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Quantification of anthropogenic effects in the landscape of Lubumbashi

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In order to understand the dynamics of the urbanization and suburbanization processes and hence to quantify the anthropogenic effects of the rapid growth of tropical cities, it is crucial to find and apply valuable methods. In this contribution, the transferability of the Rüdisser et al. (2012) "Distance to Nature" hemeroby assessment method to the landscapes surrounding the city of Lubumbashi in the Democratic Republic of the Congo, is evaluated. This methodology has the advantage of taking into account the structural connectivity of the landscape through the consideration of the distance to natural habitats. Since it has never been applied to an African city before, some adjustments (fitting of the local land use and cover types into the hemeroby levels designed for Austria; no final hemeroby level simplification) are proposed. Moreover, an analysis of the decennial (2002-2013) hemeroby dynamics is presented. The results suggest that the "Distance to Nature" methodology is transferable but requires accurate field knowledge to define the necessary reference habitats and to situate these habitats in the classified Landsat images. A dramatic decrease was noted of the "natural" and "near-natural" levels in the study area during the time period considered. In addition, 32% of the land underwent an increase in anthropogenic effects, mostly around the cities and characterized by a ribbon development pattern.

Quantification de l'anthropisation dans le paysage de Lubumbashi

Dans un contexte de croissance rapide, souvent non planifiée, des villes tropicales, il est crucial d'appliquer les méthodes les plus adéquates permettant de comprendre la dynamique de (péri)urbanisation et, ainsi, de quantifier l'anthropisation de ces villes. Dans cette étude, la transférabilité de la méthodologie d'estimation de l'hémérobie «Distance to Nature» de Rüdisser et al. (2012) est évaluée via son application au paysage entourant la ville de Lubumbashi. Cette méthode a l'avantage de prendre la connectivité structurelle en compte via le calcul de la distance aux habitats naturels. La méthodologie n'ayant encore jamais été appliquée au contexte d'une ville africaine, certains ajustements (mise en correspondance des utilisations locales du sol avec les niveaux d'hémérobie mis au point en Autriche) et amendements (suppression de la simplification finale de la classification en niveaux d'hémérobie)

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sont proposés. De plus, une analyse de la dynamique décennale (2002-2013) d'hémérobie est présentée. Les résultats suggèrent que la méthodologie « Distance to Nature » est transférable, mais que la définition des habitats de référence ainsi que leur identification sur les images Landsat classifiées requièrent une excellente connaissance du terrain. Durant cette période et sur l'étendue d'étude, les niveaux « naturel » et « proche de naturel » ont considérablement diminué. De plus, 32 % du territoire ont vu leur anthropisation augmenter, principalement autour des villes et suivant un développement en ruban.

1. Introduction

Human activities affect many ecosystems on Earth by converting or changing the original ecosystem functions in order to provide essential services (Vitousek et al., 1997). "Anthropization" refers to the impact of human activities on landscape composition, configuration and dynamics; however, this phenomenon remains difficult to quantify. As conservation biology and restoration ecology focus mainly on ecosystem composition, landscape ecology singularizes itself by considering the spatial and temporal patterns in order to understand their impact on ecological processes (Turner, 1989; Young, 2000).

The region of Lubumbashi is an interesting case study for landscape anthropization. Situated in the Katangese Copperbelt and well known for its copper and cobalt veins (Chapelier, 1957), this formerly rural area was profoundly altered by mining activities (Narendrula et al., 2012). Non-ferrous metal exploitation and processing have led to a strong industrialization of the landscapes and therefore to the creation of new towns, quarries and plants during the Belgian colonial era since the beginning of the 20th century (UMHK, 1956; Banza et al., 2009). Historically, the city was composed of a densely built-up zone with its concomitant infrastructures, today aged, surrounded by industrial zones in the suburbs (Bruneau et al., 1990). The consequences of the economical attractiveness of the mining industry have lead to a massive rural exodus and a rapid population growth (1,200,000 inhabitants in 2006, near 2,020,000 estimated in 2015); consequently divergent anthropogenic effects, mostly reported as unplanned deforestation, urbanization and suburbanization patterns, have been observed (Chapelier, 1957; Nkuku Khonde & Rémon, 2006; Groupe Huit, 2009; Vranken et al., 2013). Industrial infrastructure is now fully included into the urban tissue, and recent industries were installed just outside the urban belt (Vranken et al., 2013 ; 2014). The inhabitants of the city depend on food imports due to the heavy metal soil contamination and to the absence of a real farming tradition (Nkuku Khonde & Rémon, 2006; Vranken et al., 2014).

In order to understand the dynamics of the urbanization and suburbanization processes and to quantify the anthropogenic effects of the rapid growth of tropical cities, particularly for developing countries, it is crucial to select valid methods. Among the existing ones, the Rüdisser et al. (2012) "Distance to Nature" method, a recently developed composite indicator and methodological framework (i.e., D_2N methodology), has the advantage of taking structural connectivity of the landscape into account by considering the proximity to natural habitats; it appears as very suitable for a landscape ecological analysis in our study area. Alike most approaches, it has been developed for a temperate context. In this chapter, it will be applied for the first time on an African city. The objectives of the study therefore combine an assessment of local anthropogenic effects on landscape pattern in Lubumbashi and its hinterland and an evaluation of the transferability of the D_2N method to a non temperate context.

First, the study zone and its main natural and anthropogenic components are described. Secondly, details regarding satellite image acquisition, treatment and classification are given. Consequently, the adjustments to the D_2N method, its application and the significance of its outputs are explained. The results and discussion section highlights the anthropogenic and natural patterns for 2002 and 2013, as well as their decennial dynamics and comments the transferability of the method. Anthropization (mostly (sub)urbanization and deforestation) is expected to increase in this period. Some recommendations for future application of the methodology in a similar context are then described in the perspectives and conclusion section.

