COMMUNAUTÉ FRANÇAISE DE BELGIQUE

UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

Landscape ecological consequences of the (sub)urbanization process in an African city: Lubumbashi (Democratic Republic of Congo)

Marie ANDRE

Thesis submitted in fulfilment of the requirements for the degree of Doctor (Ph. D.) in Agronomy and Bioengineering

Co-supevisors: Jan BOGAERT

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Summary

If anthropogenic effect is a general term accounting for the influence of human activities on environment, it may also designate specific influences that may be inter- and intralinked. Thus, urbanization and suburbanization are anthropogenic processes contributing to the broad anthropogenic effect. They hide in turn other subprocesses of land transformation that will be called here the secondary spatial impacts. However, although the growing influence of the latter processes, they are still not defined consensually nor exist a comprehensive and applied-oriented methodology to delimit them.

The general objective of this thesis is to develop a spatially explicit methodology to evaluate the landscape ecological consequences of the urbanization and suburbanization processes, taking a representative city of Sub-Saharan Africa as a case study: Lubumbashi (Democratic Republic of Congo), and the last decade as the period of study. That general objective is addressed through two themes, to which correspond specific objectives. The first theme concerns the evaluation of the anthropogenic land use and land cover dynamics and the second one proposes a methodology to evaluate the expansion of urban and suburban areas, in relation with consistent definitions of the areas in the urban-rural gradient. For both themes, the propositions are based on remote sensing techniques and landscape ecology metrics.

Results show that the region of Lubumbashi underwent a global anthropisation increase mostly constituted of minor rises of anthropisation levels but impacting mainly the most natural landscape classes. Urban and suburban areas were located through the use of the proportion of built-up metric, the secondary spatial impact area through the use of adjacencies of the less natural landscape patches. The growth shape of the urban and suburban areas is concentric, except in the south-western part of the city where an affluent of the river Kafubu and its adjacent wetlands slow the urban expansion. The secondary spatial impact area dynamics seems determined, in the north-west, by the relief and, in the north-east, by a transportation axis. It is the latter dynamics that is dominant for the period. It corresponds to the so-called savanisation process, probably due to wood fuel and charcoal production.

The methodologies developed here could be improved by taking connectedness into account, by using an additional configuration metric for the definition of urban areas or by taking advantage of

spatially explicit socio-economic data. They could also be tested on mining sites, other cities and/or using images of different spatial resolution.

Résumé

Si l'anthropisation est un terme générique décrivant l'influence des activités humaines sur l'environnement, il peut aussi désigner des influences spécifiques qui peuvent être inter- et intra-liées. Ainsi, l'urbanisation et la périurbanisation sont des processus anthropiques qui contribuent à l'anthropisation globale. Ils induisent à leur tour d'autres sous-processus de transformation du territoire qui seront appelés ici les impacts spatiaux secondaires. Toutefois, malgré l'influence croissante de ces derniers processus, ils ne sont toujours pas définis de façon consensuelle ; il n'existe pas non plus de méthodologie cohérente et spatialement explicite pour les délimiter.

L'objectif général de cette thèse est de développer une méthodologie spatialement explicite pour évaluer les conséquences écopaysagères des processus d'urbanisation et de périurbanisation en considérant une ville représentative d'Afrique sub-saharienne comme cas d'étude : Lubumbashi (République Démocratique du Congo), et la dernière décennie comme période d'étude. Cet objectif général est rencontré en explorant deux thématiques qui constituent les objectifs spécifiques. La première concerne l'évaluation des dynamiques anthropiques influençant l'utilisation et l'occupation du sol et la seconde propose une méthodologie pour évaluer l'expansion des zones urbaine et périurbaine, en cohérence avec des définitions des zones comprises dans le gradient urbain-rural. Pour les deux termes, les propositions sont basées sur des techniques de télédétection et des indices paysagers.

Les résultats montrent que la région de Lubumbashi a connu un accroissement global de son anthropisation, principalement *via* des augmentations mineures des niveaux d'anthropisation, ces dernières impactant principalement les classes paysagères les plus naturelles. Les zones urbaine et périurbaine ont été localisées grâce à l'utilisation de l'indice de proportion de surface bâtie, les surfaces d'impact spatial secondaire *via* l'utilisation de la contiguïté des taches paysagères les moins naturelles. La forme de croissance des zones urbaine et périurbaine est concentrique, excepté dans la partie sud-ouest de la ville où un affluent de la rivière Kafubu et ses marécages adjacents ralentissent l'expansion urbaine. Les dynamiques des zones d'impact spatial secondaire semblent déterminées, au nord-ouest, par le relief et, au nord-est, par un axe de transport. C'est cette dernière dynamique qui est dominante durant la période d'étude. Elle correspond au fameux processus de savanisation, résultat probable de la production de bois de chauffe et de charbon.

Les méthodologies développées ici pourraient être améliorées en prenant la connectivité fonctionnelle en compte, en utilisant un indice de configuration additionnel pour la définition des zones urbaines ou en s'appuyant sur des données socio-économiques spatialement explicites. Elles pourraient également être testées sur des sites miniers, d'autres villes et/ou en utilisant des images de résolution spatiale différente.

Remerciements

Cette thèse est hautement improbable : elle est le résultat d'un improbable enchaînement d'évènements individuels dont la probabilité d'apparition était elle-même extrêmement faible.

Tout a commencé par une candidature spontanée envoyée en avril 2010. Laquelle fut suivie par l'envoi d'une offre d'emploi en juillet de la même année : on recherchait un assistant pour le master en Architecture du Paysage 2.0. Mon tout premier remerciement revient donc à l'équipe chargée d'évaluer les candidatures et qui décida de me faire confiance.

Ensuite, je remercie Grégory Mahy d'avoir tout d'abord assuré pendant plusieurs mois le rôle de « superviseur intérimaire » pour ensuite, après avoir laissé ce rôle à d'autres, avoir continué à suivre de près mes recherches. Les discussions et points de vue inattendus ont grandement contribué à enrichir cette thèse, mais aussi à m'ouvrir l'esprit.

Merci ensuite à mes deux co-promoteurs, Jan Bogaert et Philippe Lejeune, d'avoir supervisé mon travail au fil des années. Jan, je suis ravie de constater que nous avons pu trouver un langage commun et une manière de fonctionner permettant de tirer le meilleur parti de nos différences ; Philippe, merci pour ce suivi fait du mélange de perfectionnisme et de décontraction dont toi seul a le secret.

Merci ensuite aux autres membres de mon comité : Cédric Vermeulen et Yves Hanin pour avoir accepté de tenir ce rôle, mais aussi pour vos contributions à l'enrichissement de cette thèse.

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La supervision est une chose, le travail au jour le jour en est une autre. Je remercie bien sûr mes collèges de Biodiversité et Paysage pour les échanges, les coups de main, les marques de soutien et chaque sourire échangé, mais aussi les membres de l'axe de Gestion des Ressources Forestières auxquels je me suis plu à me mêler, au mess ou lors de mes quelques « stages techniques » estivaux. En particulier, merci à Isabelle Vranken pour notre fructueuse collaboration et nos discussions conceptuelles sans fin. Merci à Justine Maréchal pour son importante contribution aux premiers aspects techniques de cette thèse. Et enfin, merci à Samuel Quevauvillers pour son appui technique indispensable et sans faille.

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Je ne peux écrire cette partie de remerciements sans rendre hommage à mes collègues de la première heure, devenues entretemps des amies : Gwenn Frisson, Catherine Richard, Julie Lebrun, Joëlle Vandersteen, notre géologue Christelle Dere et notre petite physicienne Elisabeth Jérôme. Quel beau cadeau de la vie que de vous avoir rencontrées !

Merci à vous tous, amis et famille, pour votre soutien constant durant ces quelques années, bien que ce projet ait pu vous paraître fou, vu de l'extérieur, à bien des moments.

Merci à Pierre pour son enthousiasme et ses encouragements à me lancer dans ce projet.

Enfin, merci à François pour son soutien, ainsi que la précieuse coloration dont il teinte ma vie.

À vous tous, les trop tôt partis,
À Rem’s, Dr Dr Phan-Ba,
Vous dansez derrière chacune de ces lignes.

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Introduction

Anthropogenic effect, urbanization, suburbanization

A very long time ago, humankind was a species among others with little impact on its environment. Since then, anthropogenic effect, which is the generic term which accounts generally for the influence of human activities on the environment, has ceaselessly increased (Ellis et al., 2008; Solon, 1995). Nowadays, nearly no area in the world is, in one way or another, influenced by human impacts (Sanderson et al., 2002). In the literature, the term anthropogenic effect labels both causes and consequences of environmental changes as well as the change process itself. Different types may be interlinked and different levels of processes may be nested (McNeill et al., 1994). Thus, anthropogenic broad subprocesses may include deforestation (Forman, 1995; Rudel, 2009), corridor construction (Forman, 1995), desertification (Forman, 1995), agricultural intensification (Forman, 1995; Rudel, 2009), reforestation (Forman, 1995), urbanization and suburbanization (Forman, 1995; Rudel, 2009).

Indeed, as a result of the progressive sedentarization of humankind and the concomitant advent of agriculture, once the yields of the agricultural production were sufficient, secondary and tertiary sectors could develop (Mazoyer et al., 2002; Ramade, 2012). In parallel of the latter, cities were created, extended and then densificated (Mazoyer et al., 2002), phenomenons that will be grouped here under the urbanization broad designation. The two latter phenomena, extension and densification, were then reinforced by rural migration into the city (Besussi et al., 2010) and finally demographic self-sustainability (Weeks, 2010). Nowadays, the proportion of world population living in cities is superior to 50% and cities continue globally to expand (United Nations, 2015). However, a rather recent and widespread process is the creation and then extension of what are called suburban areas (Calthorpe, 2011; Hervoët, 2001). These processes will be grouped here under the suburbanization broad term. It is sometimes also called sprawl (Alberti, 2008; Ewing, 1997; Transportation Research Board, 2002), according to the characteristics of the phenomenon.

Urbanization and suburbanization have similar impacts on the environment, the range of the impacts growing often with the proximity to urban areas: local climate change (urban heat island*, longer periods of plant growth, warmer summers, milder winters) (Sukopp 1998 in Müller and Werner, 2010; Pickett et

* See the Glossary section.

al., 2001); modification of the water-soil-moisture regimes (drier in temperate zones) (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001); higher levels of nutrient inputs (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001); higher productivity and food availability for animals (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001); soil, air and water pollution (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001); disturbance such as trampling, mowing, soil change, noise and litter, fly tipping (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001); fragmentation[*] of spaces, higher proportion of introduced species, larger number of euryoecious[*] and common species (Sukopp 1998 in Müller and Werner, 2010; Pickett et al., 2001). Though, suburbanization induces specific consequences: creation of social ghettos, reinforcement of social inequalities, visual degradation of landscapes, human conflicts due to the multiplication of the stakeholders involved in the area, increased risk of fire (Bieber et al., 1993; Brück, 2002; Dubois, 2006; Halleux, 2006; Hanson, 2006; Iaquinta et al., 2000; Jaeger et al., 2010a; Larcher, 1998; Rutherford, 2010; Trefon et al., 2007). In Europe, specific negative consequences have been related: use of fields of high agricultural value for construction, rise of energy consumption and unsustainable financing of the equipment by local authorities (Brück, 2002). In developing countries, a lot of economical activities take place in suburban areas; they allow the households to be less vulnerable to the economic downturn. Though, inhabitants cruelly miss equipment and land tenure security (Briggs et al., 2001; Drakakis-Smith, 1994, 1991; Trefon et al., 2007; ULB, 2006).

In accordance with the aforementioned inter- and intralinkages between anthropogenic processes (McNeill et al., 1994), beyond these direct impact of (sub)urbanization, other processes of land transformation may be induced on the direct hinterland: land clearance for agriculture, timber production, wood fuel and charcoal production can lead to forest degradation[*] then to deforestation, agriculture may intensify to satisfy the growing demand for food of city dwellers, materials may be mined for building and pollution may result from unregulated dumping of urban waste (Ahrends et al., 2010; Clancy, 2008). The surrounding rural land cover impacted by the latter processes will be designed here by the term secondary spatial impact.

However, although the growing interest in the broad urbanization and suburbanization matters, there is no consensus among the scientific community concerning the definitions and characteristics of these processes aside the broad characteristic of expansion of impervious surfaces on other land cover. Similarly, unsurprisingly, there is no agreement on the definitions, characteristics and delimitation of the different areas included in the urban-rural gradient[*]: rural, suburban, urban fringe, sprawl, exurban,

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[*] See the Glossary section.

rurban, "banlieue", urban, among others. Some studies mention one of the areas without defining it, the exact signification is implied (Godefroid et al., 2003; Grau et al., 2008; Hermy et al., 2000) or considered as commonplace (McIntyre, 2011). The consequences of that situation is that no rigorous quantification of the effect of urbanization and suburbanization nor comparison or complementarity between similar studies is possible (Forstall et al., 2009; Macgregor-Fors, 2011).

Landscape ecology, provider of a relevant conceptual framework to study the anthropogenic effect

Mc Neill et al. (1994) highlight that the most differentiating characteristics to define the anthropogenic land use*/cover* changes are 1) the anthropogenic subprocesses involved in the main process, 2) the driving forces (political, economical, demographic or environmental) leading to that change and 3) the land cover* type affected by the change.

A phenomenon such as (sub)urbanization may be studied at different scales, from the global to the organism one but the focus scale and conceptual framework of landscape ecology seem particularly relevant when attempting to understand the link between the aforementioned differentiating characteristics. Indeed, landscape ecology is a transdisciplinary field that integrates the knowledge of other disciplines relating to higher (region, continent, planet) and lower (ecosystems, communities, populations, organisms) scales to explain respectively the context and the mechanisms involved in a landscape process (Figure 1) (Bogaert et al., 2013; Forman, 1995; Wiens et al., 1993). In this discipline, landscape is considered as an heterogeneous composition of interacting ecosystems (Forman et al., 1986). The landscape ecological patch-corridor-matrix paradigm allows the modeling of the landscape through environmentally homogeneous units called "patches" (Burel et al., 2003; Forman et al., 1986), sometimes elongated and called "corridors", dispersed in an homogeneous principal land cover* called "matrix". According to its central hypothesis, the pattern/process paradigm, landscape structure (i.e. the composition* and configuration* of the classes and patches part of the landscape) (Alberti, 2008; Li et al., 1995) and ecological processes are interrelated (Bogaert & Hong, 2004; Coulson et al., 1999; Turner, 1989). Once the pattern of the landscape has been represented using patches, its state and/or dynamics can quantitatively be interpreted using appropriate metrics (Herold et al., 2003; McGarigal, 2002).

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* See the Glossary section.

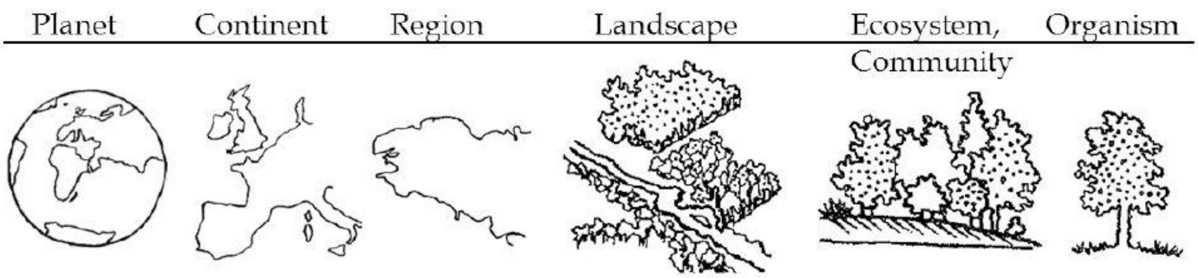


Figure 1. Study scales relating to the context (region, continent, planet) and the mechanisms involved in a landscape process (Vranken, 2015; adapted from Burel and Baudry, 2003).

If many authors propose methodologies to describe the urban spatial pattern based on metrics, none of these methodologies concern the secondary spatial impact area, allow drawing a line between the different areas of the urban-rural gradient*, are linked to a specific definition of the areas nor are applied-oriented. Finally, most of them are data demanding, suggest metrics that are correlated and/or depend on spatial resolution* (Alberti, 2008; Angel et al., 2007; Batisani et al., 2009; Bhatta et al., 2010; Christensen, 2009; Davis et al., 2005; Feranec et al., 2010; Galster et al., 2001; Glaeser et al., 2001; Hasse, 2004; Jaeger et al., 2010b; Kline, 2000; Martinuzzi et al., 2007; Nelson et al., 1999; Theobald, 2005; Torrens, 2000; Transportation Research Board, 2002). The other few methodologies that avoid these latter pitfalls are either still inadapted to suburban and secondary spatial impact areas (Kasanko et al., 2006) and/or too rigid (Macgregor-Fors, 2010). The aforementioned problematics are particularly tricky in the poorest countries due to the lack of data and resources to study and monitor the states and dynamics of their cities (Besussi et al., 2010).

Remote sensing, provider of relevant tools

Remote sensing is the process of acquisition of information (i.e. electromagnetic radiations) about an object without making physical contact with it, using aerial sensor technologies (Lillesand et al., 1979). It provides detailed, accurate and up-to-date information concerning the land use*/cover* of a landscape or a region. Its operational scale makes it an ally of choice for landscape ecology. Its large area cover and ability to map inaccessible areas give it a tremendous advantage over ground survey methods (Congedo et al., 2014; Forkuor et al., 2011; Taubenböck et al., 2009). These characteristics explain why images from earth observation satellites have been gaining always more value to map, monitor and manage earth's resources during the last decades (Forkuor et al., 2011). They are of particular interest in data-

* See the Glossary section.

poor regions facing a lack in recent and reliable spatial information (Pham et al., 2011). However, obtaining high spatial** and/or spectral resolution* images can represent a significant cost, especially if the area to be covered is important. And too low resolutions may prevent accurate discrimination of certain classes of landscape.

* See the Glossary section.

Objectives, research questions and structure of the thesis

If facing the urbanization and suburbanization processes is a concern for all parts of the world, the situation of Sub-Saharan Africa is particularly challenging, for various reasons. First, while Africa is the part of the world where the rise in urban population will be the greatest by 2050 (increase by 200%), this rise will be even stronger in Sub-Saharan Africa (United Nations, 2015). Furthermore, the latter region starts from one of the least urbanized situation of the world as it comprised, in 2014, five of the ten least urbanized countries with a percentage of urban population equal to 37% (United Nations, 2015). Secondly, like a lot of other cities in developing countries, that region is facing an important lack of data. Third, the local administrations lack technical and financial means to plan and monitor the current and expected development of the cities.

The general objective (O) of this thesis is to develop a spatially explicit methodology to evaluate the landscape ecological consequences of the urbanization and suburbanization processes in Sub-Saharan Africa. The methodology should take into account the specific constraints of that region.

The land around Lubumbashi (in the Democratic Republic of Congo) has been chosen as case study because, besides the representative size of its focal city (expressed in urban population), it is representative of these constraints as well as of the aforementioned challenges. Indeed, in Sub-Saharan Africa, excluding the cities counting less than 300 000 inhabitants which dominate currently the types of cities, medium-sized cities (1 000 000 – 5 000 000 inhabitants) are the second most represented class of cities (United Nations, 2015). Lubumbashi counted a population of 1 769 400 inhabitants in 2014 (unpublished data from Lubumbashi's Town Hall) and is therefore part of the latter category. Moreover, the estimated and/or projected growth rate of the population of Lubumbashi sticks very closely to those of the Sub-Saharan Africa, even more since 1990 and up to 2030 (United Nations, 2015). Secondly, regarding the lack of data, the last official national population census dates from 1984 (United Nations, 2015) and the last map of the city was elaborated in 1985 (Bruneau et al., 1990). Third, the city develops with almost no planning nor infrastructure on areas more… or less environmentally, socially and economically favorable.

To achieve the general objective, two themes need to be addressed. Each of them is associated with three specific objectives (SO) related to the state of the landscapes, and publications. The link between the themes and the specific objectives is as follows:

- Theme 1. Evaluation of anthropogenic land use* and land cover* dynamics
    - (SO 1) to evaluate to which reference state to compare an existing anthropised state
    - (SO 2) to evaluate the existing assessment methods to measure the anthropogenic effect
    - (SO 3) to evaluate the anthropogenic land use* and land cover* dynamics of the studied landscape
- Theme 2. Evaluation of the expansion of the (sub)urban areas of a landscape.
    - (SO 4) to highlight the discriminating characteristics of the areas in the urban-rural gradient* and propose new definitions of these areas
    - (SO 5) to evaluate the most relevant landscape metrics to locate the areas in the urban-rural gradient* areas
    - (SO 6) to evaluate the expansion of the (sub)urban areas of the studied landscape

Finally, the two approaches are integrated to fulfill the general research objective.

After a presentation of the case study, the Chapter 1 briefly describes the data used to fulfill the different objectives, the Chapter 2 details the classification process applied to the satellite images while putting it in perspective with the stumbling blocks encountered and the solutions proposed. The Chapter 3 develops and discusses in an integrated and synthetic way the main findings and the shortcomings of each methodology. Further details concerning each of the topics may be found in the full text papers (Appendix 4). Finally, in the Chapter 4, the results are put into a general perspective and the chapter 5 proposes a general conclusion. In order to keep the synthetic guideline of the document and avoid digressions, a Glossary section resumes some key terms used in the essay. The presence of a definition in the glossary for a term will be marked with an asterisk beside it. The List of Abbreviations section resumes all the abbreviations used throughout the document.

Details on the publications as well as their relation to the themes and the specific objectives may be found in the Table 1. Furthermore, the general objective, the different specific objectives, the related research questions/objectives and related publications (represented by their reference number) are

* See the Glossary section.

synthetized in the Figure 2. It should be read from top to bottom and represents the specific research questions (SQ) of the thesis in the logical order followed by the author.

To ease the correspondence between the core of the thesis and the full-text publications displayed in the Appendix 4 section, throughout the document, the reference numbers of the corresponding publications will be displayed in brackets, bold and grey.

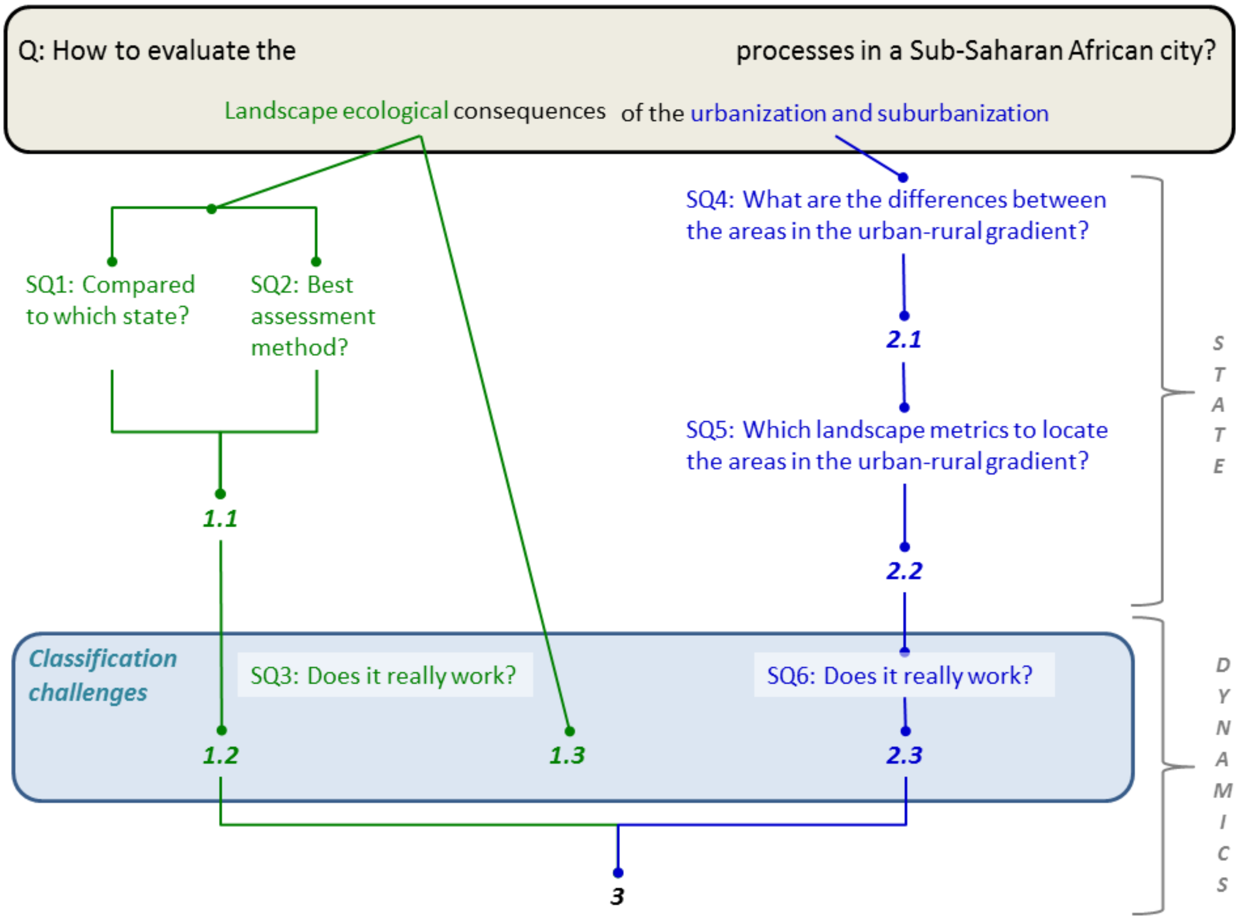


Figure 2. Mindmap of the thesis: organization of the publications (represented in by their reference number) according to 1) the general research question (Q) and its corresponding specific questions (SQ) and 2) the corresponding landscape ecology theme (in bold and grey, to the right). The color green corresponds to the perspective of the anthropogenic land use and land cover dynamics ; the color blue corresponds to the expansion of the (sub)urban areas.

Table 1. Correspondence between the reference numbers of the publication(s) (Ref. no.), their titles, their related specific objectives, the document main characteristics and the associated theme of the thesis.

Ref. no.	Title	Related specific objectives	Document main characteristics
Anthropogenic land use and land cover dynamics			
1.1	Vranken, I.*, André, M.*, Inostroza, L., Mahy, G., Visser, M., & Bogaert, J. (in preparation) Spatially explicit quantification of anthropogenic landscape change. Towards a new methodological framework. *Landscape and Urban Planning*.	SO1: Evaluate to which reference state to compare an existing anthropised state and SO2: Evaluate the existing assessment methods to measure the anthropogenic effect	Co-first author Perspective essay Peer-reviewed journal In preparation/revision
1.2	André, M.*, Vranken, I.*, Boisson, S., Mahy, G., Rüdisser, J., Visser, M., Lejeune, P., & Bogaert, J. (in press). Quantification of anthropogenic effects in the landscape of Lubumbashi. In G. Mahy, G. Colinet, & J. Bogaert (eds.) Anthropisation au Katanga. Gembloux: Presses Universitaires de Gembloux. http://hdl.handle.net/2268/186226	SO3: Apply assessment method(s) of anthropisation to a test area	Co-first author Chapter of a book Peer-reviewed book In press
1.3	Useni Sikuzani, Y., André, M., Mahy, G., Cabala Kaleba S., Malaisse F., Munyemba Kankumbi, F., & Bogaert, J. (in press). Interprétation paysagère du processus d'urbanisation à Lubumbashi : dynamique de la structure spatiale et suivi des indicateurs écologiques entre 2002 et 2008. In G. Mahy, G. Colinet, & J. Bogaert (eds.) Anthropisation au Katanga. Gembloux: Presses Universitaires de Gembloux. http://hdl.handle.net/2268/194483	SO3: Apply assessment method(s) of anthropisation to a test area	Co-author Chapter of a book Peer-reviewed book In press
Expansion of the (sub)urban areas			
2.1	André, M., Mahy, G., Lejeune, P., & Bogaert, J. (2014). Vers une synthèse de la conception et une définition des zones dans le gradient urbain-rural. Base, 18(1), 61-74. http://hdl.handle.net/2268/161968	SO4: Highlight the discriminating characteristics of the areas in the urban-rural gradient; propose new definitions of these areas	First author Review Peer-reviewed journal Published
2.2	André, M., Mahy, G., Lejeune, P., & Bogaert, J. (2012). Vers une définition unique des zones périurbaines? L'apport de l'écologie du paysage pour la segmentation du gradient urbain-rural. Penser et produire la ville au XXIème siècle. Modernisation écologique, qualité urbaine et justice spatiale. ed. Lausanne, Suisse: APERAU, "Association pour la Promotion de l'Enseignement et de la Recherche en Aménagement et Urbanisme". http://hdl.handle.net/2268/128630	SO5: Evaluate the most relevant landscape metrics to locate the areas in the urban-rural gradient areas	First author Conference proceeding Published
2.3	André, M., Useni Sikuzani, Y., Brostaux, Y., Mahy, G., Bogaert, J., Lejeune, P. (submitted) How much has that city grown? The case of Lubumbashi (DRC). *Land*.	SO6: Check the applicability of the methodology to a test area	First author Research paper Peer-reviewed journal Submitted
Integration of the two themes			
3	André, M., Mahy, G., Lejeune, P., & Bogaert, J. (2013). Le Patron urbain, un facteur influençant l'impact de l'urbanisation sur les écosystèmes: les cas de Kisangani et de Lubumbashi (RDC). Colloque international Territoires périurbains: développement, enjeux et perspectives dans les pays du sud. ed. Gembloux, Belgique: Pacodel. http://hdl.handle.net/2268/166584	O: Integration of the two latter approaches to answer the general research question	First author Conference proceeding Published

Case study

Lubumbashi is the second economic (Ravelosoa et al., 2009) and the second most populated (United Nations, 2015) city of the Democratic Republic of the Congo. It is situated in the Haut-Katanga province in the Southern part of the country (Figure 3). The administrative area of the city is approximatively 747 km² (Bruneau et al., 1990). Since the beginning of the 20^{th} century, Lubumbashi has developed along with its flourishing mining sector, due to its ideal localization in the Katangese copper belt (Bruneau et al., 1990; Chapelier, 1957; UMHK, 1956). The Figure 4a shows the global shape of the built parts of the city.

The study zone consists of a plateau that has been eroded into a wide valley by the Lubumbashi river and its tributaries (Chapelier, 1957). The altitudes of the inner-city, on the plateau, vary between 1200 and 1250 m (Sys, 1960). 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 Köppen category (Kottek et al., 2006). Currently, the vegetation cover is continuous only during the wet season (Adam, 2010).

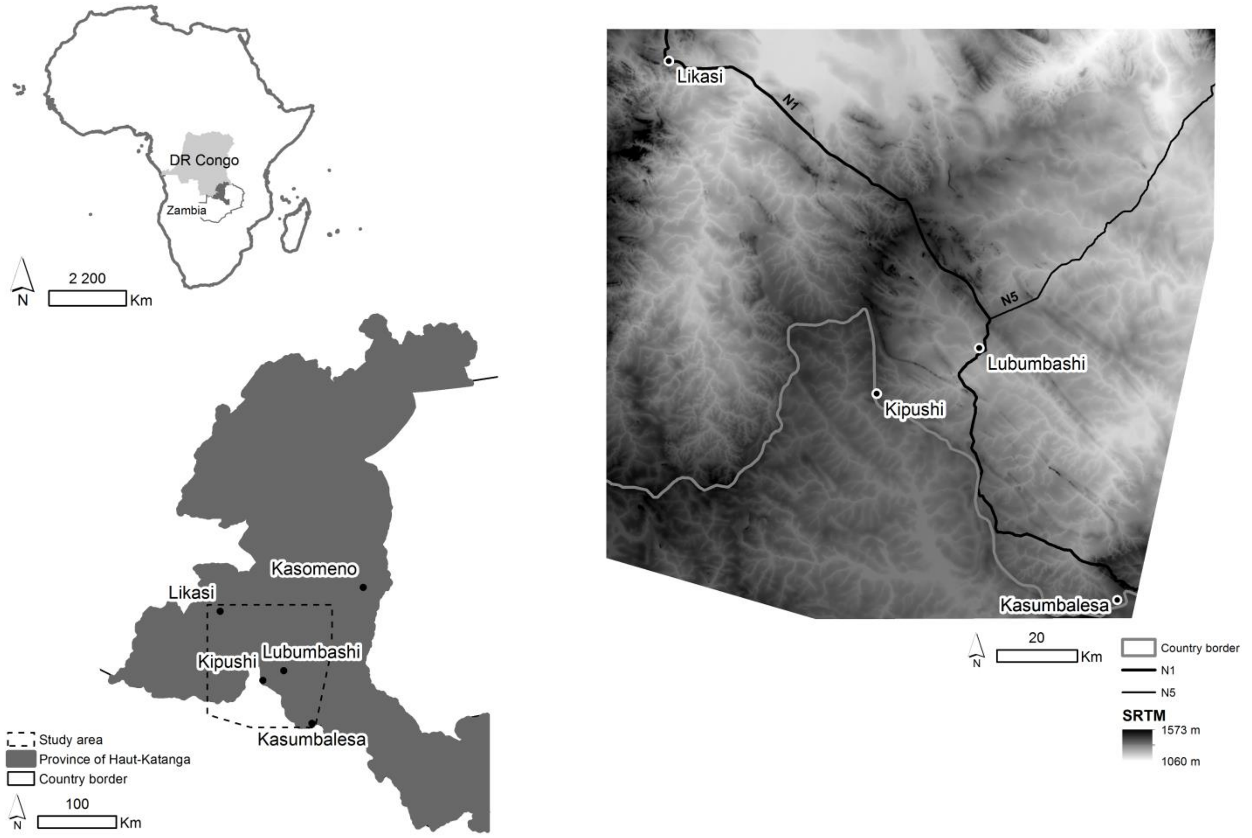


Figure 3. Situation map of the study area: Lubumbashi, its hinterland and the neighbor cities (Province of Haut-Katanga, DRC). The study area corresponds to the intersection of eight Landsat images (04/05/2002, 07/07/2002, 08/08/2002, 11/10/2002, 27/06/2013, 13/07/2013, 30/08/2013 and 05/11/2014).

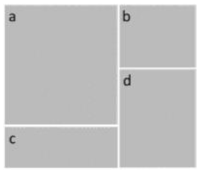
Islets of dry evergreen forest called *muhulu*, present in the area (Malaisse, 2010), could indicate that the actual climax* was *muhulu* and that *miombo* (called woodland in this thesis), the woodland forest strata that has dominated the area at least since the first observations during the colonial period, would be a disclimax* resulting from former slash and burn agriculture (Figure 4b) (Noti et al., 1996; Schmitz, 1962; Sys, 1960; White, 1983). However, this is still subject to debate as the historical and theoretical point at which human impacts begin to be taken into account addresses the issue of the relationship between human and nature (Haila et al., 1997; Machado, 2004; Mascaro et al., 2013). If woodland, more or less degraded, still covers about 50 % of the area, derived savannahs and cultivated areas, generally resulting from forest clearance by the almost annual fire (Malaisse, 2010), represent now the second largest land cover in the area (about 30 %). These diverse savannah therefore result from anthropogenic degradation and do not present the same biophysical characteristics (including floristic composition) as natural savannahs (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 significant importance on the land use, that origin is corroborated by Malaisse (2010) and an existing correlation between fire starts frequency and proximity to the city and roads (R^2 = 0.78, personal data) as well as surrounding villages (R^2 = 0.77, personal data). Moreover, the absence of correlation between fire starts frequency and proximity to industrial sites (R^2 = 0.09, personal data) also suggests that those fires are mostly operated by villagers for agriculture and charcoal production, which is a regular practice in the area (Stromgaard, 1985; Vranken et al., 2011). Besides great effects of leaching on soil structure and organic matter content, fire impacts as well edaphon through superficial depressive effect on soil fungi and animal populations (Malaisse, 1975). Bare ground is found in the areas strongly impacted by mining activities and heavy metal eolian deposits, mostly in a cone-shaped zone situated north-west of the Gecamines metal processing site (Figure 4c) (Mbenza et al., 1989; Narendrula et al., 2012; Vranken et al., 2013). Near the smelters, debris are piled into tall and wide slag heaps (Figure 4d). Natural metallophyte herbaceous flora ("copperflora") is also present in natural highly metalliferous soils (mainly copper and cobalt), generally found on hills among the forest («copper hills») (Leteinturier et al., 1999; Malaisse et al., 1994). Some species were also able to colonize the soils contaminated by metalliferous atmospheric deposits (Faucon et al., 2011). Specific features called *dembos*, natural grasslands temporarily flooded in valleys around water streams, are frequent in the area (Sys, 1960; White, 1983). Permanent wetlands are found as well round the riverbanks and depressions on impermeable ground, some of which are cultivated (Sys, 1960). Nearly all the lakes are of anthropogenic origin: reservoirs built during the colonial period. Finally, colonies of Mexican sunflower (*Tithonia diversifolia* (Hemsley) A. Gray), an invasive species for the region, have been reported to take advantage of the anthropogenic perturbed conditions to sprawl (Tiebre et al., 2012; Useni Sikuzani et al., in press).

