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Multi-temporal satellite imagery for soil sealing detection and urban growth mapping in the city of Ranchi (India)

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Introduction

Remote sensing has already proved to be a powerful tool for land planning, monitoring and management. In particular, remote sensing techniques can be useful to evaluate the impact of natural processes and human activities on environment in the context of conservation policy and sustainability. In this work we used multi-temporal satellite imagery from the Landsat space program to map urban growth dynamics occurred in the Ranchi city context (NW India). Our attention was focused on the period 1975-2011, when a strong and unregulated urban expansion affected the area (about 1900 km^2). At the moment the definition of soil sealing is not univocal (Pilieri, 2009). Land cover changes affecting urban, agricultural and natural areas are the one generally considered while speaking about soil sealing. In this work we focused on urban class that traditionally and irreversibly subtracts land to other classes. Urban areas were mapped from satellite images for 4 years (1975, 1988, 2004, 2011). Further analysis based on spatial data processing and change detection approaches permitted us to describe different urban development dynamics that affected different parts of the city and to quantify them.

Methodology

The characterization of surfaces was carried out using Landsat MSS and TM datasets available for free from USGS archives (http://glovis.usgs.gov/) by QGis and SAGA Gis free/open source software. A total of four images acquired in different time (1975, 1988, 2004, 2011) were used to map urban sprawl and human activity impacts onto natural areas through a change detection analysis in the reference period. All data were referred to the WGS84 – UTM 45N reference system. The images were initially pre-processed (calibrated and atmospherically corrected) using a simplified radiative transfer model (RTM) described by Moran et al. (1992):

$$\rho_\lambda = \frac{\pi \cdot d^2 \cdot \left(L_\lambda - \hat{L}_\lambda^{\,atm}\right)}{\tau_\lambda \cdot [\tau_\lambda \cdot \sin\beta \cdot I_\lambda + E_{down}]}$$