2. Material and methods

2.1. Study zone

Lubumbashi is the principal city of the Katanga area, situated in the Southern part of the Democratic Republic of the Congo. The study zone consists of a plateau that has been eroded by the Lubumbashi River and its tributaries into a wide valley (Chapelier, 1957). The altitudes of the inner city, situated on the plateau, vary between 1,200 and 1,250 m (Sys & Schmitz, 1959). The local climate is characterized by a wet season (from November to April) and a dry season for the rest of the year and corresponds to the Cw type according to the Köppen system (Kottek et al., 2006). Currently, the vegetation cover is only continuous during the wet season (Adam, 2010).

The presence of patches of dry evergreen forest or *muhulu* in the area (Malaisse, 2010), suggests that this is the real vegetation climax type and that the *miombo* or woodland, the dominant vegetation type since the first observations during the colonial period, should be considered a “disclimax” resulting from former slash and burn agriculture (Sys & Schmitz, 1959; Schmitz, 1962; White, 1983; Noti et al., 1996). Diverse forms of savannah, from wooded savannah to grassland, as well as bare ground, are now progressively replacing this woodland (Malaisse, 2010). Bare ground results mostly from mining activities and eolian deposits of heavy metal particles (Mbenza et al., 1989; Narendrula et al., 2012). Near the smelters, debris are piled into tall and wide slag heaps. Although forests, more or less degraded, still cover about 50% of the area, derived savannahs and cultivated areas, generally resulting from forest clearance by the almost annual fires (Malaisse, 2010), represent now the second largest land cover in the area (about 30%). These diverse savannah types therefore result from anthropogenic degradation and do not show the same biophysical characteristics (including floristic composition) as a natural savannah (Parr et al., 2014). In tropical Africa, most fires are of anthropogenic origin (van der Werf et al., 2008). In our study area, where fire practices seem to have had a significant influence on the land cover, this observation is confirmed by Malaisse (2010) and an existing correlation between the fire start frequency and the proximity to the city and to roads ($R^2 = 0.78$, personal data) as well as to surrounding villages ($R^2 = 0.77$, personal data) has been found. Moreover, the absence of a correlation between the fire start frequency and the proximity to industrial sites ($R^2 = 0.09$, personal data) suggests that those fires are mostly used by the inhabitants of the villages for agricultural and charcoal production, which is a regular practice in the area (Stromgaard, 1985; Vranken et al., 2011). Besides important effects of leaching on soil structure and organic matter content, fire impacts on the edaphon through effects on soil fungi and on animal populations (Malaisse et al., 1975). A natural metallophyte herbaceous flora ("copperflora") is also present on (natural) highly metalliferous soils (mainly copper and cobalt), generally observed on hills inside the forest ("copper hills") (Malaisse et al., 1994; Leteinturier et al., 1999). Some species were also able to colonize the soils contaminated by metalliferous atmospheric deposits (Faucon et al., 2011). Specific features locally referred to as *dembos*, i.e. natural grasslands periodically flooded in valleys close to water streams, are frequently found in the study area (Sys & Schmitz, 1959; White, 1983). Permanent wetlands, some of which are cultivated, are situated close to the riverbanks and depressions on impermeable grounds (Sys & Schmitz, 1959). Nearly all the lakes are of anthropogenic origin, i.e. reservoirs built during the colonial period.

2.2. Choice of the analytical framework

In this contribution, we will use the term "anthropization", to represent human-driven landscape changes and the D_2N methodology (Rüdisser et al., 2012) was applied, for several reasons. First, it is designed to be used at the landscape level. Secondly, it combines stretched values (gradients), under continuous variation (see Gustafson, 1998) as well as patch and categorical data (Wiens et al., 1993; Gustafson, 1998), while the analysis results are generated in both continuous and discontinuous formats, combining the advantages of the two output types. Moreover, the method considers processes (different types, intensities and frequencies of human pressures on ecosystems) and integrates the presence of secondary habitats. Structural connectivity between natural habitats, which is a crucial landscape pattern feature for ecological processes, is also included through the "Distance to Natural habitat" (D_n) component of the index. It can be evaluated even when only few other data than land cover are available. Finally, it has been conceived to facilitate the interpretation, comparison and communication of the analysis results. We implemented some adaptations to the methodology while respecting the specificities of our study zone and data availability.

2.3. Adaptation of the D_2N methodology to local land use and cover types

2.3.1. Data acquisition

We used Landsat ETM+ and OLI multispectral images, from 2002.07.07 and 2013.07.13, with a spatial resolution of 30 m (USGS, 2014). The scenes were pan-sharpened using ENVI 5.0 software and the corresponding panchromatic images in order to obtain a resolution of 15 m. The study site consists of the intersection of the area covered by the Landsat images from 2002 and 2013 (~23,400 km²).