Historically densely built (Bruneau et al., 1990), the city is nowadays rapidly and loosely growing. That extensive (sub)urbanization (Groupe Huit, 2009), along with the atmospheric deposits of non-ferrous metal particles and associated substances (Vranken et al., 2013) as well as with anthropogenic fire practices (Malaisse, 2010), lead to landscape anthropisation of the city hinterland.

The extent of the study area considered corresponds, according to the specific objective, to:

- the intersection of seven Landsat images (04/05/2002, 07/07/2002, 08/08/2002, 11/10/2002, 27/06/2013, 13/07/2013 and 30/08/2013), ie 23 400 km² (SO 3, publication 1.2);
- the intersection of two Spot images (16/07/2002 and 18/06/2008), ie 1 030 km² (SO 3, publication 1.3);
- the intersection of eight Landsat images (04/05/2002, 07/07/2002, 08/08/2002, 11/10/2002, 27/06/2013, 13/07/2013, 30/08/2013 and 05/11/2014), ie 22 357 km² (SO 6).

Figure 1. Illustrations of the case study: a) GoogleEarth image (2016) showing the global shape of the built parts of the city of Lubumbashi (DRC) (in grey and beige on the image); b) woodland (*miombo*), dominating ecosystem of our whole study area (November 2012); c) bare ground in the cone-shaped polluted zone situated north-west of the Gecamines metal processing site (February 2011) and d) Historical Union Minière du Haut Katanga (UMHK) metal processing site (nowadays Gecamines) situated in the centre of the city; in particular, its chimney and slag heap (UMHK, 1956).



Chapter 1: Synthesis of the data used

Different types of data were used in this study, depending on the research specific objective(s) addressed. To fulfill the specific objectives 1, 2 and 4, reviews of the literature were conducted. Concerning the classification of the images, depending on the specific objectives and the publications (3 -publication 1.2-, 3 -publication 1.3-, 6 or O), different sources of data were used: Landsat ETM+ and OLI images (U.S. Geological Survey, 2014a), SPOT images (Airbus Defense and Space, 2016), free digital elevation model from Shuttle Radar Topography Mission with a 90m or 30m spatial resolution* (U.S. Geological Survey, 2014b) as well as training samples extracted from GPS points collected during direct surveys between January 2012 and April 2014, from Google Earth images and from the Modis MCD14ML "Active fire" products (Giglio, 2013).

The Table 2 synthetizes the correspondence between the types of data used and the specific objective(s).

Table 2. Correspondence between the general objective (O), the specific objective(s) SO and the main types of data used. The SO 1 is to evaluate to which reference state to compare an existing anthropised state, the SO 2 to evaluate the existing assessment methods to measure the anthropogenic effect, the SO 3 to evaluate the anthropogenic land use* and land cover* dynamics of the studied landscape, the SO 4 is to highlight the discriminating characteristics of the areas in the urban-rural gradient and propose new definitions of these areas, the SO 5 is to evaluate the most relevant landscape metrics to locate the areas in the urban-rural gradient* areas and the SO 6 is to evaluate the expansion of the (sub)urban areas of the studied landscape.

Type of data	(Specific) objective(s)
• **Scientific literature**	1, 2 and 4
• **04/05/2002, 07/07/2002, 08/08/2002, 11/10/2002, 27/06/2013, 13/07/2013 and 30/08/2013 Landsat ETM+ and OLI multispectral images** • **Google Earth images**	3 (publication 1.2), 6 and O
GPS points	3 (publications 1.2 and 1.3)
• **Digital elevation model, 90m spatial resolution** • **Modis MCD14ML "Active fire" products**	3 (publication 1.2)
16/07/2002 and 18/06/2008 SPOT images	3 (publication 1.3)
• **05/11/2014 Landsat ETM+ and OLI multispectral images** • **Digital elevation model, 30m spatial resolution**	6 and O

Chapter 2: The challenge of the classification process

To fulfill the specific objectives 3 (publication 1.2), 6 and the main research objective, the images were processed globally the same way. They were first radiometrically calibrated* and pan-sharped* with the software ENVI 5.0. A filtration process was then applied on the 2002 and 2013 images in order to remove the burned areas: a new composite near infrared (NIR) band was composed from the maximum value of each pixel for the same year. Multidate 2002 and 2013 images were then recomposed taking the images of 07/07/2002 and 13/07/2013 as a basis and replacing their NIR band by the maximum filter–originating one. An oriented-object* supervised* classification was performed afterwards on the images using the eCognition software (Trimble Documentation, 2013). ArgGis was finally used to perform the other manipulations, including the calculation of the precision of the classification through the Kappa* coefficient whose values are comprised between 0 and 1; 0 representing a total inaccuracy and 1 representing a perfect accuracy (Congalton, 1991).

Different factors, specific or not to the context of Sub-Saharan Africa, complicate the classification process. As for the non specific one, first, the surface of a pixel may cover different ecosystems, land covers* or land-uses* (Pham et al., 2011). That phenomenon, known as “mixel” issue, is logically even more challenging when the spatial resolution* of the image decreases, when attempting to classify heterogeneous urban environments and/or when trying to discriminate the low density continuous built. Secondly, in the case of a regressive* or progressive* process, ecosystems constitute frequently transition states between two states. Thirdly, different land covers* may have very similar spectral signatures*. In the urban Sub-Saharan context, that issue represents a real challenge due to the high similarity between the spectral signatures* of built-up areas and bare ground (Congedo et al., 2012), the latter being potentially naturally present in natural areas during the dry season. As for the context-specific one, firstly, the seasonal variation (Congedo et al., 2012) and very fast urban dynamics may lead to misclassifications due to a possible time lag between the field survey and the image shooting date. The latter issue is exacerbated in areas where anthropogenic fire practices are common. Secondly, in Africa, due to different land management practices, borders between adjacent land cover patches are less clearly defined (Vranken et al., 2013). Given the upper considerations, the probability that analysts and classification algorithms attribute different classes to the same pixel or group of pixels is high and leads, sometimes, to virtual misclassifications and, in any case, to lower classification precisions.

The Table 3 synthetizes these classification challenges and the solution(s) proposed (1.2, 2.3). The differences in the classification processes used to fulfill the specific objectives 3 and 6 are 1) the accuracy of the digital elevation model (respectively 90 m and 30 m) used; 2) for the SO 3, the use of Modis MCD14ML "Active fire" data as training samples (Giglio, 2013); for the SO 6, 3) the use of an interannual image for 2013/14, 4) the use of a topographic position index* (Guisan et al., 1999), 5) the reduction of the number of thematic classes* and 6) the reduction of the size of the objects produced during the segmentation process*.

Table 3. Classification challenges encountered during the thesis, solutions proposed and corresponding specific objective(s). SO3 is to evaluate the anthropogenic land use* and land cover* dynamics of the studied landscape; SO 6 is to evaluate the expansion of the (sub)urban areas of the studied landscape.

Classification challenge	Solution(s) proposed	Corresponding specific objective(s)
Mixel	Pan-sharpening of the images	SO 3 and 6
	Reduction of the size of the objects	SO 6
Confusion in spectral signatures	Use of 6 bands of the multispectral images	SO 3 and 6
	Object-oriented classification	SO 3 and 6
	Use of topography data	SO 3 and 6
	Use of a topographic position index	SO 6
	Reduction of the number of thematic classes	SO 6
Transitional ecosystems	Grouping of similar ecosystems	SO 3 and 6
Time lag	Filtering of the NIR bands then creation and use of multidate images	SO 3 and 6
	Use of interannual images	SO 6

Finally, the global accuracies obtained for the SO 6 (K_{2002}: 0.73; $K_{2013/14}$: 0.63) doubled compared to those obtained in the SO 3 (K_{2002}: 0.35; K_{2013}: 0.32) (Appendix 1). Compared to other similar studies (i.e. a comparable context and discontinuous class highlighted), they are slightly lower (Forkuor et al., 2011) or higher (Congedo et al., 2012). The resulting maps of the classifications of 2002 and 2013/14 for the specific objective 6 are presented in Appendix 2.

In the large offer of different satellite images, we chose to use Landsat images (Landsat 7 ETM+ and Landsat 8 OLI) with medium spatial resolutions* ranging between 15 and 100 m. Thus, in spite of the upper consideration about the shortcomings of the spatial resolution*, for several reasons:

1) the known correlation between spatial and temporal scales (Burel et al., 2003),

2) a rise in the spatial resolution* may induce an increase in the noise in the data and therefore complicate the interpretations (Mesev, 2003),

3) their spatial coverage (the respective swaths are approximately 185 and 190 km wide, which corresponds to images of approximately 35 000 km²) (Nasa, May-6-2016; USGS, 2016),

4) their relatively high temporal resolution* (16 days), important parameter to consider when conducting multi-temporal analysis* (Forkuor et al., 2011),

5) their high spectral resolution potentially allowing for better discrimination between objects (Landsat 7 ETM+ and Landsat 8 OLI images are characterized respectively by 8 (one panchromatic*, six multispectral* and one thermal*) and 11 bands (one panchromatic*, six multispectral*, two thermal*, one coastal and one cirrus),

6) the existence of archive images since 1972 allowing for large multi-temporal analysis* and

7) the necessity to develop tools adapted to the technical and financial context of developing cities in Sub-Saharan Africa (Landsat images are available for free).

Chapter 3: Specific methodologies, main results and discussions

Measure of anthropogenic land use and land cover dynamics

In some cases, the term anthropisation is used as a synonym of anthropogenic effect. However, the former may be defined as the process of landscape changes, consequence of the latter (1.1). It is the point of view that will be also used in this document.

(SO 1) Evaluation of the reference states to which compare an existing anthropised state

When attempting to quantify and represent the anthropisation of a given area, the first point has been to inventory the existing reference states, to sort out the differences between each of them and to find out which one was the most relevant to measure anthropisation intensity (1.1).

The inventory was achieved through the consultation of the Scopus and Google Scholar databases, with "naturalness", "naturalité", "hemeroby", "hémérobie", "climax*" and "anthropisation" as keywords. A subjective selection of the references for further reading was then applied. For naturalness, due to the huge amount of results, the number of citations played a prominent role in that selection. The definitions were clearly identified as such, as well as (if so) the means to measure it.

Naturalness is defined as the characteristic of what is natural is the state of the system when no human activity has influenced it or as a measure of the difference between a reference (natural) state and the anthropised state of a system (Kowarik, 1999; Lecomte et al., 2005; Machado, 2004; Peterken, 1996; Rüdisser et al., 2012; Winter, 2012). However, in this document and to avoid confusion, we will only consider the first definition and will prefer for the second the use of the term hemeroby. Naturalness can be considered as the opposite of anthropisation (Bogaert et al., 2014; Machado, 2004) and is widely used and discussed among the scientific community (Lecomte et al., 2005; Machado, 2004; Peterken, 1996; Schnitzler et al., 2008). It can be associated to climax*, but the use of the latter term is controversial. Its climatic determinism and the existence of long-term steady conditions for climax* settlement are indeed questioned (Bournerias, 1982; Cook, 1996; Génot, 2006; Hall et al., 1995; Henderson et al., 1960). However, different types of naturalness may be found in the scientific literature:

- The “original naturalness” describes the state before the first anthropogenic land transformations (Peterken, 1996). It is sometimes called “naturalness of the first post-glacial times” or “biological naturalness” in Europe (Fuhr et al., 2010; Gilg, 2005; Lecomte et al., 2005). In restoration ecology, original naturalness is still mentioned as reference (Bakker et al., 1999; SER (Society for Ecological Restoration International Science & Policy Working Group), 2004).

- The “virtual naturalness”, also called “present naturalness”, would be the current state of the system if human had never had any impact on it (Lecomte et al., 2005; Peterken, 1996). This state takes natural evolution into account. If an ecosystem had never been impacted by human activity, even indirectly, its virtual and original naturalness would correspond to its current state.

  As for original and virtual naturalness, the kind of activities considered as natural / artificial is subject to debate because it addresses the issue of the relationship between human and nature (Haila et al., 1997; Machado, 2004; Mascaro et al., 2013).

- The “potential naturalness” or “potential natural vegetation / community” is the state that would develop if human influence disappeared and if the resulting succession were finished instantly (Hall et al., 1995; Peterken, 1996; Reif et al., 2008; Tüxen et al., 1956). In practice, it represents the self-sustaining ecosystem in the disturbed abiotic condition of the site (Hall et al., 1995). Such definition is taken as reference for less ambitious restoration projects or conservation management (Lundholm et al., 2010).

- The “future naturalness”, also referred to as “anthropogenic naturalness”, corresponds to the state that the system eventually reaches after human influence ceased and after following complete ecological succession (Gilg, 2005; Peterken, 1996; Schnitzler et al., 2008). If the system has been too deeply altered, this state differs from virtual naturalness due to global human impacts such as anthropogenic climate change or species extinction (Peterken, 1996).

At a certain intensity of anthropogenic effect on local landscape as well as its global surroundings (such as climate), some anthropogenic disturbances are so heavy that it seems impossible to go backwards towards the previous natural state. In that case, ecosystems are qualified of “novel”. Their characteristics differ from one author to another. The most consensual definition mentions (1) that a novel ecosystem has abiotic, biotic and social components that, because of anthropogenic effects, differ from those that prevailed historically in the area and (2) that those historical qualities cannot be recovered due to the crossing of ecological, environmental and social thresholds (Hobbs et al., 2013). The definition and position of this threshold, “barrier” or “point of no-return” is subject to debate (Hallett et al., 2013). A novel ecosystem can be managed to develop its functional analogy to a reference existing natural ecosystem in the same area (e.g. quarry face can be analogous to cliff) or even exploit these analogies in order to enhance the ecosystem or health services of the novel ecosystem; it will then be called “artificial analogous” (“analog” or “analogue”) (Hobbs et al., 2006; Lundholm et al., 2010). However, on the contrary to restoration it will become different from what it was before turning into “novel” (Hobbs et al., 2006).

It emerged that a reference state was missing; we proposed to call it the “restored indigeneous naturalness” which represents the “most natural” state that can be achieved once crossed the non-return threshold and through restoration actions removing the results of abiotic disturbances.

A combination of the concepts developed hereabove is presented in the Figure 5. In that figure, the “Hybrid” state corresponds to a disturbed state, when anthropogenic influence on the ecosystems/landscapes increases.

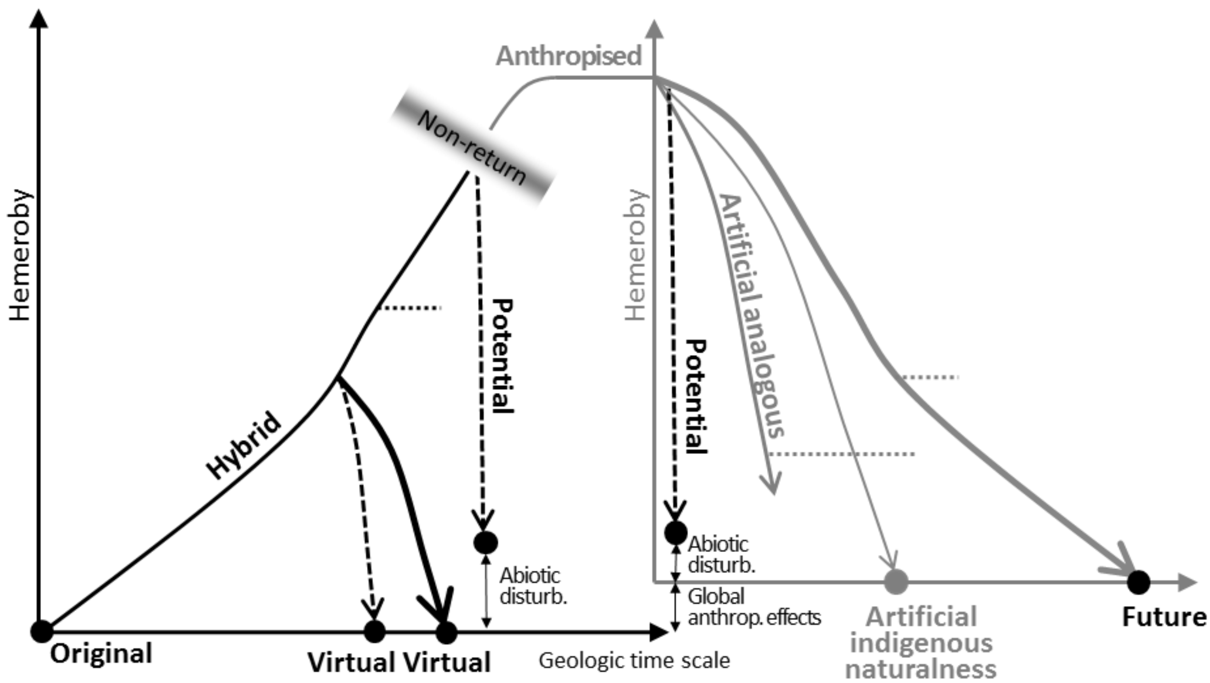


Figure 2. Graphic synthesis of the concepts related to human impacts on landscapes from ecological, landscape ecological and restoration ecological perspectives. This representation is a theoretical and simplified model of the different anthropisation trajectories that a landscape can follow. Dashed lines represent active restoration, plain upward line represents landscape evolution under increasing human disturbance, plain downward lines represent management, horizontal dotted lines represent conservation and bold line represents ecological succession. Dots represent reference states of naturalness, bold characters non reference states. The wide blurry line labelled “Non-return” represents the novel ecosystem threshold, grey elements being related to novel ecosystems.

It appears that most of the inventoried reference states are in practice very difficult to use and/or inapplicable due to one or several reasons. Either a temporal inadequacy (original* and potential* naturalnesses), a lack of knowledge concerning the ecosystems, patterns and processes in ancient times (especially in the case of landscapes with a long anthropisation history, such as tropical forests impacted by past slash and burn agriculture dating back to over 1900 years (Vleminckx et al., 2014)) (original* and virtual naturalness*) or in the distant future (future naturalness*) prevent these states from being a reference both to measure anthropisation intensity or as a goal to achieve while restoring a given site. In the latter case of restoration goal, the hard removal of the global anthropogenic effects by individual restoration projects or, even more so, the crossing of the non-return novel ecosystem* threshold prevent original* and virtual naturalness* from being reference states.

Concretely, for our case study of Lubumbashi, we chose assume that a) pre-colonial human interventions on landscape were anthropogenic, that b) the non-return novel ecosystem threshold is not yet crossed in the region and that c) global anthropogenic effects are negligible in the region. Therefore, we considered deep soil woodland as a pyroclimax* and shallow soil woodland, dry evergreen forest, natural wetlands, natural grassland as well as copper hills as virtual naturalness* (White, 1983). In this case and given the aforementioned assumptions, the virtual naturalness* state may be assimilated to the restored indigeneous state **(1.2)**.

(SO 2) Evaluation of the existing assessment methods to measure the anthropogenic effect

The assessment method to measure the anthropogenic effect is of high importance as it has consequences on pattern identifications and anthropisation level evaluation (Gustafson, 1998). In this section, we consider the existing assessment methods regularly used to evaluate it **(1.1)**.

Simple, direct measures

Simple quantitative measures of the variables (OECD, 2008) can represent landscape composition* (O'Neill et al., 1988), configuration* (Garbarino et al., 2009; Sanderson et al., 2002) or ecological processes (Garbarino et al., 2009; Margalef, 1958). These measures are directly representative for their corresponding phenomenon occurring at a given Driver Pressure State Impact Response (DPSIR)* stage, but when interpreting them at other stages or other phenomena occurring at the same stage, they form indirect indicators. For example, pollutant emissions are a measure of anthropogenic disturbance, but a surrogate for landscape anthropisation.

These quantitative measures allow powerful comparisons and less arbitrary interpretations, but they often give an incomplete perspective of the represented phenomenon (SCOPE, 2012).

Scales

Ordinal scales are the way hemeroby is represented. It gives a categorical representation of anthropisation. The main differences between the existing hemeroby scales are related to: (1) the hierarchical level to which it is applied; (2) the reference state considered; (3) the number of levels of the scale applied; (4) the variables used.

Each scale is generally designed for a given organisational level: vegetal community, ecosystem, landscape (Fanelli et al., 2004; Rüdisser et al., 2012). The number of scale levels varies from 4 to 11 and the used parameters to distinguish them are generally based on species or landscape composition and/or type of human influence (Brentrup et al., 2002; Fanelli et al., 2004; Kowarik, 1999; Machado, 2004; Peterken, 1996; Peterseil et al., 2001; Reif et al., 2008; Rüdisser et al., 2012; Steinhardt et al., 1999). The criteria defining scale levels and the distance between these levels are not always specified nor constant.

Scales are arbitrary but allow distinguishing entities and include qualitative and quantitative data, the latter in the form of simple measure or (more rarely) composite index (see below). However, the different components of the system considered can correspond to different levels, for example fauna can be more natural than flora (Lecomte & Millet, 2005), while regressive* dynamics are mixed with progressive* ones. An illustration of an hemeroby scale is given in the section relative to the SO 3.

*Composite indexes**

The aforementioned simple measures and scales can be combined into quantitative composite indexes* which integrates complex environmental conditions in one parameter which cannot be measured directly (Rüdisser, Tasser, & Tappeiner, 2012).

Specific attention should be paid to which information is actually contained in the composite index*, how their contribution to the final index was weighed and on which hypotheses it relies if it uses arbitrary classifications. Indeed, the construction of composite indexes is still subject to intense debate (Dialga et al., 2014).

(SO 3) Evaluation of the anthropogenic land use and land cover dynamics of the studied landscape

Among the existing different methods to quantify anthropisation, we chose to test the transferability of the "distance to nature" (i.e. *D_2N)* methodology of Rüdisser et al. (2012) to an African city context. That composite index*, developed in a temperate context, combines simple measures that weigh each pixel or object representing a landscape according to the structural connectivity* ("distance to natural habitat, D_n") and a scale that weighs them according to their degree of hemeroby ("degree of naturalness, N_d"). The D_n and N_d intermediate steps help to interpret the final result **(1.2)**.

Details on the methodology

The land use types provided by Rüdisser *et al.* (2012) were only suitable for Austria and similar landscapes, but their qualitative hemeroby scale provided process information on type, intensity and impacts of human activities for each hemeroby level. Based on this description and specific site knowledge on local ecosystems and activities, we were able to fit the existing land use types of Lubumbashi into the D_2N-related hemeroby scale.

As a first step, we assigned one of the seven hemeroby levels to each land use or cover potential in our study extent (about 23 400 km²). As a second step, we sorted each of the classes from our classification into the seven hemeroby levels. The Table 4 shows, for the studied landscape, the correspondence between the thematic classes* and the corresponding hemeroby levels. It reveals that in some cases, 1) intermediate hemeroby classes had to be created and 2) as some ecosystems could not be distinguished and had to be grouped in an heterogeneous land cover class, the latter was allocated to the level of hemeroby corresponding to the dominant ecosystem.

Here is the way thematic classes were sorted into hemeroby levels:

- Shallow soil woodland, dry evergreen forest, copper hills, wetlands and natural grasslands were assigned to the first level, «natural», but the classification identified only the latter two. The amount of anthropised grassland was so negligible that they were not discriminated from natural grassland;
- Deep soil woodland and streams were assigned to level 2, «near-Natural» in both cases. Indeed, water streams are in most cases of natural origin but present eutrophication;
- Regenerating forest, wooded savannah and old fallow were put in the third level («semi-natural») because those vegetation types are most of the time not found in the area before human direct intervention (Parr *et al.*, 2014). The classification did not identify the first;
- The ecosystems young fallow, savannah, bushland, pasture and grassland were assigned to level 4, «altered», corresponding to the definition given by Rüdisser *et al.* (2012);
- Young fallow, pasture and grassland had to be assigned to the level 5 («cultural»), being grouped with crops. Crops, along with anthropised wetlands and reservoirs were as well put in this level.

As the savannahs in the area mostly correspond to early stages of ecological succession to fires, the recurrent burned areas that could not be eliminated were assigned level 5 too;

- We put one of the classes («savannah/crops mosaic») in between hemeroby levels 4 and 5 because the crops land use was assigned to level 5 while savannah was assigned to level 4;
- Level 6, «artificial with natural elements», corresponded to discontinuously built areas and bare ground;
- Finally, the seventh level, «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 along a scale from 0 to 1, following the D_2N methodology and built the N_d map.

Secondly, we built a map of distance to natural habitat (D_n): this corresponds to the Euclidean distance (in meters) from each pixel of the images to the nearest natural or near-natural habitat (levels 1 and 2). Following the D_2N methodology, distances superior to 1000 m were set to 1000 m. In order to increase the effect of the proximity of anthropogenic features, we took the square root of the resulting distances. Then, we normalized the results dividing all pixel values by the maximum distance obtained in order to obtain dimensionless values ranging from 0 to 1.

Thirdly, we multiplied the N_d maps by the D_n maps and normalized the result from 0 to 1 dividing by the maximum value obtained in order to maximize the variation range of the results and re-scale it in the same way than the other normalised indexes. This gave the D_2N maps.

The final D_2N maps were initially represented by Rüdisser et al. (2012) according to a four-level scale, but were represented using a continuous scale in our application of the chosen methodology (Figure 6). Indeed, it appeared that the first induced information loss and the second corresponded better to the continuous African spatial structure (Vranken et al., 2013).

In addition to the D_2N methodology, we highlighted the dynamics of anthropogenic influence in Lubumbashi between 2002 and 2013 by subtracting 2002 to 2013 D_2N values, constructing a post-classification change detection map (Figure 7a). That step aims at evaluating anthropisation changes during the period. We constructed a transition matrix* to show how the natural and near natural classes changed during the 2002-2013 period.

Table 4. Rüdisser's hemeroby scale (2012) («Degree of naturalness») and its adaptation to the region of Lubumbashi (RDC). The four first columns are extracted from Rüdisser et al. (2012). The fifth column shows ecosystem correspondence to the seven hemeroby levels, while the two last columns (dashed lines) show the level of each land use and land cover classes of the classified Landsat images.

Hemeroby level	Description: Type of anthropogenic influence	Description: Ecosystem patterns and processes	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
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, Wetlands, Natural grassland, Copper hills	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, Streams
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, Pastures	4	Savannah and bushland
					4.5	Savannah / crops 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	Anthropised wetlands, Crops, Reservoirs, Anthropised grasslands	5	Anthropised wetlands; Crops, pastures, grassland and young fallow; Recurrent burned areas; Reservoirs
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 soil	6	Discontinuous built, Bare soil
7. Artificial	soil sealing over 30%	Artificial systems or structures	Continuous urban fabric, industrial or commercial units, road and rail networks	Continuous built, Slag heap	7	Continuous built, Slag heap

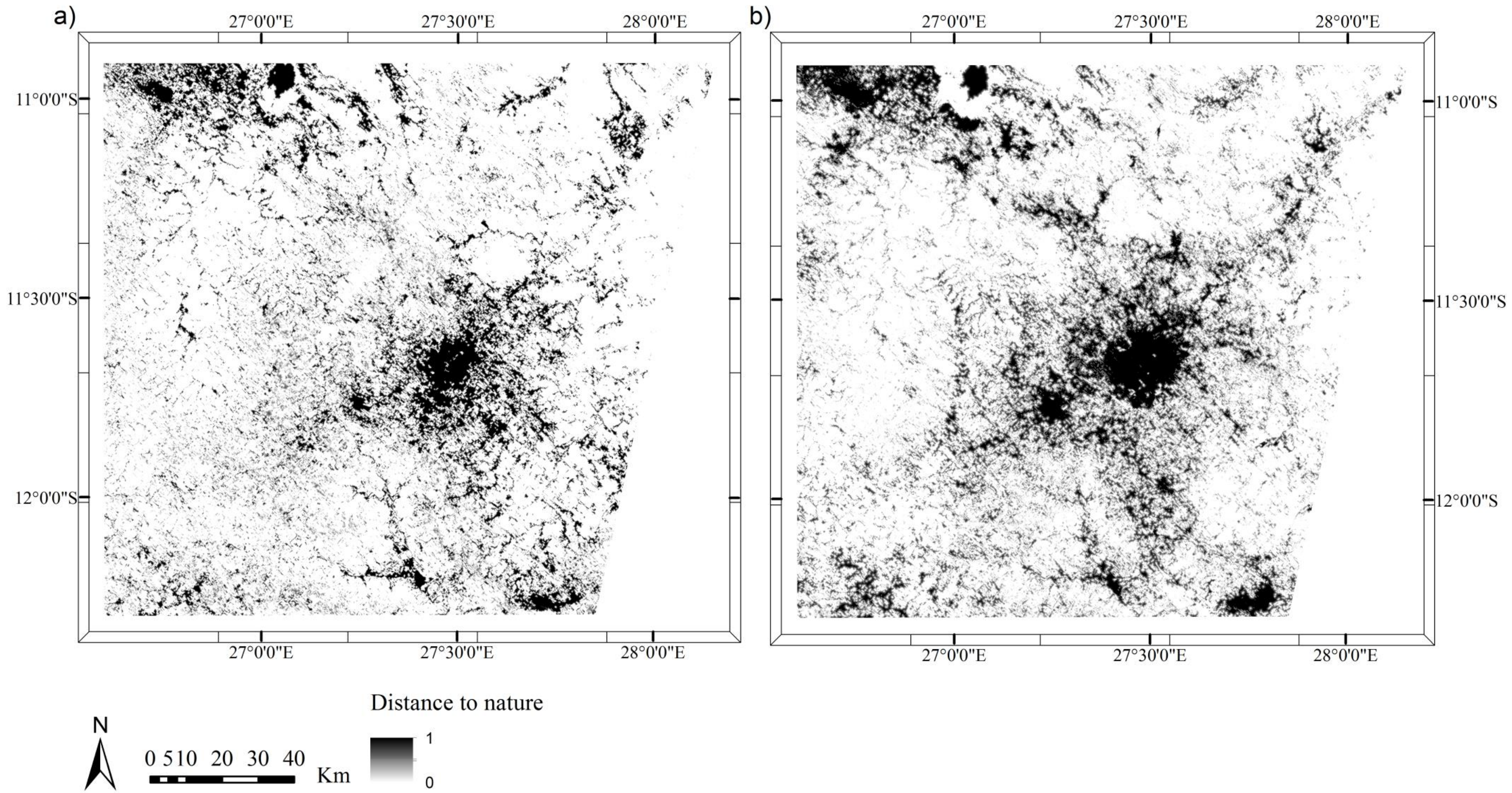


Figure 6. Application of the Rüdisser et al. (2012) «Distance to nature» methodology to the landscape of Lubumbashi (DRC) in 2002 (a) and 2013 (b). An index value of 0 means the lowest distance to nature; a value of 1 means the highest distance to nature.

Results and discussion

Implementation of the methodology to our case study

The results of the application of the D_2N methodology in our study area show that between 2002 and 2013, 46% of the study area underwent an anthropisation change; most of which consisted of minor to moderate changes (43% of the area concerned anthropisation level changes inferior or equal to 0.5) (Figure 7b). The net balance between increases and decreases shows that 17% of the study area underwent a global anthropisation increase, mostly constituted of minor rises of anthropisation levels (24.5% of the area concerned anthropisation level rises inferior or equal to 0.3). The anthropisation increase is mainly concentrated around the cities and the transportation axis, following respectively a concentric-ring and a linear development (Figure 7a) (Forman, 2008). The anthropisation level most impacted by the rise of anthropisation is the Natural and Near-natural one, to the benefit of all the other levels (Figure 7c). Surprisingly, the highest gains in naturalness are mainly dispersed around the suburban belts of the cities (Figure 7a). We explained that phenomenon by young fallow developing into forests, misclassifications or set-aside (Groupe Huit, 2009).

However, this implementation pointed out the difficulty to combine accurate thematic resolution* (and thus hemeroby levels) and high precision of classification in the context of our study: we obtained a Kappa coefficient* (Congalton, 1991) of 0.349 for 2002 and 0.316 for 2013 for 15 thematic classes*. Both parameters seem in fact inversely proportional. We also highlighted that the consequences of the misclassifications would be higher if the confusion occurred between classes of different hemeroby* levels and if it concerned classes considered as Natural or Near-natural. In our case, the most problematic confusion is the misclassification of wooded savannah as woodland because it artificially naturalizes the landscape. Furthermore, due to coarse spatial resolution* and too low thematic resolution*, the ecological dynamics (progressive* or regressive series*) followed by a patch could not be taken into account in its hemeroby level definition. Eventually, the very large extent of the study area (23 400 km²) did not highlight much anthropisation during the period. Indeed, in 2002 as in 2013, it is still the Natural or Near-natural hemeroby levels that dominate the landscape. However, the proportion of these levels notably reduced during the decade (75% then 60%).

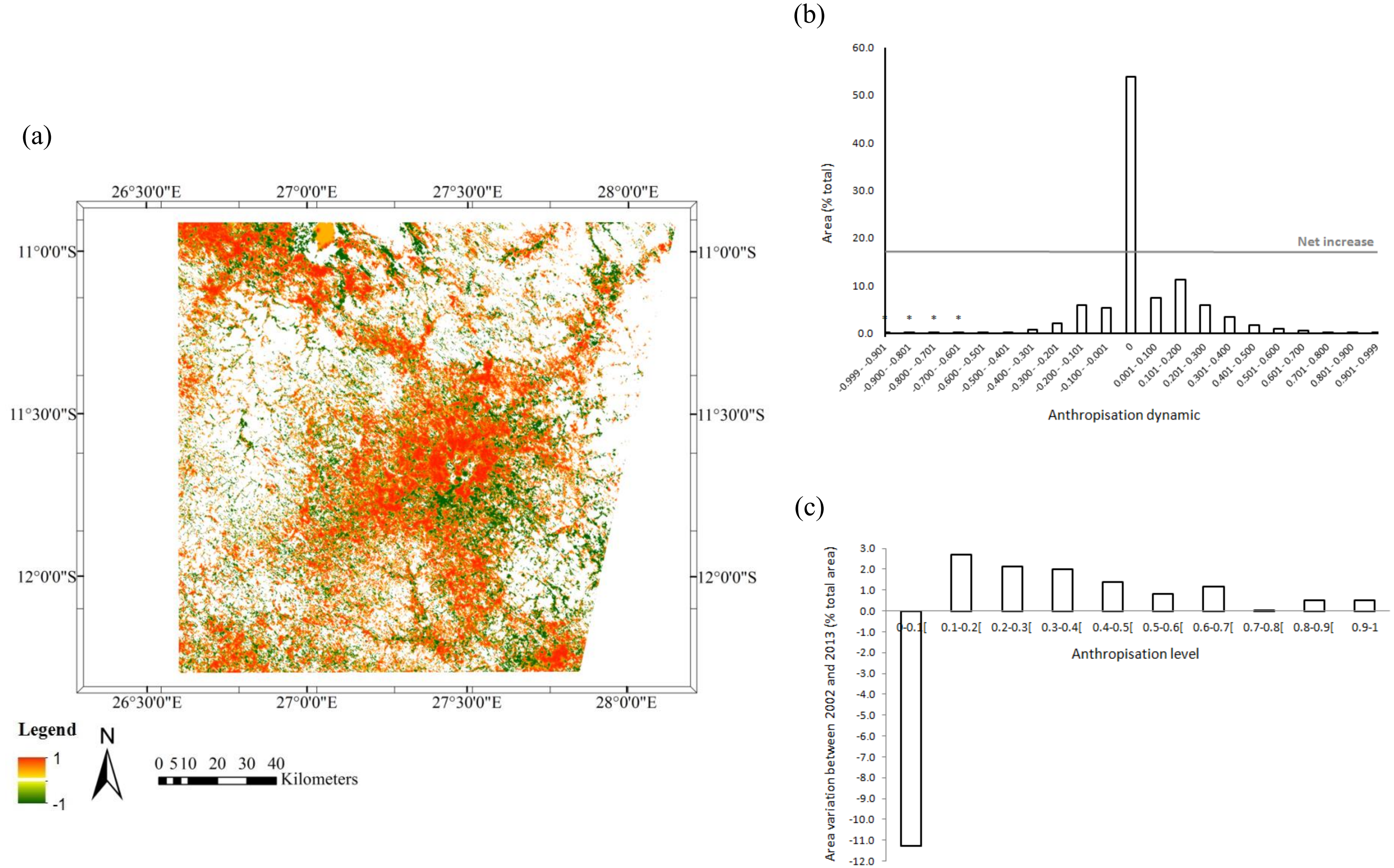


Figure 7. Dynamics of anthropisation levels (*D₂N*) between 2002 and 2013 in Lubumbashi (DRC). For (a) and (b), the numbers from -1 to 1 represent the number of anthropisation levels respectively lost or gained during this period; 0 represents no anthropisation level change. The map (a) shows the localisation of the dynamics, while the graph (b) shows the percentage of the total area concerned by each change type (* represents values superior to 0 but below 0.1%). The bar diagram (c) shows the percentage of the total area increase of each anthropisation level between 2002 and 2013, ranging from 0 (less anthropised level) to 1 (most anthropised level).

