the mechanisms of expansion and densification. These mechanisms are then discussed in the context of their ecological implications with a view of suggesting viable designs for further urban expansion in Switzerland and elsewhere.

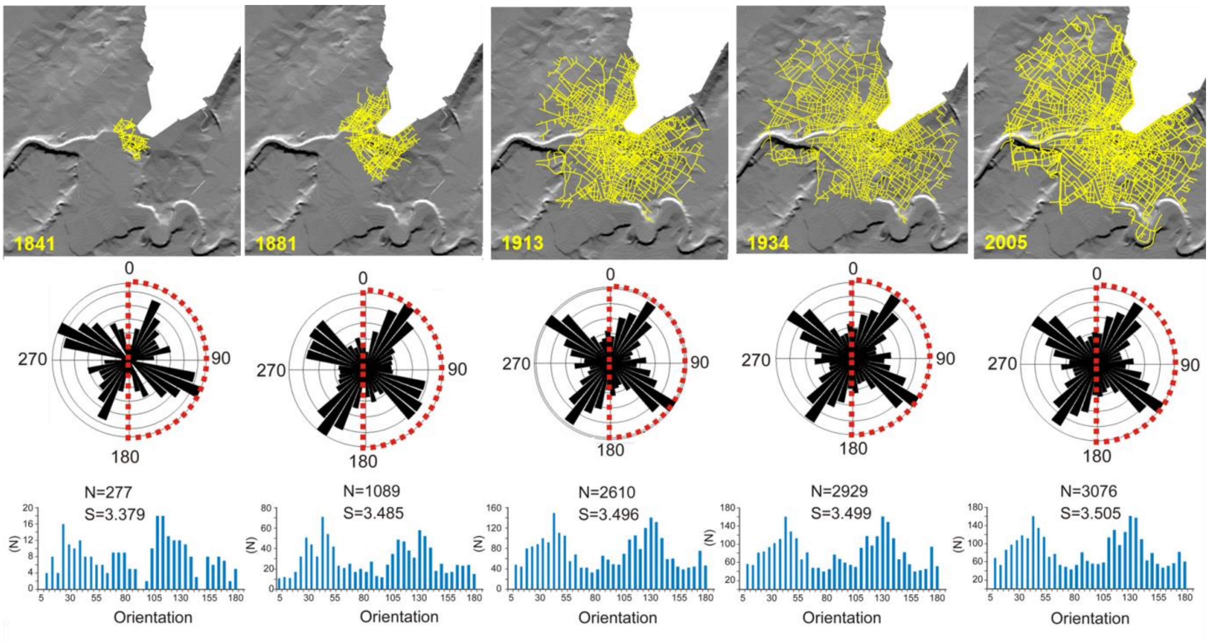

Figure 1: Growth of the street network of Geneva from 1841 to 2005. Rose diagrams and histograms show the orientation of the streets. N = number of streets; S = orientation entropy.

THE STREET NETWOKR OF GENEVA

Over a period of 165 years, the street network of Geneva has greatly expanded (Figure 1). In 1841 the total street network comprised 277 streets, whereas in 2005 (the last update) the network comprised 3076 streets. Thus, during this period the number of streets increased by a factor of about 11. During the same period, the area covered by the street network and the city increased from about 0.6 km^2 to about 16 km^2, showing that the area has grown by a factor of about 27, that is much more than the number of streets.

The street network has certain remarkable characteristics (Figure 1). First, at its initiation (in 1841) the streets had two main orientations or directions, a NW-direction and an ENE-direction. These two main directions have been maintained through the city development for 165 years. This is seen in the rose diagrams and histograms in Figure 1. As a consequence, the street-orientation entropy – a measure of dispersal or spreading in orientation or azimuth – has been essentially the same during the enormous growth of the city over the 165 years.

Second, all the length-size distributions of the streets during this period are power laws (Figure 2). This means that most of the streets are comparatively short while a few are comparatively long. As the street network has grown, the length of the longest streets has increases, and so has the length range of the streets. This means that while the shortest streets of the network at any time are of similar length, the longest streets have become gradually longer as the network evolved. Thus, in contrast with the street-orientation entropy which has remained essentially constant during the network evolution (Figure 1), the street-length entropy, a measure of the length range and thus the average length, has gradually increased during the growth of the network (Figure 2). This implies that as the street network grew, the average length of the streets, hence the length-entropy, increased.