In order to obtain a minimal surface of burned areas (which were very abundant in our study zone), we applied a filter of the spectral signature of the burned areas on a set of calibrated Landsat images shot at different dates of the same year (05.04, 07.07, 08.08 and 10.11 for 2002, 06.27, 07.13 and 08.30 for 2013). We consequently recomposed a multidate image for each year based upon the filtered original images before performing a multiresolution segmentation using all spectral bands of both images. Afterwards, we performed a supervised object-oriented classification based on spectral values and a shuttle radar topography mission (SRTM) image with a 90 m resolution (Trimble Documentation, 2013). The training sets for this classification were defined by, i) direct field surveys regularly conducted between January 2012 and April 2014, ii) the MODIS MCD14ML "Active fire" product with a detection confidence of 100% and, iii) the freeware licenced version of Google Earth© imagery (from 2002 and 2012) for remote areas (Giglio, 2013). Both segmentation and classification were performed using the eCognition© software. After a first land cover classification (13 classes), we refined the results to display more pertinent information on the land cover and for specific patches. Because it was not possible to distinguish which wetlands were cultivated according to their spectral signature, a proximity rule was applied: wetland segments touching anthropogenic lands (burned areas, continuous and discontinuous built-up areas, cropland, pastures, young fallow and slag heap) were assumed to be potentially cultivated at least sporadically and were considered as anthropized. These lands were called "anthropized wetland" while the uncultivated ones were denoted as "wetland". As for the reservoirs, firstly classified as "water", another kind of proximity rule was used in order to identify them: water segments sharing 70% or more of their edges with other water segments were assigned as "reservoir", while the others were labeled "stream". This classification refinement is particularly relevant for the quantification of anthropogenic impacts. The aforementioned method allowed to distinguish 14 land use and cover classes: "natural grassland", "wetland", "stream", "woodland", "wooded savannah and old fallow", "savannah and bushland", "savannah-crop mosaic", "reservoir", "cropland, pasture, grassland and young fallow", "anthropized wetland", "recurrent burned area", "slag heap", "discontinuous built-up and bare soil" and "continuous built-up". The classified Landsat images were exported in raster format with 25 m resolution, as in Rüdisser et al. (2012), for further treatment in ArcGIS©.

2.3.2. Data analysis

In order to obtain the D_2N index values, we proceeded in three steps.

First we created the hemeroby scales and maps, referred to as "Degree of Naturalness" (N_d) by Rüdisser et al. (2012). The term hemeroby was used here since it corresponds to a scale positively correlated with anthropization (Jalas, 1955; Kowarik, 1990), as opposite to naturalness, and the purpose of the analysis methods of Rüdisser et al. (2012) was to develop an anthropization-oriented index.

The land use and cover types provided by the seminal paper of Rüdisser et al. (2012) are only suitable for Austrian and similar landscapes, but the presented qualitative hemeroby scale provides information on the type, intensity and impact of human activities for each level considered. Based on this description and on our knowledge of the local ecosystems and activities (e.g., agricultural practices), we were able to fit the existing land use and cover types of Lubumbashi into the D_2N-related hemeroby scale.

We assigned one of the seven hemeroby levels to each land use or cover present in our study area; we sorted each of the 14 classes from our classification into the seven hemeroby levels. The decision tree used in the field to discriminate the land use and cover classes, based on Trochain (1957), Letouzey (1982) and Bellefontaine et al. (1997), is shown in Appendix 1. When some ecosystems could not be distinguished individually and had to be grouped into a common heterogeneous land cover class, the latter was allocated to the level of hemeroby corresponding to the dominant ecosystem of the group (Table 1). Shallow soil woodland, dry evergreen forest, copper hill, wetland and natural grassland were assigned to the first level, "natural", but the classification enabled to identify only the latter two types. The amount of anthropized grassland was too small to discriminate this type from natural grassland. Deep soil woodlands and streams were assigned to level 2, "near-natural". Indeed, water streams are in most cases of natural origin but characterized by eutrophication. Regenerating forest, wooded savannah and old fallow were put in the third level, "semi-natural", because those types were generally not found in the area before human intervention (Parr et al., 2014). The classification did not identify the first type. Young fallow, savannah, bushland, pasture and grassland were assigned to level 4, "altered", corresponding to the definition given by Rüdisser et al. (2012). In the class interpretation, young fallow, pasture and grassland had to be assigned to the level 5, "cultural", being grouped with croplands. Anthropized wetlands and reservoirs were also put in this category. As the savannahs in the area mostly correspond to early stages of ecological succession to fires, those recurrent burned areas that could not be eliminated were also assigned to level 5. We put the "savannah/crop mosaic" between hemeroby levels 4 and 5 because croplands were to be assigned to level 5 while savannah was assigned to level 4. Level 6, i.e. "artificial with natural elements", corresponded to discontinuously built areas and bare ground. Finally, level 7, "artificial", with soil sealing over 30%, was assigned to continuous built areas and slag heap. After performing those operations, we divided each pixel value by seven to normalize the class values according to a scale from 0 to 1, following the D_2N methodology and we were able to generate the N_d map.

Secondly, we composed the map with the distances to natural habitat (D_n); this distance corresponds to the Euclidean distance (in meters) from each pixel to the nearest natural or near-natural habitat (levels 1 and 2). Following the D_2N methodology, distances superior to 1,000 m were set to 1,000 m. In order to increase the effect of the proximity of anthropogenic features, we took the square root of the resulting distances. We normalized the results by dividing all pixel values by the maximum distance observed in order to get dimensionless values ranging from 0 to 1.

Table 1. Rüdisser's et al. (2012) hemeroby scale ("Degree of Naturalness") and its adaptation to the region of Lubumbashi. The four first columns are extracted from Rüdisser et al. (2012). The fifth column shows the correspondence of the encountered ecosystem types to the seven hemeroby levels, while the two last columns show the hemeroby level of each land use and land cover class in the classified Landsat images.