Theoretical aspects of the methodology

As mentioned above (SO 2), the construction of composite indexes is subject to debate (Dialga et al., 2014). The D_2N index has great advantages: feasibility and practicability with few data, ease of understandability and interpretation, inclusion of anthropogenic influences and connectivity. On the other side, reservations may be expressed concerning the following aspects: 1) the inclusion of the D_n factor in the calculation of the Rüdisser's anthropisation index naturalizes the representation of the landscape. Indeed, a patch composed of any landscape class will be attributed a low D_2N value if it is close to a Natural or Near-natural habitat but the reverse is not true and 2) N_d and D_n arise from the same data and are therefore correlated. However, the choice of multiplying rather than adding the parameters appears to be a good 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 distance to the nearest Natural or Near-natural habitat, they will never be attributed a lower value than 0.1665. Indeed, the addition tends to anthropise the representation of the landscape.

Quantification of anthropisation: panel of simple measures versus composite indexes

A recent study based on SPOT images evaluated the anthropisation of the landscape of Lubumbashi for a shorter period (16/07/2002 – 18/06/2008) and study area (1030 km²) based on visual interpretation and a panel of simple measures: transition matrices*, composition* and configuration* metrics **(1.3)**. Moreover, it identified the landscape spatial processes based on a decision tree algorithm that integrates some of the former simple measures (Bogaert, Ceulemans, et al., 2004; Useni Sikuzani et al., in press). The composition metrics used were mostly class-based: the maximal patch area (a_{max}) per class, the mean patch area ($\bar{a}$) per class, the median patch area (a_m) per class, the total patch area (a_t) per class, a dominance metric (D')* derived from McGarigal et al.'s (2002) Largest Patch Index, defined as the area of the largest patch of the corresponding class divided by the total class area and multiplied by 100, the total perimeter per class (p) and the number of patches per class (n). It used also a metric based on the whole landscape composition: the perturbation metric (U) which represents the ratio between the cumulative area of anthropised classes and natural classes (O'Neill et al., 1988). The decision tree algorithm must be applied separately at each landscape class; it is based on the main descriptors of the landscape configuration: the total patch area (a_t) per class, the number of patches per class (n) and the total perimeter per class (p). The classification highlighted the following classes: built-up, anthropised vegetation, *Tithonia diversifolia*, forest and wetlands. The results from the transition matrix show that the main dynamics for the period are the loss of forests (-9.4% of the whole study area) and the increase in the surfaces of anthropised vegetation and built-up (respectively + 6.1% and + 4.9% of the whole study area). The rise in the perturbation metric values indicates an increase in the anthropisation of the area during the period. The landscape spatial processes corresponding to the anthropised classes were the aggregation (built-up and anthropised vegetation) and creation of patches (*Tithonia diversifolia*); these corresponding to the natural classes (forest and wetlands) were the suppression of patches.

The gross conclusions of both analysis go in the same direction: an increase of the anthropisation of Lubumbashi's landscape(s). However, caution is required in further comparing the results due to the different analysis period and extent and due to the different nature of the metrics used (simple versus composite). The D_2N methodology has the great advantages of 1) including finer information on the hemeroby of ecosystems (the division of landscape classes in "anthropised" and "natural" ones includes already a coarse notion of hemeroby), 2) including the notion of structural connectivity and 3) representing the results with continuous values. The composition metrics used in both studies are quite easy to handle by an uninformed public, to the contrary of the configuration* metrics, composite index* and decision tree algorithm, which interpretation are less intuitive. Concerning the second study, the decision tree algorithm has at least the advantage to synthetize some of the simple metrics through the identification of a spatial process. In any case, a cartographic representation of a phenomenon appears to be a good way to communicate about a phenomenon (in this case, anthropisation dynamics) to an informed or uninformed public besides offering valuable and quick insights into correlation of factors (in this case, presence of roads, rivers, topography etc.) and thereby, possible identification of the pressures leading to the dynamics. A cartographic representation of (some of) the values of the configuration* metrics across the landscape for a target landscape class, for example using a zonal statistics, could therefore help to better handle them.

If these first results appear promising for the evaluation of the anthropisation of an area, in order to achieve our main goal of evaluating the landscape ecological consequences of the specific urbanization and suburbanization processes, it appears essential to apply the methodology developed above to narrower areas corresponding respectively to the those impacted by the urbanization, the suburbanization and the development of the secondary spatial impact. It is the topic of following section.

Measure of the expansion of the (sub)urban areas

(SO 4) Identification of the discriminating characteristics of the areas in the urban-rural gradient and proposition of new definitions of these areas

To narrow the evaluation of anthropisation to the specific case of the urbanization and suburbanization processes of Lubumbashi, the first step has been to sort the characteristics used in the literature to define the urban and suburban areas in order to propose "new" consistent definitions **(2.1)**.

Details on the methodology

This phase of the research was completed in two steps. The first was exploratory: using scientific geographical literature, all the terms commonly used to describe the different areas of the urban-rural gradient* were compiled. The review of the second step was based on scientific publications, through the Web of Science and Google Scholar databases as well as ecology, geography and urbanism books and on grey literature, through Google Scholar. The terms identified during the first step were used as keywords and for each of them, the corresponding characteristics and types of characteristic were compiled. The characteristics had to be objective and could either be part of a definition clearly identified as such or dispersed throughout the document. The researches of publications on Web of Science and Google Scholar were not limited to a given discipline. The consulted references dated from 1956 up to 2011 and were not restricted to a given geographical area. The reference research stopped for a given term when at least one consensual characteristic allowed its discrimination from another. Two terms were considered as synonyms when their most cited characteristics were the same. A total of 106 references was consulted.

The characteristics were then sorted according to their citation frequency. The characteristics finally retained to define each of the areas were discriminating and possessed at least two of the following attributes: 1) to be quantified, 2) to be integrative, 3) to be consensual, 4) to not have a continuous range of values and 5) to be easily acquired **(2.1)**.

Results and discussion

These "new" definitions are presented in the form of a flow chart (Figure 8) constructed using the discriminating and most relevant characteristics identified for each area of the urban-rural gradient*. It should be read from top to bottom, answering "yes", "no" or "not stated" to each question. When two characteristics are mentioned at the same decision level, both must be encountered to be able to answer "yes". A specific area is thus defined by the discriminating characteristics arising from the logical choices observed. In practice, a circle of which the observer would be the center and whose radius has a length greater than the average length of the surrounding parcels must be considered.

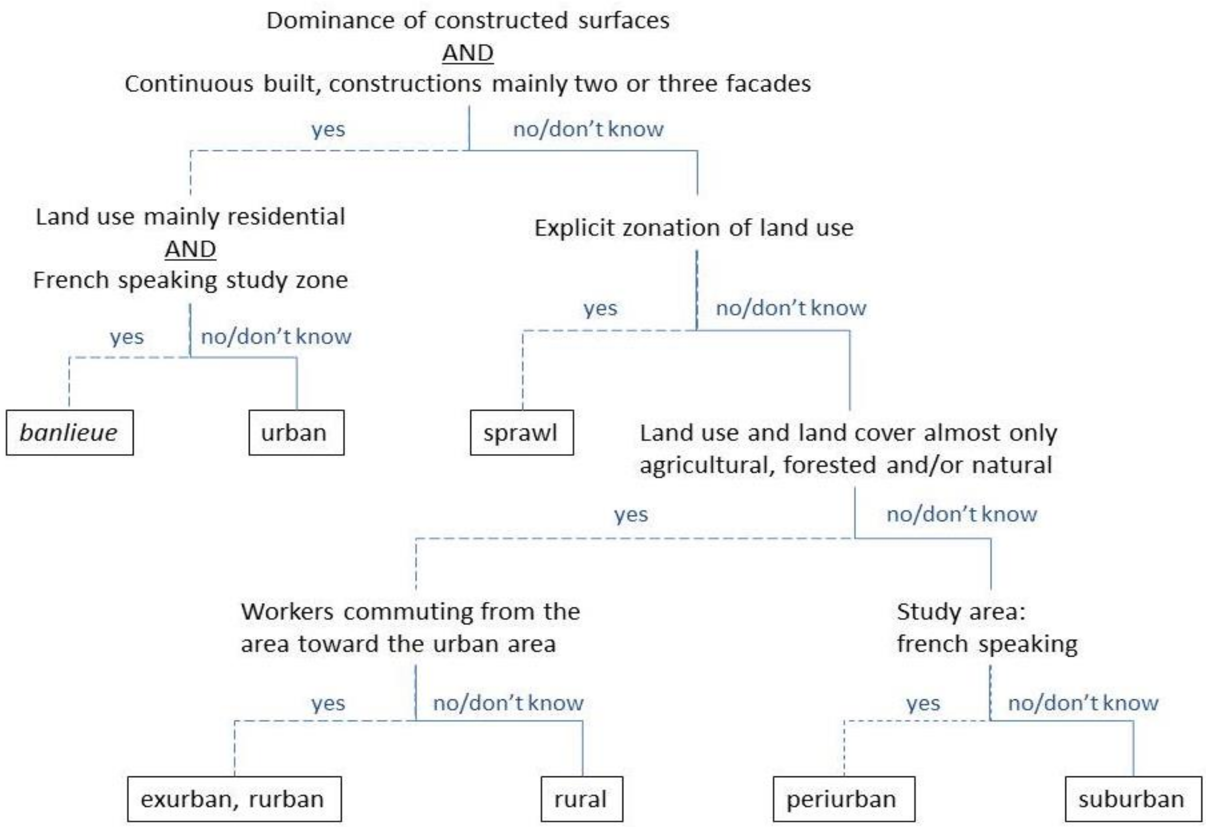


Figure 8. Flow chart of the definitions of the areas in the urban-rural gradient. Dotted lines represent an answer "yes" and continuous lines a "no" or "not stated" answer to at least one criteria.

Thus, urban areas are defined as areas where built-up and where attached or semi-detached houses dominate. In French speaking places, there is an additional criterion: residential land-use must dominate. Suburban areas are defined as places where built-up or where attached or semi-detached houses does not dominate, where there is no explicit zonation of land use and where land is not exclusively dedicated to agricultural, forestry or natural land cover* or use*.

If these definitions, through the flow chart, are a first step in the direction of consistent definitions for the different areas, they are not perfect: 1) depending on the scale/radius chosen, the identification of the area may change. One should therefore always specify the analysis scale considered; 2) the characteristic of "zonation of land use" requires to consider a greater radius than the other land uses and is therefore difficult to handle in practice. Some authors mention that sprawl areas are not suitable for pedestrian; people are therefore highly dependent on their individual cars (Alberti, 2008; Angel et al., 2007; Ewing et al., 2003; Galster et al., 2001; Wolman et al., 2005). Some other precise the criteria "zonation of land use" by mentioning commercial strip settlements along major roads (Lopez et al., 2003; Razin et al., 2000). The combination of the latter criteria could therefore be an alternative to distinguish sprawl, on condition that the flow chart is reorganized. Indeed, rural and exurban areas are seldom equipped for pedestrians. The resulting alternative flow chart is shown in the Figure 9.

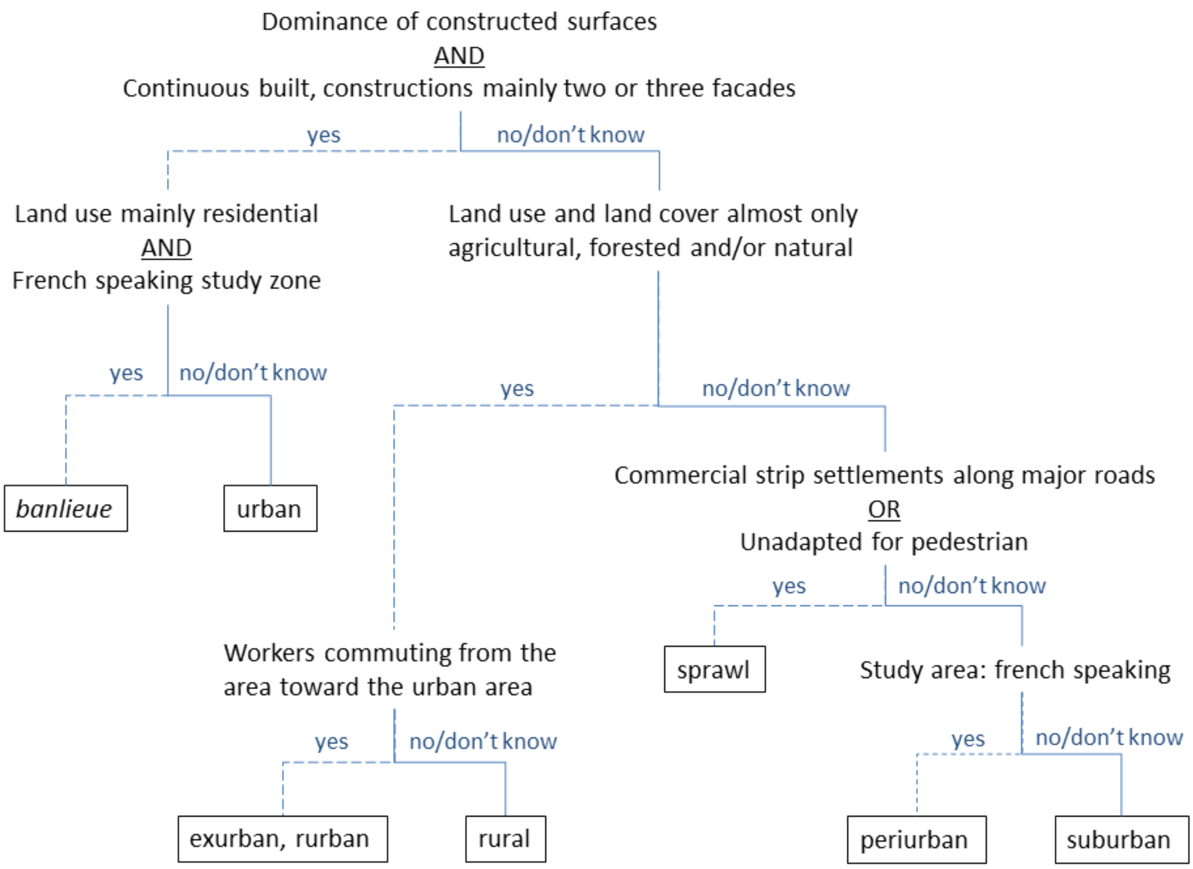


Figure 9. Alternative flow chart of the definitions of the areas in the urban-rural gradient. Dotted lines represent an answer "yes" and continuous lines a "no" or "not stated" answer to at least one criteria.

(SO 5) Evaluation of the most relevant landscape metrics to locate the areas in the urban-rural gradient

The second step has been to match the characteristics stated above with corresponding landscape metrics in order to identify the areas on satellite images (2.2).

It appears that theoretically, they can be differentiated through the use of the same metrics. Four of them relate to built patches: density*, the distance to the nearest neighbor* which evaluates the isolation of a patch in the landscape (Clark et al., 1954), aggregation* which evaluates the distribution of the patches in the landscape (Clark et al., 1954), proximity* which weights the isolation of the patches in the landscape by their surface (Gustafson et al., 1994) and two relate to the matrix: dominance* which quantifies the dominance or equitability between the classes of the landscape (Turner et al., 1988b) and dominant class which is a qualitative metric representing the dominating landscape class for a given landscape extent.

(SO 6) Evaluation of the expansion of the (sub)urban areas of the studied landscape

That part of the study can be divided into three steps. The first consists of the calculation of a landscape metric on satellite images and is linked to the SO 5. The second is the practical implementation of the definitions proposed (SO 4) to identify the areas on the field. The last is to merge the two previous in order to set the thresholds of the landscape metric values to identify each area on the satellite images **(2.3)**. It allows the validation of the methodologies developed in the two first steps and the quantitative clarification of the terms “dominate” and “not exclusively” used in the definitions.

Details on the methodology

Calculation of a landscape metric on satellite images

The patch-based metrics proposed were rapidly invalidated due to the lack of cadastral information in our case study. In fact, on the satellite images, assuming that individual buildings could be highlighted, without cadastral information, individual dwellings can not be discriminated within the same built patch. Attached or semi-detached houses can thus not be highlighted. The “proportion of built-up” metric (in terms of surface) was finally selected due to its easier applicability than the two matrix-based metrics. Indeed, it was assumed to be a good indicator of the position in the urban-rural gradient*, the proportion of built-up being supposed to decline with increasing distance from the city center (dominant land cover in urban areas, lower presence in suburban areas and negligible in rural areas). Moreover, the two other matrix-based indexes had necessary to be used in combination and relied on the detection of all the landscape classes. The proportion of built-up metric, to the contrary, requires only the identification of the built-up class, reducing the potential bias caused by misclassifications.

However, in our case, due to the aforementioned “mixel” issue and the classification methodology chosen (object-based), individual buildings can not be highlighted. To alleviate this problem, continuous built patches were therefore discriminated from discontinuous during the classification process. The corresponding pixels were attributed a built proportion value corresponding to the middle value of a class ranging respectively from 50% to 100% (i.e. 75%) and from 0% to 50% (i.e. 25%).

Practical identification of the urban-rural gradient areas

799 GPS* points were collected during a field mission in November and December 2012. They identified the urban, *banlieue*, suburban and rural areas of the urban-rural gradient following the definitions detailed through the fulfillment of the specific objective 4 (Figure 8). The rurban area could not be identified due to a lack of data on commuting comportments. The sprawl area was practically difficult to identify an was therefore omitted. Concerning the lack of precision of the terms "dominate" and "not exclusively" used in the definitions, 1) a situation of domination was identified when the proportion of the built surface exceeded 50% and 2) "not exclusively" was interpreted as inferior to 75%. However, few borderline situations were encountered; land cover and/or use were in most case clearly dedicated to agriculture, forestry or nature, or not at all.

The Figure 10 shows different representative pictures of the urban-rural gradient areas for our case study, both on the field and on a high spatial resolution satellite view (from GoogleEarth). It shows 1) that if two places may seem similar on the ground and quite different on the satellite image, the reverse is also true and 2) the heterogeneity of land covers corresponding to the same area.

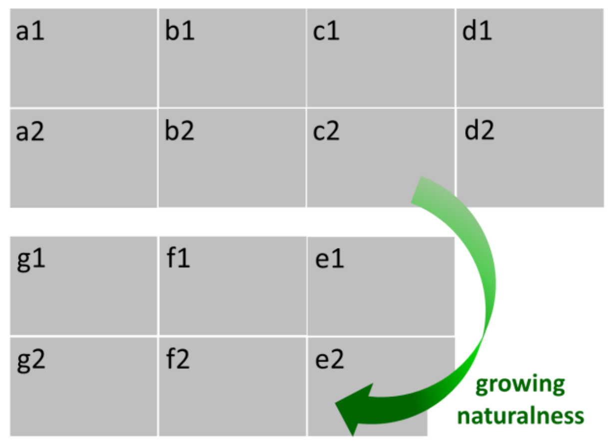
Adjustment of the landscape metric thresholds

The thresholds between the different areas were obtained through ten recursive partitionings* (Breiman, 1984) matching, for each GPS point collected on the field, the built densities of 2013/14 calculated on the satellite image and the name of the area. Given that spatially explicit land use data were not available, the *banlieue* area could not be identified on the satellite image and was assimilated to the urban area. The partitionings were performed with the R software (rpart package, Gini rule for splitting) (Therneau, Atkinson, & Mayo Foundation, 2015; Therneau, Atkinson, & Ripley, 2015). The set of built density thresholds corresponding to the Kappa* maximum (Congalton, 1991) was retained. If that set corresponded to different Kappa*, an average Kappa* was calculated. The R code is available in Appendix 3 (**2.3**).

Delimitation of the secondary spatial impact area

Along with the identification and delimitation of the urban and suburban areas, the limits of the secondary spatial impact area of the urbanization were set as the aggregation of the adjacent patches centered on Lubumbashi that correspond to the Altered, Cultural, Artificial with natural elements and Artificial hemeroby* levels, net of the urban and suburban areas.

Figure 10. Field (1) and corresponding satellite GoogleEarth (2) pictures of representative urban, suburban and rural areas of Lubumbashi (DRC), following a gradient of increasing naturalness. The red cameras on the GoogleEarth pictures represent the exact locations where the field pictures were taken. a) Urban area: a1) Commune Annexe district, 04/12/2012, a2) 01/01/2013. b) *Banlieue* area: b1) Kamalondo district, 10/12/2012, b2) 22/01/2013. c) Suburban area: c1) Commune Annexe district, 23/11/2012, c2) 11/01/2013. d) Suburban area: d1) Commune Annexe district, 10/12/2012, d2) 22/01/2013. e) Suburban area: e1) Commune Annexe district, 19/11/2012, e2) 22/01/2013. f) and g) Rural area: f1 and g1) Outside the administrative border of the city considered in the study, 29/11/2012, f2 and g2) 03/06/2012.



Results and discussion

The thresholds between areas were determined with a maximum and an average (for that set of thresholds) precision of respectively 0.68 and 0.51 (kappa* coefficient -Congalton, 1991-), which are respectively qualified as "good" and "moderate" by Landis and Koch (1977).

The urban, suburban and rural areas are characterized by respective proportions of built-up superior to 49.7%, between 49.7% (excluded) and 21.1% (included) and inferior to 21.1%. These thresholds correspond to those sometimes stated in the literature (Angel et al., 2007; Kazmierczak et al., 2010; Macgregor-Fors, 2011; Marzluff et al., 2001; McKinney, 2008).

During the decade 2002-2013/14 and partly due to the emergence of an urban area in the city of Kipushi, it is the urban area that experienced the greatest relative net increase (percent compared to its surface in 2002) compared to the other areas. However, when comparing in terms of absolute surface, it is the secondary spatial impact area that grew most (Table 5).

Table 5. Net surface increases between 2002 and 2013/14, compared to the surfaces in 2002, of the different areas (urban, suburban, secondary spatial impact) corresponding to the city of Lubumbashi (DRC).

	Area 2002 (km^2)	Area 2013/14 (km^2)	Net increase (km^2)	Net increase (% 2002)
Urban	26.3	100.0	73.7	280
Suburban	115.2	191.9	76.7	67
Secondary spatial impact	1293.3	2009.5	716.3	55

The growth shape of the urban and suburban areas (Figure 11) corresponds to the concentric-rings model (Forman, 2008), except in the south-western part of the city where an affluent of the river Kafubu and its adjacent wetlands slow the urban expansion. If the important increase rate of the urban area seems to indicate a spatial densification of Lubumbashi's city center, these results should be put into perspective of 1) the appearance of an urban area in the city of Kipushi (the results show that the global densification corresponds partly to an increase of building density and partly to dense new built areas) and 2) the comparison between the growth rate of the urban and suburban area (+ 116.34%) and of the population (+ 55%) both for the administrative entity of Lubumbashi, which indicates a population dedensification of the city, which is similar to global tendencies. The secondary spatial impact area dynamics seems determined, in the north-west, by the higher elevations of the relief and, in the north-east, seems to respond rather to the linear/transport-corridors development model (Forman, 2008), following the national road 5 leading to Kasomeno (Figures 3 and 11). The latest result is consistent with those of Vranken et al. (2011) for the same region and is similar to U.S. and European urbanization patterns (Besussi et al., 2010; Brück, 2002; Ewing, 2008; Grosjean, 2010).

Some comments have to be made concerning the methodology followed. First, the detection of the secondary spatial impact area is based on pixels adjacency. It is thus very sensitive to the conversion of some key pixels from one hemeroby level to another and therefore to the classification precision. The fact that wooded savannah and old fallows are excluded from the secondary spatial impact areas may also be subject to debate; these ecosystems were here considered as sufficiently less impacted by urbanization to be excluded.

Figure 11. Urban, suburban and "secondary spatial impact" areas in the neighbourhood of the city of Lubumbashi (DRC) a) in 2002 and b) in 2013/14.

Landscape ecological consequences of the urbanization and suburbanization processes in Lubumbashi

To address the main objective of this thesis, the last step consists of the combination of the two methodologies detailed above. However, only the N_d index will represent the anthropisation to avoid the naturalization bias introduced through D_n (see above).

The Table 6 shows, for the studied landscape, the correspondence between the thematic classes* highlighted in the specific objectives 3 and 6 and the corresponding hemeroby* levels.

Table 6. Correspondence between the hemeroby levels and the thematic classes highlighted to fulfil the specific objectives 3 and 6 of the thesis, according to the adaptation of the methodology of Rüdisser et al (2012) **to the region of Lubumbashi (DRC).**

Corresponding hemeroby level	Classification	
	Specific objective 3	Specific objective 6
Natural	Natural grasslands	Natural grasslands and wetlands
	Wetlands	
Near-natural	Streams	Streams
	Woodlands	
Near/semi-natural		Woodlands, wooded savannahs and old fallows
Semi-natural	Wooded savannahs and old fallows	
Altered	Savannahs and bushlands	
Altered/cultural	Savannah/crops mosaics	Savannahs, bushlands, young fallows and anthropogenic herbaceous vegetation
Cultural	Anthropised wetlands	Reservoirs
	Crops, pastures, grasslands and young fallows	
	Recurrent burned areas	
	Reservoirs	
Artificial with natural elements	Discontinuous built-up and bare ground	Discontinuous built-up and bare ground
Artificial	Slag heap	Slag heap
	Continuous built-up	Continuous built-up

Transition matrices* show the landscape class dynamics corresponding to the dynamics of each interest areas, i.e. the class areas lost or gained by each interest areas, considering also their internal landscape dynamics.

The Figure 12 represents the latter results, with landscape classes grouped per hemeroby level according to the same classification than for the specific objective 6. It shows that, compared to the total area gained, lost unchanged of each interest area, expressed in % (Figure 12a), the dynamics of urban areas has induced a dramatic increase of the single Artificial hemeroby* class (namely Continuous built and Slag heap) to the detriment of all more natural classes. The dynamics of suburban areas has provoked an increase of, mainly, the Artificial hemeroby* level, but also of the Artificial with natural elements level (i.e. Discontinuous built and bare soil) to the disadvantage of other classes. The dynamics of secondary spatial impact areas induced mainly an increase of the Altered and cultural level (namely the Savannahs, bushlands, young fallows and anthropogenic herbaceous vegetation and the Reservoir classes), to a lesser extent of the Artificial with natural elements level (i.e. Discontinuous built and bare ground class) and of the Artificial level, to the main detriment of the Near and semi-natural level (namely Woodlands, wooded savannahs, old fallows and Streams classes). The Figure 12b represents the same results than the Figure 12a but uses absolute areas instead of relative. It highlights that during the last decade, the main spatial impact of the global process of (sub)urbanization in Lubumbashi is probably the conversion of the classes composing the Near and semi-natural level to the main benefit of the classes composing the Altered and cultural level, through the expansion of the secondary spatial impact area.

Wood fuel and charcoal production are plausible culprits for that dynamics which represents the most impacting urbanization sub-process, both in terms of impacted surface as well as in terms of biodiversity lost. However, urbanization and suburbanisation impact as well the Near and semi-natural level, along with the Altered and cultural level, but in much smaller proportions.

Such a dynamics corresponds to the so-called “savanisation” process already highlighted for the period ranging from 1956 to 2009 by Munyemba and Bogaert (2014), although for a different study extent.

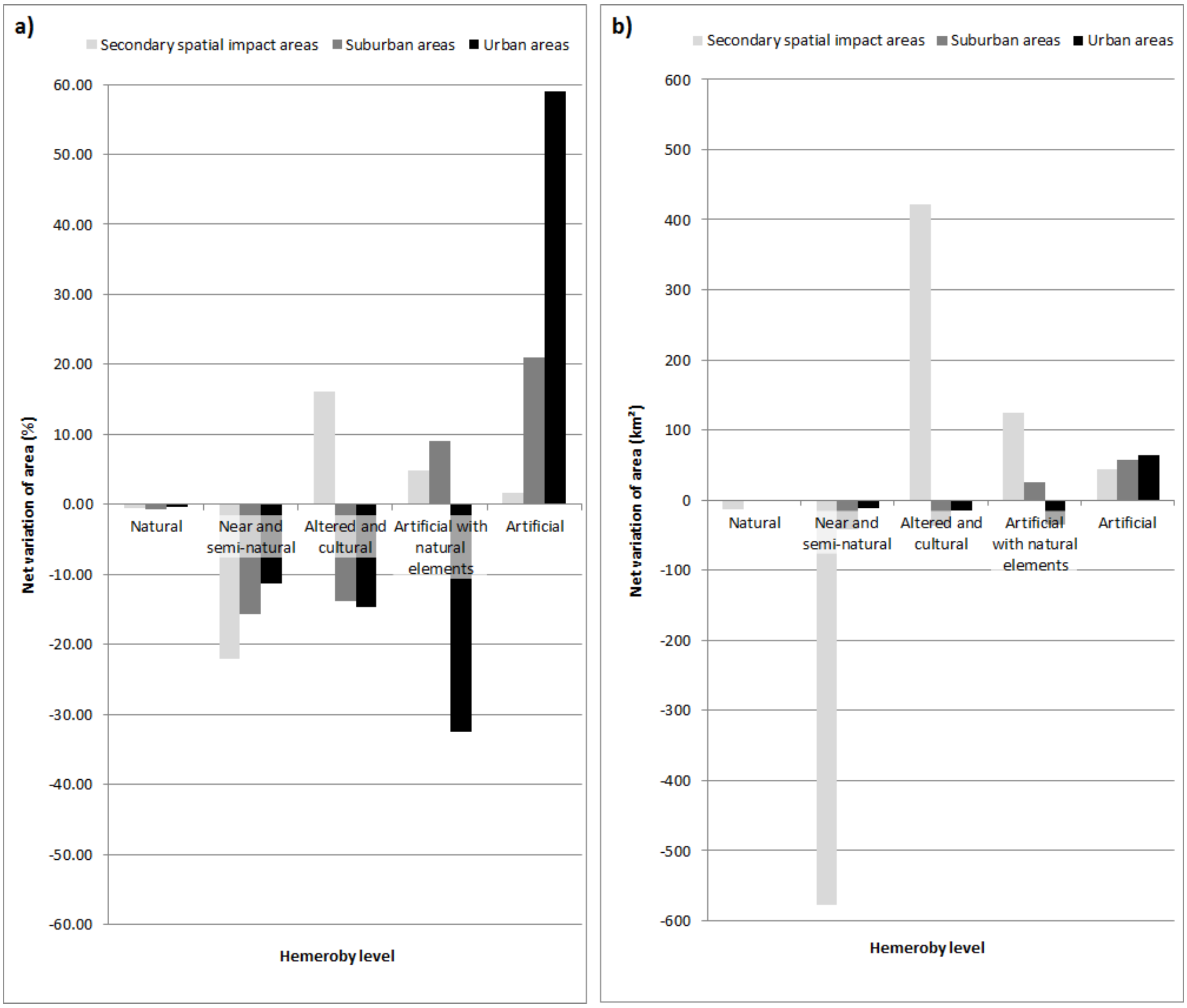


Figure 12. Landscape dynamics corresponding to each interest area (urban , suburban, secondary spatial impact area) between 2002 and 2013/14 in Lubumbashi (DRC), per hemeroby level. The net variations of area refer to the total of area gained, lost unchanged of each interest area, per hemeroby level compared to the total area gained, lost unchanged of each interest area, expressed) in % and b) in gross area, expressed in km².

Chapter 4: General discussion

This thesis is based on the urban-rural gradient* model, which assumes concentric differences in the composition* and configuration* of the land use* as one moves from the center of the city (McIntyre, 2011). This model has been considered as relevant regarding the objectives of the study because of its complementarity with the landscape ecology metrics (Luck et al., 2002). Moreover, it is one of the most widely used by scientists of various disciplines, allowing to potentially build cross-disciplinary bridges. However, as any model, it is not perfect. Thus, firstly, the concentric characteristic is less appropriate for megapolices* or cities that have grown in an anisotropic way, even if the latter case in not an absolute contraindication as we could experience in the present study (McIntyre, 2011). Some cities or part of cities may show more complex city patterns: sectoral (Borsdorf et al., 2002; De Blij, 1977; Forman et al., 1986; Miller, 1981), multiple nuclei (De Blij, 1977; Forman et al., 1986; Miller, 1981), polarized (Borsdorf et al., 2002), fragmented (Borsdorf et al., 2002), leapfrog (Ewing, 1994), diffused (Grosjean, 2010)…. Secondly, this model is less adapted to patterns including industrial land uses or big structures like hospitals. Thirdly, if biota are assumed to respond to the urban-rural gradient in a gradient fashion, there exist thresholds and rapid transitions that may not correspond to the cutoffs of the different areas (urban, suburban,…) (McIntyre, 2011)… and in some cases, human impacts are even not a function of distance from a city center and show complex (spatial) patterns (Alberti, 2008; McDonnell et al., 1990). In some cases, it may be useful to build a city zonation independent of the urban-rural gradient areas and using only study-specific data (e.g. floristic data). Finally, some cities may present a so continuous pattern along the urban-rural gradient that it may not be possible to set a clearcut between areas. In our case, the kappa values obtained for the recursive segmentation have allowed the identification of the areas but a possible continuous characteristic may be another parameter to explain the values obtained.

The approaches developed here to measure the anthropogenic land use and land cover dynamics (SO 3, 1.2 and SO 6), adds value compared to the more traditional approaches only based on land use and land cover. Indeed, it organizes the latter according to their degree of naturalness/anthropisation, which adds a characteristic to them and allows for more precise and richer discussions on the landscape dynamics. It allowed for the identification of the secondary spatial area within the rural area. From a practical point of view, the classification of the land use and land cover provides a logical thread if groupings are necessary during the classification process. From a theoretical point of view and ideally, it may encourage the researchers to have a deeper reflection on the reference state they use and on the criteria used to assess the degree of naturalness. The last two points may not be consensual but their mention in publications may help to increase the awareness and transparency on implicit assumptions that lie behind the studies.

It proves difficult to combine in more depth the two themes of the thesis, and particularly to place all the areas of the urban-rural gradient of Lubumbashi in relation to the concepts of reference and anthropised states detailed in the SO 1, for a number of reasons that are illustrated schematically in the Figure 13 and detailed hereafter. First, scientific informations and/or consensus are missing concerning the overrun (or not) of the novel ecosystem threshold. In particular, 1) the impact of the global anthropogenic effects and its reversibility are little known for the region; this has a consequence on the place of all the areas in relation to the reference and anthropised states and 2) the resilience of the ecosystems situated in the rural area as well as in the non artificial suburban area is not documented enough. Scientific consensus is also missing concerning the ecosystems constituting the climax* of the region; this has an influence on the potential place of the rural (not part of the secondary spatial impact area) area, and in particular of the woodland ecosystem, in relation to the states. Finally, if the threshold is considered as crossed in the artificial suburban area and in the urban area, technical information will be necessary to know which novel ecosystem(s) may constitute the most relevant goal(s) for each abiotic condition of the areas in the region. Secondly, there may be a strong heterogeneity of the hemeroby levels of the ecosystems for a given area. For Lubumbashi, it concerns particularly the rural and suburban areas, the urban area being strongly dominated by the artificial hemeroby level (91% of its surface in 2013/14). Finally, the costs of each potential path and the political choices adopted condition the crossing (or not) of the threshold, as well as the novel ecosystem goal that will possibly be targeted. Indeed, as exposed above (SO 1), the novel ecosystem threshold is a theoretical synthesis of ecological, environmental and social thresholds (Hobbs et al., 2013). However, the Figure 14 constitutes an attempt to represent the trajectories of two theoretical pieces of landscape around Lubumbashi given the assumptions stated in the SO 1. It shows that two pieces of the same global landscape may follow different (anthropisation) trajectories, depending on factors such as the topography, nature/fertility of the soils, infrastructures, economical opportunities etc.

