Geoderma 268 (2016) 100–107

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Mapping of soil sealing by vegetation indexes and built-up index: A case study in Madrid (Spain)

Pilar García *, Eugenia Pérez

University Complutense of Madrid, Faculty of Geography and History, Regional Geographic Analysis and Physical Geography, Profesor Aranguren s/n, Madrid 28040, Spain

A R T I C L E I N F O

Article history:
Received 26 May 2015
Received in revised form 2 July 2015
Accepted 13 January 2016
Available online 5 February 2016

Keywords:
Soil sealing
Supervised classification
Vegetation index
Built-up index

A B S T R A C T

This study analyzes the most suitable methods for detecting and measuring the soil sealing change caused by urban growth in the city of Madrid, Spain, using remote sensing techniques and GIS. Some irreversible, negative effects of soil sealing are impermeable ground and modified ecosystems (bio-geochemical cycle, water cycles, loss of biodiversity, etc.), which alter matter and energy flows and the ecological functions of the soil. Urban development has often been more concerned with viability and financial profit, to the detriment of the environment. Multi-temporal studies on the processes are assisted by several types of technologies providing geographical information, together with large cartography, photogrammetric and satellite databases. The best soil sealing detection is carried out based on principal component analysis of the images and the SAVI index. Supervised classifications show that from 1984 to 2013 soil sealing in the municipality of Madrid and its surroundings has risen from almost 15% to 24%, an increase of 9%.

1. Introduction

Soil sealing in heavily populated areas with high urban growth is one of the most important environmental problems in Europe, affecting large cities and coastal areas in particular (Blum et al., 2004; Van-Camp et al., 2004 Castillo et al., 2004; Ojeda and Villar, 2006; García Rodríguez and Pérez González, 2007; Montanarella, 2007; Romero Díaz et al., 2011; Valera et al., 2006, 2011; Moreira, 2012; García Rodríguez et al., 2014; Munafo and Tombolini, 2014; Salvati et al., 2014). Poor urban planning and non-compliance with regulations on land use lead to the disappearance of very fertile soil and to increased degradation (Blum, 1998; Lavalle et al. Moland Project, 2001, EEA, 2006, 2012; Harb Rabia, 2012). The prime objective of Spain's proposal for the EU 2020 sustainable development strategy is protecting and improving land across the European Union, with special emphasis on soil sealing (http://www.eeb.org/press/2009) and treating degradation caused by unsustainable practise in land use.

"Soil sealing is understood to be the action of permanently covering an area of land with artificial, impermeable material, such as cement or asphalt" (EEA, 2012). Therefore, it refers to the transformation of natural soil through artificial, impermeable materials. Some irreversible, negative effects of soil sealing are impermeable ground and modified ecosystems (bio-geochemical cycle, water cycles, loss of biodiversity, etc.), which alter matter and energy flows and the ecological functions of the soil. Urban development has often been more concerned with viability and financial profit, to the detriment of the environment. At a time when forestry, agricultural and livestock activities have declined significantly, urban planning has paid scant attention to soil quality, with a large amount of high and medium quality land being sealed.

Mapping soil sealing using images is difficult, due to the uniformity of built-up zones which are often interspersed with natural spaces, and to the variability in buildings: houses, blocks of flats, industrial units, transport routes, leisure areas, etc. Several authors have put forward various methods of analysis in an attempt to solve the problem (Effland and Pouyat, 1997; Nizeyimana et al., 2001; Zhang et al., 2002; Wu, 2004; Añó Vidal et al., 2005; Moeller, 2005; Kampouraki et al., 2006; Sánchez et al., 2009; Scalenghe and Ajmone-Marsan, 2009; Tomás et al., 2010; Escudero et al., 2010; Pérez González and García Rodríguez, 2013; García Rodríguez and Pérez González, 2014), although results vary considerably depending on the precision required, the scale and the conditions in the study area. Zha et al. in 2003 proposed a Normalised Difference Built-up Index (NDBI) to map urban areas automatically.

The main aim of the project is to be able to quantify the sealed and unsealed land remaining in an urban municipality using various geographic information systems (Erdas Imagine, 2013 and ArcGis-10). The objective is to assess the surface areas that still permit some soils to be maintained, together with their associated functions (infiltration capacity, preservation of biodiversity, etc.). To this end, an analysis was made of several applications for semi-automatic classification provided by satellite remote sensing. Since medium and high spatial resolution satellite images are freely available it is an economical way of updating sealed surfaces. Special emphasis is placed on checking the

* Corresponding author.
E-mail addresses: mpgarcia@ucm.es (P. García), meperez@ucm.es (E. Pérez).

http://dx.doi.org/10.1016/j.geoderma.2016.01.012
0016-7061/

reliability of the Normalised Difference Built-up Index (NDBI) and on proposing the most satisfactory classification for measuring sealed soils.

The objectives are divided into the following sections:

- To identify the most suitable combinations of spectral bands from the Landsat and Spot satellites to map out areas of sealed soils
- To select spectral, radiometric and spatial improvements that better discriminate between various types of sealing
- To conduct a semi-automatic classification of sealed surfaces from the image obtained with the most suitable spectrum improvement
- To calculate the percentage of soil sealed over the last thirty years from a multi-temporal analysis of satellite images from several different classifications
- To compare the results from the classifications with the actual terrain and with the available digital cartography
- To assess the reliability of soil sealing measurements by applying the confusion matrix
- To re-classify sealed soils using detailed cartography and the real status of the land to improve results
- To determine what type of land (with its agrological capacity) is affected by the sealing process
- To update sealed surfaces maps, since the availability of free, medium and high spatial resolution satellite images makes it possible to do this economically.