Hemeroby level	Description		Examples of land use types found in Austria	Potential ecosystems (land use/land cover) in the area of Lubumbashi	Matching hemeroby class	Classified ecosystems (land use/land cover) in the area of Lubumbashi
	Type of anthropogenic influence	Ecosystem patterns and processes				
1. Natural	No or only minimal anthropogenic influence (e.g. global pollution)		Bare rock, sparsely vegetated areas, glaciers and perpetual snow, inland marshes, peatbogs, natural forests	Shallow soil woodland, dry evergreen forest, wetland, natural grassland, copper hill	1	Wetland, natural grassland
2. Near natural	Anthropogenic influences	Structure and type of ecosystem is basically the same as naturally expected at the side but some characteristics (e.g. plant species composition) are altered	Natural grasslands (above timberline), moors and heathland, water bodies, sustainably managed forests	Deep soil woodland, water	2	Woodland, stream
3. Semi natural	Anthropogenic activities	The naturally occuring ecosystem is no longer present but has been transformed into a new ecosystem type because of anthropic activity	Alpine meadows substituting forest pastures, fallow land	Regenerating forest, wooded savannah, old fallow	3	Wooded savannah and old fallow
4. Altered	Regularly disturbing anthropogenic activities (e.g. drainage, regular passing over, intense fertilisation)	Changed ecosystem type, edaphon regularly disturbed	Vineyard, intensively used grasslands, plantation of energy forests	Young fallow, savannah, bushland, grassland, pasture	4	Savannah and bushland
					4,5	Savannah/crop mosaic
5. Cultural	Intense and regular impacts	Destruction of the natural occuring edaphon. Natural occuring floristic elements are reduced to a minimum (< 25% coverage)	Arable land, green urban areas, sport and leisure facilities	Anthropized wetland, crop, reservoir, anthropized grassland	5	Anthropized wetland, crop, pasture, grassland and young fallow, recurrent burned area, reservoir
6. Artificial with natural elements	Intensive and irreversible changes of terrain and landscape structure; soil sealing up to 30%	Natural elements only in the form of secondary biotopes	Rural settlements, mineral extraction sites, dump sites, airports	Discontinuous built, bare ground	6	Discontinuous built, bare ground
7. Artificial	Soil sealing over 30%	Artificial systems or structures	Continuous urban fabric, industrial or commercial unit, road and rail networks	Continuous built, Slag heap	7	Continuous built, Slag heap

Thirdly, we multiplied the N_d values by the D_n values and normalized the results for a range from 0 to 1 (division by the maximum value) in order to maximize the variation range of the results and to rescale it similarly to the other normalized indexes. In this way, the D_2N maps were obtained. The Rüdisser et al. (2012) methodology also reclassifies the results into four final levels, but in our case, the choice was made to keep the continuous variation to enable a detection of the finest nuances of the variation in anthropogenic effects.

2.4. Analysis of anthropization dynamics

In addition to the D_2N methodology, we highlighted the dynamics of the anthropogenic disturbance in the Lubumbashi region between 2002 and 2013 by subtracting the 2002 from the 2013 D_2N values, hence creating a post-classification change detection map. We composed a transition matrix to show how the natural and near natural classes changed during the 2002-2013 period.

3. Results and discussion

3.1. Adaptation of the D_2N methodology to local land use and cover types

3.1.1. Data acquisition

As for the image classification precision, the obtained Kappa coefficients were rather low (0.349 for 2002 and 0.316 for 2013, see confusion matrices in Appendix 2) (Congalton, 1991). These rather low values may be due to different factors. First, seasonal variation is relatively pronounced in the study area, especially with regard to fire dynamics, which may have led to misclassifications (Congedo & Munafò, 2012). Secondly, bare grounds have a similar spectral signature as built-up areas (Congedo & Munafò, 2012). Thirdly, the fast urban dynamics in the area may have lead to differences between the field survey observations and the satellite data given the time elapsed between both data collection periods. Fourthly, spatial pattern in Africa is rather loose (*sensu* low density of pattern elements) when compared to Northern hemisphere landscapes: land cover patches are less clearly delimited (Vranken et al., 2013), probably due to differences in land planning practices. This could lead to confusion between adjacent land covers. Fifthly, due to the medium spatial resolution of the images, pixels can contain different ecosystems (a phenomenon known as the "mixel" problem) but since they have to be attributed to a single class, the final class will not be representative of the entire pixel area (Pham & Yamaguchi, 2011). Finally, ecosystems, as often responding to regressive or progressive processes, are seldom "pure" but often correspond to transition states from one ecosystem to another. Analysis and classification algorithms could set the threshold between borderline land covers differently, leading to virtual misclassifications.

It should however be noted that the accuracy of the classifications is also inversely proportional to the thematic resolution considered (number of land cover classes): if a lower number of classes had been preferred (e.g., 7), the Kappa coefficient would have risen (to 0.49 in our example for the year 2013). Note that Congedo & Munafò (2012) obtained a Kappa value of 0.57 for a similar area using Landsat images, but their classification contained only 5 classes, against 14 in the current study. We preferred in the current study to prioritise a finer thematic resolution in order to obtain a more relevant classification to enable the elaboration of the hemeroby scale. The aforementioned considerations do however not question the validity of the D_2N methodology, which was applied as a post-treatment on the classified images.

The consequences of eventual misclassifications will depend on: i) the confusion between classes of distinct hemeroby levels, ii) the definition of the reference states (natural and near-natural levels) and other hemeroby levels and, iii) the correct classification (user precision) of these reference states. Errors in the two latter points have multiplicative effects on the results, given that the D_2N methodology is based on the hemeroby levels and on the distance to natural and near-natural sites, and given that the dynamics map depends on the two D_2N maps. In the case of the current study, the most problematic misclassification was the identification of wooded savannah (level 3) as woodland (level 2) (see Appendix 2), which tends to "naturalize" the landscape.

3.1.2. Data analysis

The application of the D_2N methodology to Lubumbashi in 2002 and 2013 (Figure 1) evidences the anthropization degree in the area. The dark spots represent the highest levels of human impact and correspond to the urbanized zones (4% of total area in 2002, 11% in 2013). The study area includes several urban zones, the largest of which is Lubumbashi (situated in the center-right part of the map), followed by: i) Likasi, situated along the Tshangalele Reservoir, Northwest of Lubumbashi, ii) Kipushi, the closest dark zone Southwest to the city of Lubumbashi and, iii) Kasumbalesa, located at the extreme Southeast of the study area. The natural or near-natural landscape classes form the landscape matrix (about 60% of the total extent, against 75% in 2002); its connectivity seems interrupted by urban and cultivated areas.