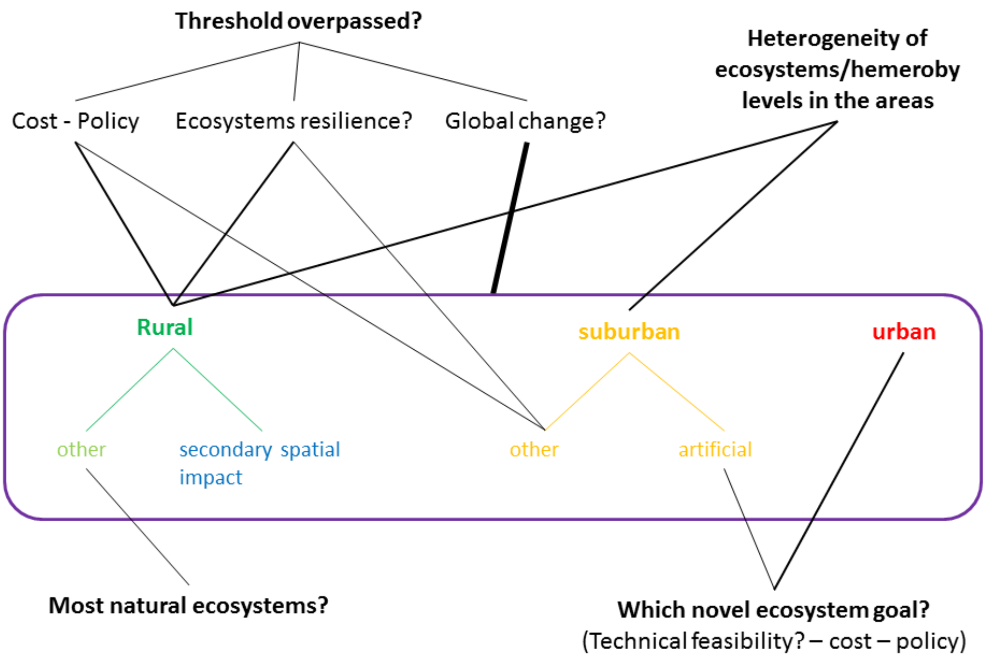


Figure 13. Scheme of the stumbling blocks preventing from matching all the areas of the urban-rural gradient of Lubumbashi (DRC) with the concepts of reference and anthropised states detailed in the SO 1. The arrows link the stumbling blocks to the concerned area. The main stumbling blocks are represented in bold characters and those which refer to unresolved scientific questions contain a question mark. "artificial" refers to the artificial hemeroby level decribed by André et al. (in press)**.**

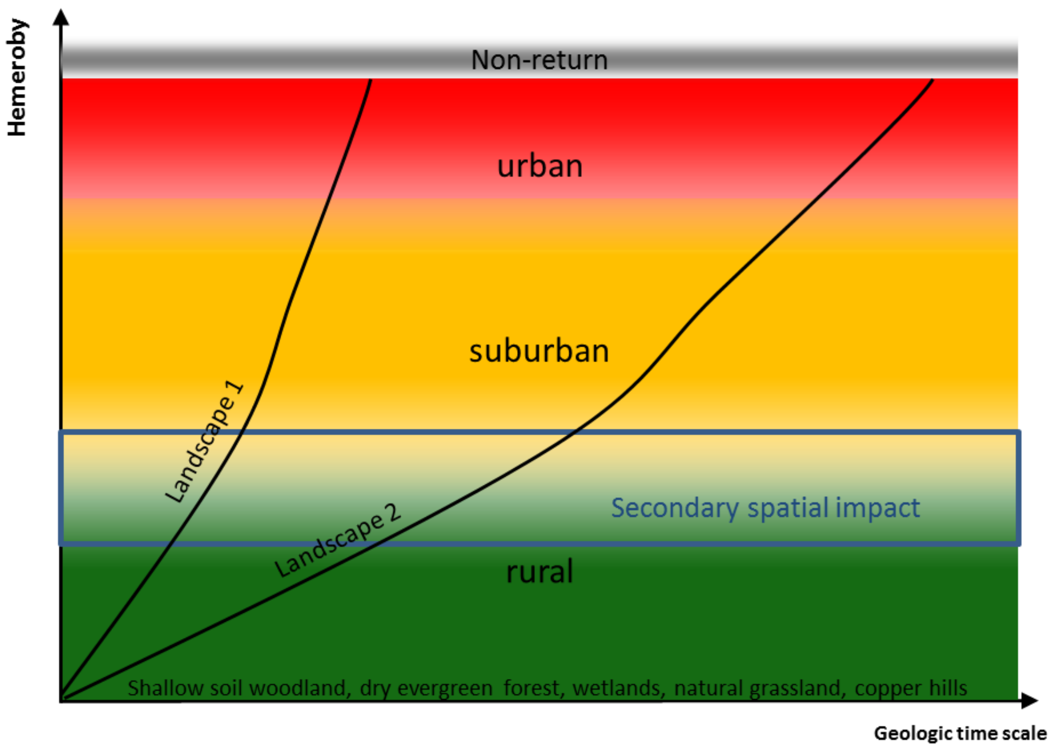


Figure 14. Representation of the trajectories of two theoretical pieces of landscape around Lubumbashi (DRC) matching the areas of the urban-rural gradient (and the secondary spatial impact area) with the concepts detailed in the SO 1. The stated assumptions are that a) pre-colonial human interventions on landscape were anthropogenic, that b) the non-return novel ecosystem threshold is not yet crossed in the region and that c) global anthropogenic effects are negligible in the region.

Finally, from a philosophical point of view, the underlying assumption behind the concept of naturalness such as presented in this document is that the novel ecosystems are less natural that those which prevailed historically in the region. That assumption should be linked to an assumed superiority of biodiversity on any other ecosystem service or value. This is subject to debate and may not be a universal point of view. Indeed, in a (sub)urban context, the novel ecosystems may render more ecosystem services than more natural one and could therefore be more suitable.

Chapter 5: Perspectives

Data and methods

Classification process

The newly freely available Sentinel 2 multispectral images* are characterized by 13 spectral bands ranging from the visible to the short wave infrared, with resolutions ranging from 10 m to 60 m, a large swath of 290 km and temporal resolutions of 5 days at the equator (Drusch et al., 2012). They could therefore constitute an intersecting alternative to the Landsat images used here, with the same advantages and adequacy to the Sub-Saharan context detailed above.

Concerning the classification process, there exist other methodologies that have proven useful in the context of urban areas with medium spatial resolution images. A comparison of results obtained with them could be interesting. The main one are the soft (also called fuzzy) classification (Powell et al., 2007; Ridd, 1995) and change analysis techniques (Sonter et al., 2014). In the first case, rather than attributing a class to each pixel, the latter may have different degrees of membership to several classes. The second case may be employed in multi-date analysis*. Rather than classifying all images part of a time series, change images are first produced by subtracting a date-1 band from the corresponding date-2 band. In a second step, only changed pixels are classified. Other authors have also explored the fusion of coarse resolution data with nightlight and population data but such methodologies are not relevant here because of a lack of such data for the region considered (Schneider et al., 2003). Zha et al. (2003) proposed also a method based on a built-up index easily calculated but the latter methodology is not adapted to the discrimination of the discontinuous built-up class which is necessary in our case.

Measure of anthropogenic land use and land cover dynamics

When setting the reference natural state from which evaluating the hemeroby levels of land covers, we made some assumptions. Further studies on ecosystems resilience* could help evaluating the relevance of the assumption concerning the non crossing of the non-return threshold. In the same vein, studies on global anthropogenic effects in the region could prove useful, as well as, when appropriate, studies on which novel ecosystem(s) may constitute the most relevant goal(s) for each abiotic condition of the areas in the region

Taking connectedness* into account could provide a finer idea of the hemeroby level of patches. This parameter in currently not considered in the methodology of Rüdisser et al. (2012). The extrapolation method of Wiens et al. (1993) could constitute a way to implement it: first, investigate the relationship between individual behaviour (including human activities, in our case) and patch design on micro-landscape with analogous patterns and populations, then study the relationship between these smaller scale cases and a larger landscape, and finally to model this relationship to extend it on large scale.

Measure of the expansion of the (sub)urban areas

Concerning the delimitation of urban areas, the combination of built density with a configuration* (Turner et al., 2015) metric could correspond better to the definition of the urban areas given through the fulfillment of the specific objective 4 and therefore increase the accuracy of the identification of these areas. Moreover, complementing the composition metric proposed in this document with a configuration metric would avoid the common metrics statistical correlation highlighted by Bogaert and Hong (2004).

Testing the methodology developed here using images of higher spatial resolution could be interesting to check the effect of spatial resolution on the accuracy of the recursive partitioning.

If implementing the methodology on other cities of developed countries, one should pay attention to discriminate (sub)urban non agricultural, nor forested nor natural-oriented green spaces. Indeed, such green spaces could be part of the suburban area although not covered with discontinuous built. Land use data may help distinguishing such spaces.

If available, some data could have allowed a finer segmentation of the urban-rural gradient. In particular:

- Up-to-data and regular population inventory, per commune and/or per district. This could allow comparing the urban and suburban expansions per city districts with the evolution of the corresponding population and thus refine conclusions on the dedensification of the city, Indeed, it is difficult to say at this stage if the dedensification concerns the whole city, highly dense districts of Kenya or Kamalondo (which could be a good news, from a sanitary point of view) or the affluent peripheral districts (Bruneau et al., 1990).
- Spatially explicit land use data as well as cadastral data layer could allow the potential identification on satellite images of the sprawl and *banlieue* areas in the urban-rural gradient*
- Data on the population commuting comportment could allow the potential identification on satellite images of the rurban area.

Landscape ecological consequences of the urbanization and suburbanization processes

The classification obtained in this study combined to the unavailability of some spatially explicit data did not allow to conduct finer analysis on the (sub)urbanization drivers and processes. However, such analysis could help planners and decision makers to propose the most appropriate responses (Besussi et al., 2010; McIntyre, 2011). In concrete terms, the following could prove useful:

- A finer classification making accurately the distinction between woodland, regenerating or degrading forest, wooded savannah and old fallow would allow to highlight the forest processes occurring in the study area. Indeed, besides deforestation, forest degradation, although difficult to monitor, reduces significantly carbon stocks (Ahrends et al., 2010).
- That finer classification, combined to field data collection on the activities occurring in different forest places at different distances form the city center (charcoal or wood fuel production, timber logging, non-timber forest products), could help to better understand the link between the land cover dynamics, economic activities and other factors (type and authority responsible for the forest management, distance to roads,…). It could also allow to identify which factors influence the most the deforestation and forest degradation* rates. A similar analysis has already been conducted in the region of Dar es Salaam by Ahrends et al. (2010).
- More specifically, a deeper understanding of the woodfuel production practices (carbonization techniques and yields, percentage of replanting after exploitation) and supply chain (volume produced, income generated) in the region of Lubumbashi would prove useful (Marien et al., 2013).

As stated above, mining activities are of paramount importance in the development of Lubumbashi and its surroundings. It could then be interesting to conduct the same kind of analysis on the impact of mining activities on the surrounding land use and land cover. It would need the identification of the primary and secondary impact areas of the mining sites, then combine them with anthropogenic land dynamics maps. A similar analysis has already been developed by Sonter et al. (2014). It could allow the comparison and combination between impacts induced by (sub)urbanization with those induced by mining.

The city of Lubumbashi has been taken as case study because it was assumed to be representative for the demography, lack of data, of means and of planning challenges of other big cities or developing cities in Sub-Saharan Africa. However, applying the methodology developed here to other cities could confirm the relevance of that assumption as well as highlight nuances between different cities. It could also test the robustness of the methodology to different contexts.

Management: recommendations and research needs

This study has highlighted the landscape ecological consequences of both urbanization and suburbanization processes of the city of Lubumbashi. Some management recommendations and research needs arise from the main conclusions of the study. They will be presented according to the area (general, urban, suburban, secondary spatial impact, other rural areas) to which they correspond most and are illustrated in the schematic Figure 15.

In general, a functioning rule of law is a prerequisite for all the other recommendations detailed below. Regulatory tools must exist and the authority must have the will and capacity to enforce them (Marien et al., 2013). This could increase the land security and reduce corruption (Marien et al., 2013).

Urban and suburban areas

Groupe Huit (2009) has made recommendations in the context of the elaboration of a potential Reference Urban Plan for Lubumbashi. They evaluated the potential land management solutions in order to respond to the expected population growth until 2023. Some of the recommendations concern more urban planning or architectural issues and will not be detailed here. However, they underlined some issues that have potential impacts on landscape. First, they claim that what they identify as the excessive sprawl of the city is a consequence of a lack of a masterplan of the city. Thus, the distinction and identification of, at least, building from non-building areas could help guiding the future (sub)urban expansion. Secondly, they highlight confusion in the roles and responsibilities of the administrative actors. Thus, cadastral agents seem to overpass their missions and perform tasks basically dedicated to urban planning agents like allotment drawing, without having the necessary skills for it. As one of the consequences, the minimum parcel size in 2009 was 1600m², which is not a sustainable size to face the future parcels demands. In the suburban area, in addition, the customary law constitutes a supplementary actor adding to the confusion (Briggs et al., 2001; Trefon et al., 2007; ULB, 2006). ULB (2006) argue that in the latter case, a mutual recognition of the “legal pluralism” could be a solution. Another problem is the land speculation on the immediate surroundings of the city that conducts builders candidates to areas distant of more than 15 km from the centre. Fourth, in relation with the lack of a masterplan, with a lack of inclusion of public equipment funding in the parcels prices and with the non-application of the law retroceding the land to the State in case of land use change (agricultural land to building land for example), there is no longer public land reserves in the immediate surroundings of the urban and surburban areas of Lubumbashi. Besides resulting in infrastructure issues, this situation potentially leads to a lack of green spaces throughout the city. Indeed, such spaces may potentially render ecosystem services* useful for the citizens: water regulation and sanitation, food production, phytostabilisation in the polluted soil areas etc. (the two first were particularly topical in 2009 due to the implementation of the "Urban water supply project" financed by the World Bank) (Costanza et al., 1997; Groupe Huit, 2009; Shutcha et al., 2010). However, a preliminary study of identification and prioritisation of the needs, for different parts of the city, should be undertaken. The latter could help identifying the most relevant type of green space in each part of the city before starting a more concrete feasibility study. At a further stage, if an increase of the biodiversity of an area through the creation of a green space was identified as an objective, the application of the D_2N methodology using finer spatial resolution cartography could help prioritize areas to protect and/or degraded ecosystems to restore. Furthermore, Lubumbashi is described by Bruneau (1990) as an horizontal city, which means that it is built mainly of single storey buildings. It could be interesting to better understand why. Indeed, increase the proportion of multi storey buildings constructions could help reduce the floor space of the buildings and thus 1) limit or slow the expansion of the urban and the most densely built part of the suburban areas and 2) release some space for public land reserves in already densely populated areas. Finally, raise awareness of the urban population/green space managers/(sub)urban farmers to the potential ecosystem services returned by the vegetation of their gardens/public green spaces/parcels, if managed adequately, could also have a significant impact on the biodiversity of the city. However, ULB (2006) highlights that land security is a prerequisite to foster sustainable resources exploitation by (sub)urban farmers.

Rural area

Secondary spatial impact area

As stated above, due to the tremendous impacted surface and biodiversity lost, a better management of the secondary spatial impact expansion area is essential.

In particular, wood fuel and charcoal production are suspected of playing a central role in the woodland degradation* and/or disappearance. Indeed, altough it is difficult to quantify due to its complex and informal nature (Marien et al., 2013), FAO (2005) considers that in Africa and South-East Asia, 80 to 90% of the extracted wood is intended to be used as woodfuel. It is followed (or coupled) in many cases by cultivation (the so-called "slash and burn" practice). In this context, the multiplication of agroforestry areas around the city could constitute an interesting solution to meet the population needs while reducing pressure on natural resources. The project Afodek is a first step in this direction (Gret, 2014). This 2000 ha agroforestry project implemented in 2013 in the west of Lubumbashi, beyond the suburban area, consists of corn and *Acacia auriculiformis* A.Cunn. ex Benth plantations, the latter being a fast-growing evergreen tree originating from Australia, Indonesia and Papua New Guinea (Contu, 2012; Proces, pers. comm.). However, uncertainties regarding property and potential informal digging threaten the mid- and long-term sustainability of the project (Gret, 2015; Proces, pers. comm.). Similar effect of unsustainable cultivation practices due to a lack of land security may be expected in the secondary spatial impact areas as in the urban and suburban areas. There is still a lot to be done to assess the possibility of using native woodland species instead of *Acacia auriculiformis* (Hick, pers. comm.; Proces, pers. comm.; Sileshi et al., 2007). Indeed, a native alternative could increase the benefits for the biodiversity playing in that case both a preventive and a curative role in woodland degradation* and deforestation. Moreover, *Acacia auriculiformis*, to the contrary to native woodland species, is not adapted to local fire practices, which could be a supplementary threat to the project sustainability (Hick, pers. comm.). A better access to seeds for farmers (Sileshi et al., 2007) would also help improve the system. However, agroforestery competes with national and international policies that are still promoting crop monocultures (Sileshi et al., 2007).

A sustainable agriculture intensification could also possibly help to reduce the pressure on natural ecosystems. However, investigations are still necessary on the conditions under which, in the Sub-Saharan context, agricultural intensification is possible and on the conditions influencing a potential joint forest clearing reduction (Carr, 2004a).

Whether in the case of increasing agroforestry or of agriculture intensification, the education (if possible continuous) of farmers is essential (Carr, 2004b in Sileshi et al., 2007; Marien et al., 2013; Sileshi et al., 2007).

Assisted natural regeneration techniques and an increase of woodfuel plantations, coupled with fair remuneration of farmers (to compensate for higher labour costs due to tree management) may also diminish the pressure on natural resources (Marien et al., 2013; Sileshi et al., 2007).

Finally, strenghthening of the whole woodfuel supply chain by the state would allow the formal and sustainable development of the sector (Marien et al., 2013).

Natural, near-natural and semi-natural areas

Two often quoted solution to slow the secondary spatial impact expansion are fuel switching, for example to LPG, kerosene, electricity, and improved biomass-stoves (Clancy, 2008; Marien et al., 2013). But the obstacles are numerous: relative price, practical cooking considerations, availability of appropriate appliances and taste among others (Clancy, 2008). A lot is still to be done to deeply understand the barriers to the switching as well as to possibly, if appropriate, propose relevant solutions. An improvement of the carbonization process yields could also help reducing the impacts of woodfuel consumption (Marien et al., 2013).

Participatory forest management, through the realization and implementation of simple plans for resource management, allows for more sustainable forestry (Marien et al., 2013).

On a governance point of view, a potential tax differential encouraging sustainable woodfuel production in dedicated, rationally managed plantations or in lands subject to simple management plans could be an effective incentive (Marien et al., 2013). Nevertheless, the sectors of forestry receive often little resources from the national budgeting process to support sustainable management, develop appropriate technical information and enforce regulation (Barany, 2004; Mlay et al., 2003). The existing legislation on woodfuel cutting is not adapted, incomplete and seldom enforced (Marien et al., 2013). Improvement in this regard is essential.

Eventually, some forest chosen for their particular good state, diversity, species composition and/or location could receive a protective status.

Overall rural areas

Finally, the tackling of the secondary spatial impact area expansion into natural, near-natural and semi-natural areas overtakes the power and action possibilities of a single municipality. It requires reflection on a larger scale. Some examples of larger scale measures are presented below.

Roads have shows to be an important driver for the expansion of the secondary spatial impact area. Due to the fact that their construction is an important economic development driver, particularly precious in regions cumulating isolation and developing status, it can hardly be hampered. However, a particular care can be taken in the choice of their alignment, giving if possible preference to the alignment alternatives crossing less precious land covers.

Finally, on a financial point of view, the opportunity of obtaining revenues from the REDD+ program, from payments for ecosystem services or from the state could constitute critical incentives for the actors to implement one or several of the measures exposed hereabove, provided that a significant share of the revenue actually go to the stakeholders group that effectively implemented the measure(s) (Bidaud, 2012; Campbell et al., 2007; Marien et al., 2013).

A typology of cities

According to the spatially explicit dynamics patterns of the urban and suburban areas, it could be interesting to develop a typology of cities. Such a typology could discriminate cities with a rapidly changing urban area and/or suburban area from those that are more static. It could then help planners and policy makers to propose measures to manage the (sub)urbanization processes on a case-by-case basis.

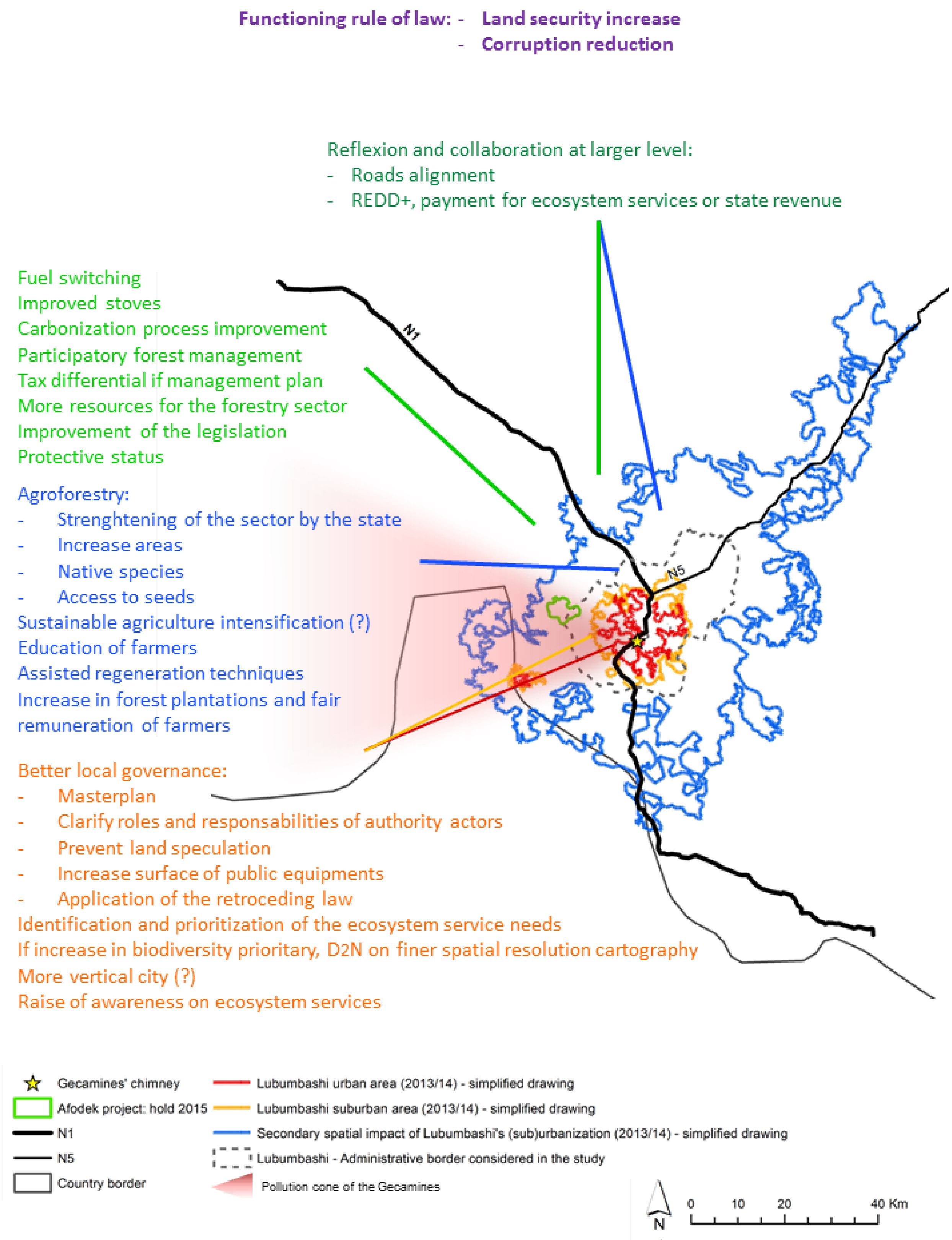


Figure 15. Diagram of the land management recommendations and perspectives arisen in the study. The color purple refers to a global recommendation, the color blue to recommendations concerning the secondary spatial impact area of the rural area, the color light green to the natural, near-natural and semi-natural parts of the rural area, the color dark green to all the rural area and the color orange concerns both the suburban and the urban areas of Lubumbashi (DRC). The question mark indicates a thematic whose relevance should be explored.

Chapter 6: Conclusion

The methodology developed in this thesis allowed to highlight the land cover types affected by the urbanization, suburbanization and secondary spatial area extension. It shows that in terms of net variation of area and biodiversity lost, the latter overpasses the two others. It is the Near and semi-natural hemeroby level that is most impacted, which corresponds to the Woodlands, wooded savannahs, old fallows and Streams land cover classes. Another part of the study showed that a national road linking Lubumbashi to another city is the main expansion driver of that secondary spatial impact area. The combination of the two latter observations highlights again the tremendous anthropisation driver that represents road construction on land cover change (Bamba et al., 2010; Forman, 1995; Vranken et al., 2011).

List of abbreviations

D_2N: distance to nature

D_n: distance to natural habitat

DPSIR: Driver Pressure State Impact Response

DRC: Democratic Republic of Congo

ETM+: Enhanced Thematic Mapper Plus

GPS: global positioning system

N_d: degree of naturalness

NIR: near infrared

OLI: Operational Land Imager

Q: general research question

SO: specific objective

SQ: specific research question

SRTM: shuttle radar topography mission

Glossary

(Clark and Evans') aggregation index (R):	Evaluates the distribution of the patches in the landscape. May be calculated with the formula $R = \overline{z_\iota}/\overline{r_a} = 2\overline{z_\iota}\sqrt{\rho}$ where $\overline{z_\iota}$ is the mean of the series of distances to nearest neighbor, calculated as $\overline{z_\iota} = \sum_{i=1}^{n} z_i/n$ and where $\overline{r_a}$ is the expected mean distance to the nearest neighbor for a random distribution of the patches, calculated as $\overline{r_a} = 1/2\sqrt{\rho}$. The values of this metric range between 0 (when the patches are maximally aggregated) and 2.1491 (when the patches are maximally spaced). The distribution is said to be aggregated when R is significantly inferior to 1, to be random when R is equal to 1 and to be even when it is significantly superior to 1 (Clark et al., 1954).
Climax:	Defined by Bournerias (1982) as the dynamic outcome or maturation state of changing plant communities and related biocenoses. However, although widely used concept, it is also strongly discussed among the scientific community; its climatic determinism and the existence of long-term steady conditions for climax settlement are indeed questioned (Bournerias, 1982; Cook, 1996; Génot, 2006; Hall et al., 1995; Henderson et al., 1960).
Composite index:	Metric that integrates complex environmental conditions in one parameter which cannot be measured directly (Rüdisser, Tasser, & Tappeiner, 2012).
Composition:	One of the two categories describing the landscape pattern or structure. Type, number, relative abundance and surface of ecosystems or landscape classes (Li et al., 1995).
Configuration:	One of the two categories describing the landscape pattern or structure. Number, shape, size and spatial arrangement of patches across the landscape (Forman et al., 1986; Li et al., 1995).
Connectedness:	Functional connectivity; fact that two habitat patches are linked, from the point of view of one or more individual or species, so that it/they can move from one patch to another even though they are not physically connected (Burel et al., 2003).
Density metric (ρ):	May be calculated with the following formula: $\rho = n/E$ where n is the number of built patches and E is the extent of the study area. The values of this metric range between 0 (when there is no patch) and infinity (when there is an infinite number of patches), for a given area.
Digital elevation model:	Digital cartographic dataset of elevations, sampled at regularly spaced horizontal intervals, in xyz coordinates (USGS, 2012).
Disclimax:	Stable vegetation developed after an anthropogenic disturbance (Henderson et

	al., 1960). See Climax.
Distance to the nearest neighbor metric (z_i):	Evaluates the isolation of a patch in the landscape through the distance from the border of the patch *i* to the border of the nearest patch. The values of this metric range between 0 (when two patches are adjacent) and infinity (when an infinite distance separate two patches) (Clark et al., 1954).
(Turner's) dominance index (*D*):	Quantifies the dominance or equitability between the classes of the landscape. may be calculated with the formula $D = Hmax - H$ where $Hmax = \ln M$ with *M* the number of landscape classes and *H* the Shannon's heterogeneity index; $H = -\sum_{j=1}^{m} p_j \ln p_j$, where p_j is the proportion of the class *j* in terms of surface. There is a dominance situation of one or several class(es) regarding the others when that index reaches $Hmax$ and there is a perfect equitability between the classes when the value reaches 0 (Turner et al., 1988a).
Dominance index (*D'*):	Dominance metric derived from McGarigal et al.'s (2002) Largest Patch Index, defined as the area of the largest patch of the corresponding class divided by the total class area, multiplied by 100. The closer the largest patch is to 100, the more there is a dominance situation and the smaller the largest patch is, the more equitability there is between the patches. In the latter case, the value approaches 0.
DPSIR:	Acronym for the Driver Pressure State Impact Response Analysis framework that integrates the (environmental) problems within a social, economic and environmental context and presents them in the form of a causality chain (Smeets et al., 1999).
Ecosystem services:	Benefits human populations derive, directly or indirectly, from ecosystem functions (habitat, biological or system properties or processes of ecosystems) (Costanza et al., 1997).
Error matrix:	Square array of numbers set out in rows and columns that express the number of sample units assigned to a category relative to the actual verified category. The columns and rows usually represent respectively the verified data and the classification (Congalton, 1991).
Euryoecious:	Adjective designating an organism able to live under variable conditions (The Collins english dictionary, 2016)
Forest degradation:	Long-term reduction of the overall potential supply of goods and services by the forest, including carbon storage, wood production and biodiversity conservation (Ahrends et al., 2010).
Fragmentation:	Breaking up of one or several patches of a class into smaller one resulting in unevenly separated patches. It is one of the five degradation processes of a class, in the context of landscape pattern dynamics (Bogaert, Ceulemans, et al., 2004).

Future naturalness: State that the system eventually reaches after human influence ceased and after following complete ecological succession (Gilg, 2005; Peterken, 1996; Schnitzler et al., 2008). If the system has been too deeply altered, this state differs from virtual naturalness due to global human impacts such as anthropogenic climate change or species extinction (Peterken, 1996).

Kappa coefficient: Discrete multivariate technique of accuracy assessment. Based on the representation of the classification accuracy of remotely sensed data in the form of an error matrix*. Calculated with the formula

$$K = \frac{N\ \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} * \ x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} * x_{+i})}$$

Where r is the number of rows of the matrix, x_{ii} is the number of observations in row *i* and column *i*, x_{i+} and x_{+i} are respectively the marginal totals of row i and column i and *N* is the total number of observations (Congalton, 1991). The values of the kappa coefficient are comprised between 0 and 1; 0 representing a total inaccuracy and 1 representing a perfect accuracy.

Land cover: Characteristics of the land surface (natural or artificial) derived from direct observations (Anderson et al., 1976; Fisher et al., 2005)

Land use: Characteristics of the land surface derived from direct observations and socioeconomic interpretation of the activities being held (Anderson et al., 1976; Fisher et al., 2005)

Megapolis: Consensual part of the definition: very large urban areas often comprised of two or more formerly separate cities that have grown and merged. Also called metropolitan area.

According to the authors, it is formed only of urban areas (Forman et al., 1986; McIntyre, 2011) or may comprise outlying counties with well-defined links to the central county or counties based on commuting patterns (Heimlich et al., 2001; Office of Management and Budget, 2000).

Multispectral image: Image that contains more than one spectral band, formed by sensors able of separating light reflected from the earth into discrete spectral bands, providing therefore higher spectral resolution than panchromatic images (Gene, May-5-2016).

Multi-temporal analysis: Also called diachronic analysis. Analysis of a dynamics by examining the evolution of a single study case along different stages of the phenomenon (Baker et al., 1982).

Naturalness: State of the system when no human activity has influenced it (Vranken et al., in preparation). It is widely used and discussed among the scientific community (Lecomte et al., 2005; Machado, 2004; Peterken, 1996; Schnitzler et al., 2008)

	and is considered by some authors, and in this contribution, as the opposite of anthropisation (Bogaert et al., 2014; Machado, 2004). Also a measure of the difference between natural and current state called "degree or level of naturalness" (Kowarik, 1999; Lecomte et al., 2005; Machado, 2004; McRoberts et al., 2012; Peterken, 1996; Rüdisser et al., 2012). In the latter case, the term "hemeroby" will be preferred here (see "Hemeroby") to avoid confusion.
Novel ecosystem:	Abiotic, biotic and social components of an ecosystem that, because of anthropogenic effects, differ from those that prevailed historically in the area. The latter qualities of ecosystems be recovered due to the crossing of ecological, environmental and social thresholds (Hobbs et al., 2006).
Oriented-object classification:	Image classification processing in two steps: 1) creation of objects (segmentation process) and 2) classification of the created objects. Both steps may take into account the internal and external context of the objects (Definiens, 2013).
Original naturalness:	State of the system before the first anthropogenic land transformations (Peterken, 1996).
Panchromatic image:	Single band covering a broad range of wavelengths; usually used in context of collecting information from the whole visible spectrum (Nasa, May-6-2016). Allows smaller detectors to be used while maintaining a high signal to noise ratio, providing therefore higher spatial resolution than multispectral images (Gene, May-5-2016).
Pan-sharpening:	Type of data fusion that combines lower-spatial resolution (and higher spectral resolution) multispectral image with higher-spatial resolution panchromatic image to produce a high spatial and spectral resolution multispectral image (Padwick et al., 2010).
Potential naturalness:	State of the system that would develop if human influence disappeared and if the resulting succession were finished instantly (Hall et al., 1995; Peterken, 1996; Reif et al., 2008; Tüxen et al., 1956)
(ecological) Progressive series:	Sequence leading an ecosystem to its terminal evolutionary state (Encyclopaedia Universalis, 1999).
(Gustafson's) proximity index (*PX*):	Weights the isolation of the patches in the landscape by their surface. May be calculated with the formula $PX = \sum_{i=1}^{n}(S_i/z_i)$ where S_i is the surface of the patch *i* considered. The value of this metric range between 0 (when two patches are adjacent) and infinity (when an infinite distance separate two patches and/or when the size of the patches tends to infinity) (Gustafson et al., 1994).
Pyroclimax:	Climatic ecosystem maintained constant by the repeated action of fire (Métro, 1975). See Climax.

Radiometric calibration:	Set of techniques during image processing that correct the sensor-target illumination geometry, sensor calibration and atmospheric scattering and absorption (Yang et al., 2000). Radiometric calibration is particularly important when conducting multi-temporal analysis, to ensure comparability between images shot at different times.
Recursive partitioning	Statistical multivariate analysis method that breaks the data into *k* terminal groups according to splitting variables. The data is first separated into two groups then the process is repeated separately on each sub-group, recursively, until the sub-groups either reach a minimum size or until no improvement can be made. The splitting rules are often presented in form of a decision tree (Breiman, 1984; Therneau, Atkinson, & Mayo Foundation, 2015).
(ecological) Regressive series:	Sequence taking an ecosystem away from its terminal evolutionary state (Encyclopaedia Universalis, 1999).
Resilience:	Capacity, for an ecosystem or a landscape that underwent structure change due to a disturbance, to recover to its previous state (Pimm, 1984).
Segmentation process:	See “Oriented-objects classification” above.
Spatial resolution:	Size of the pixels recorded in a raster image.
Spectral signature:	Pattern of electromagnetic radiation characterizing a chemical, compound or land cover (Esri, May-5-2016). Spectral signature analysis techniques use the variation in the spectral reflectance or emittance of objects as a method of identifying the objects (Nasa, May-6-2016).
Structural connectivity:	Adjacency, proximity of two habitat patches (Burel et al., 2003).
Supervised classification:	Image classification process guided by a user who defines training sites, i.e. areas that are known to be representative of a particular land cover class. The software determines the spectral signature of the pixels within each training area and uses mean and variance values in order to assign each pixel in the image to the class to which it matches most (Creutzburg, 2012).
Temporal resolution:	Expected repeat time between measurements over the same location (Nasa, May-6-2016)
Thematic class:	Land cover or land use class (see above).
Thematic resolution:	Level of details included in a map legend or image classification to distinguish the different land cover classes in the represented landscape (Bailey et al., 2007); number of thematic classes of a map.
Thermal band:	General term for intermediate and long wavelength infrared-emitted radiation,

	as contrasted to short wavelength reflected infrared radiation. In practice, generally refers to infrared radiation emitted in the 3-5 µm and 9-14 µm atmospheric windows (Nasa, May-6-2016).
Topographic position index:	Index calculated for each cell of a digital elevation model* as the difference between the elevation of the cell and the mean elevation of all the cells of a moving circular window centered on the cell of interest (Guisan et al., 1999). Values superior or inferior to zero mean that the cell represents respectively a local top or valley.
Transition matrix:	Table of replacement rates or surfaces over a time period for all landscape classes present (Forman et al., 1986). The diagonal corresponds to the stable classes.
Urban heat island:	Modification of the original microclimate in urbanized areas resulting in higher temperatures than in the surrounding areas. It may be measured as the maximum difference between the background rural temperature and the highest urban temperature (Alberti, 2008).
Urban-rural gradient:	One of the models used to describe the structure and functions of urban ecosystems. In this model, as one moves from the center of the city, differences are expected in the type, size, shape and spacing of various forms of land use. Usually assumed to be concentric (McIntyre, 2011).
Virtual naturalness:	Current state of the system if human had never had any impact on it (Lecomte et al., 2005; Peterken, 1996). Compared to “original naturalness” (see above), it takes natural evolution into account (Vranken et al., in preparation).