where ρ_λ is the at-the-ground reflectance value, L_λ is the at-sensor-radiance [$W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$] obtained by applying gain and offset values supplied with Landsat images, $\hat{L}_\lambda^{atm}$ is the upwelling atmospheric scattered radiance [$W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$], d the Sun-Earth distance coefficient (astronomical units), E_{down} the scattered downwelling contribution (that we assumed equal to $\pi \cdot \hat{L}_\lambda^{atm}$), τ_λ the atmospheric transmittance, β the sun incidence angle (rad) calculated at each position (pixel) using a DEM and I_λ the sun irradiance [$W \cdot m^{-2} \cdot \mu m^{-1}$]. Atmospheric correction was performed applying the Dark Object Subtraction approach (DOS – Chavez, 1996), to reduce atmospheric scattering. In order to minimize residual spectral differences among scenes of the time series, a further inter-calibration step was achieved. This very important step assumed that invariant surfaces, like buildings or other manmade structures, should maintain the same spectral behavior along time. We therefore identified some areas (well visible on all the images) having this peculiarity. Correspondent reflectance values were then extracted and compared by scatterplots. We assumed the 1988 scene as reference; other images were relatively corrected according to a linear regression model calibrated on the basis of the invariant pixels. Correlation coefficient values (Pearson) for all tested regressions was over 0.79. Efficiency of inter-calibration was tested by comparing residual reflectance differences of invariant pixels of different images with uncertainty reference values obtained by applying Variance Propagation Law (VPL – Borgogno-Mondino et al., 2016) to RTM. After the inter-calibration step we found that about the 99% of residual differences were lower than uncertainty thresholds (min. 0.022, max 0.041). Referring to corrected images, we focused on five classes (1 - urban areas, 2 - open canopy forest, 3 - close canopy forest, 4 - crop areas, 5 - water bodies), useful to describing soil sealing dynamics. To improve discriminability among classes some spectral indexes were derived from the original bands previously calibrated. The Normalized Differencing Vegetation Index (NDVI – Rouse et al., 1974), the Normalized Differencing Water Index (NDWI – Gao, 1996) and the Normalized Differencing Built-up Index (NDBI – Zha et al., 2003) were calculated and jointly considered with the original bands to calculate correspondent Principal Components (PC) by Principal Component Analysis (PCA). On screen image interpretation was achieved to select those components that better permitted to separate urban from other classes. Selected PCs were different for each image: PC1 and PC2 for 1975; PC1, PC2, PC3 and PC4 for 1988; PC2, PC3 and PC4 for 2004; PC2, PC3 and PC4 for 2011. A cluster analysis was achieved considering the selected PCs by K-means with 10 classes. Clusters were interpreted on screen to label the urban ones. Urban clusters were finally merged to generate a single urban class that we used to mask PCs stacks. This permitted us to operate a second cluster analysis (K-means, 4 classes) focusing on pixels other from urban. Mapped clusters were labelled referring to the average spectral signature of the assigned pixels. We finally obtained 4 LULC maps by merging urban with other classes. LULC maps accuracy was tested by confusion matrix comparing them with LULC maps from the Indian Space Research Organization (ISRO) available for the years 2006 and 2012. We randomly selected 300 ground control points for comparison. No reference data were available for 1975 and 1988 maps. We, therefore, assumed classification accuracy comparable to the one of 2004 and 2011. A change detection analysis was finally achieved comparing couple of successive images (1975-1988, 1988-2004, 2004-2011). For each period changes were mapped and labelled ("from-to"). Corresponding transition matrixes were also generated to quantify the size of changes. Those areas where soil sealing occurred were interpreted to characterize urban sprawl dynamics. For this task we generated, from the obtained LULC maps, a Urban Density Map (UDM). Urban density was calculated using a sliding window of 150 x 150 m (5 x 5 pixels) running over the processed LULC map; at each position urban density was calculated as *100*(urban pixels/total pixels)*. We performed a new cluster analysis (K-means, 5 classes) using the 4 UDMs previously generated. Result was interpreted according to the average temporal profile of each cluster, permitting to remove from urban maps, those pixels probably representing bare soil erroneously classified as "urban". A second cluster analysis (K-means, 4 classes) was finally achieved using cleaned UDMs, focusing on the remaining pixels. Four clusters of differently developed urban areas were finally mapped, permitting to interpret when, where and how urban development (therefore soil sealing) occurred in the area.

Results and discussion

LULC maps generated during the classification step showed an overall accuracy (tested for 2004 and 2011 images) of about 83%. Conversely vegetation classes (2, 3 and 4) show a not negligible class commission (averagely 18%). Commission concerns especially transitional areas (ecotones) and probably also depends on the different seasonality of compared data. Change detection achieved comparing classification results, brought to generate 3 tables reporting the size of changes and 3 maps locating the changes occurred in the considered periods. Since we investigated soil sealing determined by urban sprawl the main focus of this work was on the urban class. Table 1 demonstrates that built-up areas progressively expanded from 15.86 km^2 in 1975 up to 87.06 km^2 in 2011. The majority of soil sealing affected classes 2 and 4 (open canopy forest and crop areas) and was concentrated along the main road network, in the suburban areas and in the remaining empty spaces closed within the old city. A further reading of urban sprawl dynamics was based on UDM analysis. By classifying UDMs we recognized 4 different types of evolution suffered from different parts of the Ranchi city (figure 2). The one falling in the class called "city center" (C1) showed a progressive closure of remaining void spaces in the original city core and moved to saturation. The one labeled as "rather saturated" (C2) showed a rapid improvement (measured by the slope of the UD graph) in the period 1988-2004, pushing those areas to a rapid, saturation that in 2011, was almost reached. In areas belonging to classes "Fringe type 1" (C3) and "Fringe type 2" (C4) urban sprawl started moderately in 1988, and rapidly accelerated in the following period (more for Fringe type 2 class). These areas are the ones future planning politics should concentrate their attention on. By comparing the average class value of urban density with its standard deviation (assumed as proxy of uniformity of density within the class), it can be noticed that, for C1, standard deviation decreased continuously from 1975 up to 2011, suggesting that all empty spaces still remaining in the old city texture were filled by new artifacts increasing area homogeneity in terms of urban density. Conversely other classes showed a moderate augmentation of standard deviation along years, suggesting that the urban expansion model adopted by the Ranchi municipality in new areas tended to a diffuse sprawl where buildings and spaces almost equally alternates.