To generate the N_d map, Rüdisser et al. (2012) used a huge amount of data (forest hemeroby, CORINE classification, road networks, etc.), some of which were available as stretched values, but were integrated as a discontinuous and qualitative hemeroby scale, and displayed as a categorical map. In our first approach, we followed the same guidelines, except that less data were available for our study zone.

Patches of the same land use or cover type can be characterized by divergent anthropogenic dynamics. For example, a particular savannah area may result from a regressive series associated with fire disturbance, while another land with a similar vegetation may result from a progressive series, i.e. ecological succession, associated to an ending of previous disturbances. In the present study, such distinction between progressive and regressive series could not be made. This is partly due to the relatively coarse spatial resolution of the data and to the lack of precision with regard to the classification process (map categories (can) include different land covers, sometimes corresponding to different hemeroby levels).

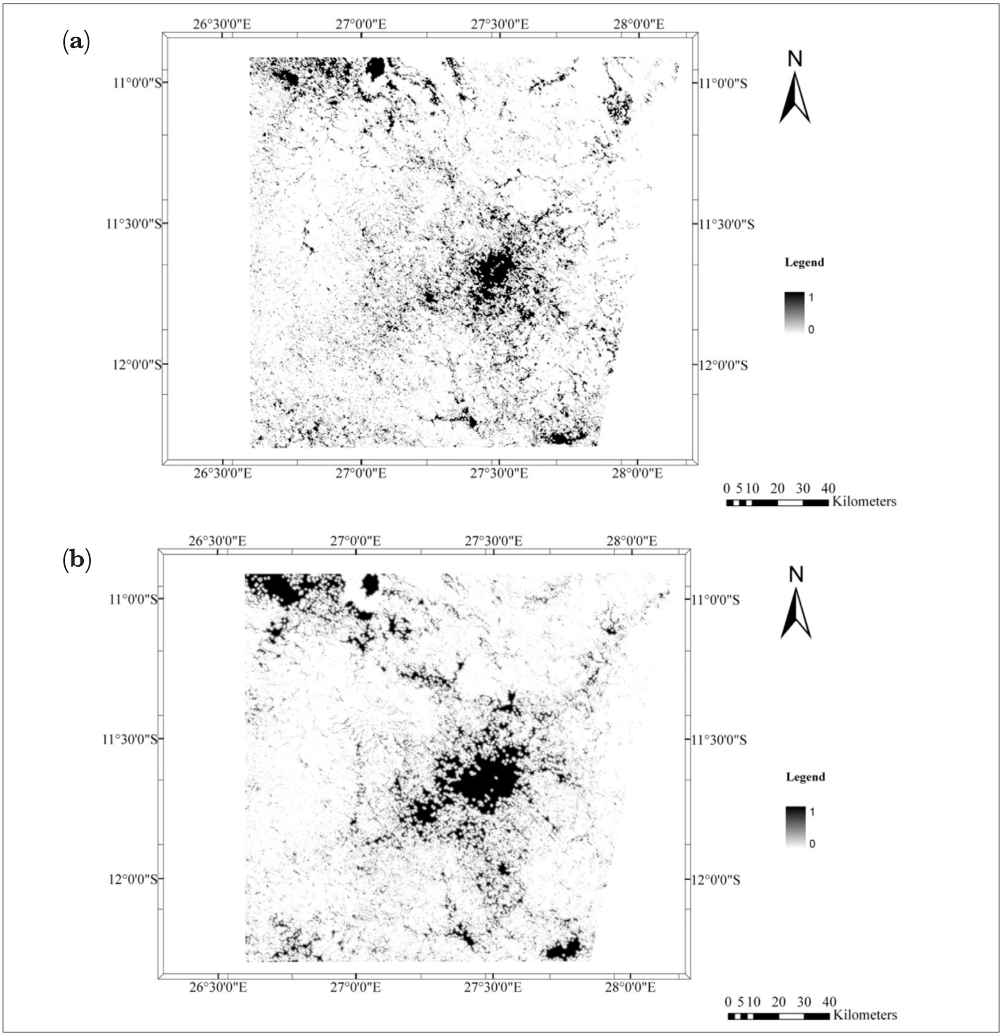

Figure 1. Application of the Rüdisser et al. (2012) "Distance to Nature" methodology to the region of Lubumbashi in 2002 (**a**) and 2013 (**b**). An index value of 0 reflects the shortest distance to nature; a value of 1 indicates a maximum distance to nature.

The choice of the ecosystems corresponding to the reference states and their identification on the classified image is of particular importance. In the case of the Katanga province, woodland vegetation is said to correspond to a "pyroclimax" on deep soils (dry evergreen forest being the natural vegetation in this case) but to a natural vegetation on shallow soils (Lawton, 1978; Schmitz, 1962; White, 1983), which was the choice made (see Table 1). However, this is to some extent controversial among scientists (Mahy, personal communication). In Table 1, level 1 is considered as virtual naturalness, considering the pre-colonial human interventions on landscape structure as anthropogenic, distinct from nature (Peterken, 1996; Lecomte & Millet, 2005; Vranken et al., in preparation).