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Appendix

Appendix 1: Confusion matrices

Table 7. Confusion matrix for the classification of the 2002 Landsat image of Lubumbashi (DRC) (1.2)

Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crops, pastures, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crops mosaic	Water	Wetland	Wooded savannah	
Continuous Built	7	1	0	12	0	0	7	0	1	0	25.0
Crops, pastures, 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/crops 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 8. Confusion matrix for the classification of the 2013 Landsat image of Lubumbashi (DRC) (1.2)

Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crops, pastures, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crops mosaic	Water	Wetland	Wooded savannah	
Continuous Built	15	2	0	9	0	0	0	2	1	0	51.7
Crops, pastures, 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/crops 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											

Table 9. Confusion matrix for the classification of the 2002 Landsat image of Lubumbashi (DRC) (2.3)

Classified data	Reference data						User's accuracy (%)
	Continuous built-up	Discontinuous built-up and bare ground	Natural grasslands and wetlands	Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Water	Woodland, wooded savannah and old fallow	
Continuous built-up	10						100.0
Discontinuous built-up and bare ground	3	24					88.9
Natural grasslands and wetlands		2	21	2			84.0
Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	1	2	5	9	1	3	42.9
Water					14		100.0
Woodland, wooded savannah and old fallow	1	2	4	4		27	71.1
Producer's accuracy (%)	66.7	80.0	70.0	60.0	93.3	90.0	
Overall accuracy: 77,8%; Kappa statistic: 0,73							

Table 10. Confusion matrix for the classification of the 2013/14 Landsat image of Lubumbashi (DRC) (2.3)

Classified data	Reference data						User's accuracy (%)
	Continuous built-up	Discontinuous built-up and bare ground	Natural grasslands and wetlands	Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Water	Woodland, wooded savannah and old fallow	
Continuous built-up	12	6	2	1	1		54.5
Discontinuous built-up and bare ground	2	24					92.3
Natural grasslands and wetlands			17	1	1	1	85.0
Savannah, bushland, young fallow and anthropogenic herbaceous vegetation			3	7	2	4	43.8
Water			1		9		90.0
Woodland, wooded savannah and old fallow	1		7	6	2	25	22.0
Producer's accuracy (%)	80.0	80.0	56.7	46.7	60.0	83.3	
Overall accuracy: 69,6%; Kappa statistic: 0,63							

Appendix 2: Resulting maps of the classifications of 2002 and 2013/14 for the specific objective 6

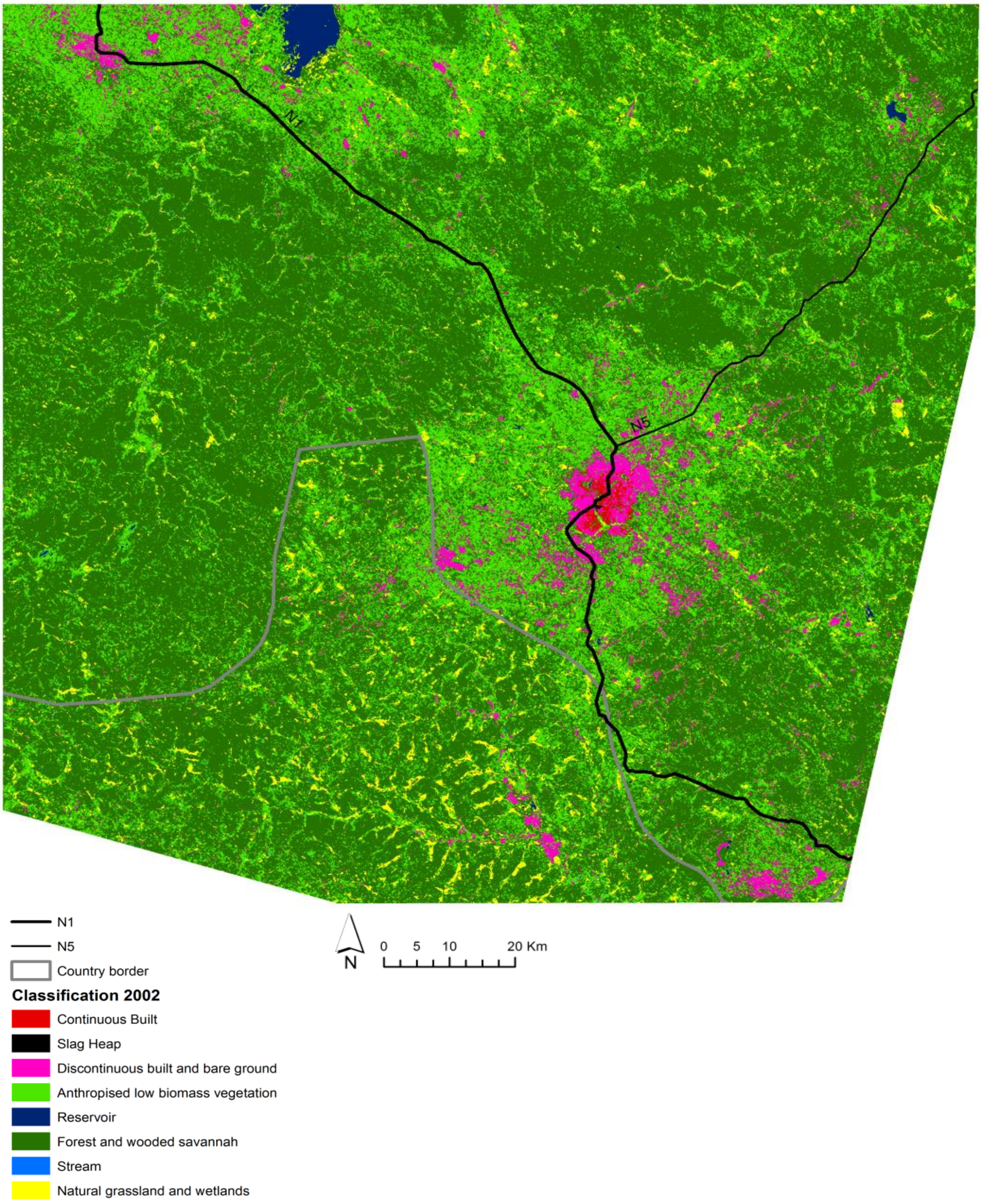


Figure 16. Resulting map of the classifications of the landscape centred on Lubumbashi (Province of Haut-Katanga, DRC), based on 04/05/2002, 07/07/2002, 08/08/2002 and 11/10/2002 Landsat images.

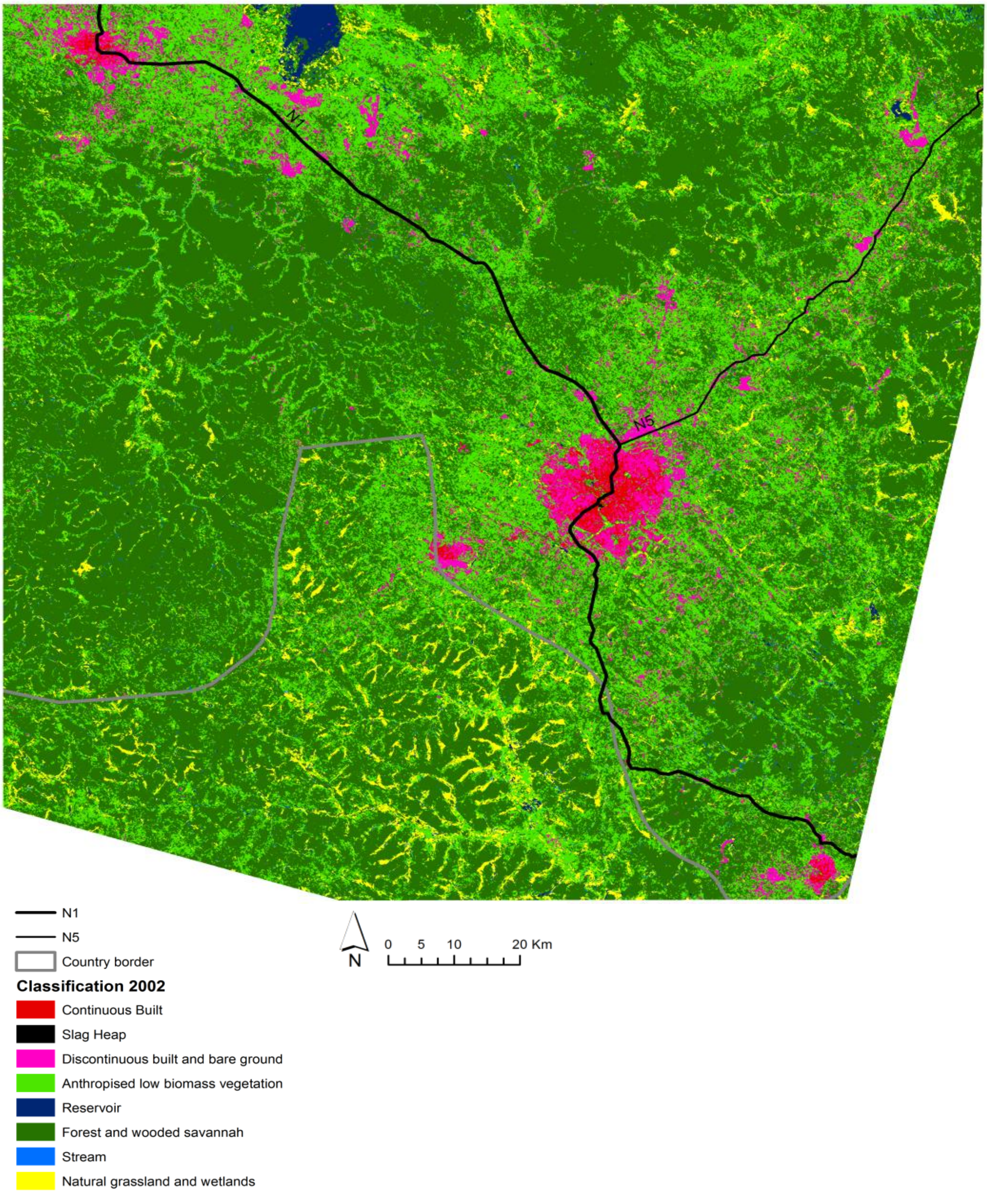


Figure 17. Resulting map of the classifications of the landscape centred on Lubumbashi (Province of Haut-Katanga, DRC), based on 27/06/2013, 13/07/2013, 30/08/2013 and 05/11/2014 Landsat images.

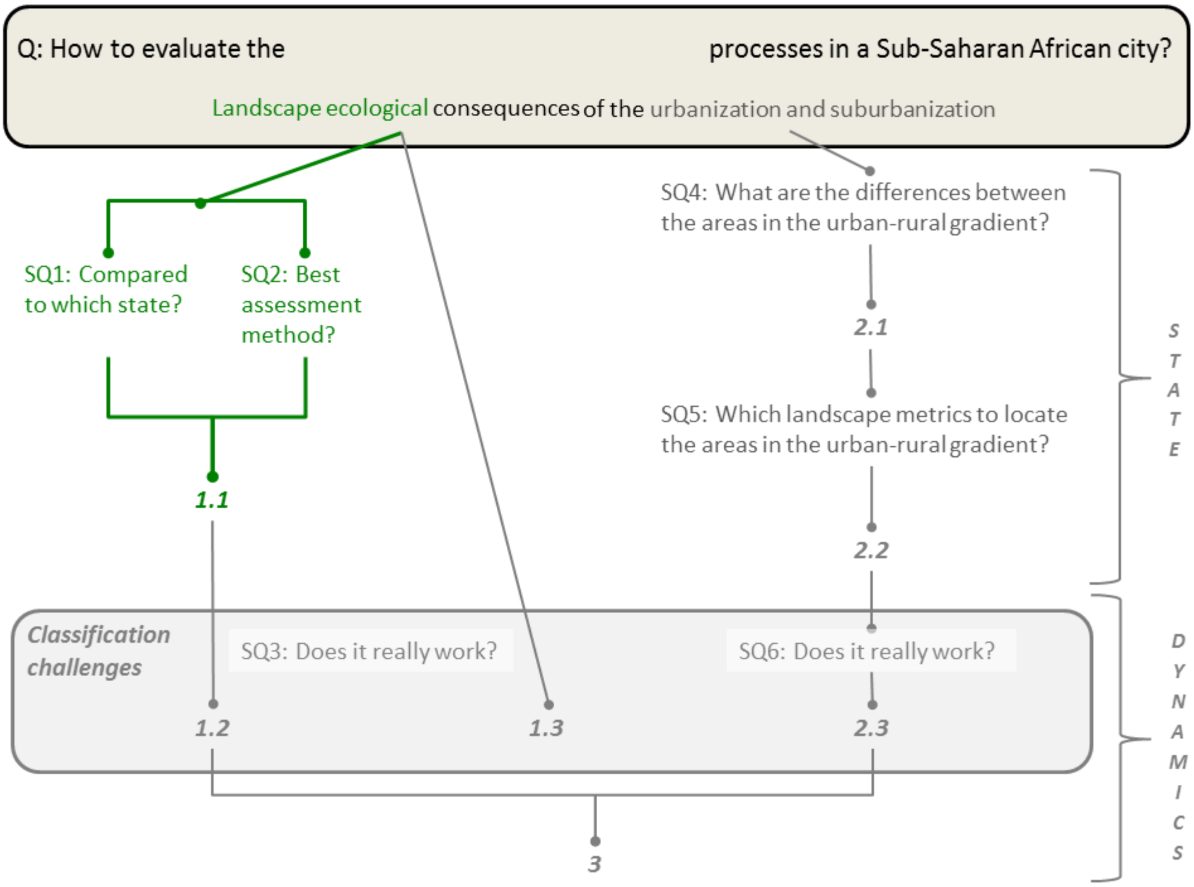
Appendix 3: R code for the recursive partitioning

```
setwd("D:/ ")
donnees<-read.csv2(".csv")
nli<-dim(donnees)[1]
nCV<-10
K<-numeric(nCV)
randK<-sample(1:nli)
for(n in 1:nCV){
subK<-randK[((n-1)/nCV*nli+1):(n/nCV*nli)]
library(rpart)
cl.rp<-rpart(zoneSsBanlieue~GRIDCODE,data=donnees,parms=list(split='gini'),minbucket=50,subset=-subK)
print(cl.rp)
conftab<-with(donnees[subK,],table(zoneSsBanlieue,predict(cl.rp,donnees[subK,],type="class")))
print(conftab)
tempK<-0
for(i in 1:length(levels(donnees$zoneSsBanlieue))){
tempK<-tempK+sum(conftab[i,])*sum(conftab[,i])
}
K[n]<-(sum(conftab)*sum(diag(conftab))-tempK)/(sum(conftab)^2-tempK)
print(K[n])
}
mean(K)
mean(K)+c(-1,1)*1.96*sd(K)/sqrt(nCV)
```

Appendix 4: Publications

Publication 1.1

Spatially explicit quantification of anthropogenic landscape change. Towards a new methodological framework.



Publication 1.1
Spatially explicit quantification of anthropogenic landscape change. Towards a new methodological framework

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Abstract. Anthropogenic disturbances impact the whole biosphere, at least indirectly, and are of major concern in various disciplines and policies. However, most studies are very specific to their thematic, creating their own reference framework without connection with other research on related purposes in other disciplines. This plethora of terms and concepts in turn impedes comprehensive tackling of that issue and complementarity between studies.

Here, we give an integrated approach of the concern that could be at the basis of land planning and environmental management practices and policies. To do so, we first briefly sort the different concepts from various disciplines related to the anthropogenic landscape changes. We then organize the variables, formats and methods regularly used to assess them, using the levels of study and paradigms of landscape ecology, a discipline of great integrative power. We combine these paradigms with the Drivers-Pressures-State-Impacts-Response (DPSIR) framework to reorganize the causal logic of anthropogenic disturbance and to highlight the potential effect of response actions undertaken at each step. The strengths of the existing assessment material and methods are finally combined into guidelines for a new analytical framework; we propose an action-oriented type of naturalness and a general methodology to evaluate landscape anthropisation. Our methodology combines easily acquired data sets of categorical, stretched and object-oriented formats. It is based on the assessment of ecological processes as well as on landscape pattern and dynamics. It is oriented to evaluate anthropogenic landscape change on a complete, exportable and clear way.

Keywords. anthropogenic effect; novel ecosystem; hemeroby; naturalness; landscape ecology;

environmental indicator

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Introduction

Human impacts on the environment have existed for so long that little or no area in the world is now considered as untouched, at least indirectly (Ellis & Ramankutty, 2008; Sanderson, Jaiteh, Levy, Redford, Wannebo, & Woolmer, 2002). Humans transform the ecosystem patterns and processes (Bogaert, Vranken, & André, 2014; Burel & Baudry, 2003; Ellis & Ramankutty, 2008; Sanderson et al., 2002). This environmental, policy making and land planning issue is addressed by various disciplines such as botany, conservation management, geography as well as population, restoration and landscape ecology (Jalas, 1955; Lambin & Geist, 2006; Naiman, Holand, & Decamps, 1988; O'Neill, Krummel, Gardner, Sugihara, Jackson, DeAngelis, Milne, Turner, Zygmunt, Christensen, Dale, & Graham, 1988; Peterken, 1996; Solon, 1995). Though some interactions already exist between these disciplines, each focuses on its own issue of interest, analysing such anthropogenic transformations with its own terms and analysis framework (focus scale, hierarchical level and variables of interest) (Green & Sadedin, 2005). The causes and consequences of human activities are therefore generally explored separately.

However, combining such information in a more transdisciplinary, action-oriented approach could prove a remarkable breakthrough, not only for fundamental research but also regarding sustainable development and policy making. On the other hand, many problems in ecology and resource management are related to landscape use. In that context, the focus scale of landscape ecology may bring the appropriate framework. This discipline relies on the “pattern and process paradigm”, which states that landscape structure (namely its composition and configuration) and ecological processes are interdependent (Turner, 1989). Although centred on the hierarchical level “landscape” (being groups of interacting ecosystems), the knowledge of many other disciplines at higher and lower scales are used in landscape ecology to understand the context and the mechanisms involved (Bogaert & André, 2013; Wiens, Stenseth, Horne, & Ims, 1993).

In order to approach a comprehensive and transdisciplinary analysis, the concepts and methods used to represent human impacts on landscapes will be analysed within the Driver Pressure State Impact Response (DPSIR) framework throughout this review (Ness, Anderberg, & Olsson, 2010). This sustainable policy-oriented analysis framework is frequently employed in reports in order to assess environmental problems, but is increasingly used in scientific articles as well. It integrates these problems within a social, economic and environmental context and presents them in the form of a causality chain so as for which action could be undertaken to tackle them (Smeets & Weterings, 1999).

This article has three main objectives: (1) to sort the different concepts from various disciplines related to the anthropogenic landscape changes, (2) to organise the data formats, variables and methods regularly used to assess them, (3) to combine the strengths of the existing assessment materials and methods into guidelines for a general methodology, towards more completeness, exportability and clarity for the evaluation of anthropogenic landscape change.

Current concepts

This section presents the concepts, sheltering disciplines and practices as well as underlying challenges to characterise human impact on the environment. These conceptions strongly influence the way human impacts on landscapes are measured. The most frequently employed terms, their synonyms, the nuances and relationships between each of term are described below and illustrated in Fig. 2.

Anthropisation, anthropogenic effect

Anthropogenic effect, often employed in its plural form, is a general expression accounting for any kind of influence of human activities on the environment (Barima, Djibu, Ndayishimiye, Bomolo, Lubemba, Mongo, Bamba, Mama, Toyi, & Kasongo, 2011; Bogaert, Vranken, & André, 2014; Ellis & Ramankutty, 2008; Solon, 1995). In landscape ecology, the phenomenon is studied as for the impact intensity of human activities on landscape composition, configuration and dynamics (Bogaert, Barima, Ji, Jiang, Bamba, Iyongo Waya Mongo, Mama, Nyssen, Dadouh-Guebas, & Koedam, 2011; Vranken, Mama, Djibu, Munyemba, Bamba, Barima, Visser, & Bogaert, in preparation). The term *anthropisation* is more frequently used by Latin languages speakers than in English (Bogaert et al., 2011; Bogaert, Vranken, & André, 2014; Burel & Baudry, 2003; Diallo, Bamba, Barima, Visser, Ballo, Mama, Vranken, Maiga, & Bogaert, 2011; Inostroza, 2012; Machado, 2004). However, those terms are not exactly synonyms, the former being defined as the process of landscape changes as a consequence of the latter (Bogaert, Vranken, & André, 2014). They are nevertheless used without distinction by most authors. Several other expressions are employed to represent similar phenomena: anthropogenic disturbance(s), anthropogenic impact(s) / pressures, anthropogenic land-cover / landscape change, human disturbance / footprint, human impact / influence on land surface, etc. (Garbarino, Weisberg, & Motta, 2009; Hannah, Lohse, Hutchinson, Carr, & Lankerani, 1994; Lambin & Geist, 2006; Laurance, 2004; Machado, 2004; Menon & Bawa, 1997; Pielke, Walko, Steyaert, Vidale, Liston, Lyons, & Chase, 1999; Sanderson et al., 2002; Solon, 1995). The term landuse is also related to anthropogenic effects: the human use of land (Brentrup, Küsters, Lammel, & Kuhlmann, 2002; Haberl, Batterbury, & Moran, 2001; Ramankutty, Graumlich, Achard, Alves, Chhabra, DeFries, Foley, Geist, Houghton, Goldewijk, Lambin, Millington, Rasmussen, Reid, & Turner, 2006).

Those expressions show that cause and consequence are not always clearly specified. In order to clarify what is actually focused, the causality chain related to this phenomenon, Fig.1, organises its different elements according to the DPSIR framework. This analysis framework was developed by the European Environmental Agency to classify environmental indicators in a causal chain and analyse environmental problems regarding the relationship between the ecological and human dynamics in a comprehensive and transdisciplinary (Ness, Anderberg, & Olsson, 2010; Smeets & Weterings, 1999). This sustainable policy-oriented analysis framework is increasingly used in scientific articles. The DPSIR framework highlights the issues that can be addressed when providing responses to environmental problems caused by human intervention. For ecosystem service-oriented analysis of environmental issues, the EBM-DPSER (Kelble, Loomis, Lovelace, Nuttle, Ortner, Fletcher, Cook, Lorenz, & Boyer, 2013), a variant of the DPSIR, can also be used. The original version has however been kept here for its simplicity and polyvalence. The focused causal stages most generally addressed in landscape ecology are there put in perspective with the pattern / process paradigm. The “Driver”, underlying cause of anthropogenic effect on landscapes is the presence of humans, considering their density, but also their lifestyle (Lambin & Geist, 2006). Through activities performed to support human needs, they generate environmental “Pressures” that influence ecological processes and modify the “State” of the landscape in its composition as well as its configuration (Lambin & Geist, 2006; Sanderson et al., 2002). This influence is called anthropogenic effect and the landscape in this state is considered as anthropised (Bogaert, Vranken, & André, 2014). “States” are generally observable through landscape patterns, while “Pressures” act more directly on processes. That landscape structural change has in turn “Impacts” on ecological processes, disturbing local biocoenosis (Naiman, Holand, & Decamps, 1988).

What is not directly highlighted in the original DPSIR framework itself is that multiple feedbacks may arise (Ness, Anderberg, & Olsson, 2010). Processes affected by pattern change can affect landscape pattern in turn and *vice versa* (Bogaert, Vranken, & André, 2014; Forman & Godron, 1986; Lambin & Geist, 2006; Laurance, 2004).

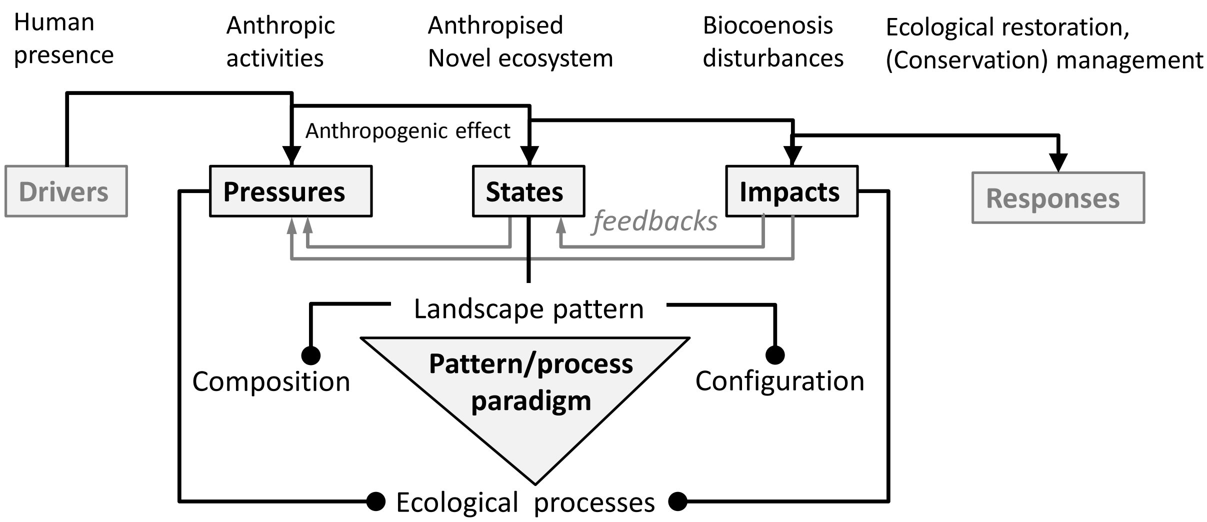

Fig. 1. Combined DPSIR framework and landscape ecology's pattern / process paradigm applied to the issue of human impact on landscapes. Black boxes represent the focus of landscape ecology.

It should be noted that the notion of anthropogenic impacts on ecosystems and landscapes are not necessarily detrimental to ecological processes (see "ecosystem management" below). For example, species diversity increases in moderately anthropised landscapes or man-made ecosystems have already been observed (Bird, Bird, Codding, Parker, & Jones, 2008; Chakraborty & Li, 2011; Naiman, Holand, & Decamps, 1988; Piqueray, 2007). Distant drivers, such as delocated production or transformation of goods, also do not fit well to the DPSIR framework (Cumming, Olsson, Chapin III, & Holling, 2013).

Reference states

The reference states can be used either as a departure point to measure anthropisation intensity or as a goal to achieve while restoring a given site. There is a plethora of reference states that are all difficult to define specifically or achieve in a concrete case.

Naturalness

"Naturalness", i.e. the characteristic of what is natural is the state of the system when no human activity has influenced it. It can be considered as the opposite of anthropisation (Bogaert, Vranken, & André, 2014; Machado, 2004). It was first used in botany and ecology (Kowarik, 1999; Lecomte & Millet, 2005; Machado, 2004; Reif & Walentowski, 2008; Rüdisser, Tasser, & Tappeiner, 2012; Steinhardt, Herzog, Lausch, Müller, & Lehmann, 1999; Tüxen & Preising, 1956; Winter, 2012) and is widely used and discussed among the scientific community (Lecomte & Millet, 2005; Machado, 2004; Peterken, 1996; Schnitzler, Génot, Wintz, & Hale, 2008). It can be associated to climax, but the use of the latter term is controversial. Its climatic determinism and the existence of long-term steady conditions for climax settlement are indeed questioned (Bournerias, 1982; Cook, 1996; Genot, 2006; Hall, 1995; Henderson, Kenneth, & Henderson, 1960). "Wilderness" is frequently used in Australia and wrongly applied as a synonym to naturalness, given that wilderness implies remoteness and large extent (Machado, 2004; Peterken, 1996).

Naturalness is also a measure of the difference between natural and current states called "degree or level of naturalness" (Kowarik, 1999; Lecomte & Millet, 2005; Machado, 2004; Peterken, 1996; Rüdisser, Tasser, & Tappeiner, 2012; Winter, 2012). However, for this measure, we will prefer the use of the term hemeroby in order to avoid confusion (see "Hemeroby" below).

Distinguishing what is natural and what is not requires defining what is considered as artificial or detrimental to nature. The historical and theoretical point at which human impacts begin to be taken into account is subject to debate because it addresses the issue of the relationship between human and nature (Haila, Comer, Hunter, Samways, Hambler, Speight, Hendricks, Herrero, Dobson, Smith, & Yu, 1997; Machado, 2004; Mascaro, Harris, Lach, Thompson, Perring, Richardson, & Ellis, 2013). Most authors consider anthropogenic land transformation as artificial (Ellis & Ramankutty, 2008). Its can begin with agriculture (Lecomte & Millet, 2005; Mazoyer & Roudart, 2006), or industrialisation (Mackey, Lesslie, Lindenmayer, Nix, & Incoll, 1998). Those thresholds were not simultaneous everywhere (Mazoyer & Roudart, 2006).

"Original naturalness" describes the state before the first anthropogenic land transformations (Peterken, 1996). It is sometimes called "naturalness of the first post-glacial times" or "biological naturalness" in Europe (Fuhr & Brun, 2010; Gilg, 2005; Lecomte & Millet, 2005). In restoration ecology, original naturalness is still mentioned as reference (Bakker & Berendse, 1999; SER, 2004). However achieving original naturalness is practically not possible, nor meaningful: natural changes and disturbances have occurred since the first human impacts (IPCC, 2007; Lecomte & Millet, 2005; Sutherland, Newton, & Green, 2004; Winter, Fischer, & Fischer, 2010).

"Virtual naturalness", also called "present naturalness", would be the current state of the system if human had never had any impact on it (Lecomte & Millet, 2005; Peterken, 1996). This state takes natural evolution into account. If an ecosystem had never been impacted by human activity, even indirectly (which is actually nowhere the case), its virtual and original naturalness would correspond to its current state.

As for original and virtual naturalness, even when reaching a consensus about the kind of activities considered as natural / artificial, practical characterisation of the corresponding state is particularly difficult to achieve in the case of landscapes with a long anthropisation history, such as tropical forests impacted by past slash and burn agriculture dating back to over 1900 years (Vleminckx, Morin-Rivat, Biwolé, Daïnou, Gillet, Doucet, & Drouet, 2014).

“Potential naturalness” or “potential natural vegetation / community” is the state that would develop if human influence disappeared and if the resulting succession were finished instantly (Hall, 1995; Peterken, 1996; Reif & Walentowski, 2008; Tüxen & Preising, 1956). In practice, it represents the self-sustaining ecosystem in the disturbed abiotic condition of the site (Hall, 1995). Such definition is taken as reference for less ambitious restoration projects or conservation management (Lundholm & Richardson, 2010).

“Future naturalness”, also referred to as “anthropogenic naturalness”, corresponds to the state that the system eventually reaches after human influence ceased and after following complete ecological succession (Gilg, 2005; Peterken, 1996; Schnitzler et al., 2008). If the system has been too deeply altered, this state differs from virtual naturalness due to global human impacts such as anthropogenic climate change or species extinction (Peterken, 1996).

Novel ecosystem

The term “Novel ecosystem” originates from ecology and is mostly employed by restoration ecologists (Mascaro et al., 2013). At a certain intensity of anthropogenic effect on local landscape as well as its global surroundings (such as climate), some anthropogenic disturbances are so heavy that it seems impossible to go backwards towards the previous natural state: Novel ecosystems characteristics differ from one author to another. The most consensual definition mentions (1) that a novel ecosystem has abiotic, biotic and social components that, because of anthropogenic effects, differ from those that prevailed historically in the area and (2) that those historical qualities cannot be recovered due to the crossing of ecological, environmental and social thresholds (Hobbs, Higgs, & Hall, 2013). The definition and position of this threshold, “barrier” or “point of no-return” is subject to debate (Hallett, Standish, Hulvey, Gardener, Suding, Starzomski, Murphy, & Harris, 2013).

Hemeroby

Hemeroby represents the measure of the difference between a reference (natural) state and the anthropised state of a system. It is an integrative measure of the degree of human influence, intended or not (Jalas, 1955 ; Kowarik, 1990). This concept originates from botany in Europe and has mostly been applied to plant species (Jalas ; Kowarik, 1990), forest communities (Acosta, Blasi, Carranza, Ricotta, & Stanisci, 2003; Rüdisser, Tasser, & Tappeiner, 2012; Sukopp, 1976), ecosystems

(Kowarik, 1990) and more recently landscapes, principally agrarian and forested (Milanova, Arshinova, & Kotchurov, 1992 ; Renetzeder, Schindler, Peterseil, Prinz, Mücher, & Wrbka, 2010; Rüdisser, Tasser, & Tappeiner, 2012).

This concept is similar to anthropogenic effect, although its quantification methods are different. Naturalness equals the zero degree of hemeroby. There exist different definitions of the reference state, though hemeroby rarely specifies which one is taken (Brentrup et al., 2002; Fanelli & De Lillis, 2004; Peterken, 1996; Rüdisser, Tasser, & Tappeiner, 2012; Steinhardt et al., 1999).

Responses to anthropisation

Depending on the stage of anthropogenic impact undergone by the ecosystems of interest, Humans can give different types of "Responses" to environmental disturbances, which tackle different stages in the causality chain (Fig. 1) (Ness, Anderberg, & Olsson, 2010; Smeets & Weterings, 1999). The sooner Humans intervene in a response strategy, the less harmful for the virtual naturalness of the ecosystem. Those response actions are, by ascending anthropogenic impact: Avoid, Minimise, Rectify, Compensate, Enhance (Rajvanshi, 2008).

"Avoiding" the potential impact of human activities falls within the frame of biological conservation (or conservation management) (Gutzwiller, 2002; Rajvanshi, 2008). This process consists in preserving an area from anthropogenic disturbance in order to protect local biodiversity or contribute to its recovery after restoration or management (see below) (Gutzwiller, 2002; SER, 2004; Weddell, 2002).

"Minimising" the spatio-temporal scale of the impact during design and construction of human infrastructures is usually addressed in environmental impact assessment studies (Rajvanshi, 2008).

"Rectification" and "compensation" are forms of environmental management generally addressed by restoration ecology or, in the case of agro-ecosystems, agroecology (Fischer, Abson, Butsic, Chappell, Ekroos, Hanspach, Kuemmerle, Smith, & von Wehrden, 2014; Rajvanshi, 2008; SER, 2004). The latter are the processes of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed towards less disrupted ecological processes and spatial patterns (SER, 2004). They suppose the existence of a reference ecosystem that will serve as model (SER, 2004). Rectification is applied to hybrid ecosystems (see below), while compensation is applied to novel ecosystems (Rajvanshi, 2008).

A novel ecosystem can as well be managed to develop its functional analogy to a reference existing natural ecosystem in the same area (e.g. quarry face can be analogous to cliff) or even exploit these analogies it in order to enhance the ecosystem or health services of the novel ecosystem; it will then be called "artificial analogous" ("analog" or "analogue") (Hobbs, Arico, Aronson, Baron, Bridgewater, Cramer, Epstein, Ewel, Klink, & Lugo, 2006; Lundholm & Richardson, 2010). However, on the contrary to restoration it will become different from what it was before turning into "novel" (Hobbs et al., 2006). The response action is called is this case "enhancement" (Rajvanshi, 2008).

The restored indigenous naturalness concept: a new, operational reference state

Most of the naturalness definitions cannot actually be achieved. Yet, for restoration purposes, an operational definition of naturalness representing a more ambitious reference state than potential naturalness could prove useful. In that direction, we propose a new reference: the "restored indigenous naturalness" (Fig. 2). It represents the maximal naturalness that can be locally achieved, the natural ecosystem present if there had never had been any local or direct disturbance, even abiotic. Landscapes with no direct human disturbance would also be in this new type of natural state, being subject to global disturbances but not local ones. So, any restorative action could be situated along a hemeroby scale, the minimum of which would be this maximal attainable naturalness. Its adaptation to specific cases would however lead to the recurrent question associated with reference states definition: how to know what would be there? In practice, reference states are often used based on functional similarities to current ecosystems and historical data on species composition and biotope, when available (SER, 2004).

Graphic synthesis

A combination of the main concepts developed hereabove is presented in Fig. 2. Considering at first a landscape completely preserved from human influence under growing human impact (hemeroby scale), the state in which this landscape was before being disturbed is the original naturalness. As time and other local and global natural disturbances go by, if anthropogenic influence increases, the landscape is then in "Hybrid state". If by that time human disturbance ceases, it can recover what it would be like if no human had ever influenced it, either rapidly through active restoration or more slowly through ecological succession: this state is its virtual naturalness. After the non-return threshold is crossed, the landscape is anthropised and its composing ecosystems are then considered novel due to the changes in biotic composition, but also local and global abiotic conditions (double arrows). If the anthropogenic effect on this landscape stops increasing, its hemeroby reaches a plateau, and if anthropogenic effect ceases or decreases, the hemeroby level decreases as well.

However, as the ecosystems are now novel, they cannot recover their previous state: this is represented using a second hemeroby scale, showing that the evolution towards "more naturalness" follows a different path. If no management is applied to the landscape, ecological succession will lead progressively to future naturalness. Either on hybrid or novel ecosystems, potential naturalness can be used as a reference for restoration: the "most" natural ecosystems that can occur in disturbed global and local abiotic conditions. Restored indigenous naturalness can represent the "most natural" state achievable through restoration possibly followed by conservation: it goes further than potential naturalness, removing the result of abiotic disturbances (e.g. soil pollution) from the site. Artificial analogous landscapes result from another form of novel ecosystem response: it uses the result of human disturbances as a departure point to build a new landscape.