Tab. 1. Transition matrix showing changes occurred in the area in the three analyzed periods (1975-1988, 1988-2004, 2004-2011).

	Classes [km²]	1	2	3	4	5	Total "before"
		1988					
1975	**1 – Urban Areas**	13.49	0.06	0.23	2.05	0.03	15.86
	2 – Open Canopy Forest	0.12	11.06	16.13	30.86	0.00	58.17
	3 – Close Canopy Forest	0.17	33.13	99.11	61.74	0.00	194.15
	4 – Crop Areas	16.20	35.51	28.61	1552.07	0.27	1632.66
	5 – Water Body	0.02	0.06	0.29	7.08	20.58	28.03
	Total "after"	30.00	79.82	144.37	1653.80	20.88	1928.87
		2004					
1988	**1 – Urban Areas**	28.32	0.09	0.23	1.35	0.01	30.00
	2 – Open Canopy Forest	0.18	13.21	33.84	32.53	0.06	79.82
	3 – Close Canopy Forest	0.40	7.50	113.44	22.84	0.19	144.37
	4 – Crop Areas	31.31	42.81	63.94	1509.43	6.31	1653.80
	5 – Water Body	0.00	0.01	0.00	0.37	20.50	20.88
	Total "after"	60.21	63.62	211.45	1566.52	27.07	1928.87
		2011					
2004	**1 – Urban Areas**	59.12	0.01	0.01	1.06	0.01	60.21
	2 – Open Canopy Forest	0.22	20.54	19.05	23.80	0.01	63.62
	3 – Close Canopy Forest	1.24	6.73	147.01	56.47	0.00	211.45
	4 – Crop Areas	26.33	44.23	50.30	1445.01	0.65	1566.52
	5 – Water Body	0.15	0.00	0.00	3.67	23.25	27.07
	Total "after"	87.06	71.51	216.37	1530.01	23.92	1928.87

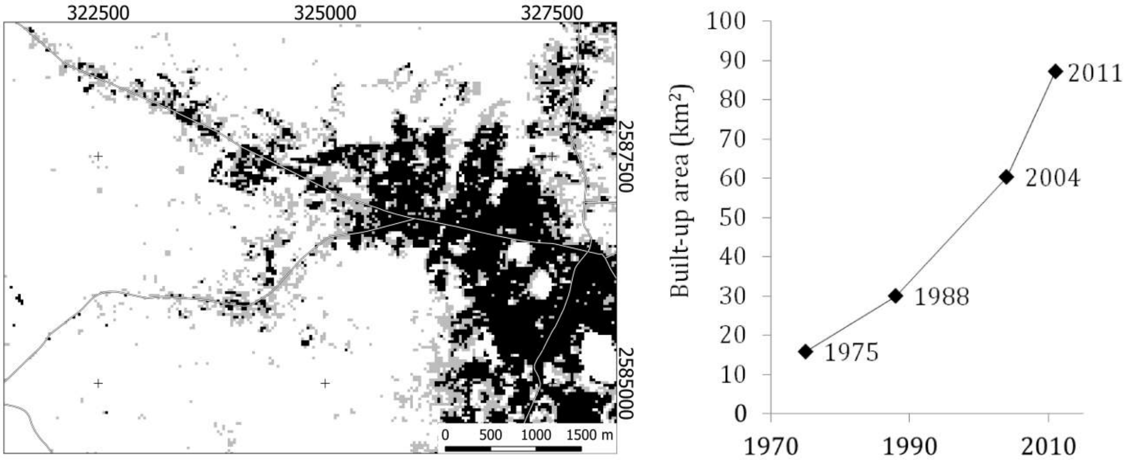

Fig. 2. (left) Example of map (subset from the original) showing urban development occurred in the period 2004-2011. Black = unchanged urban areas; grey = new urban areas. Reference frame: WGS84 – UTM 45N. (right) Graph relating to the increment of build-up areas for the reference period.