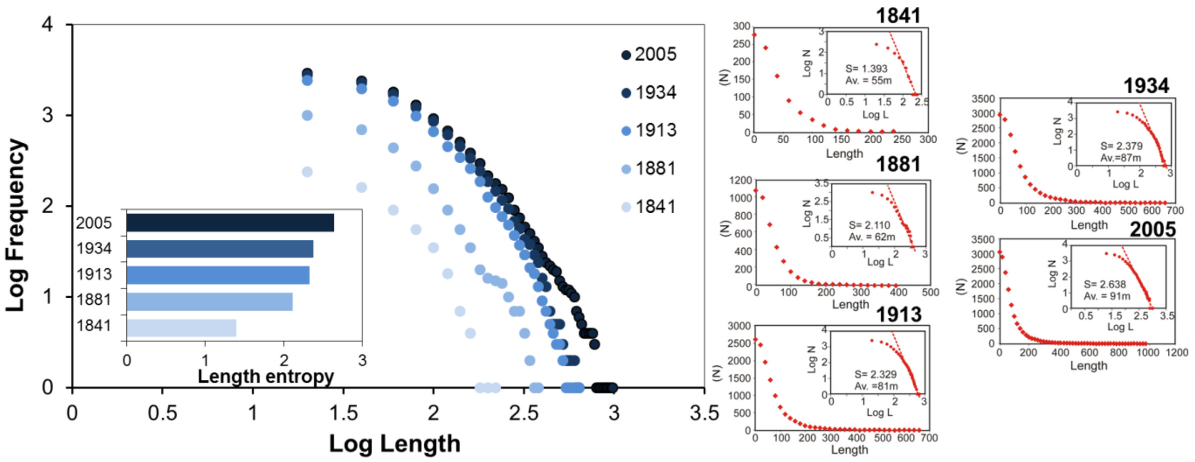

Figure 2: Power-law length-size distribution of streets in Geneva during the period 1841-2005. The length distributions are shown on log-log (log-transformed) plots (left) and ordinary plots (right). The length entropy increase over the period is indicated on the inset.

The third remarkable feature of the street network evolution is that its growth has not always gone hand in hand with the population growth. For Geneva the population growth during the 165-year period has been rather steady whereas the street network has grown more irregularly (in steps) as indicated by the cumulative length of the network (Figure 3). In particular, there was a very rapid growth in the cumulative length of the street network from 1881 to 1913, and to a lesser extent from 1913 to 1934. Since that time the cumulative street length has grown at a slower rate than the population. One reason for this difference in the growth rate of the street network and the associated population is that a street network must reach a certain minimum size, here measured as the cumulative street length, to interconnect the entire city. The network grows in steps for this interconnection to be possible. After the rapid growth from 1881 to 1934, the network was very large in relation to the population, and thus far from used to its full transport capacity. From then on the rate of population growth has been faster than that of the street network, simply because the capacity of the network was so large after 1934 that it could, theoretically, serve a much larger population. So gradually, the population is 'catching up' with the street network.