The choice not to apply the final four-level D_2N scale used in Rüdisser et al. (2012) was justified in two ways. First, continuous variations of the D_2N values appear more precise: simplifying them in only 4 levels, as opposed to 7 levels in the original scale, represents information loss. Secondly, African spatial structure is rather continuous (Vranken et al., 2013) and is consequently accepted to be better represented by continuous transitions between anthropization levels. Attention should therefore be given to the fact that the presented results, showing a dominance of natural or near-natural classes, are caused by the very large extent of the study zone (~23,400 km²); this observation could give the erroneous impression that the urbanization trends characterizing the region of Lubumbashi do not lead to a higher frequency of anthropogenic effects of the area.

From a theoretical point of view, some observations could be formulated concerning the applied methodology of Rüdisser et al. (2012). The construction of composite indexes is still subject to debate (Dialga et al., 2014). However, the D_2N index has important advantages: feasibility and practicability with limited data availability, results easy to understand and interpret, consideration of anthropogenic influences and structural connectivity. On the other hand, the method should be applied with caution due to the following aspects: first, the inclusion of the notion of connectivity in the calculation of the anthropization index has the tendency to naturalize the representation of the landscape; indeed, given that only distances to natural or near-natural habitat were considered, the inclusion of the latter notion in the analysis decreases the D_2N values of the urban and cultivated areas, making them "to benefit" from the proximity of those areas; a patch will be attributed a low D_2N value if it is situated close to a natural or near-natural habitat, while the inverse is not true, and secondly, N_d and D_n are based upon the same data and are therefore not independent. However, the choice of multiplying rather than adding the parameters appears to be a justifiable choice. Indeed, if the range of values of D_2N remains the same in both cases, for ecosystems not belonging to the natural nor near-natural levels, whatever their distance to the nearest natural or near-natural habitat, they will never be attributed a lower value than 0.1665. Addition would tend to "anthropize" the representation of the landscape.

3.2. Anthropization dynamics between 2002 and 2013

The overall darker colour of the 2013 image (Figure 1), as well as preliminary observations on figure 2(a), suggest that during the considered time period, the studied area underwent an increase of anthropogenic effects mainly concentrated around the cities and spreading as a ribbon development (Ewing, 1994; Dumont & Bossé, 2006). The suburban zones of Lubumbashi and Kipushi appear to have almost merged, while they were still spatially separated in 2002. Furthermore, although natural and near-natural areas still dominate the area, they are now strongly disintegrated or fragmented.

The relative changes in anthropization level, quantified in figure 2(b), show that about 46% of the lands have known an anthropization level change in 11 years. Moderate increases dominate these dynamics (24.5% of total extent increased by 0.3 or less in D_2N value). The zones encountering anthropization increase cover about

32% of the total area, while the area characterized by an anthropization decrease only represents 15%, which confirms the overall increase of human-induced land use and land cover changes.