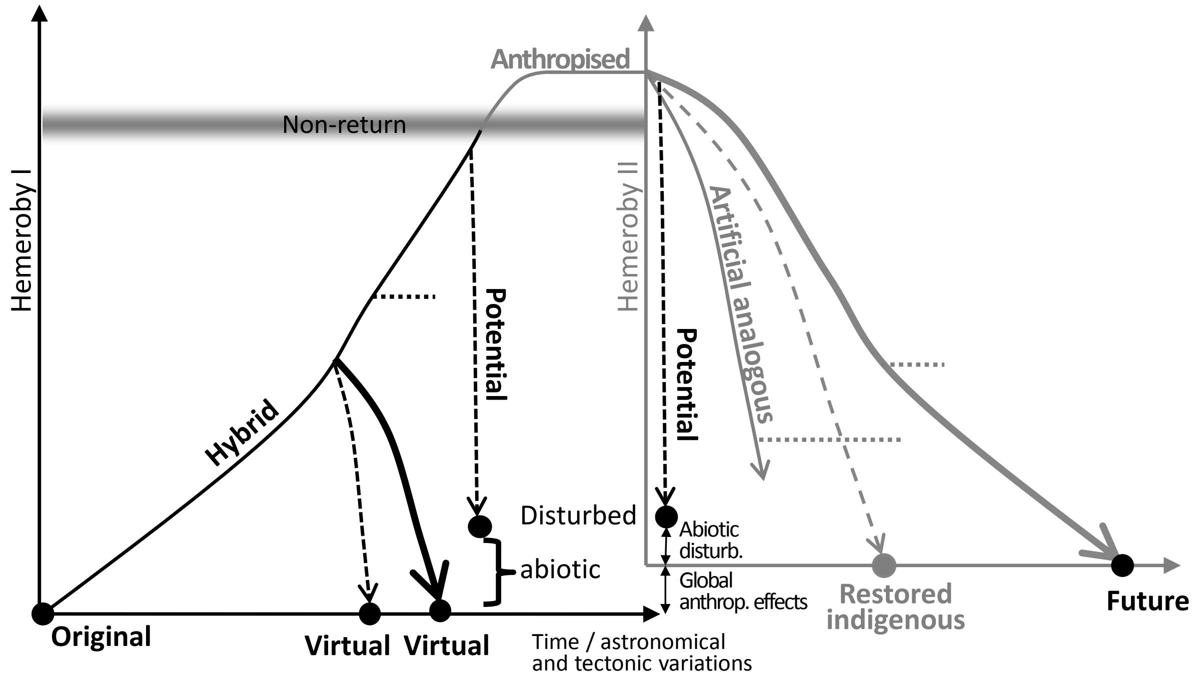

Fig. 2. Graphic synthesis of the concepts related to human impacts on landscapes from ecological, landscape ecological and restoration ecological perspectives. This representation is a theoretical and simplified model of the different anthropisation trajectories that a landscape can follow. Dashed lines represent active restoration, plain upward line represents landscape evolution under increasing human disturbance, plain downward lines represent management, horizontal dotted lines represent conservation and bold line represents ecological succession. Dots represent reference states of naturalness, bold characters non reference states. The wide blurry line labelled "Non-return" represents the novel ecosystem threshold, grey elements being related to novel ecosystems.

Current assessment materials, issues and methods

Each data model provides its own capabilities, which influences the representation and analysis of the variable distribution. The assessment method chosen has in turn also consequences on pattern identifications and anthropisation level evaluation (Gustafson, 1998). In this section, we consider the existing assessment materials (variables and data formats) and methods regularly used to evaluate the concepts presented above. We then highlight their strengths and the issue of data availability.

Variables

When applied at landscape level, hemeroby, naturalness and anthropisation are quantified using the same variables. In order to put in perspective which quantification focused on causes and which on consequences, these anthropisation variables were classified according to the DPSIR framework (Fig. 3).

Economy and population variables are used to represent human presence as a Driver of anthropisation. Generally, such variables are population density and revenue (Haberl, Batterbury, & Moran, 2001; Menon & Bawa, 1997; Sanderson et al., 2002).

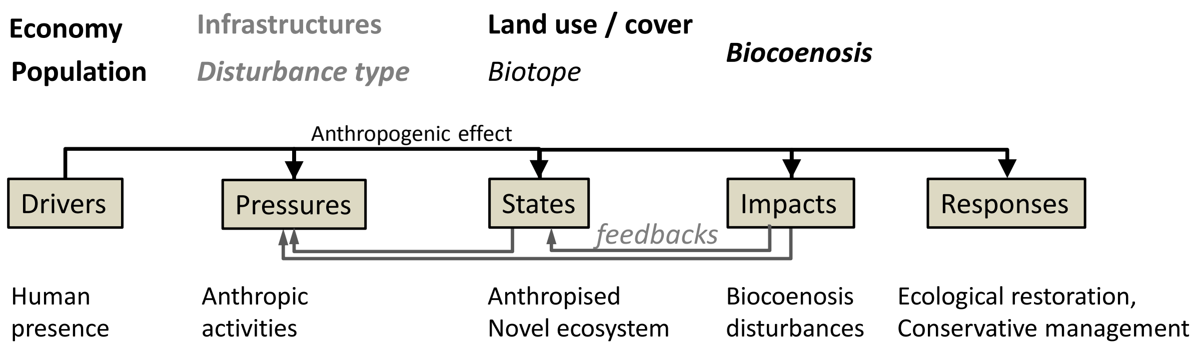

Fig. 3. Thematic variable types (up) related to the quantification of human impact on landscapes, reported in each corresponding stage of the DPSIR framework. Human impact stages are reminded under the boxes. Bold characters represent categorical variables, italic one represent stretched data and grey characters represent patch variables.

Human activities are regularly quantified using infrastructures and disturbance type (input, output, structural biotope transformation), as Pressures. The data used in this case are linear, punctual or polygon infrastructures like roads, farms, electric power plants, quarries, villages, *etc*. (Garbarino, Weisberg, & Motta, 2009; Menon & Bawa, 1997; Sanderson et al., 2002). Though those are used as proxies for disturbance processes, disturbances like the amount of emitted pollutant, field nutrient or the surface of cleared forest can also be measured *per se* (Brentrup et al., 2002), which can be described as stress factors (*sensu* Grime (1979)).

State represents the landscape anthropisation phenomenon *per se*. Anthropised state in itself is generally quantified using landuse and landcover data at landscape level (Bogaert, Vranken, & André, 2014; Foley, DeFries, Asner, Barford, Bonan, Carpenter, Chapin, Coe, Daily, & Gibbs, 2005; O'Neill et al., 1988; Pielke et al., 1999; Vranken, Djibu Kabulu, Munyemba, Mama, Iyongo Waya Mongo, Bamba, Laghmouch, & Bogaert, 2011). At finer scales, biotope descriptive variables are also used, like pollutant concentration, fertilizer or percentage of soil sealing (Peterseil & Wrbka, 2001; Rüdisser, Tasser, & Tappeiner, 2012). The Impacts of the anthropised state on biotic communities are measured using biocœnosis parameters, such as species origin, abundance or diversity (Fanelli & De Lillis, 2004; Machado, 2004; Reif & Walentowski, 2008).

Responses to anthropisation (see below) are mainly evaluated using the variables primarily dedicated to States and Impacts, used in this case as proxies (Ruiz-Jaen & Mitchell Aide, 2005). According to SER (2004), restoration success indicators should also include variables relating to Pressures.

Data format

The three main data types used to represent ecological and landscape variables are stretched values / continuous data (gradients), categorical maps (classes) and patches (patch dynamics) (Gustafson, 1998; Wiens et al., 1993).

Categorical mapping

Categorical mapping is the simplest and most widely employed thematic cartography method in various disciplines to represent vector or raster data (Boots & Csillag, 2006). This representation involves discontinuous variation of the data, often arbitrarily defined (Gustafson, 1998). This format is used in all levels of the DPSIR framework. Pressures are represented through the variables infrastructures and disturbance, States through landuse/cover and Impacts through biocoenosis parameters.

This format lacks thematic resolution: all the local ecosystems (patches) classified in the same landcover may not be evenly affected by anthropogenic disturbances (André, Vranken, Visser, & Bogaert, in revision; Stromgaard, 1985; van der Werf, Randerson, Giglio, Gobron, & Dolman, 2008).

Stretched values

Stretched values are used to represent the spatial distribution of data under continuous variations (Gustafson, 1998). They are also called “point data”, but we chose to exclude this term here in order to avoid confusion with data represented as point features in Geographic Information Systems (GIS) softwares. As for categorical mapping, this format is used in all levels of the DPSIR framework. Pressures are represented in the form of proxies for disturbance processes like the amount of emitted pollutant, field nutrient or the surface of cleared forest, States in the form of biotope stress factors and Impacts through biocœnosis parameters.

Its continuous nature makes it more thematically precise, suitable and frequently used to study transitions along relief, climate or diverse ecological gradients like edge effect (Gustafson, 1998; Sutherland, Newton, & Green, 2004). Stretched values are generally represented using raster maps. They make less assumption about the nature of spatial structure (Gustafson, 1998).

Patch, patch dynamics approach: an object-oriented approach

Ecosystems can also be studied for their individual properties as habitat patches. This is often referred to as "Patch dynamics" in landscape ecology because this format is used to distinguish the evolutionary trajectories of individual patches (Wiens et al., 1993). Such representation is the expression of the patch-corridor-matrix model in landscape ecology (Forman, 1995). This object-oriented approach is exploited by image analysis softwares such as eCognition® that create objects with distinct identifiers and characteristics, comparable with attribute tables of vector layers in Geographic Information Systems (GIS) (Trimble Documentation, 2013).

The patch dynamics approach combines advantages of both categorical mapping and stretched values: it distinguishes entities trajectories and it highlights individual habitat specificities. It is at the interface between ecology and landscape ecology, between spatial patterns and ecological processes (Wiens et al., 1993). However, it is only representing Pressures variables (infrastructures and disturbance) in the DPSIR framework, probably due to the practical difficulty to collect the necessary data to the patch dynamics representation.

The issue of data availability

Data availability is a critical issue in the places where accurate data on infrastructure and socio-economic data are scarce. This is particularly the case in developing countries, though those areas represent considerable interest for land planning and conservation (Groombridge, Jenkins, Centre, & Programme, 2002; Sanderson et al., 2002). It should be noted however that the availability of data acquired by field survey may be correlated with human accessibility to landscapes. In the case of anthropogenic effect assessment, this may lead to substantial bias, whereas creating access to it represents potential future disturbance (Ruiz-Gutiérrez & Zipkin, 2011). In that context, the stretched or categorical values originating from remote sensing represent an essential tool.

Current assessment methods of anthropisation

Simple, direct measures

Simple quantitative measures of the variables (OECD, 2008) can represent landscape composition (O'Neill et al., 1988), configuration (Garbarino, Weisberg, & Motta, 2009; Sanderson et al., 2002) or ecological processes (Garbarino, Weisberg, & Motta, 2009; Margalef, 1958). These measures are directly representative for their corresponding phenomenon occurring at a given DPSIR stage, but when interpreting them at other stages or other phenomena occurring at the same stage, they form indirect indicators. For example, pollutant emissions are a measure of anthropogenic disturbance, but a surrogate for landscape anthropisation.

These quantitative measures allow powerful comparisons and less arbitrary interpretations, but they often give an incomplete perspective of the represented phenomenon (SCOPE, 2012).

Scales

Ordinal scales are the way hemeroby is represented. It gives a categorical representation of anthropisation. The main differences between the existing hemeroby scales are related to: (1) the hierarchical level to which it is applied; (2) the reference state considered; (3) the number of levels of the scale applied; (4) the variables used.

Each scale is generally designed for a given organisational level: vegetal community, ecosystem or landscape (Fanelli & De Lillis, 2004; Rüdisser, Tasser, & Tappeiner, 2012). The number of scale levels varies from 4 to 11 and the used parameters to distinguish them are generally based on species or landscape composition and/or type of human influence (Brentrup et al., 2002; Fanelli and De Lillis, 2004; Kowarik, 1999; Machado, 2004; Peterken, 1996; Peterseil & Wrbka, 2001; Reif and Walentowski, 2008; Rüdisser, Tasser, & Tappeiner, 2012; Steinhardt et al., 1999). The criteria defining scale levels and the distance between these levels are not always specified nor constant.

Scales are arbitrary but allow distinguishing entities and include qualitative and quantitative data, the latter in the form of simple measure or (more rarely) composite index (see below). However, the different components of the system considered can correspond to different levels, for example fauna can be more natural than flora (Lecomte & Millet, 2005), while regressive dynamics are mixed with progressive ones.

Composite indexes

The aforementioned simple measures and scales can be combined into quantitative composite indexes which integrates complex environmental conditions in one parameter which cannot be measured directly (Rüdisser, Tasser, & Tappeiner, 2012).

Specific attention should be paid to which information is actually contained in the composite index, how their contribution to the final index was weighed and on which hypotheses it relies if it uses arbitrary classifications. Comparisons would be eased if similar methods could be applied on different landscapes.

Guidelines towards an integrated methodology

The ideal data should be based on easy acquisition, formatted to distinguish patch trajectories and connectivity, comparable with other areas, and as direct, objective and complete as possible.

If stretched values are acquired by remote sensing or aerial imagery, spatial as well as temporal location rules can be defined by combining the aforementioned stretched values with categorical maps. If so, a limited field survey and spatial modelling would distinguish a maximal number of patches originating from different dynamics or encountering different anthropogenic pressures would be isolated, as developed in André et al. (in revision). Therefore, the patch dynamics perspective could be approached by refining categorical mapping through its combination with stretched values.

Taking connectivity into account is possible by calculating the “distance from natural habitat” gradient as stretched values (Rüdisser, Tasser, & Tappeiner, 2012). Such information represents interesting perspectives for land planning, conservation and restoration by highlighting which areas should be preferably protected or restored. The effect of adding or removing natural patches in the landscape could be simulated in this way. To take functional connectivity into account, Wiens et al. (1993) propose extrapolations: first, investigate the relationship between individual behaviour (including human activities, in our case) and patch design on micro-landscape with analogous patterns and populations, then study the relationship between these smaller scale cases and a larger landscape, and finally to model this relationship to extend it on large scale.

Rüdisser, Tasser & Tappeiner (2012)’s methodology already combines many of the aforementioned advantages. Therefore, a prototypal methodology based on Rüdisser, Tasser & Tappeiner (2012) was developed (Fig. 4). From the sources mentioned in the first grey rectangle, different variable types related to the quantification of anthropogenic effects on landscape can be acquired (see Variables above). In this way, even if few large scale social or infrastructure inquiries were performed, proxies could be found by relying on other DPSIR stages. This should ease the methodology application to more remote areas or where few data are available, like developing countries (André et al., in revision).

Appropriate georeferenced categorical and stretched data can be crossed, at a given period of time or following a time series. In the latter case, post-classification change detection maps may help the distinction of individual habitat patches following or resulting from different (anthropogenic or natural) dynamics. A simple example of post-classification change detection to refine the categorical mapping towards patch dynamics is the way to distinguish old fallow from woodland in Katanga. Using remotely sensed images of good classification precision but coarse thematic resolution, that distinguishes forest covers and herbaceous vegetation (grassland, savannah or crops) at different periods of time in the same area, it is possible to distinguish the forest patches that were previously herbaceous vegetation (old fallow) from the forest patches that were already forest before. In that case, the temporal resolution should be adapted to the phenomenon studied, here tree growth and slash and burn agriculture.

Infrastructure information can also help identify the type of disturbance encountered by a given habitat patch, distinguishing it from other patches from the same land cover. Other disturbance information, such as fire (extent, frequency *etc.*), can be directly acquired from satellite imagery. Sorting this information, a discontinuous hemeroby scaled map can be defined. Compared to classical hemeroby scales, this data contains additional location information. Various methods to cross stretched data with categorical maps can be applied. As a first example, during the classification process, training sets can be defined on several (categorical or stretched) layers at the same time, such as altitude gradient maps with multispectral satellite image of the same area. In that case, the classification will be performed according to the combination of attributes from the aforementioned data layers. As a second example, when the data are standardised, numeric combinations such as multiplication can be performed in order to combine them, such as multiplying one layer by the other, as performed by Rüdisser *et al.* (2012) or André et al. (in revision).

Along with stretched values representing other anthropogenic disturbances, a hemeroby map called “degree of naturalness” by Rüdisser, Tasser & Tappeiner (2012) can be designed. This map can represent continuous patch dynamics, being the product of specific patch dynamics information and stretched values. Other stretched data are added in order to include habitat connectivity into anthropogenic effect assessment: distance to the most natural habitats, according to the map of degree of naturalness. Crossing this information with the aforementioned map gives the final output: the anthropisation map (see André et al. (in revision)).

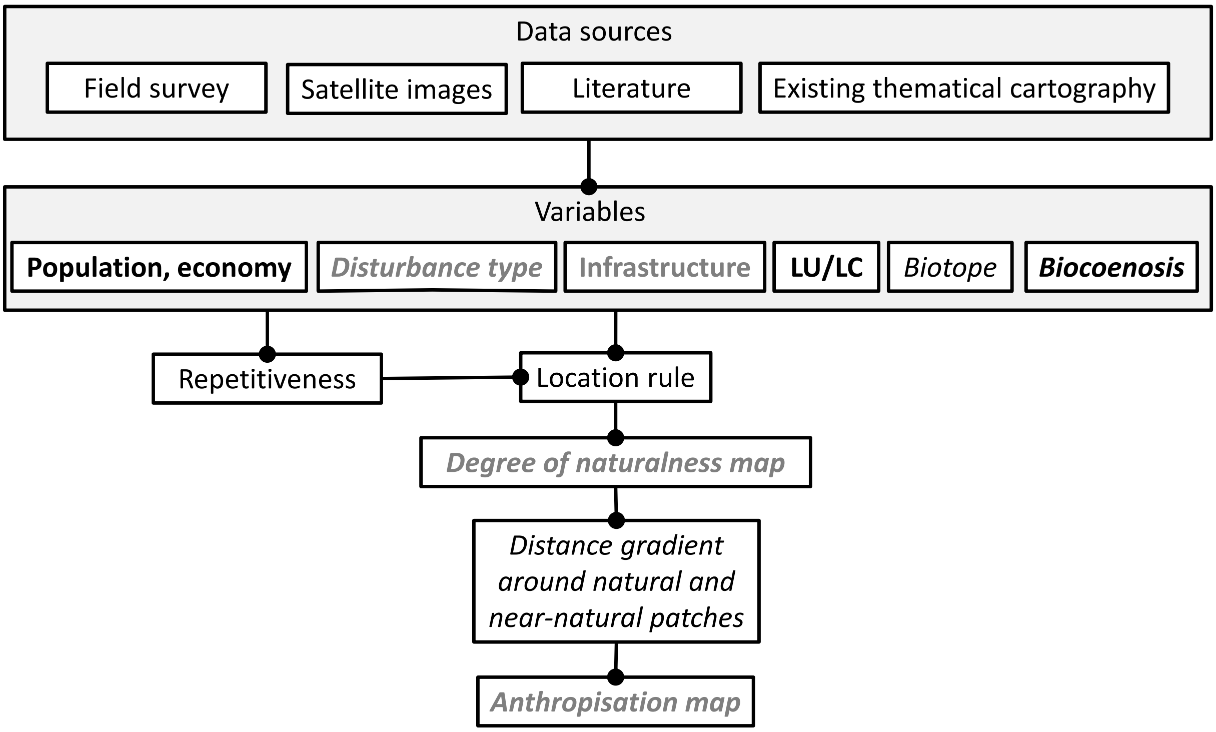

Fig. 4. Proposal for a new methodological framework to spatially quantify anthropisation. Bold characters represent categorical maps, italic characters represent stretched values, grey characters represent patch data. The latter correspond to patch dynamics data if measures are repeated across time. LU/LC: Landuse / Landcover

Conclusion

Anthropisation concepts and variables refer to system states, pressures and ecological impacts without distinction, while its quantification strongly depends on the reference states, which are practically complex to determine for specific sites. Anthropisation is quantified with direct, but partial measures, qualitative scales or composite indexes. Data are formatted as discrete categorical maps or continuous stretched values (gradients).

We propose a new reference state corresponding to the currently most ambitious restoration objective or the currently most preserved area: restored indigenous naturalness. We also suggest guidelines towards a new, action-oriented and composite methodology that distinguishes individual patch characteristics and dynamics while relying on easily accessed data. The key of this framework is to combine categorical mapping with stretched values and diachronic observation.

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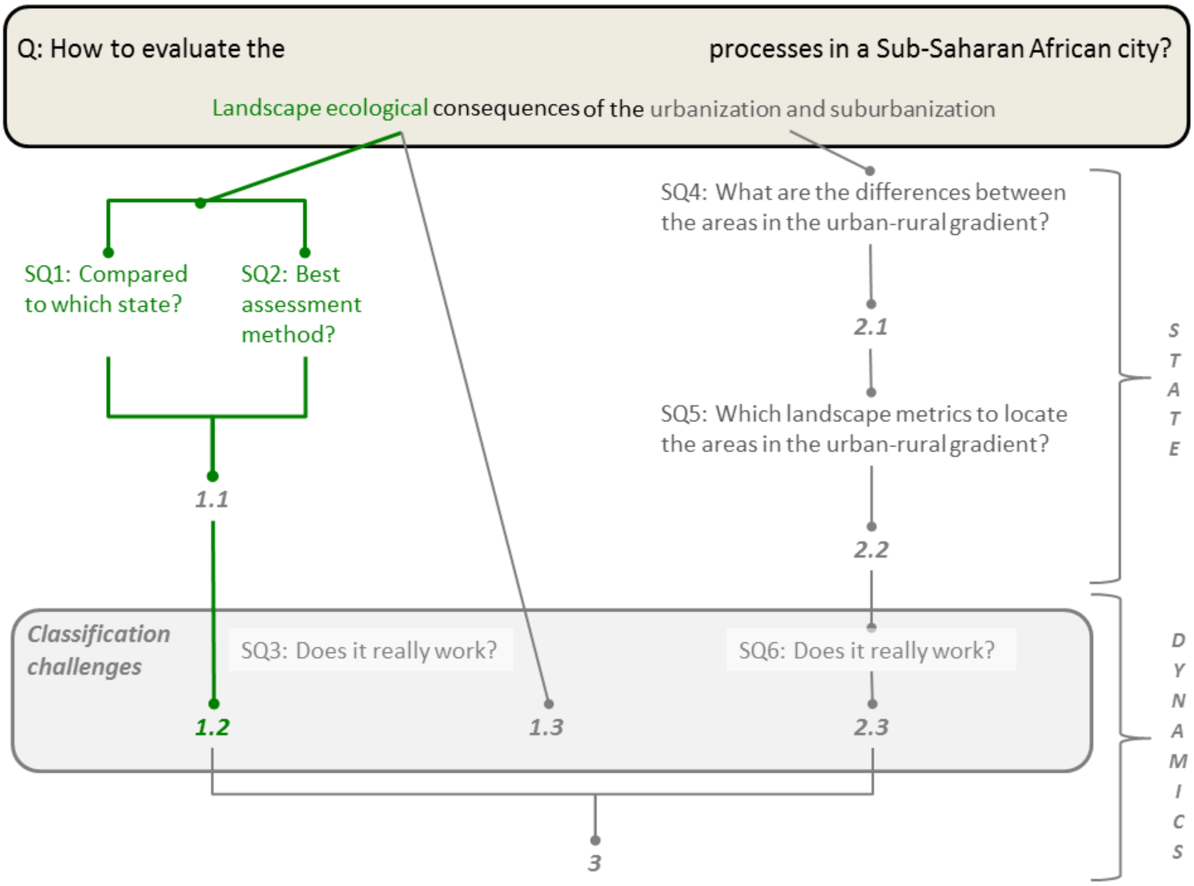
Publication 1.2

Quantification of anthropogenic effects in the landscape of Lubumbashi



Publication 1.2
Quantification of anthropogenic effects in the landscape of Lubumbashi

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Abstract. In order to understand the dynamics of the (sub)urbanization and so, 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 landscape surrounding the city of Lubumbashi (DRC) is evaluated. That methodology has the advantage of taking structural connectivity into account by computing the distance to natural habitats. As it had never been applied to an African city before, some adjustments (fitting of the local land uses types into the hemeroby levels designed for Austria) and amendments (no final hemeroby level simplification) are proposed. Moreover, an analysis of the decanal (2002-2013) hemeroby dynamics is presented. Results suggest that the Distance to Nature methodology is transferable but requires accurate field knowledge to define reference habitats and to identify them in the classified Landsat images. There was a dramatic decrease of the «natural» and «near-natural» levels in the study extent during the studied period. In addition, 32% of the land underwent anthropisation increase, mostly around cities and following a ribbon development.

Keywords. anthropogenic influence; hemeroby; land cover mapping; landscape; land cover change; tropical Africa

Résumé. 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 (RDC). 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 du sol locales avec les niveaux d'hémérobie mis au point en Autriche) et amendements (suppression de la simplification finale de la classification en niveaux d'hémérobie) 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.

Mots clés. influence anthropique; hémérobie; cartographie de l'occupation du sol; paysage; changement d'occupation du sol; Afrique tropicale

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Introduction

Human affects many Earth's ecosystems by converting/changing the original ecosystem functions to provide essential requirements (Vitousek *et al.*, 1997). Anthropisation is studied as for the impact of human activities on landscape composition, configuration and dynamics but remains difficult to quantify. As conservation biology and restoration ecology focus on ecosystem composition, the landscape ecology brings considerations about the spatial and temporal patterns to infer this impact on ecological processes (Turner, 1989, Young, 2000).

The region of Lubumbashi is representative for landscape anthropisation in Katanga: situated in the Katangese copper belt and well known for its copper and cobalt veins (Chapelier, 1957), this formerly rural zone developed for mining development (Narendrula *et al.*, 2012). Non-ferrous metal exploitation and processing have led to a strong industrialisation and therefore to the building of new towns, quarries and plants under Belgian colonialism since the beginning of the 20th century (Banza *et al.*, 2009, UMHK, 1956). Historically, the city consisted of a densely built-up zone provided infrastructures, today aged, and industrial areas in the suburbs (Bruneau *et al.*, 1990). However, the consequences of the economical attractiveness of mining industries, leading to a massive rural flight and a rapid population growth (1,200,000 inhabitants in 2006, near 2,020,000 estimated in 2015), are different anthropogenic effects, mostly reported as unplanned deforestation, urbanization and suburbanization patterns (Chapelier, 1957, Groupe Huit, 2009, Khonde *et al.*, 2006, Vranken *et al.*, 2013). Industrial infrastructure is now fully included into the urban fabric, and recent industries installed just outside the urban belt (Vranken *et al.*, 2014, Vranken *et al.*, 2013). The inhabitants of the city depend on food imports due to the heavy metal soil contamination and the absence of a tradition of farming (Khonde *et al.*, 2006, Vranken *et al.*, 2014).

In order to understand the dynamics of the (sub)urbanization and to quantify the anthropogenic effects of the rapid growth of tropical cities, particularly for developing countries, it is crucial to select valid methods. Human activities can be assessed in three ways. First, using simple index and proxies of anthropogenic activities like area of a certain land use type, road and population density.

Secondly, using a qualitative hemeroby scale, which will assess how much local naturalness has been disturbed or replaced, based on general criteria of disturbing processes and resulting land cover. Thirdly, anthropogenic effects on landscapes can also be represented by composite indicators of any of the aforementioned tools (Vranken *et al.*, submitted). Among the existing methods, the Rüdisser *et al.* (2012) «distance to nature» composite indicator and methodological framework (i.e., D_2N methodology), a recent method that has the advantage of taking structural connectivity into account by computing the distance to natural habitats, appears most suitable for a landscape ecological analysis in our study zone. As most approaches, it has been implemented in a temperate context. In this chapter, it will be applied for the first time to the context of an African city. The objectives of the study are therefore to assess the effect of local activities on landscape spatiotemporal structure in Lubumbashi and its hinterland as well as to evaluate the transferability of the method to a different context.

First, we describe the study zone and its main natural and human components. We go on summarizing the details of satellite image acquisition, treatment and classification we used to obtain a land cover map of the area. Then, we detail the adjustment we brought (calculation of the decadal anthropisation dynamics) to the D_2N method, its application and the meaning of its outputs. The results and discussion section highlights the anthropogenic and natural patterns for each of the two years (2002 and 2013), their decadal dynamics and comments the transferability of the method. Anthropisation (mostly (sub)urbanization and deforestation) is expected to increase within this period. Some recommendations for future application of the methodology in the same context are then detailed in the perspectives and conclusion section.

Material and methods

Study zone

Lubumbashi is the capital city of Katanga, a province in the Southern part of the Democratic Republic of the Congo (DRC). The study zone consists of a plateau that has been eroded into a wide valley by the Lubumbashi River and its tributaries (Chapelier, 1957). The altitudes of the inner-city, on the plateau, vary between 1200 and 1250 m (Sys, 1960). The local climate is characterised by a wet season (from November to April) and a dry season for the rest of the year and corresponds to the Cw Köppen category (Kottek *et al.*, 2006). Currently, the vegetation cover is continuous only during the wet season (Adam, 2010).

Islets of dry evergreen forest called *muhulu*, present in the area (Malaisse, 2010), could indicate that the actual climax was *muhulu* and that *miombo* (called woodland in this paper), the woodland forest strata that has dominated the area at least since the first observations during the colonial period, would be a disclimax resulting from former slash and burn agriculture (Noti et al., 1996; Schmitz, 1962; Sys, 1960; White, 1983). Diverse forms of savannah, from wooded savannah to grassland, as well as bare soils are now progressively replacing the woodland (Malaisse, 2010). Bare soils result mostly from mining activities and heavy metal eolian deposits (Mbenza *et al.*, 1989, Narendrula *et al.*, 2012). Near the smelters, debris are piled into tall and wide slag heaps. If forest, more or less degraded, still covers about 50 % of the area, derived savannahs and cultivated areas, generally resulting from forest clearance by the almost annual fire (Malaisse, 2010), represent now the second largest land cover in the area (about 30 %). These diverse savannah therefore result from anthropogenic degradation and do not present the same biophysical characteristics (including floristic composition) as natural savannahs (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 significant importance on the land use, that origin is corroborated by Malaisse (2010) and an existing correlation between fire starts frequency and proximity to the city and roads (R^2 = 0.78, personal data) as well as surrounding villages (R^2 = 0.77, personal data). Moreover, the absence of correlation between fire starts frequency and proximity to industrial sites (R^2 = 0.09, personal data) also suggests that those fires are mostly operated by villagers for agriculture and charcoal production, which is a regular practice in the area (Stromgaard, 1985, Vranken *et al.*, 2011). Besides great effects of leaching on soil structure and organic matter content, fire impacts as well edaphon through superficial depressive effect on soil fungi and animal populations (Malaisse *et al.*, 1975). Natural metallophyte herbaceous flora (“copperflora”) is also present in natural highly metalliferous soils (mainly copper and cobalt), generally found on hills among the forest («copper hills») (Leteinturier *et al.*, 1999, Malaisse *et al.*, 1994). Some species were also able to colonize the soils contaminated by metalliferous atmospheric deposits (Faucon *et al.*, 2011). Specific features called *dembos*, natural grasslands temporarily flooded in valleys around water streams, are frequent in the area (Sys *et al.*, 1959, White, 1983). Permanent wetlands are found as well round the riverbanks and depressions on impermeable ground, some of which are cultivated (Sys *et al.*, 1959). Nearly all the lakes are of anthropogenic origin: reservoirs built during the colonial period.

Choice of the analytical framework

Vranken *et al.* (submitted) expose, analyse and criticise in details the different concepts and quantifications related to anthropogenic effects assessment. According to this contribution, we will refer to anthropogenic effects assessment and associated terms using the term “anthropisation”, that represents human-driven landscape changes (Vranken *et al.*, submitted). Here, the D_2N methodology (Rüdisser et al., 2012) was chosen for several reasons: first, it is designed to be used at the landscape level; then, it combines stretched values (gradients, under continuous variation, see Gustafson (1998) and Vranken et al. (submitted)), patch and categorical analyses (Gustafson, 1998, Wiens *et al.*, 1993), while the resulting values exist in both continuous and discontinuous variations, combining the advantages of the two output types. Moreover, it takes processes (different types, intensities and frequencies of human pressures on ecosystems) into account and integrates the presence of secondary habitats. Structural connectivity between natural habitats, which is important to ecological processes, is also included through the «distance to natural habitat» (D_n) component of the index. It can be evaluated even when few other data than land cover are available. Finally, it has been conceived to facilitate the interpretation, comparison and communication of the results. We implemented some adaptations to the methodology according to Vranken *et al.* (submitted) and the specificities of our study zone and data availability.

Adaptation of the D_2N methodology to local landscape classes

Data acquisition

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

In order to obtain a minimal surface of burned areas (that were very abundant in our study zone), we applied a filter for the spectral signature of the burned areas on a set of Landsat calibrated images shot at different moments 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 then recomposed a multidate image for each year from the filtered original images before performing a multiresolution segmentation using all the 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 90m resolution (Trimble Documentation, 2013). The training sets for this classification were defined by 1) direct field surveys regularly conducted between January 2012 and April 2014, 2) the Modis MCD14ML « Active fire » products with a detection confidence of 100% and 3) the freeware licenced version of Google Earth© imagery (from 2002 and 2012) for the remote areas (Giglio, 2013). Both segmentation and classification operations were performed using the eCognition© software. After a first land cover based classification (13 classes), we refined the results to display more information on the land cover and specific patches. As it was not possible to distinguish which wetlands were cultivated according to their spectral signature, a proximity rule was used : wetland segments touching anthropogenic ones (burned areas, continuous and discontinuous built-up areas, crops, pastures, young fallow and slag heap) were assumed to be potentially cultivated at least sporadically and therefore considered as anthropised. These latest were called «anthropised wetlands» while the uncultivated ones were called «wetlands». As for the reservoirs, first identified as «water», another kind of proximity rule was used in order to isolate them: water segments sharing 70% or more of their edges with other water segments were assigned as «reservoirs», while the others were labeled «streams». This classification refinement is particularly relevant for the quantification of anthropogenic impact. The aforementioned method allowed to distinguish 14 land use/cover classes: «natural grasslands», «wetlands», «streams», «woodland», «wooded savannah and old fallow», «savannah and bushland», «savannah-crops mosaic», «reservoir», «crops, pastures, grasslands and young fallow», «anthropised wetlands», «recurrent burned areas», «slag heap», «discontinuous built-up and bare soil» and «continuous built-up». The Landsat classified images were then exported in raster format with 25m pixels, as in Rüdisser *et al.* (2012) for further treatment in ArcGIS©.

Data analysis

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

First we built hemeroby scales and maps, called « degree of naturalness » (N_d) by Rüdisser et al. (2012). We preferred using the term hemeroby here because, following Vranken *et al.* (submitted), hemeroby corresponds to a scale positively correlated with anthropisation, to the contrary to naturalness, and the purpose of Rüdisser *et al.* (2012) was an anthropisation-oriented index.

The land use types provided by Rüdisser *et al.* (2012) were only suitable for Austria and similar landscapes, but their qualitative hemeroby scale provided process information on type, intensity and impacts of human activities for each hemeroby level. Based on this description and specific site knowledge on local ecosystems and activities, we were able to fit the existing land use types of Lubumbashi into the D_2N-related hemeroby scale.

As a first step, we assigned one of the seven hemeroby levels to each land use or cover potential in our study extent. As a second step, we sorted each of the 15 classes from our classification into the seven hemeroby levels. The decision tree used by the analyst in the field to discriminate the land cover classes, based on Trochain (1957), Letouzey (1982) and Bellefontaine *et al.* (1997) is shown in

Appendix 1. As some ecosystems could not be distinguished and had to be grouped in an heterogeneous land cover class, the latter was allocated to the level of hemeroby corresponding to the dominant ecosystem (Table 1). Shallow soil woodland, dry evergreen forest, copper hills, wetlands and natural grasslands were assigned to the first level, «natural», but the classification identified only the latter two. The amount of anthropised grassland was so negligible that they were not discriminated from natural grassland. Deep soil woodland and Streams were assigned to level 2, «near-Natural» in both cases. Indeed, water streams are in most cases of natural origin but present eutrophication. Regenerating forest, wooded savannah and old fallow were put in the third level («semi-natural») because those vegetation types are most of the time not found in the area before human direct intervention (Parr *et al.*, 2014). The classification did not identify the first. The ecosystems 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 crops. Crops, along with anthropised wetlands and reservoirs were as well put in this level. As the savannahs in the area mostly correspond to early stages of ecological succession to fires, the recurrent burned areas that could not be eliminated were assigned level 5 too. We put one of the classes («savannah/crops mosaic») in between hemeroby levels 4 and 5 because the crops land use was assigned to level 5 while savannah was assigned to level 4. Level 6, «artificial with natural elements», corresponded to discontinuously built areas and bare soils. Finally, the seventh level, «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 along a scale from 0 to 1, following the D_2N methodology and built the N_d map.

Secondly, we built a map of distance to natural habitat (D_n): this corresponds to the Euclidean distance (in meters) from each pixel of the images to the nearest natural or near-natural habitat (levels 1 and 2). Following the D_2N methodology, distances superior to 1000 m were set to 1000 m. In order to increase the effect of the proximity of anthropogenic features, we took the square root of the resulting distances. Then, we normalized the results dividing all pixel values by the maximum distance obtained in order to obtain dimensionless values ranging from 0 to 1.

Thirdly, we multiplied the N_d maps by the D_n maps and normalized the result from 0 to 1 dividing by the maximum value obtained in order to maximize the variation range of the results and re-scale it in the same way than the other normalised indexes. This gave the D_2N maps. Rüdisser (2012)'s methodology also reclassifies the results in four levels, but in our case, the choice was made to keep the continuous variation in order to detect the finest nuances of anthropisation variation.

Anthropisation dynamics analysis

In addition to the D_2N methodology, we highlighted the dynamics of anthropogenic influence in Lubumbashi between 2002 and 2013 by subtracting 2002 to 2013 D_2N values, constructing a post-classification change detection map. That step aims at evaluating anthropisation changes during the period. We constructed a transition matrix to show how the natural and near natural classes changed during the 2002-2013 period.