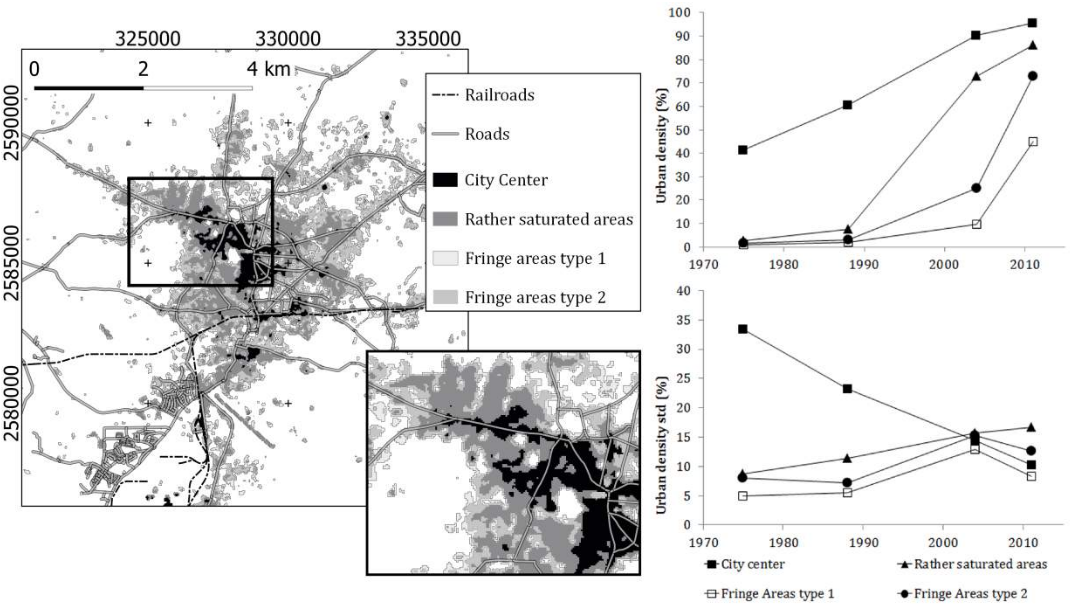

Fig. 3. (left) Classification of built-up areas on the basis of the temporal trend of urban density. (right) Temporal trends of urban density (above) and standard deviation of urban density (below).

Conclusions

This study demonstrates that soil sealing by urban growth heavily affected Ranchi in the reference period (1975-2011). Free satellite data from the Landsat space program proved, once more, to be effective in mapping land cover macro-classes. It also demonstrated that, if time series are used, some further discriminants can be added to improve results, and in particular mapping of urban areas. Classification results from multispectral satellite images, once processed with some specific zonal statistics (e.g. urban density map generation), can help to map city zones that suffered from different urbanization models. UDMs classes showed average temporal profiles similar to those expected from general population growth models, suggesting a direct relationship between urban landscape modification and population increment in urban areas. Change detection analysis proved that a drastic growth of the city started after 1988, first saturating the city center (class C1) and then moving towards peripheral areas that reacted differently (classes C2, C3 and C4). This general boost was probably related to the administrative independence of Jharkhand reached in 2000. From a quantitative point of view we found that in the Ranchi area, built-up class increased of about six times from 1975 to 2011. Fastest growth occurred after 1988. From that moment on the city center (class C1) continued with the same regular development started in the previous years and, in 2004, saturation was reached. New urban sectors started differently, moving from the center out. Urban growth proceeded not symmetrically, but followed some privileged directions. The first growing phase concerned C2 in the period 1988-2004, while a second phase slowly started in 1988 accelerating from 2004 on (classes C3 and C4). Looking at urban density standard deviation we could guess that the new phases of urban growth have a different built-up strategy (if compared with the older ones), where buildings are maintained more spaced, suggesting a “diffuse” city model.

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