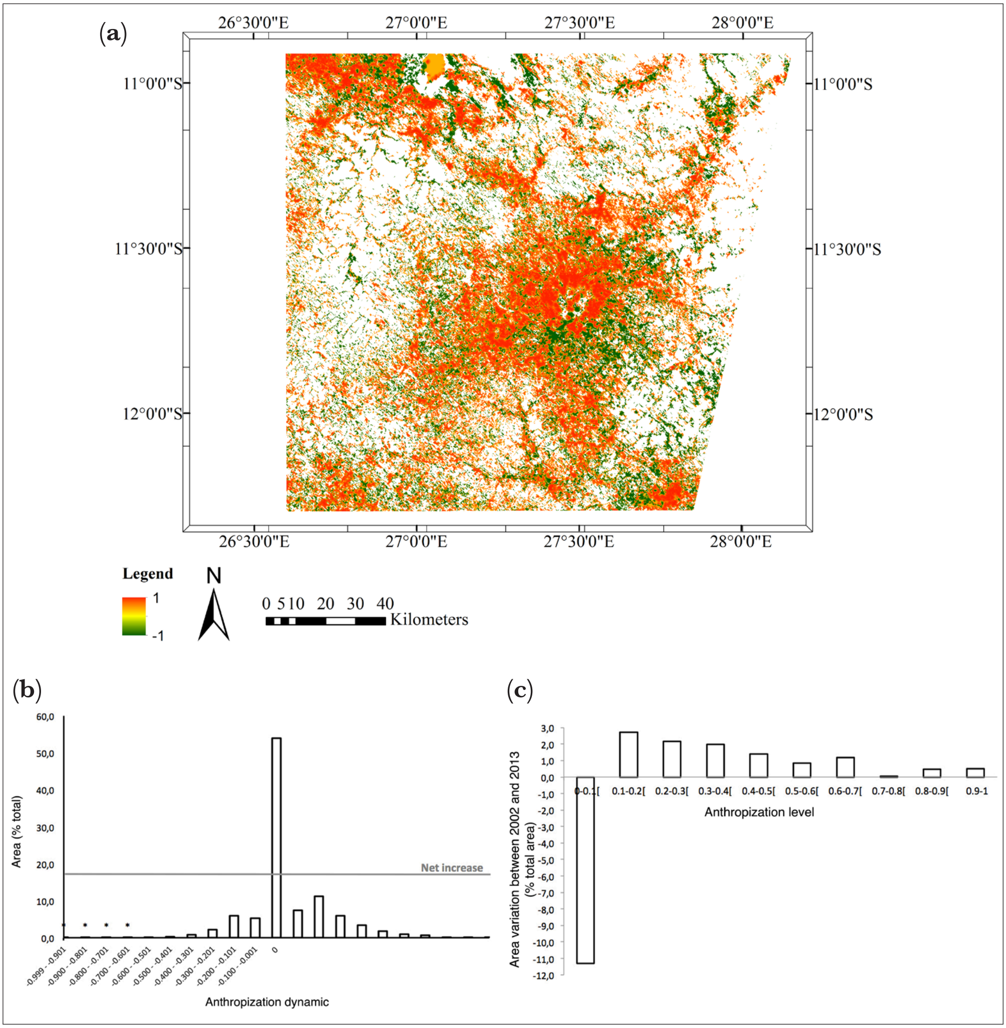

Figure 2. Dynamics of anthropization levels (D_2N) between 2002 and 2013 in the Lubumbashi region. For (**a**) and (**b**), the values from -1 to 1 represent the number of anthropization levels respectively lost or gained during the considered time period; 0 represents no anthropization level change. In (**a**), the localisation of the dynamics is shown, while (**b**) presents the percentage of the total area concerned by each change type (* represents values superior to 0 but below 0.1%) and concerned by the net increase in anthropization (horizontal bar). The net increase is defined as the area that encountered an increase in anthropization minus the area that encountered a decrease. The bar diagram (**c**) shows the percentage of the total area increase of each anthropization level between 2002 and 2013, ranging from 0 (lowest anthropized level) to 1 (highest anthropized level).

The area change for each anthropization level between 2002 and 2013 (Figure 2(c)) suggests that the dominant dynamics are: i) a dramatic decrease (about 11% of total extent) in the natural and near-natural levels and, ii) a substantial increase in intermediate levels of anthropization, probably following the aforementioned anthropization dynamics. The transition matrix shows that the natural and near-natural areas lost between 2002 and 2013 correspond mostly to "woodland" converted into "anthropized wetland" and to "woodland" and "natural grassland" converted into "recurrent burned area", "cropland, pasture, grassland and young fallow" and/or "wooded savannah and old fallow".

It should also be noted (Figure 2(a)) that the highest gains in naturalness are mostly dispersed near the outskirts of the cities. This phenomenon may be linked to young fallow developing into forest, image misclassifications or set-aside practices (Groupe Huit, 2009). The observed ribbon development pattern is similar to urbanization patterns observed in U.S. and European cities (Ewing, 1994; Brück, 2002; Grosjean, 2010).

4. Perspectives and conclusions

This first attempt to apply an hemeroby-based quantitative analysis of anthropogenic effects to a region in tropical Africa appears promising. It should also be applied on other Southern hemisphere cities in order to compare and assess the relevance of the current results. It should also be confronted to other methodologies applied on the same area but the lack of information currently available at this scale remains a limiting factor for such type of comparative analysis. Even this case study could benefit from supplementary information regarding to local field data, vegetation dynamics and land use practices.

The functional aspect of connectivity should also be taken into account when evaluating the configurational aspects of landscape anthropization (Tischendorf & Fahrig, 2000). For example, a large compact patch tends to shelter more interior and rare species, while having a less positive impact on structural connectivity than various corridors (Turner, 1989). The methodology could be amended in order to take that functional factor into account and could even developed to be species-oriented.

With regards to the distinction between progressive and regressive series, a better assessment of these phenomena could be feasible using more data, with a better spatial and temporal resolution or when producing smaller objects by means of segmentation. This approach would also enable the generation of similar post-classification change detection maps as in this contribution as well as N_d transition matrices in order to study specific patch dynamics. Reliable thematic maps such as up-to-date infrastructure could also be added, as in Rüdisser et al. (2012). In this case, specific attention should be given to weighing the respective influences of each type of human activity or disturbance data, in order to avoid redundancy and bias.

Considering the application of the method, the mutual influences of anthropized and natural lands, highlighted by the introduction of a distance gradient, present interesting perspectives for land planning, conservation management and ecological restoration. Indeed, the impact of adding or removing natural patches in the landscape depending on the distance to existing natural habitats and on the surrounding land use types could be simulated using D_2N maps. This could enable to prioritize areas to protect and/or degraded ecosystems to restore. It should however be noted that this methodology does not distinguish the intrinsic natural habitat richness or conservation interest linked to its specific composition, which is necessary to every conservation management option and should be complementarily examined (Séleck et al., 2013).

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Appendix 1: Decision tree for the discrimination of land cover

Figure 3 shows the decision tree used by the analyst in the field to identify the land cover of the sample points. The analyst considered homogeneous imaginary circles of 10 m radius. Inside those circles, the land cover was evaluated. The iterative evaluation begins with the consideration of the presence of bare soil: if it covered the entire circle, then the sample point was identified as “bare soil”. Otherwise, if built surfaces were present and if the size of the separation area between the constructions was superior to their width or if there was no dominance of built surfaces, the sample point was assigned to “discontinuous built”. Alternatively, it was attributed to “continuous built”. If the amount of built surfaces was null or negligible, then the analyst evaluated the moisture of the field. In case of wet fields, the sample point was assigned to “wetland”. Otherwise, the height of the herbaceous layer was evaluated (plants with a height inferior to 2 m are considered as “herbaceous”). If it was considered as high, the tree crown cover was evaluated (a “tree” is considered as a wooded plant with a height superior to 8 m). If it was null, then the shrub cover was considered (“shrubs” are considered as plants with a height between 2 and 8 m). If the shrub cover was zero, then the sample point was attributed to “grassland”. Otherwise (shrub cover of 0-50%), it was attributed to “bushland”. If the tree cover ranged between 1 and 25%, the sample point was assigned to “savannah”. If it ranged between 25 and 60%, it was attributed to “wooded savannah”. When the height of the herbaceous layer was low or when this cover was absent, as previously mentioned, the tree crown cover was evaluated. When inferior to 40%, as aforementioned, shrub cover was evaluated. When null, the sample point was assigned to “pasture”. When superior to 0 but inferior to 40%, when the presence of ridges on the ground was recognized, the sample point was attributed to “crop”. Otherwise, it was assigned to “young fallow”. When the shrub cover ranged between 40 and 80%, the point was assigned to “old fallow”. When the tree crown cover was superior to 40%, then the height of the trees was also considered. Indeed, when trees with a height superior to 15 m had a crown cover superior to 60%, the sample was attributed to “woodland”. Otherwise, it was assigned to “old fallow/regenerating forest”. The criteria used in the decision tree were documented in Ruelle et al. (n.d.), Trochain (1957), Letouzey (1982) and Bellefontaine et al. (1997). No sample points could be collected in the field for the following classes: “natural grassland”, “stream”, “savannah/crop mosaic”, “recurrent burned area”, “reservoir” and “slag heap”. These land use and cover classes were identified by means of Google Earth imagery.