2. Study area

The municipality of Madrid, which covers 607 km^2, was chosen because it includes several types of urban design and transport infrastructure (the old town, subsequent expansions, residential areas, new urban developments, large parks, industrial estates, roads, railways, etc.), and surroundings with unsealed soils for farming and forestry (*Monte de El Pardo*) as well as abandoned or fallow land (Fig. 1).

In 1986, the city had a population of 3,068,132 which rose to 3,166,135 in 2014 (www.madrid.es). Such a small increase is no proportional to the size of urban expansion. At present, there is a density of 5154 people per km^2 and a floating population of 5 million.

The city of Madrid lies in the centre of Spain, at an altitude of 660 m; it has a Mediterranean climate, very dry in summer, but veering slightly towards the continental. Therefore, the forest vegetation is predominantly evergreen (*Quercus ilex*, *Pinus* sp., etc.), with a stratum of xerophilous shrubs (*Cistus ladanifer*, *Lavandula pedunculata*, *Rosmarinus officinalis*, *Thymus vulgaris*, etc.). Agriculture mainly consists of crops grown on non-irrigated land (harvested in summer). Crops in the stretch to the south of the river Manzanares are irrigated, with summer being the time of maximum growth, so the land is almost completely covered.

In the municipality of Madrid, over 50% of the land is urbanised, 15% in the process of constructing new districts, and 35% is protected and regulations do not permit building (almost all protected land is in the north–west of the city). The oldest urban structure is inside the first ring-road, called the "central almond", and comprises the city centre and developments, from various periods and with different building densities, and green or unsealed areas.

The soils on which the city of Madrid was built, and which have now disappeared (García Rodríguez and Pérez González, 2011) were calcic and haplic luvisols. In the south, haplic luvisols with some fluvisols, cambisols, leptosols (rendsic and mollic) and calcaric regosols are being sealed. In the north–east of the city (Barajas airport and vicinity), some of the haplic calcisols still exist, and in the north–west, in the Monte de El Pardo, there are unsealed regosols and dystric and eutric cambisols with some luvisols.

With regard to the potential capacity of the land for agricultural use, classified from I to VI in descending order of agrological capacity (Klingebiel and Montgomery, 1961), the city of Madrid rests on mostly low-quality, class IV soils that are subject to erosion. In the east there is a large area of more fertile class II and III soils which, due to the growth of Madrid to the east and south over the last few decades, have been lost because of sealing. Nonetheless, in the north–west, which is protected by the *Monte de El Pardo*, class IV and V soils still exist, giving rise to the strange paradox that mostly the fertile soil has been lost in Madrid, while the poorer land remains unbuilt. The obvious explanation for this is that the first urban settlements were built on fertile agricultural land. At present, however, priority must be given to conserving soil, or part of it, as this enables other natural factors which are extremely beneficial to the quality of the urban environment.

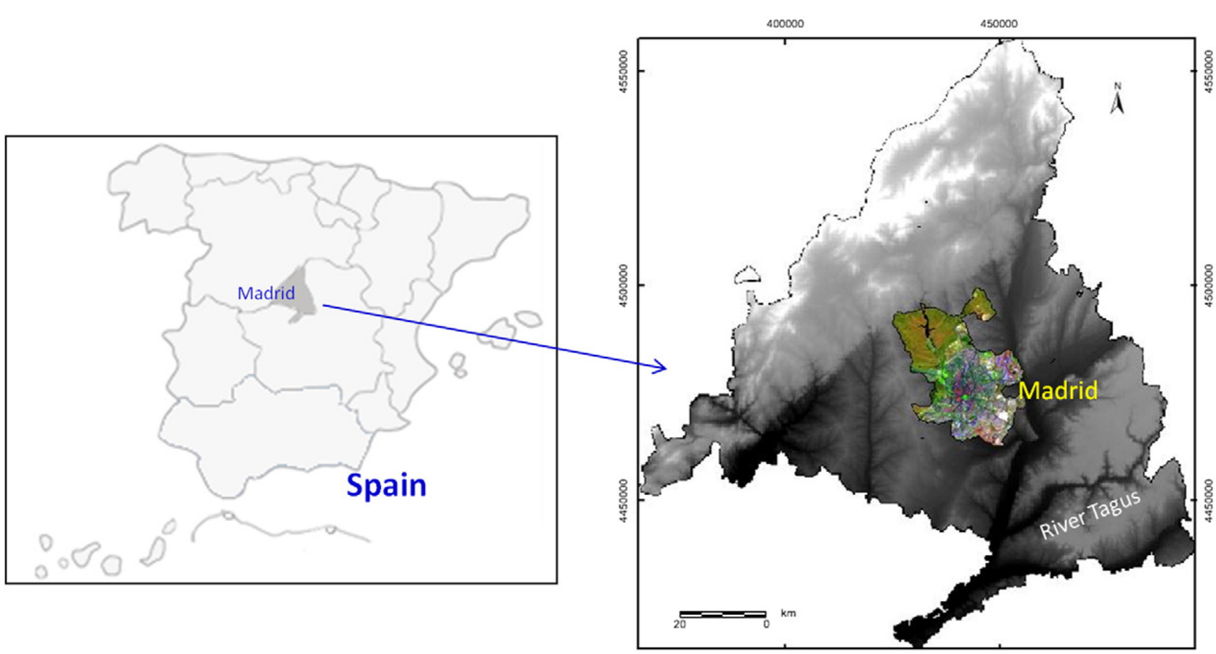

Fig. 1. Study area (Madrid, Spain).