Modelling and Mapping Urban Soils

J.J. Stoorvogel[1], I. van Manen[1], and V. Vasenev

[1] Wageningen University, Soil Geography and Landscape Group, Wageningen, The Netherlands
[2] Agrarian-Technological Institute, Peoples' Friendship University of Russia, 117198, Miklukho-Maklaya str., 6, Moscow, Russia

Jetse.Stoorvogel@wur.nl

Abstract. Urbanization is an important trend in global land cover change and seriously impacts the soil resources. However, there is no clear definition for urban areas. As a result estimates of urbanization and its effects on soil resources vary widely. Urbanization can be modelled in different ways with a specific focus on environmental conditions, temporal dynamics and spatial patterns. The processes underlying urbanization require a hybrid approach that combines the different methods. Similarly, the unique conditions of the urban environment require specific surveying techniques for the soil resources. The global debate on urbanization and its environmental impacts calls for a rapid standardization of definitions and methodologies to come with proper information on rates and impacts.

Keywords: Soil survey, Land cover modelling, soil classification

1 Introduction

National soil surveys often excluded the urban areas despite the fact that it was clear that soil surveys could contribute to urban planning. The Soil Survey Manual (Soil Survey Division Staff, 1993) recommended urban areas to be mapped intensively with 2nd order at scales between 1:12:000 and 1:31,000. However, many soil surveys aimed at agricultural development or forestry and excluded the urban areas (Figure 1). Over the past decades the interest of the surveyors clearly changed and with a new focus on environmental impacts and carbon sequestration, the need for a better insight in soil resources is now being recognized. Soil classifications are now adapted to include the anthropogenically changed soils. The Soil Taxonomy (Soil Survey Staff, 1994) was updated on the basis of the recommendations of the International Committee on Anthropogenic Soils (ICOMANTH) to include an Anthropic Epipedon but also a range of different subgroups for human-altered and human-transported soils: the Anthraquic subgroup for irrigated rice fields, the Anthrodensic subgroup for compacted soils, the Anthropic subgroup for soils with artefacts, the (Happlo-)plaggic subgroups for soils with a plaggen epipedon, The Anthroportic subgroup for soils with human-transported material, and the Anthraltic subgroup for soils developed in human-altered topsoils. Also the World Reference Base for soil resources (IUSS Working Group WRB, 2015) was updated and now includes various anthropogenic diagnostic horizons like the Anthraquic and Hydragric horizons for paddy soils and the Hortic horizon for enriched topsoils but also at the highest level with the definition of Anthrosols and Technosols. However, although the soil classification has been adapted, very little attention has been paid to modelling and mapping of urban soils. This chapter aims to further explore the main issues related to modelling the expansion of urban areas and mapping soils in urban areas.

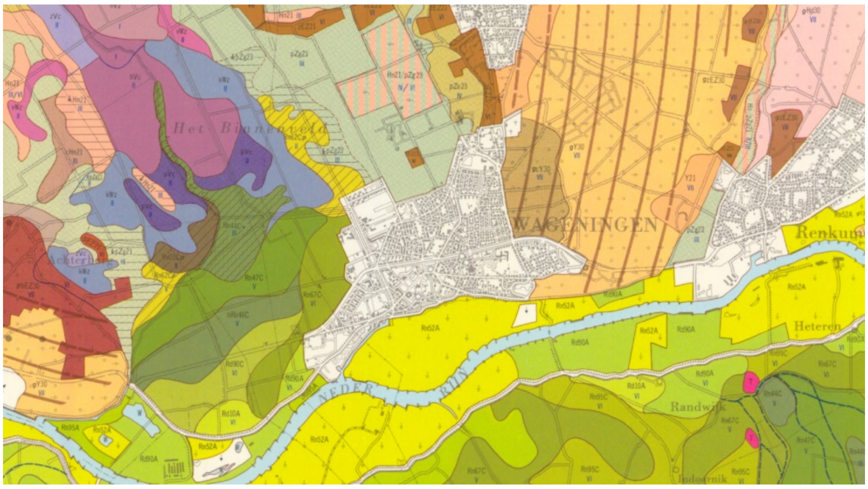

Figure 1: Urban soils as they are excluded from the 1:50,000 Dutch soil survey.

2 What are urban areas?

Although the definition of urban areas seems rather trivial, in practice, the definition seems to rely heavily on the application. The soil survey manual defines urban land as land that is mostly covered by streets, parking lots, buildings, and other structures of urban areas. This definition mainly excludes areas like parks and other green areas in the urban environment and focuses mostly on the sealed areas. McIntyre *et al.* (2000) provide an overview of different definitions of the area. Their review shows that different elements are considered. Urban areas can be defined on the basis of i) the fraction of sealed areas, ii) population density, iii) energy use, and iv) the function of land (*e.g.*, residential, industrial, and recreational). In addition scale plays a role, an individual building is not an urban area, but an area consisted of "houses and lawns" is considered to be an urban area (McIntyre *et al.*, 2000). Or there needs to be a minimum population (density). Although it may be obvious that different applications define urban areas in different ways, the multitude in definitions clearly hampers scientific studies and discussions on urban soils. Basically, different groups are talking about different things. If one looks at the global scale, the different definitions of urban areas can lead to tremendous differences in the urban area estimates as illustrated in Table 1. This means that one should be very careful in the selection of a particular map particularly if the area of urban areas plays an important role. For other applications this is less important. A commonly acclaimed effect of urbanization is that the expansion of urban areas takes place on fertile agricultural land and that urbanization can be considered a threat to food security. An overlay of the different maps of urban areas from Table 1 over the S-world soil map of the world (Stoorvogel *et al.,* 2016) shows that despite the large differences in the total area, the relative impact of urbanization on land is similar (Table 2). All maps indicate that urban areas cover around 55% soils that are suitable or agricultural use.