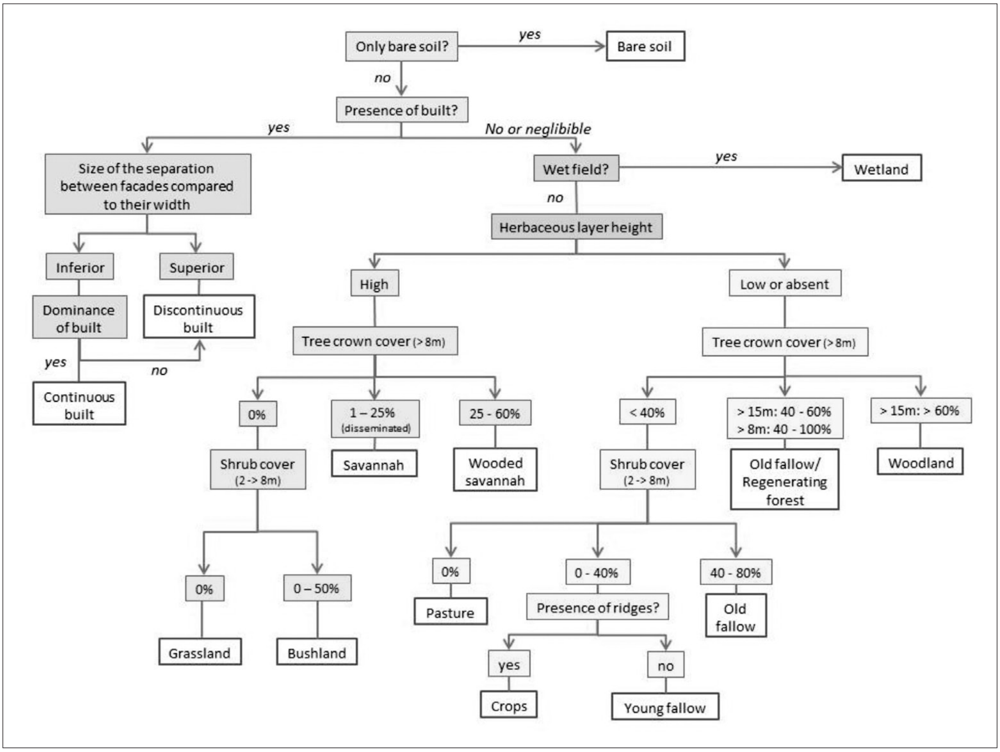

Figure 3. Decision tree used by the analyst in the field to identify the land cover of the sample points.

Appendix 2: Confusion matrices for the classification of the Landsat images of Lubumbashi

Table 2. Confusion matrix for the classification of the 2002 Landsat image.

2002											
Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crop, pasture, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crop mosaic	Water	Wetland	Wooded savannah	
Continuous Built	7	1	0	12	0	0	7	0	1	0	25,0
Crop, pasture, grassland and young fallow	2	10	1	7	0	3	5	1	4	0	30,3
Natural grassland	0	2	7	0	0	1	0	3	1	4	38,9
Discontinuous built, bare soil	5	1	0	10	0	0	1	0	1	0	55,6
Woodland	0	0	6	0	15	3	1	0	0	8	45,5
Savannah, bushland	0	0	0	0	0	0	0	0	0	0	0,0
Savannah/crop mosaic	0	0	0	0	0	0	0	0	0	0	0,0
Water	0	0	0	0	0	0	0	11	0	0	100,0
Wetland	1	0	0	0	0	0	0	0	8	0	88,9
Wooded savannah	0	0	1	0	0	8	0	0	0	0	0,0
Burned area	0	1	0	1	0	0	1	0	0	3	
Producer's accuracy (%)	46,7	66,7	46,7	33,3	100,0	0,0	0,0	73,3	53,3	0,0	
Overall accuracy: 41.2% Kappa statistic: 0.349											

Table 3. Confusion matrix for the classification of the 2013 Landsat image.

2013											
Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crop, pasture, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crop mosaic	Water	Wetland	Wooded savannah	
Continuous Built	15	2	0	9	0	0	0	2	1	0	51,7
Crop, pasture, grassland and young fallow	0	6	0	2	1	4	9	3	3	0	21,4
Natural grassland	0	0	5	0	0	0	0	2	2	2	45,5
Discontinuous built, bare soil	0	1	0	15	0	0	0	1	2	0	78,9
Woodland	0	2	4	0	8	6	0	1	0	5	30,8
Savannah, bushland	0	1	0	1	0	0	1	0	0	0	0,0
Savannah/crop mosaic	0	0	0	0	0	0	1	0	0	0	100,0
Water	0	0	0	3	0	0	0	5	0	0	62,5
Wetland	0	0	0	0	2	0	0	1	5	0	62,5
Wooded savannah	0	2	5	0	4	3	4	0	1	3	13,6
Burned area	0	1	1	0	0	2	0	0	1	5	
Producer's accuracy (%)	100,0	40,0	33,3	50,0	53,3	0,0	6,7	33,3	33,3	20,0	
Overall accuracy: 38.2%											
Kappa statistic: 0.316											