Table 1. Rüdisser's hemeroby scale (2012) («Degree of naturalness») and its adaptation to the region of Lubumbashi (RDC). The four first columns are extracted from Rüdisser et al. (2012). The fifth column shows ecosystem correspondence to the seven hemeroby levels, while the two last columns (dashed lines) show the level of each land use and land cover classes of 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, Wetlands, Natural grassland, Copper hills	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, Streams
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, Pastures	4	Savannah and bushland
					4.5	Savannah / crops 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	Anthropised wetlands, Crops, Reservoirs, Anthropised grasslands	5	Anthropised wetlands; Crops, pastures, grassland and young fallow; Recurrent burned areas; Reservoirs
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 soil	6	Discontinuous built, Bare soil
7. Artificial	soil sealing over 30%	Artificial systems or structures	Continuous urban fabric, industrial or commercial units, road and rail networks	Continuous built, Slag heap	7	Continuous built, Slag heap

Results and discussion

Adaptation of the *D_2N* methodology to local landscape classes

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). This may be due to different factors: firstly, seasonal variation is strong in the area, especially concerning fire dynamics, and may have led to misclassifications (Congedo *et al.*, 2012). Secondly, bare soils have a very similar spectral signature to built-up areas (Congedo *et al.*, 2012). Thirdly, the very fast urban dynamics in the area may have lead to differences between the field surveys and image captures given the time elapsed between both. Fourthly, spatial structure in Africa is loose, compared to Northern countries: land cover patches are less clearly delimited (Vranken et al., 2013), probably due to differences in land planning practices. This may lead to confusion between adjacent land covers. Fifthly, due to the medium spatial resolution of the images, pixels may contain different ecosystems (this phenomenon is known as the "mixel" problem) but have to be attributed to a single class, therefore not representative of the entire pixel area (Pham *et al.*, 2011). Finally, ecosystems, as often responding to regressive or progressive processes, are seldom "pure" but often reflect transition states from one ecosystem to another. Analysts and the classification algorithms may settle the threshold between borderline land covers differently, leading to virtual misclassifications.

It should however be noted that the accuracy of the classifications is inversely proportional to the thematic resolution (number of land cover classes): if a lower number of classes had been put forward (for example 7), the Kappa would have risen (to 0.49 in this example, for the year 2013). Note that Congedo *et al.* (2012) obtained a Kappa value of 0.57 on a similar area using Landsat images, but their classification contained only 5 classes, against 13 in the current study. Here, we chose to privilege thematic resolution in order to obtain relevant classification for the elaboration of our 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 the misclassifications depend on: (1) the confusion between classes of distinct hemeroby levels, (2) the definition of the reference states (natural and near-natural levels) and other hemeroby levels, (3) 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 both hemeroby levels and distance to natural and near-natural levels, and given that the dynamics map depends on the two D_2N maps. In the case of this research, the most problematic misclassification is the erroneous classification of wooded savannah (level 3) as woodland (level 2) (see Appendix 2), which naturalises the landscape.

Data analysis

The application results of the D_2N methodology to Lubumbashi in 2002 (Figure 1a) and 2013 (Figure 1b) show the anthropisation levels in the area. The dark spots represent the highest levels and correspond to the urbanised zones in the area (4% of total area in 2002, 11% in 2013). The extent of this study area includes several urban zones, the largest of which is Lubumbashi (center-right), followed by Likasi, along the Tshangalele Reservoir, Northwest of Lubumbashi, Kipushi, the closest dark zone Southwest to the city and Kasumbalesa, at the extreme Southeast of the study area. The natural or near-natural landscape classes compose the matrix (about 60 % of the total extent, against 75% in 2002); its connectivity seems hampered by urban and cultivated areas.

Given that only the distance to natural or near-natural habitat have been considered for the calculation of the connectivity, the inclusion of the latter notion in the analysis naturalizes the representation of the landscape as it decreases the D_2N values of the urban and cultivated areas, making them benefit from the proximity of those areas. Therefore, the inclusion of the notion of connectivity in the analysis naturalises the representation of the landscape.

Dark spots, representing the highest levels, correspond to the main urbanised zones in the area, the largest of which is Lubumbashi (center-right), followed by Likasi, along the Tshangalele Reservoir, Northwest of Lubumbashi, Kipushi, the closest dark zone Southwest to the city.

To build their N_d map, Rüdisser et al. (2012) used a large amount of data (forest hemeroby, CORINE classification, roads, etc.), some of which were available as stretched values, but were integrated as a discontinuous and qualitative hemeroby scale, 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 cover may follow different anthropogenic dynamics. For example, one savannah area may result from a regressive series that can be linked with fire disturbance, while the other may result from a progressive series, i.e. ecological succession, linked with the end of previous disturbances. In the present study, such distinction between progressive and regressive series could not be achieved yet. This is partly due to coarse data spatial resolution and lack of classification precision (map categories include here different land covers, sometimes displaying different hemeroby levels).

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 Katanga, woodland 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 choicemade (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 pre-colonial human interventions on landscape structure as anthropogenic, distinct from nature (Lecomte *et al.*, 2005, Peterken, 1996, Vranken *et al.*, submitted).

The choice not to apply the four-level D_2N scale displayed in Rüdisser *et al.* (2012) is justified by two facts. First, continuous variations of the D_2N values appear more precise: simplifying them in only four levels, while there were seven levels in the original scale, represents information loss. Secondly, African spatial structure is continuous (Vranken *et al.*, 2013) and so appears best represented using continuous transitions between anthropisation levels. Attention should be given to the fact that the results, showing dominant natural or near-natural classes, are due to the very large extent of the study zone (23,400 km^2). It may give the wrong impression that the urbanization of Lubumbashi does not lead to much anthropisation in the area.

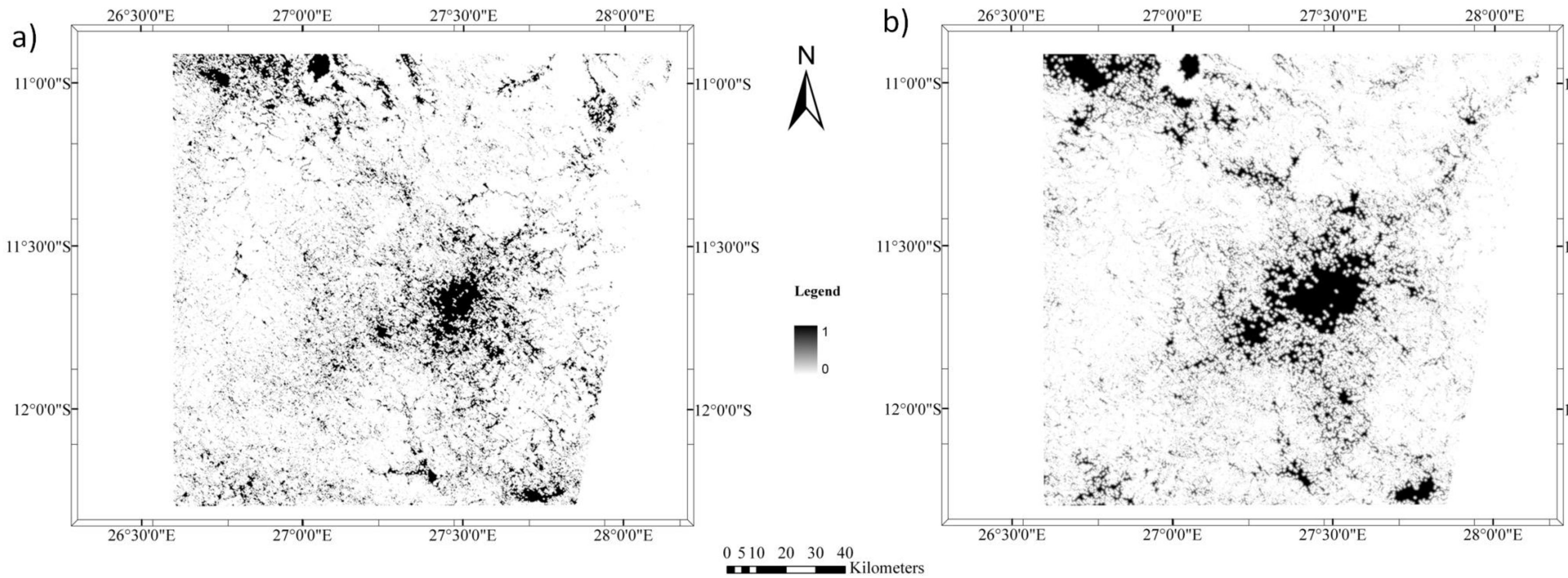

Figure 1. Application of the Rüdisser et al. (2012) «Distance to nature» methodology to the landscape of Lubumbashi (DRC) in 2002 (a) and 2013 (b). An index value of 0 means the lowest distance to nature; a value of 1 means the highest distance to nature.

Anthropisation 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 period, the studied area underwent an anthropisation increase principally concentrated around the cities and spreading as a ribbon development (Dumont *et al.*, 2006, Ewing, 1994). Thus, the suburban zones of Lubumbashi and Kipushi appear to have almost merged, while they were still separated in 2002. Furthermore, though natural and near-natural areas still dominate the area, they are now strongly fragmented.

The relative changes in anthropisation levels, quantified in Figure 2 (b), show that about 46% of the land underwent an anthropisation level change in 11 years. The moderate increases dominate the anthropisation dynamics (24.5 % of total extent increased by 0.3 or less in D_2N value). The zones encountering anthropisation increase cover 32 % of the total area, while the total anthropisation decrease only represents 15 %, which confirms an overall anthropisation increase.

The area change for each anthropisation level between 2002 and 2013 (Figure 2 (c)) shows that dominant dynamics are dramatic decrease (about 11 % of total extent) in the natural and near-natural level and substantial increase in intermediate levels of anthropisation, probably following the aforementioned anthropisation dynamics. The transition matrix shows that the natural and near-natural areas lost between 2002 and 2013 corresponds mostly to «woodland» converted to «anthropised wetlands» and to «woodland» and «natural grasslands» converted to «recurrent burned areas», «crops, pastures, grasslands and young fallow» and «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, misclassifications or set-aside (Groupe Huit, 2009). The observed ribbon development is similar to the urbanization patterns in U.S. and European cities (Brück, 2002, Ewing, 1994, Grosjean, 2010).

Perspectives and conclusion

This first attempt to apply an hemeroby based anthropogenic effect quantification to a region in tropical Africa appears promising. It should be applied on other southern cities in order to compare and assess the relevance of the results. It could also be confronted to other methodologies applied on the same area but the lack of information currently available at this scale is a limiting factor for such implementation. Even this case study still lacks relevant information specific to local data, dynamics and practices.

The functional part of connectivity must be taken into account when evaluating the configurational aspects of landscape anthropisation (Tischendorf *et al.*, 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 corridor-shaped patches (Turner, 1989). The methodology could be amended in order to take that functional factor into account and could even be species-oriented.

Concerning the distinction between progressive and regressive series, this should be more feasible using more data, with better spatial and temporal resolution or producing smaller objects by means of segmentation. This would also allow building the same post-classification change detection maps as in this contribution as well as N_d transition matrixes to study specific patch dynamics. Reliable thematic maps such as up-to-date road net, activities and infrastructure could also be added, as in Rüdisser et al (2012). In this case, specific attention should be given to weighing respective influences of each human activity or disturbance data, in order to avoid redundancy and biases.

Considering the methodology application, the mutual influences of anthropised and natural landscape, highlighted by the introduction of a distance gradient, open interesting perspectives for land planning, conservative management and restoration. Indeed, the consequence 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 help prioritize areas to protect and/or degraded ecosystems to restore. It should however be noted that this methodology does not distinguish the natural habitat richness or conservation interest linked to their specific composition, which is necessary to every conservative management and should be complementarily examined (Séleck et al., 2013).

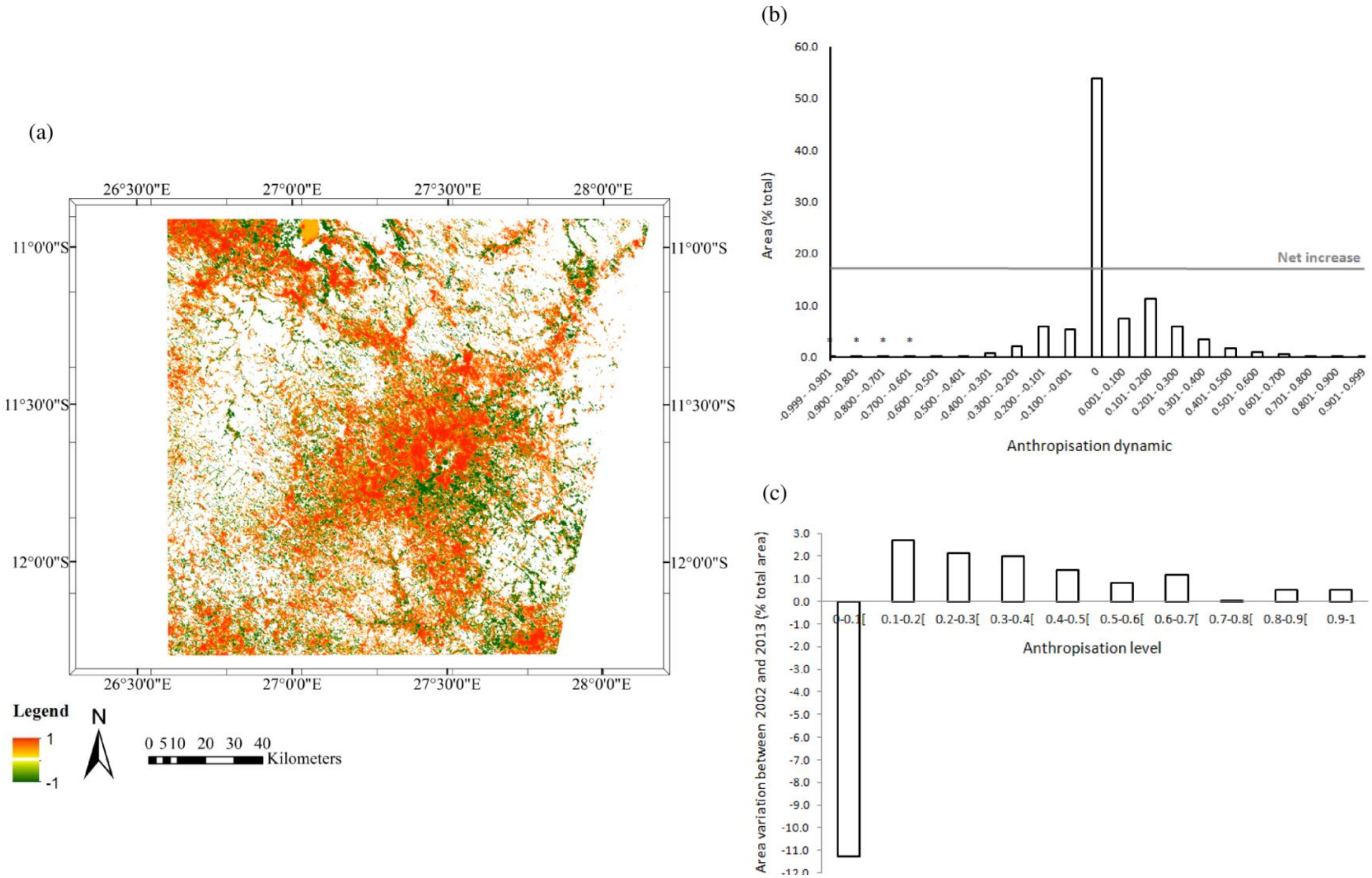

Figure 2. Dynamics of anthropisation levels (*D_2N*) between 2002 and 2013 in Lubumbashi (DRC). For (a) and (b), the numbers from -1 to 1 represent the number of anthropisation levels respectively lost or gained during this period; 0 represents no anthropisation level change. The map (a) shows the localisation of the dynamics, while the graph (b) shows 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 anthropisation (horizontal bar). The net increase is defined as the amount of area that encountered an increase in anthropisation minus the amount of area that encountered a decrease. The bar diagram (c) shows the percentage of the total area increase of each anthropisation level between 2002 and 2013, ranging from 0 (less anthropised level) to 1 (most anthropised level).

List of Abbreviations

D_2N: Distance to nature (index, map, methodology)

D_n: Distance to natural habitat

DRC: Democratic Republic of the Congo

N_d: Degree of naturalness

SRTM: shuttle radar topography mission

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Appendix

Appendix 1: Decision tree for the discrimination of land covers

The Figure 3 shows the decision tree used by the analyst in the field to deduce the land cover of the samples points. The analyst placed herself in 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 between 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 field, the sample point was assigned to “wetland”. Otherwise, the height of the herbaceous layer was evaluated (plants with a height inferior to 2m 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 8m). If it was null, then the shrub cover was considered (“shrub” are considered as plants with a height between 2 and 8m). If the shrub cover was null, 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 “crops”. 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 trees was also considered for the segregation. Indeed, when the trees with a height superior to 15m had a crown cover superior to 60%, then 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 Bellefontaine *et al.* (1997), Letouzey (1982), Ruelle *et al.* (n.d.), Trochain (1957). No sample points could be collected in the field for the following classes: natural grassland, streams, savannah/crop mosaic, recurrent burned areas, reservoirs and slag heap. These land cover classes were identified by means of Google Earth.

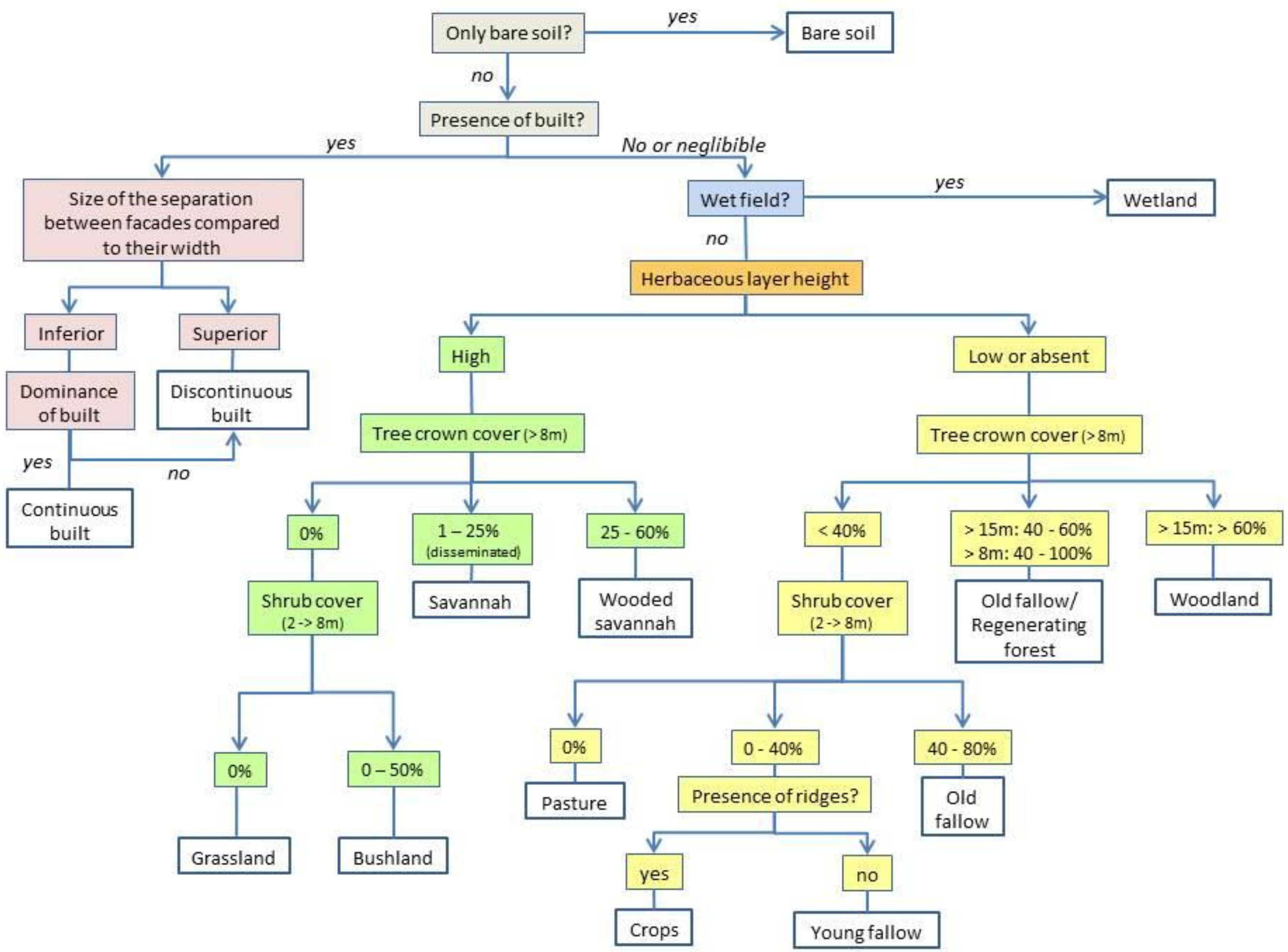


Figure 3. Decision tree used by the analyst on the field to deduce the land cover of the samples points.

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

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

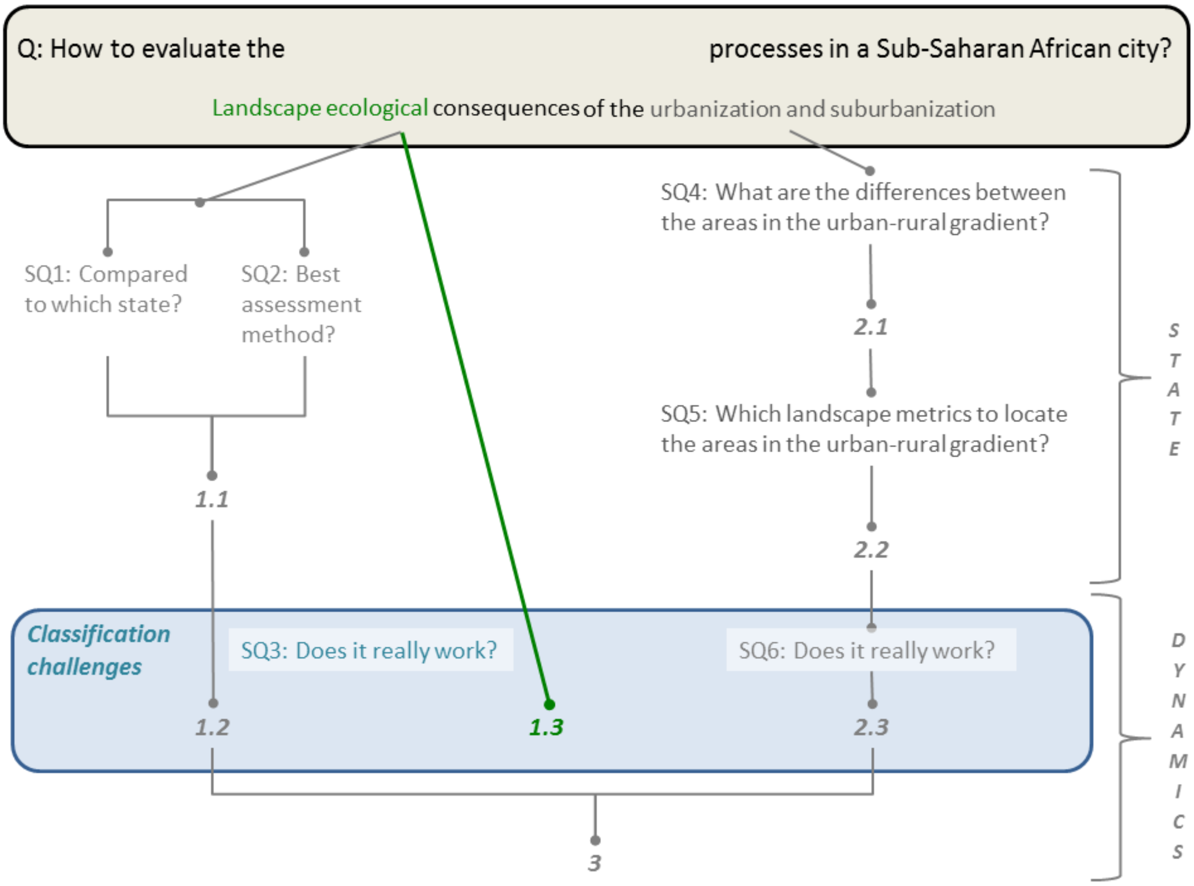
Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crops, pastures, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crops mosaic	Water	Wetland	Wooded savannah	
Continuous Built	7	1	0	12	0	0	7	0	1	0	25.0
Crops, pastures, 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/crops 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 image

Classified data	Reference data										User's accuracy (%)
	Continuous Built	Crops, pastures, grassland and young fallow	Natural grassland	Discontinuous built, bare soil	Woodland	Savannah, bushland	Savannah/ crops mosaic	Water	Wetland	Wooded savannah	
Continuous Built	15	2	0	9	0	0	0	2	1	0	51.7
Crops, pastures, 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/crops 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											

Publication 1.3

Interprétation paysagère du processus d'urbanisation à Lubumbashi (RD Congo): dynamique de la structure spatiale et suivi des indicateurs écologiques entre 2002 et 2008



Publication 1.3

Interprétation paysagère du processus d'urbanisation à Lubumbashi (RD Congo): dynamique de la structure spatiale et suivi des indicateurs écologiques entre 2002 et 2008

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Résumé. Lubumbashi est l'une des grandes villes d'Afrique subsaharienne, avec un taux annuel de croissance démographique d'environ 5 %. Cette croissance démographique entraine une expansion rapide du bâti associée à plusieurs problèmes environnementaux. La présente étude vérifie l'hypothèse selon laquelle l'expansion du bâti entraine une réduction d'habitats naturels et crée des conditions favorables à l'expansion des colonies de *Tithonia diversifolia,* une espèce exotique invasive.

A partir de deux images SPOT de 2002 et 2008, appuyée des missions de terrain, sept classes d'occupation du sol ont été obtenues et la fiabilité de la classification a été vérifiée. La dynamique paysagère a été mise en évidence à travers une matrice de transition, par le calcul d'indices de structure spatiale et l'identification des processus de transformation spatiale. Il ressort des résultats obtenus que le bâti couvrait 32 % du paysage en 2008 contre 22,6 % en 2002. Sa croissance, suivie de celle de *T. diversifolia* et de végétation anthropisée, s'opère au détriment des classes naturelles. L'effet de l'anthropisation s'est traduit par l'augmentation de l'indice de perturbation qui est ainsi passé de 1,9 à 3,3 en 6 ans, confirmant que dans la zone d'étude les classes naturelles sont supprimées parallèlement à l'agrégation et création des classes anthropiques. La région d'étude a subi des changements importants liés à la croissance urbaine, ce qui nécessite une mise en place des politiques efficientes d'aménagement et gestion urbaine pour inverser cette tendance.

Mots clés. Lubumbashi, structure spatiale, analyse diachronique, croissance urbaine, classes naturelles.

Abstract. Lubumbashi is one of the fastest growing African cities with annual population growth rates of 5 %. Its urban population growth leads to a rapid urban growth associated with several environmental problems. This study test hypothesis that rapid built-up growth is followed by natural habitats decrease and creates favorable conditions for the spread of *Tithonia diversifolia,* an invasive specie. From two SPOT satellite images from 2002 and 2008 supported by field visits, seven land cover classes were obtained and the accuracy of the classification was verified. Landscape dynamic has been demonstrated through a transition matrix, by calculating spatial pattern metrics and identification of spatial transformation processes. The results obtained show that built-up covering 32 % of the landscape in 2008 against 22.6 % of the landscape in 2002. Its growth, followed by *Tithonia diversifolia* and anthropogenic vegetation, operates to the detriment of natural classes. The effect of human impact was translated by the increase of disturbance index which increased from 1.9 to 3.3 in six years, confirming that in the study area, natural classes are removed parallel to aggregation and creating of anthropogenic classes. The study area has undergone significant changes related to urban growth, which implies establishing efficient urban planning and management policies to reverse this trend.

Keywords. Lubumbashi, spatial pattern, diachronic analysis, urban growth, natural classes

Introduction

La population urbaine mondiale est passée de 14 % en 1900 à 54 % en 2014 (United Nations, Departement of Economic and Social Affairs, Population Division, 2014) et selon les projections, ce taux devrait être de 70 % en 2050 (Marzluff et *al.,* 2008). Le processus d'urbanisation, considéré lent dans les pays développés (Turan et *al.,* 2010), est cependant au cœur d'actualités dans les pays en développement (Vermeiren et *al.,* 2012). Par la croissance des surfaces bâties, l'urbanisation exerce une pression importante sur les écosystèmes et ressources naturels (Alberti, 2005). Ce problème se pose avec acuité car les zones urbaines qui n'occupent que près de 6 millions de km² de la surface terrestre, sont attendues d'augmenter de plus de 1 million de km² d'ici 2030 (Tian et *al.,* 2005).

En Afrique subsaharienne, on assiste à une croissance importante des villes consécutive à une démographie galopante (Kayembe et *al.,* 2009 ; Vermeiren et *al.*, 2012) ; ce qui ne va pas sans poser des questions d'ordre environnemental. En effet, consécutivement à l'expansion rapide des villes, il surgit dans cette région, sans contrôle ni assistance technique aucune, des zones d'habitats informels (Augustjin-Beckers et *al.*, 2011) où la pauvreté des citoyens conduit à des pratiques très dégradantes des écosystèmes naturels (UN-Habitat, 2010). A titre d'exemple, en Afrique du Sud, McConnachie & Shackleton (2010) ont montré que les banlieues relativement pauvres se caractérisent par 14 fois moins de couvert végétal que les quartiers où le niveau de vie est plus élevé.

En Afrique subsaharienne, le changement d'utilisation du sol entraine donc une dynamique de la structure spatiale des paysages matérialisée par la suppression de la couverture végétale et son remplacement par d'autres catégories d'occupation du sol (Bogaert et *al.*, 2008). En effet, comparativement aux pays européens, les travaux de Kestermont et *al.* (2011) ont montré que les pays africains exercent une pression proportionnellement plus forte sur le changement d'utilisation du sol. Par ailleurs, les perturbations des écosystèmes créent des conditions favorables à l'expansion des espèces invasives (McKinney, 2006), à l'instar du tournesol mexicain (*Tithonia diversifolia* Hemsley, A. Gray) reporté comme espèce exotique invasive (Tiébré et *al.,* 2012). Pourtant, Vermeulen et *al.* (2011) s'accordent à dire que les éléments et formations végétales présents dans les zones périphériques des villes vont devenir très importants pour le développement durable dans un avenir proche.

Comme dans d'autres villes d'Afrique subsaharienne, Lubumbashi enregistre une croissance démographique rapide (UN-Habitat, 2014). De 1984 à 2009, sa population a triplé passant de 600 000 (Nkuku & Rémon, 2006) à 1 500 000 habitants alors que sa surface bâtie a quintuplé dans la même période, passant de 37 km² à 170 km² (Munyemba & Bogaert, 2014). Dans cette ville, le rythme et les formes actuelles de l'urbanisation entrainent des difficultés et dysfonctionnements dans la planification de l'occupation du sol (Mulongo et *al.,* 2014).

La maitrise des changements spatiaux rapides induits par l'urbanisation est cruciale afin d'éclairer les conséquences écologiques et de minimiser les impacts d'une urbanisation sauvage (Ramachandra et *al.,* 2013). Pour cette raison, cette étude a pour objectif de caractériser le processus d'urbanisation à Lubumbashi à partir de la télédétection couplée aux méthodes de l'écologie du paysage. Nous vérifions l'hypothèse selon laquelle la croissance urbaine entraine une réduction d'habitats naturels et crée des conditions favorables à l'expansion des colonies d'espèces invasives.

Milieu, matériel et méthodes

Milieu d'étude: la ville de Lubumbashi et sa zone périphérique

La ville de Lubumbashi, née de la mise en valeur des gisements cuprifères (Chapelier, 1957), est située au sud-est de la République Démocratique du Congo (11°39' Sud et 27°28' Est) et est le chef-lieu de la province du Haut-Katanga. La ville est composée de 43 quartiers répartis dans les communes Lubumbashi, Kenya, Kampemba, Katuba, Kamalondo, Ruashi et Annexe. Le climat est du type CW_6 selon le système de classification de Köppen, caractérisé par une saison de pluie (de novembre à mars) et une saison sèche (mai à septembre) ; avril et octobre constituent les mois de transition. Les précipitations annuelles s'élèvent à 1270 mm et la température moyenne annuelle est d'environ 20°C (Leblanc & Malaisse, 1978). La végétation primaire de la ville de Lubumbashi est la forêt claire du type *Miombo* (Malaisse, 1997), actuellement soumise à une forte anthropisation à proximité de la ville (Munyemba & Bogaert, 2014). La couverture pédologique est du type ferralitique avec un pH eau oscillant autour de 5,2 (Kasongo et *al.,* 2013). La ville est sur une surface d'aplanissement, accidentée par quelques collines d'orientation nord-ouest sud-est et de faible dénivellation (Leblanc & Malaisse, 1978). Le site urbain et périurbain de Lubumbashi se trouve entre 1200 et 1300 m d'altitude.

Matériel et méthodes

Données

La zone d'étude de 1030 km^2, couvrant la ville de Lubumbashi et son hinterland, a été isolée sur deux images satellitaires SPOT du 16/07/2002 et du 18/06/2008 (résolution spatiale : 10m) (Images Spot © CNES (2012), distribution Spot Image S.A). Un GPS a servi pour la reconnaissance des classes d'occupation du sol durant les travaux de terrain. Les logiciels SAGA GIS 2.1.2. et Arcview GIS 3.3 ont été utilisés pour le traitement de données.

Classification des occupations du sol et évaluation de la précision de classification

Une classification supervisée, validée après vérification des classes d'occupation du sol sur le terrain, a été effectuée par l'algorithme de maximum de vraisemblance (Mama et *al.,* 2013). Des enquêtes de terrain, des entretiens, les connaissances locales et l'expérience de la zone d'étude ont été utilisés comme données de référence dans le choix des zones d'entrainement.

Le choix des classes d'occupation du sol est important parce qu'il influence sur les résultats et les interprétations ultérieures (Zhou & Wang, 2011). Pour ce faire, compte tenu de la résolution spatiale des images acquises et de l'objectif de l'étude, les occupations du sol ont été classées en bâti, sol nu, végétation anthropisée (champs, savanes herbeuses, gazon, jeunes jachères), *Tithonia diversifolia* (les colonies de tournesol mexicain), forêt (forêt claire, dense et galerie, savanes boisées, vieille jachère), marécage et eau. Les classes bâti, *T. diversifolia* et végétation anthropisée constituent les classes « anthropiques » alors que les classes forêt et marécage constituent les classes « naturelles ». L'indice de Kappa ($\widehat{K}$) a été appliqué pour vérifier la fiabilité de la classification (Skupinski et *al.,* 2009).

Mise en évidence de la dynamique de composition et de la structure spatiale

Pour réduire l'effet « sel et poivre » observé, un filtre majoritaire à l'aide d'une fenêtre de 3 * 3 pixels a été appliqué comme technique de lissage (Armenteras et *al.,* 2013). En effet, O'Neill et *al.* (1996) recommandent une taille minimale de tache de 2 à 5 fois plus grande que la résolution des pixels. Les deux images ainsi apprêtées et comparables ont été utilisées pour la mise en évidence des changements entre 2002 et 2008.

Afin d'étudier les rapports entre la structure spatiale du paysage et les processus écologiques en termes quantifiables (Bogaert & Mahamane, 2005), des indices de structure spatiale ont été calculés, à savoir : l'aire maximale (a_{max}), l'aire moyenne ($\overline{a}$), l'aire médiane (a_m), l'aire totale (a_t), un indice de dominance (D) dérivé du Largest Patch Index de McGarigal et al. (2002), défini comme le rapport de l'aire de la plus grande tache de la classe d'occupation du sol par l'aire totale de la même classe, le périmètre total (*p*), le nombre de taches par classe d'occupation du sol (*n*) et l'indice de perturbation (*U*) défini comme le rapport de l'aire cumulative des classes anthropiques dans le paysage et de l'aire cumulative des classes naturelles (O'Neill et *al.,* 1988).

Par ailleurs, l'arbre de décision de Bogaert et *al.* (2004), basé sur les éléments principaux de la configuration du paysage que sont le nombre de taches, l'aire totale et le périmètre total (Bogaert &

Mahamane, 2005), a été appliqué pour identifier les processus de transformation spatiale des classes naturelles et anthropiques (Barima et *al.,* 2009).

Enfin, une matrice de transition a été créée pour identifier les fréquences de transition entre classes au cours de l'intervalle de temps étudié. Cette matrice, obtenue par superposition des cartes d'occupation du sol, indique (i) la proportion de l'occupation du sol en 2002 (lignes) qui a changé en une autre catégorie d'occupation du sol en 2008 (colonnes) et (ii) la stabilité éventuelle des classes sur la diagonale.