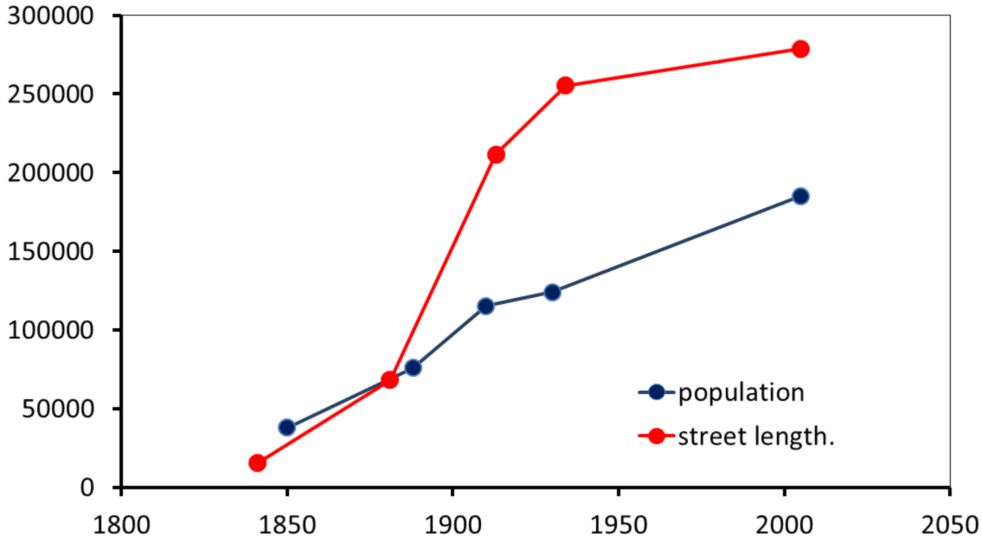

Figure 3: Population growth (number of people, blue curve) and cumulative street length growth (in metres, red curve) in Geneva from 1841-2005.

DENSIFICATION AND EXPANSION – ECOLOGICAL IMPACT

The street network of Geneva has grown through two main mechanisms during the 165-year period: expansion and densification. The results (Figure 4) show that in all the measured periods expansion has dominated. However, in the past 100 years, the contribution of densification is clearly greater than earlier in the history of the city. Expansion means that the land covered by the network and almost entirely used for human activities gradually increases, as is reflected in the area covered by the city increasing from 0.6 km^2 to about 16 km^2 over the 165-year period. It follows that the area covered by fields and woodlands and available to plants and animals has reduced by nearly 15 km^2 during this period.

Densification have different ecological effects in that less fraction of the rural area, with fields and woodlands, is made urban (and thus covered by streets and buildings). Normally, densification implies that the green areas available for plants and animal inside the city reduce in size. However, a densified or compact city commonly has shorter average transport distances for its inhabitants, so that there may be less fuel demand and normally less CO_2 emissions per capita than in more dispersed or spread cities [2].

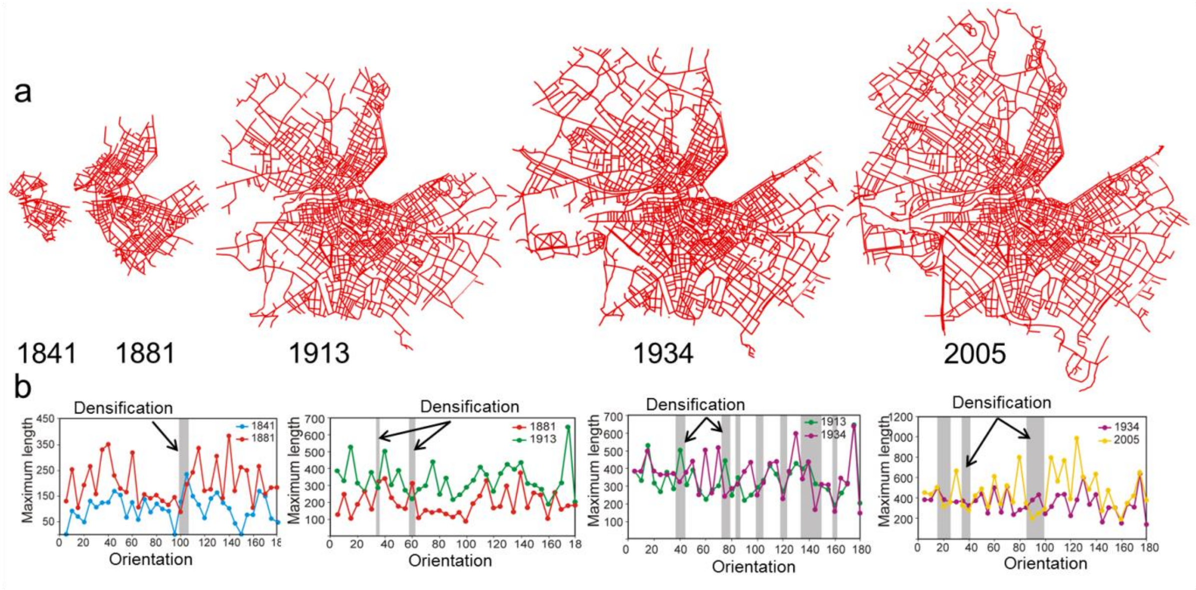

Figure 4: (a) Evolution of the street network of Geneva from 1841 to 2005. (b) Densification (grey zones) and expansion (white zones) during the evolution of the street network.