Table 1: The global area of urban areas according to different sources.

Source	Urban area (10^3 km^2)	% of land surface	Reference
GlobCover	477	0.22%	Bontemps *et al.*, 2010
GRUMP	5,283	2.51%	Ciesin *et al.*, 2011
ISA[1]	8,675	4.11%	
Population Density[2]	12,676	6.01%	Ciesin, 2016
Average	***6,778***	***3.21%***	

[1]Based on the global night-time lights map using the conversion provided by Elvidge *et al*. (2007)

[2]Re-interpreted using the criteria provided by Short Gianotti *et al.*, 2016

Table 2: The area of urban areas covering land that is potentially suitable for agriculture.

Base map	Area of fertile soils covered by urbanization (10^3 km^2)	% of urban area that covers soils potentially suitable for agriculture
GlobCover	275	61.8%
GRUMP	2,966	57.4%
ISA[1]	4,941	58.2%
Population Density[2]	5,983	42.7%
Average	***3,541***	***55.0%***

3 Modelling urbanization.

Urbanization can be monitored closely through *e.g.,* remote sensing. However, predicting urbanization into the future is more challenging, while the evaluation of potential effects of the urbanization process on global or local soil resources is pivotal. In land cover dynamics modelling in general three different approaches are being followed relying on: i) regression analysis, ii) trend analysis using Markov chains, and iii) cellular automata. Various modelling approaches can be applied. The models based on regression analysis, look for environmental conditions where certain land cover classes occur through *e.g.,* a logistics regression. A good example is the Clue model by Verburg and Overmars (2009). In the case of urbanization one can expect that urbanization will take place on relatively flat terrain in the proximity of existing urban areas. An alternative modelling approach is a trend analysis, where the probability of a particular land cover change relies on changes in the past. A good example is provided by Muller and Middleton (1994). In the case of urbanization it can be expected that there is a certain sequence of land use change prior to the urbanization: nature – pasture – extensive agriculture – intensive agriculture – peri-urban agriculture – urban areas. A particular location in the sequence helps to identify the probability of urbanization. Finally, there are the cellular automata in which land cover changes strongly depend on the surrounding environment (*e.g.,* Fuglsang *et al.,* 2013). Of course, this is very obvious in urbanization trends where urban areas expand rather than that new urban areas develop. The three modelling approaches are very distinct and base themselves on the environmental conditions, temporal trends, and spatial patterns. In reality, often more hybrid methods are implemented. Markov chains are, for example, stratified on the basis of environmental conditions, or spatial parameters (*e.g.,* distance to roads) are included in the regression models. The proper modelling of urbanization requires an integrated approach that can make use of each of the modelling approaches. However, this has repercussions for the data requirements: auxiliary environmental data are required for the regression models, time series are required for the Markov chains, and high resolution maps are required for the cellular automata. In addition, very strict definitions of urban areas are required See Section 2). The latter is particular true (and problematic) for the time series.

4 Mapping urban soils

Standard soil surveying techniques rely on aerial photo interpretations and intensive field work with a high density of soil observations (Soil Survey Division Staff, 1993). Initially soil classification systems were not suited to deal with the urban environment. This has been resolved with the recent updates of *e.g,.* the Soil Taxonomy and the World Reference Base for Soil Resources. However, we are still facing the problem that the surveying techniques are not suited for the urban environment. The specific characteristics of urban soils with abrupt changes and management effects require new approaches to be developed. Recently soil surveying techniques have received significant updates through the introduction of geostatistics and the intensive use of auxiliary and legacy data. The so-called digital soil mapping (McBratney *et al.*, 2003) has proven to be very effective in agricultural and natural environments. However, its application in urban environments is still hampered by the specific urban conditions (Vasenev *et al.,* 2014): i) useful auxiliary data on management history and functional zones are often lacking whereas this may be one of the main soil forming factors, ii) the abrupt changes require very high observation densities, iii) typically, urban areas are found as islands in a landscape resulting in very clustered observations and problems to interpolate, and iv) soil profile have a very specific build up with the so-called cultural layer within the soil profile. The specific conditions in the urban areas require specific soil surveying techniques as attempts to map them with standard soil surveying techniques or digital soil mapping are doomed to fail.

5. Conclusions

With the rapid urbanization worldwide, there is an urgent need for standardization of the definitions of urban areas, modelling of the urbanization models, and soil surveying techniques for the urban environment. Although many of the building blocks are there, the scientific community needs to put them together and come up with clear answers for the global debate.

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