Compact cities are commonly thought to be marked by biodiversity decrease [3, 4]. There is, however, also some evidence for biodiversity increase. For example, in a study of cities in Switzerland, Home et al. [5] conclude that cities are the sites of high biodiversity. Their conclusion is partly based on the ecological effects of heat islands (the city temperatures being higher than in the surrounding rural areas), and partly on the fact that cities provide the sites for a variety of imported exotic plants and animals that can thrive in the urban ecosystem but could not do so in its rural surroundings. This conclusion applies particularly to various thermophilous plants and animals that prefer urban systems. More general studies suggest that biodiversity reaches its peak at 'medium' or moderate urbanization, that is, in suburban areas (and thus not in very compact areas). By contrast, the biomass may be highest in the highly urbanized, that is, compact areas [6]. Clearly more quantitative studies are needed so as to explore not only the exact ecological impacts of different urban forms and densities (urban compactness) but also how the impact may change from one place to another, within cities and between cities.

DISCUSSION AND CONCLUSIONS

The effects of densification (resulting in city compactness) and expansion (resulting in city dispersal or spreading) have been the principal mechanisms of the growth of the city of Geneva during the past 165 years (Figures 1 and 4). The same mechanisms and street-network structures have been identified in many other cities in countries such as the Britain and Iran [7]. Like in Geneva, expansion is the most common mechanism of growth in these cities, but during certain periods densification may dominate. The results from Geneva, however, show some aspects of city growth that have not been identified before. One of these is the observation that the rate of population increase may 'lag behind' the rate of street-network increase (Figure 3). While there may be clear reasons for such rate differences, they are presumably costly and avoidable to a large degree with proper modern planning.

Given that densification results in more compact cities, with less average human-travel distances and less land being urbanized, making cities more compact may be a viable planning scenario for city growth in various countries, including Switzerland. Compact cities may also be generally more energy efficient than disperse cities [8]. One major issue, however, is the impact of urban densification in comparison with expansion on the urban ecosystem. Increasing land fragmentation and less green areas within compact cities may have negative impact on habitats and biodiversity. Biodiversity loss is widely regarded as making the ecosystem more vulnerable [4]. Also, there are indications that the greatest biodiversity occurs at the margins of the urban areas, where the suburbs and the rural areas meet and where many heat-seeking plants and animals may live (heat-island effects) while being unable to survive in the rural areas themselves. Since such areas are generally proportionally larger the more spread (less compact) the city, this indication would favour city growth through expansion. In addition, it has been suggested that the urban biodiversity reaches its peak at a 'medium' or moderate urbanism, and then declines with higher urbanism or more compact cities [6].

In conclusion, efficient use of energy and land may favour densification and compact cities. Densification may also favour some aspects of the general ecosystem, while other aspects of the ecosystem are better served through expansion as the main mechanism of city growth.

ACKNOWLEDGEMENT

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REFERENCES

1. Swiss Federal Statistical Office (SFSO). Neuchâtel, Switzerland, 2013.
2. Makido, Y., Dhakal, S., Yamagata, Y.: Relationship between urban form and CO_2 emissions: Evidence from fifty Japanese cities. Urban Climate 2, 55–67, 2012.
3. Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M.: Global change and the ecology of cities. Science 319, 756-760, 2008.
4. MacDougall, A.S., McCann1, K. S. Gellner, G., Turkington, R.: Diversity loss with persistent human disturbance increases vulnerability to ecosystem collapse. Nature 494, 86- 90, 2013.
5. Home, R., Moretti, M., Sattler, T. Bauer, N., Hunziker, M.: BiodiverCity, A transdisciplinary approach to urban ecology, in Macias, A. & Mizgajski, A., (eds.) Implementation of landscape knowledge in practice, Wydawnictwo Naukowe UAM, Poznan, pp. 134-140, 2010.
6. Adler, F.R., Tanner, C.J.: Urban ecosystems. Cambridge University Press, Cambridge, 2013.
7. Mohajeri, N., Gudmundsson, A.: The evolution and complexity of urban street networks. Geographical Analysis 46, 345–367, 2014.
8. Mohajeri, N., Gudmundsson, A., Scartezzini, J.L. Statistical-thermodynamics modelling of the built environment in relation to urban ecology. Ecological Modelling 307, 32-47, 2015.