Résultats

Cartographie de l'occupation du sol à Lubumbashi de 2002 à 2008

La classification des images SPOT a permis d'obtenir deux cartes montrant l'évolution des classes anthropiques et naturelles entre 2002 et 2008 (Figure 1). Les résultats de l'analyse de la performance de la classification donnent pour chacune des images classifiées les précisions globales de 87,3 % et 86,9 % et les $\widehat{K}$ de 75,3 % et 74,1 % respectivement pour les deux périodes de l'étude (Tableaux 1 et 2). Les classes forêt et eau (*Pr* = 100 %) sont celles qui n'ont pas été affecté par les échantillons des autres classes. Par contre, la classe « sol nu » semble avoir été plus souvent confondue à d'autres classes. L'analyse visuelle des cartes montre une diminution de la couverture des classes naturelles en 2008 au détriment des classes anthropiques, par rapport à la situation de 2002. Dans la suite de l'analyse, les classes « eau » et « sol nu » ne seront pas considérées étant donné leur faible proportion dans le paysage (< 5 %).

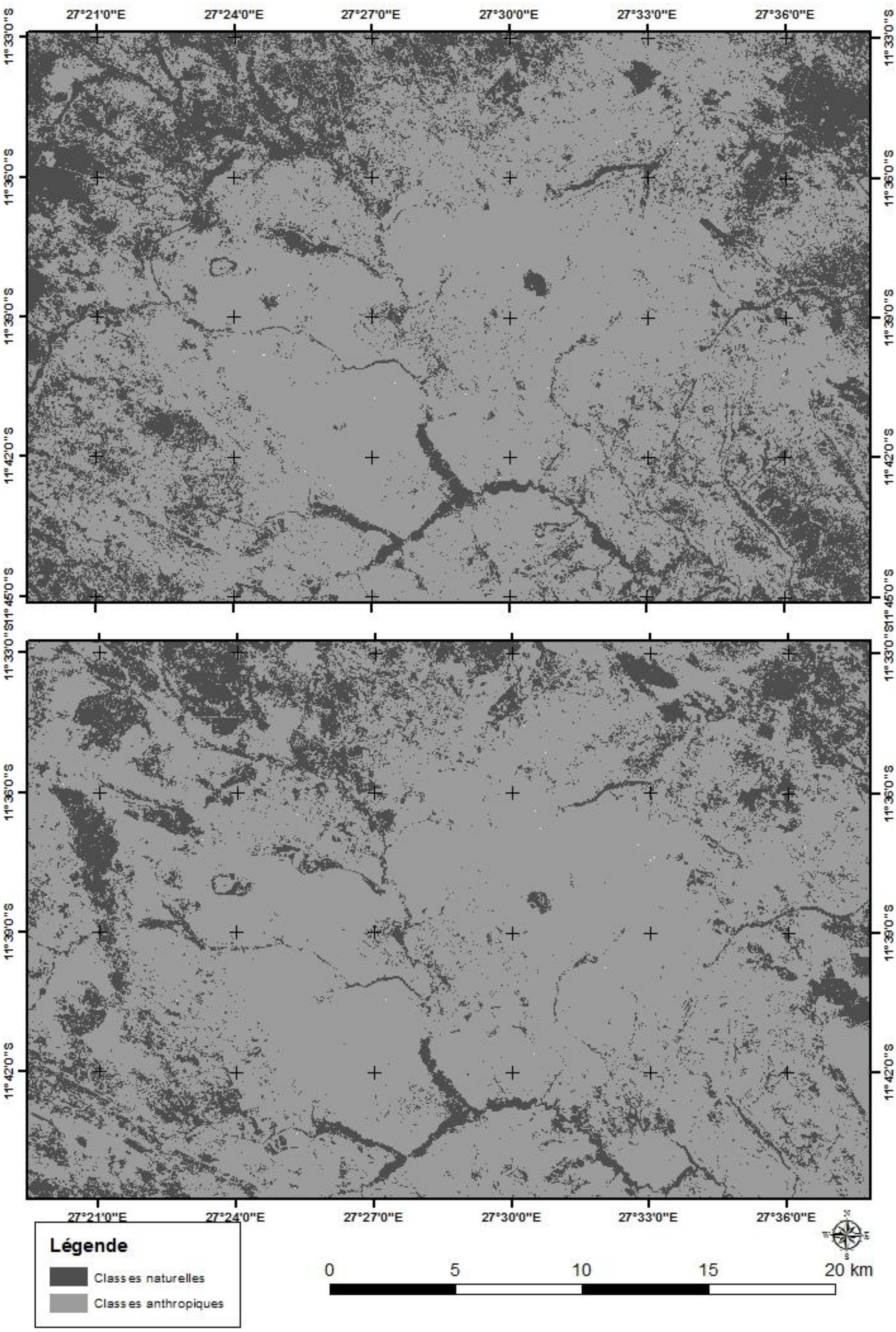

Figure 1. Evolution des classes naturelles et anthropiques (illustration de l'indice de perturbation, U) dans le paysage urbain de Lubumbashi de 2002 (en haut) à 2008 (en bas).

Tableau 1. Matrice de confusion de la classification de l'image SPOT de 2002. Tit : Tithonia diversifolia ; Va : végétation anthropisée ; Mar : marécage ; Pu : la précision de l'utilisateur ; Pr : la précision du réalisateur.

Nombre d'échantillons	**Données classifiées**								
Données de références	**Bâtis**	**Sol nu**	**Tit**	**Va**	**Mar**	**Forêt**	**Eau**	**Total**	**Pr (%)**
Bâtis	14	6	0	0	0	0	0	20	70
Sol nu	6	12	9	0	0	0	0	27	44,4
Tit	0	0	210	2	0	0	0	212	99
Va	0	0	11	10	4	0	0	25	41,6
Mar	0	0	0	3	11	0	0	14	78,6
Forêt	0	0	0	0	0	15	0	15	100
Eau	0	0	0	0	0	0	10	10	100
Total	20	18	230	15	15	15	10	**323**	
Pu (%)	70	66,7	91,3	66,7	73,3	100	100	**Précision globale=87,3%** $\widehat{\boldsymbol{K}} = \mathbf{75,3}\ \%$	

Tableau 2. Matrice de confusion de la classification de l'image SPOT de 2008. Tit : Tithonia diversifolia ; Va : végétation anthropisée ; Mar : marécage ; Pu : la précision de l'utilisateur ; Pr : la précision du réalisateur.

Nombre d'échantillons	**Données classifiées**								
Données de références	**Bâtis**	**Sol nu**	**Tit**	**Va**	**Mar**	**Forêt**	**Eau**	**Total**	**Pr (%)**
Bâtis	15	3	0	0	2	0	0	20	70
Sol nu	5	11	15	0	0	0	0	31	44,4
Tit	0	4	210	3	1	0	0	218	99
Va	0	0	5	11	3	0	0	19	41,6
Mar	0	0	0	1	9	0	0	10	78,6
Forêt	0	0	0	0	0	15	0	15	100
Eau	0	0	0	0	0	0	10	10	100
Total	20	18	230	15	15	15	10	**323**	
Pu (%)	70	66,7	91,3	66,7	73,3	100	100	**Précision globale=86,9%** $\widehat{\boldsymbol{K}} = \mathbf{74,1}\ \%$	

Dynamique de composition

Le paysage est resté dominé par la végétation anthropisée, avec des couvertures respectives de 43107 et 44308 ha en 2002 et 2008. Cette dernière a constitué la classe la plus stable, avec 34094 ha. Entre ces deux périodes, les transformations les plus importantes ont été la croissance des aires totales des classes anthropiques et la réduction de celles des classes naturelles (tableau 3). Entre 2002 et 2008, 2308 ha de forêt ont évolué vers le bâti, 8609 ha en végétation anthropisée et 682 ha ont été colonisés par *T. diversifolia*. Par ailleurs, 2093 ha de marécages ont évolué vers le bâti et 288 ha en végétation anthropisée. Pendant ce temps, la croissance de *T. diversifolia* s'opère dans la zone bâtie et au détriment de la forêt, des marécages et de la végétation anthropisée. En somme, on observe quatre grands processus qui se sont déroulés dans le paysage en 6 ans. Premièrement la stabilité relative de la végétation anthropisée. Deuxièmement la dégradation des écosystèmes naturels, traduite par la réduction de l'aire totale des forêts et marécages. Troisièmement, l'expansion légère de *T. diversifolia* et enfin l'expansion du bâti considérée comme le phénomène le plus dominant.

Tableau 3. Matrice de transition illustrant, en ha la surface des classes, la transformation de leur aire entre 2002 (rangées) et 2008 (colonnes). Les valeurs des classes « sols nus » et « eau » ne sont pas présentées et par conséquent la somme des valeurs des li lignes et colonnes ne correspond pas aux aires totales de classes sur les deux périodes d'étude.

	Bâti	Végétation anthropisée	T. diversifolia	Forêt	Marécage	Total 2002
Bâti	21206	1035	390	356	315	23331
Végétation anthropisée	1624	34094	233	1594	693	43107
T. diversifolia	902	164	206	20	3	1385
Forêt	2308	8609	682	17302	309	29807
Marécage	2093	288	0	712	2575	5076
Total 2008	**33122**	**44308**	**1513**	**19996**	**3721**	

Evolution de la configuration du paysage lushois de 2002 à 2008

Les grandes taches de forêts et de *T. diversifolia* ont été morcelées entre 2002 et 2008, ce qui se traduit par la diminution de leur valeur de *D.* Pour le bâti, la valeur de *D* est passée de 50 % en 2002 à 70 % en 2008, traduisant une augmentation relative de la taille des grandes taches dans le paysage. La végétation anthropisée et le marécage ont connu une stabilité de la dominance de leurs grandes taches. A côté de la dominance, la tendance à l'anthropisation du paysage est confirmée également par la diminution des aires maximales des taches des classes naturelles et une nette progression des grandes taches des classes anthropiques; sauf pour *T. diversifolia* (tableau 4). L'aire médiane augmente pour le bâti et pourrait par conséquent traduire une fusion de petites taches en 2008. En revanche, les classes « forêt » et « *T.diversifolia* » enregistrent une diminution de l'aire médiane contre une stabilité pour les marécages. Enfin, le tableau révèle que l'aire moyenne diminue pour toutes les classes, sauf pour le bâti dont l'aire moyenne a quasiment doublé en 6 ans (tableau 4).

Tableau 4. Evolution, en ha, de l'aire moyenne, maximale et médiane de taches de différentes classes d'occupation du sol entre 2002 et 2008.

Classes d'occupation du sol	$\overline{a}$		a_{max}		a_m	
	2002	**2008**	**2002**	**2008**	**2002**	**2008**
Bâti	1,34	2,24	10984,0	23803,5	0,2	0,3
Végétation anthropisée	1,45	1,08	10631,7	11708,7	0,2	0,2
T. diversifolia	0,05	0,04	8,2	2,2	0,4	0,1
Forêt	0,70	0,54	6887,9	1928,1	0,2	0,1
Marécages	0,31	0,23	178,2	141,6	0,1	0,1

Les classes anthropiques enregistrent l'agrégation et la création comme processus de transformation spatiale, justifiée par l'augmentation de l'aire totale suivie d'une diminution ou augmentation du nombre de taches. En revanche, pour les classes naturelles, on note une diminution du nombre de taches et de l'aire totale en 2008 par rapport à 2002. Le processus de transformation spatiale observé pendant cette période est la suppression (tableau 5), traduisant ainsi l'importance du phénomène de dégradation du milieu et donc de l'anthropisation des classes naturelles. Cette tendance à l'anthropisation du paysage est confirmée par l'évolution de l'indice de perturbation *(U)* qui est passé de 1,9 à 3,3 en 6 ans, montrant que les taches des classes naturelles sont davantage remplacées par les classes anthropiques dans le paysage.

Tableau 5. Indices de configuration des classes d'occupation du sol en 2002 et 2008 dans le paysage urbain de Lubumbashi. ***PTS :*** **Processus de transformation spatiale ; A : Agrégation ; C : Création ; S : Suppression. Les valeurs de l'indice de dominance sont en %.**

Classes d'occupation du sol	*n*		*p (km)*		*D (%)*		*PTS*
	2002	2008	2002	2008	2002	2008	
Bâti	17735	15031	15221,6	11468,5	50	70	A
Végétation anthropisée	29631	27057	21133,1	12553,1	30	30	A
T. diversifolia	27760	35623	2608,1	2408,7	1	0	C
Forêt	43622	39077	14707,9	9340,4	20	9	S
Marécages	15068	13683	8475,1	4007,3	4	4	S

Discussion

Approche méthodologique

L'urbanisation est un processus d'extension spatiale des zones urbaines par la transformation des utilisations du sol rurales en utilisations du sol urbaines, ce qui entraine le changement de structure spatiale et des processus écologiques des paysages (Antrop, 2001). L'évaluation des propriétés des paysages découle de l'hypothèse centrale de l'écologie du paysage, le *pattern/process paradigm,* selon lequel les processus paysagers et écologiques dépendent des patrons spatiaux et vice versa (Bogaert et *al*., 2004 ; Bogaert & André, 2013). Pour vérifier cette hypothèse centrale à Lubumbashi, l'impact de l'urbanisation sur les écosystèmes naturels a été évalué à partir des images SPOT à moyenne résolution spatiale.

La classification supervisée des images SPOT a donné des valeurs de précision acceptables selon l'échelle donnée antérieurement par Skupinski et *al.* (2009). En effet, dans une étude de l'occupation des sols, lorsque l'indice de Kappa évalué dans les opérations de classification est supérieur à 61 %, la classification adoptée est considérée recevable et les résultats peuvent être judicieusement utilisés (Jessen et *al.,* 1994). La qualité de la classification peut s'expliquer par le regroupement des formations végétales anthropisées en une seule classe et la saison d'acquisition des images satellitaires (Barima et *al.,* 2010 ; Mama et *al.,* 2013). Toutefois, certaines taches de sols nus ont été confondus à du bâti lors de l'évaluation de la classification, sans affecter significativement la fiabilité de la classification. Cette source de biais de classification a déjà été signalée par Vermeiren et *al.* (2012) dans l'étude sur la simulation de la croissance urbaine à Kampala.

La conversion des paysages naturels sous l'influence de l'urbanisation entraîne des changements irréversibles dans la configuration spatiale des paysages (Breuste et *al.,* 2008), dont la quantification nécessite l'utilisation des indices de structure spatiale (Herold et *al.,* 2003). Le choix des indices a porté sur le nombre des taches, l'aire (des taches et des classes) et le périmètre. Ces indices sont considérés comme les éléments essentiels de la configuration du paysage (Bogaert & Mahamane, 2005). En outre, l'indice de perturbation (O'Neill et *al.,* 1988) a été appliqué en vue de quantifier la dégradation des écosystèmes naturels.

Les transformations spatiales des classes naturelles et anthropiques ont été mises en évidence à travers l'arbre de décision de Bogaert et *al.* (2004). Cette méthode de détermination des processus de transformation structurale du paysage présente de nombreux avantages tels que la simplicité et la rapidité d'exécution (Bogaert et *al.*, 2004 ; Barima et *al.,* 2009). Par ailleurs, Zhou & Wang (2011) suggère en plus l'utilisation des matrices de transition pour quantifier la dégradation des écosystèmes sous l'influence de l'urbanisation. Ainsi, la matrice de transition a permis de réaliser le potentiel de monitoring de l'urbanisation à travers la dynamique spatio-temporelle d'une espèce invasive et des classes naturelles.

Urbanisation et dynamique de composition et de configuration spatiale du paysage lushois

Les résultats de la dynamique de composition montrent que la croissance des classes anthropiques se fait au détriment des classes naturelles. Le constat le plus remarquable dans l'évolution de l'occupation du sol est l'évolution grandissante du bâti qui s'accompagne d'une suppression d'habitats naturels. En effet, avec un taux annuel de croissance urbaine de 7 %, les résultats suggèrent que la ville croit plus rapidement que la population (5 % par an entre 2010-2015) (UN-Habitat, 2014). Comparées à d'autres villes en Afrique subsaharienne, le taux annuel de croissance urbaine était de 4 % entre 1995 et 2005 à Kinshasa (Kayembe et *al.,* 2009), 6,5 % à Harare entre 1984 et 2013 (Kamusoko et *al.,* 2013) et 21,1 % à Kampala entre 1989 et 2010 (Vermeiren et *al.,* 2012). Cela confirme la croissance urbaine relativement rapide observée en Afrique subsaharienne par UN-Habitat (2014). Toutefois, cette croissance des vastes surfaces urbaines discontinues et à faible densité de population dans les zones rurales autour des villes (Briggs & Mwamfupe, 2001), conduit au phénomène de dédensification des villes tel qu'observé par Angel et *al.* (2011) dans la plupart des villes du monde.

Nos résultats montrent une conversion de formations naturelles en espace bâti. Cette situation a été reportée antérieurement à Lubumbashi (Frauman, 2004 ; Munyemba & Bogaert, 2014) et des observations similaires ont été faites dans d'autres villes (Bamba et *al.,* 2010 ; Diallo & Bao, 2010 ; Ouedraogo et *al.,* 2010). En effet, la forêt a régressé de 33 % en 6 ans, soit une moyenne annuelle de 5,5 % supérieur au taux de régression annuel de 1,4 % rapporté par Munyemba & Bogaert (2014) entre 1956 et 2009. Cette différence de taux de régression des forêts se justifie par la différence d'étendue entre notre étude et celle de Munyemba & Bogaert (2014), montrant ainsi l'importance de l'échelle spatiale en écologie du paysage (Bogaert & Mahamane, 2005). En effet, notre milieu d'étude renferme moins de zones rurales et par conséquent l'impact de l'urbanisation sur les écosystèmes des zones périphériques est plus significatif.

Outre le couvert forestier, nos résultats montrent également une régression des marécages à un taux annuel de 4,5 %. Les corridors marécageux régressent au profit du bâti et sont envahis en même temps par les colonies de *T. diversifolia.* Ces résultats confirment d'une part les conclusions de Adeoye (2012) qui indiquent une progression du bâti sur les espaces marécageux au Nigeria et de l'autre celles de Bigirimana (2012) qui signalent la présence des espèces invasives dans les marécages de Bujumbura (Burundi).

La méthode de détermination des processus de transformation structurale du paysage par l'arbre de décision de Bogaert et *al.* (2004) a révélé que la forêt et les marécages subissent la suppression en faveur de la création et agrégation des classes anthropiques. Les diverses pressions anthropiques et la croissance urbaine seraient les principales causes de cette dégradation des écosystèmes naturels. Les résultats obtenus reflètent la réalité de la tendance de la dynamique du paysage à Lubumbashi où la croissance démographique s'accompagne des besoins élevés en espaces (Nkuku & Rémon, 2006) et en ressources (Munyemba & Bogaert, 2014). De plus, nos résultats corroborent les conclusions de Bogaert et *al*. (2011) qui indiquent que les classes anthropiques, entre autres les zones urbaines ou industrielles et les cultures, enregistrent des processus de transformation spatiales différents de ceux des classes naturelles. Toutefois, une faible tendance à la régénération de forêts a été enregistrée dans la matrice de transition (13 %). A ce niveau, il convient de signaler que la conversion du bâti en forêt est attribuable à la confusion entre le bâti (constitué entre autres des routes en terre battue) et le sol nu lors de la classification. Il s'agirait en effet d'une présence des plantations d'arbres en ville sur d'anciens sols nus, notamment les plantations d'*Acacia sp* mises en place par la municipalité. Toutefois, cette tendance de la conversion du bâti en végétation est signalée par Frauman (2004) comme une présence de la végétation hydrophile herbacée que la classification ne permet pas de différencier des forêts.

La progression des classes anthropiques modifie la composition du paysage lushois, ce qui se traduit par l'augmentation de l'indice de perturbation entre 2002 et 2008. Ces résultats corroborent ceux de Munyemba & Bogaert (2014) qui indiquent une anthropisation progressive des paysages dans la région de Lubumbashi entre 1956 et 2009. Une tendance similaire a été observée dans d'autres villes africaines (Jansen et *al.,* 2008 ; Ouedraogo et *al.,* 2010 ; Bamba et *al.,* 2010b). En effet, Mama et *al.* (2014) indiquent que les pressions humaines actuelles sur les ressources forestières sont en rupture avec les capacités de régénération des formations végétales naturelles qui sont ainsi sérieusement menacées.

Par ailleurs, dans ce paysage fortement anthropisé, les colonies de *T. diversifolia* ont enregistré une croissance de 9 % entre 2002 et 2008. En effet, l'anthropisation des paysages s'accompagne des changements de composition et configuration (Breuste et *al.*, 2008) et certaines espèces, les espèces invasives notamment, profitent de ces dégradations pour coloniser de nouveaux (Vanderhoven et *al.,* 2005). Toutefois, la progression relativement modeste de *T. diversifolia* est dû au fait que l'espèce est souvent rasée sur le terrain vague pour ériger le bâti, en même temps qu'elle s'installe sur de nouveaux sites perturbés. En plus, le milieu d'étude inclut également les éléments ruraux alors que l'espèce est notamment plus concentrée en zone (péri)urbaine. Par conséquent, l'aire totale de *T. diversifolia* est importante comme indicateur de l'anthropisation du paysage ; ce qui implique que sa structure spatiale dans le paysage est davantage plus déterminée par les actions anthropiques que les processus naturels.

Implications et conséquences pour l'aménagement des zones vertes en milieux urbain et péri-urbain

Notre étude a révélé que la ville de Lubumbashi s'étend au détriment des écosystèmes naturels présents autour de la ville, ce qui est typique pour la plupart des villes des pays en développement en général (Bogaert et *al.,* 2014) et plus particulièrement des villes congolaises telles que Kisangani (Bamba et *al.,* 2010), Kinshasa (Vermeulen et *al.,* 2011), Mweka et Moba (Potapov et *al.,* 2012). En effet, les transformations spatiales rapides, entrainées par l'expansion urbaine rapide à Lubumbashi sont responsables de la suppression des forêts et marécages en même temps que la propagation de *T. diversifolia.* Cela a des profondes implications pour la gestion des écosystèmes naturels à Lubumbashi, de même que des terres agricoles présentes autour de la ville (Nkuku & Rémon, 2006). En effet, au Bénin, les études de Toyi et *al.* (2013) ont montré que la vitesse de l'anthropisation des paysages est telle que les plantations d'arbres ne pourront même pas compenser les pertes de formations végétales boisées dans les décennies à venir.

Les résultats de notre étude impliquent que les écosystèmes qui résistent à la pression de l'urbanisation et celles colonisées par les espèces invasives ne pourraient pas remplir des fonctions écologiques fournies par les écosystèmes originels, cela suite à la différence de structure et composition des espèces (Liu et *al.,* 2013). Par conséquent, il est important de conserver les écosystèmes naturels dans le paysage urbain à Lubumbashi où la faiblesse de l'organisation et de l'administration de l'espace urbain est criante (GROUPE HUIT, 2009).

Ainsi, tout plan d'aménagement durable devra intégrer des zones vertes dans et autour de la ville de Lubumbashi, étant donné que la végétation influence directement le sol et le climat urbain (Alberti, 2005) et fournit des services écosystémiques bénéfiques aux citadins (Bolund & Hunhammar, 1999). En effet, la suppression du couvert végétal entraine une recrudescence d'inondations, l'augmentation de la température, la dégradation des écosystèmes naturels en augmentant ainsi leur sensibilité aux invasions biologiques (Bolund & Hunhammar, 1999 ; Zhou et *al.,* 2004 ; Alberti, 2005).

Les débats sur l'urbanisme durable, intégrant la nature dans le développement urbain, sont plus que de sujets d'actualité en Afrique subsaharienne où il a été démontré que la proportion du couvert végétal diminue rapidement (Cilliers et *al.,* 2013). Pourtant, avec des politiques efficientes d'aménagement et planification des infrastructures vertes, les villes pourraient jouer un grand rôle dans le maintien des espèces et la fourniture des services écoystémiques (Hostetler et *al.,* 2011). Il est donc important de pouvoir concilier ces résultats de l'anthropisation des paysages avec la politique d'aménagement de la municipalité dans l'optique d'un développement durable.

Conclusion

Ce travail avait pour objectif l'interprétation du processus d'urbanisation dans la ville de Lubumbashi entre 2002 et 2008, à partir des méthodes d'écologie du paysage associés à la télédétection et aux systèmes d'informations géographiques.

Nos résultats confirment que la zone d'étude comporte des milieux dynamiques et en forte mutation. L'équilibre écologique des forêts et marécages est fortement perturbé par l'expansion du bâti, de *T. diversifolia* et de la végétation anthropisée. Trois grands processus de transformation spatiale ont été identifiés : l'agrégation du bâti et végétation anthropisée, la création des taches de *T. diversifolia,* enfin la suppression des marécages et de forêts. La configuration spatiale du paysage a changé en 6 ans, en dépit du fait que la matrice du paysage est restée dominée par la végétation anthropisée. Le taux de croissance annuel du bâti est de 7 % alors que la forêt et les marécages ont régressé à des taux annuels de 5,5 % et 4,5 % respectivement, durant la même période.

La matrice de transition révèle que la croissance du bâti s'est principalement opérée au détriment de la végétation anthropisée, de la forêt et des marécages. En revanche, la réduction du nombre de taches et aires totales de classes naturelles parallèlement à la progression des classes anthropiques traduit d'une anthropisation du paysage urbain de Lubumbashi.

Ces informations devraient permettre aux décideurs et aux aménageurs du territoire de prendre des mesures adéquates pour inverser la tendance actuelle de l'urbanisation en vue de préserver les écosystèmes naturels, tout en empêchant la propagation de *T. diversifolia*.

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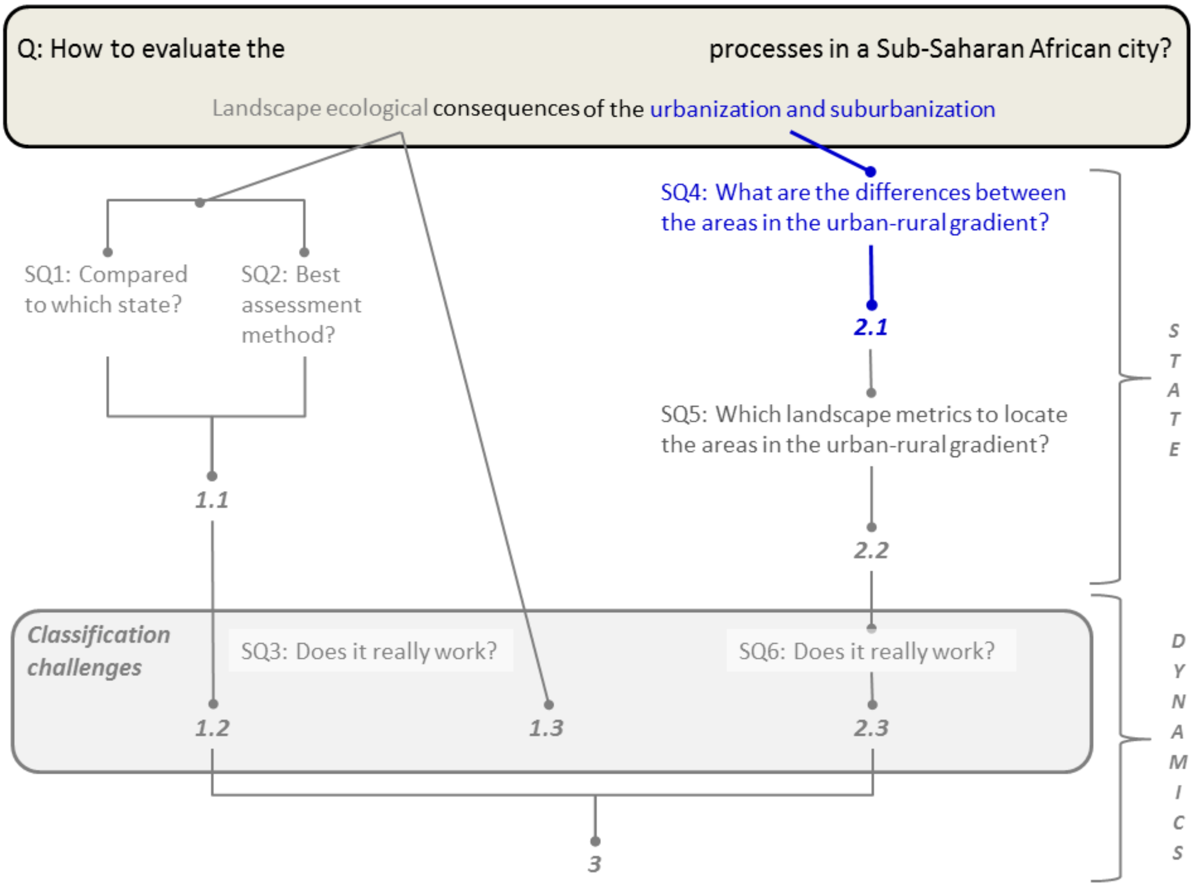
Publication 2.1

Vers une synthèse de la conception et une définition des zones dans le gradient urbain-rural



B A S E Biotechnol. Agron. Soc. Environ. 2014 **18**(1), 61-74 *Le* **Point** *sur :*

Vers une synthèse de la conception et une définition des zones dans le gradient urbain-rural

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À l'heure où les villes ne cessent d'augmenter leur emprise sur les paysages, leur étude ainsi que celle des zones qui les ceinturent sont plus que jamais des sujets d'actualité. Paradoxalement, les notions se rattachant à ces zones restent assez floues. En effet, les scientifiques de différentes disciplines peinent à leur donner une définition et des limites acceptées par tous ; ils les mentionnent sans les définir. Cette pratique empêche la complémentarité et la comparaison entre études. Cette revue bibliographique a mis en évidence la variété de termes utilisés pour décrire les différentes zones s'organisant le long du gradient d'urbanisation ainsi que les caractéristiques qui y sont relatives. Ces dernières ont été évaluées selon leur importance relative dans la littérature ainsi que selon une série de critères. Enfin, de nouvelles définitions pour les différentes zones ont été proposées en vue de leur identification sur le terrain.
Mots-clés. Zone urbaine, zone périurbaine, relation ville campagne, écologie, terminologie.

Toward a synthesis of the concept and a definition of the zones in the urban-rural gradient. The increasing footprint of urbanization on landscapes justifies the study of cities and the zones surrounding them. Paradoxically, the concepts relating to these zones remain unclear. Scientists from different disciplines diverge when defining these zones or their limits; they even often mention the zones without any definition. This practice excludes comparison between studies. By means of bibliographic research, the variety of terms used to describe the different zones composing the urban-rural gradient has been evidenced, as well as the characteristics of the zones themselves. They have been evaluated according to their relative importance and according to a series of criteria. Finally, new definitions for the different zones have been proposed in order to enable their identification in the field.
Keyword. Urban areas, suburban areas, rural urban relations, ecology, terminology.

1. INTRODUCTION

1.1. Urbanisation et zones périurbaines

L'urbanisation est un phénomène d'anthropisation des paysages indéniable à l'heure actuelle. La population urbaine représentait 14 % de la population mondiale en 1920, elle a atteint 50 % en 2000 et devrait augmenter à près de 60 % en 2030 (Rodiek, 1995 ; Grimm et al., 2008). Les villes ne cessent donc d'augmenter leur emprise sur les paysages dont elles font partie. L'étude des espaces qui les ceinturent, le phénomène de leur extension dans les régions rurales ainsi que les schémas conceptuels de leur morphologie et dynamique interne sont plus que jamais des sujets d'actualité (De Blij, 1977 ; Borsdorf et al., 2002 ; Halleux, 2006 ; Bhatta et al., 2010 ; Gaston, 2010).

Plus particulièrement, les zones périurbaines, situées à une frontière floue entre le rural et l'urbain, sont le terrain de multiples phénomènes ayant des répercussions, souvent perçues comme négatives, sur notre société. Les conséquences et enjeux qui en découlent varient selon les régions du monde mais d'aucuns s'accordent à dire que le phénomène de périurbanisation mène en général à la formation de ghettos sociaux, au renforcement des inégalités sociales, à la dégradation visuelle des paysages, à des conflits humains dus à la multiplication des acteurs y vivant ou y pratiquant une activité, à une dégradation de la biodiversité et à un risque accru d'incendies (Bieber et al., 1993; Larcher, 1998; Iaquinta et al., 2000; Brück, 2002; Dubois, 2006; Halleux, 2006; Hanson, 2006; Trefon et al., 2007; Jaeger et al., 2010; Rutherford, 2010). En Europe, des conséquences négatives telles que l'utilisation de terrains de grande valeur agricole pour la construction, l'augmentation des consommations d'énergie ainsi que le financement des équipements par la collectivité ont été signalées (Brück, 2002). En Afrique, les zones périurbaines sont le siège de nombreuses activités économiques, permettent aux ménages d'être moins vulnérables aux fluctuations économiques mais leurs habitants y manquent cruellement d'équipements et de sécurité foncière (Drakakis-Smith, 1991 ; Drakakis-Smith, 1994 ; Briggs et al., 2001 ; ULB, 2006 ; Trefon et al., 2007).

1.2. Un labyrinthe sémantique

Paradoxalement, les scientifiques de différentes disciplines peinent à donner une définition des caractéristiques et des limites acceptées par tous aux notions de « rural », de « périurbain », d'« *urban fringe* », d'« étalement urbain », d'« exurbain », de « banlieue » et d' « urbain » (pour ne citer que les termes principaux). C'est ainsi, par exemple, qu'il est difficile de connaitre avec certitude l'identité et la taille de la ville la plus étendue du monde car le palmarès varie selon les auteurs (Forstall et al., 2009). De plus, certaines études mentionnent une de ces zones sans la définir, la signification exacte étant sous-entendue (Hermy et al., 2000 ; Godefroid et al., 2003 ; Grau et al., 2008). De nombreux auteurs considèrent les définitions mêmes comme triviales (McIntyre, 2011). L'absence de définitions et de caractéristiques communes à tous peut mener à des interprétations différentes des localisations et contextes des sites étudiés (Forstall et al., 2009 ; MacGregor-Fors, 2011). Cela a pour conséquences qu'aucune comparaison rigoureuse ou complémentarité n'est possible entre études portant sur le même sujet (Forstall et al., 2009 ; MacGregor-Fors, 2011).

La présente contribution cherche à répondre aux quatre objectifs suivants:

– identifier, par une recherche bibliographique, les différentes zones présentes dans le gradient urbain-rural ainsi que les caractéristiques et types de caractéristiques utilisés pour définir les zones les plus souvent citées ;
– évaluer l'importance relative de ces caractéristiques et types de caractéristiques pour chaque zone puis pour l'ensemble des zones en fonction de leur fréquence de citation ;
– évaluer les caractéristiques principales selon une série de critères, en vue de leur intégration dans de nouvelles définitions et de l'identification des zones sur le terrain ;
– sur base des caractéristiques retenues, proposer des définitions univoques pour les zones les plus souvent citées dans la littérature.

2. ÉTUDE BIBLIOGRAPHIQUE DES DÉFINITIONS ET CARACTÉRISTIQUES DES DIFFÉRENTES ZONES

Les divers termes utilisés pour désigner les différentes zones dans un gradient urbain-rural ainsi que les caractéristiques utilisées pour décrire ces zones ont été recherchés dans 100 références issues d'une recherche bibliographique (**Annexe 1**). L'absence d'une liste exhaustive des termes existant souligne l'intérêt de la présente contribution. Certains termes tels que « *wildland-urban interface* » ou « *extra-urban* » n'ont pas été retenus car ils n'ont été rencontrés qu'une seule fois (MacGregor-Fors, 2010 ; Rutherford, 2010). En ce qui concerne les zones périurbaines, ses caractéristiques rassemblent en réalité les définitions qui concernent les zones désignées comme « *périurbaines* » et « *suburban* ». En effet, après examen des descriptions de chacun de ces deux termes, il apparait qu'ils correspondent à la même notion, la seule chose qui les différencie étant la langue de l'auteur (francophone pour les zones périurbaines). Par conséquent, seul le terme « *périurbain* » sera employé dans la suite du texte. Par ailleurs, aucun consensus au sein des auteurs n'a été relevé pour le terme « *urban fringe* » qui n'est donc pas présenté dans la présente contribution. Enfin, la notion de « ville diffuse » n'a pas été prise en compte dans cette analyse car elle correspond à un type d'urbanisation qui n'est pas issu d'un pôle urbain attractif ; il ne se situe donc pas à proprement parler dans le gradient urbain-rural auquel s'intéresse cette étude (Grosjean, 2010). Dès lors, ont été retenues les zones désignées comme « urbaines », « de banlieue », « périurbaines », « exurbaines », « d'étalement urbain » (patron) et « rurales ». La recherche s'est appuyée sur la littérature scientifique (articles et rapports), la référence la plus ancienne datant de 1956. La recherche s'est arrêtée à l'année 2011 incluse. L'étude ne s'est pas résumée à une région géographique ni à une discipline particulière, de manière à rendre les résultats les plus représentatifs possible. Ainsi, les études examinées concernent des disciplines aussi diverses que les sciences politiques, la démographie, l'écologie, l'écologie du paysage, l'économie, la géographie, la planification, la psychologie, la télédétection, la sociologie et la médecine. Seules les caractéristiques correspondant à une réalité physique ont été prises en compte. Ainsi, par exemple, une caractéristique telle que « aménagement du territoire moins sophistiqué » n'a pas été prise en compte. Par contre, aucun jugement *a priori* n'a été porté sur la pertinence des caractéristiques ni sur leur précision. Pour chaque référence et chaque terme cité, les caractéristiques utilisées pour définir la zone ont été compilées. Lorsque le même auteur citait à plusieurs reprises le même critère dans différentes publications, celui-ci n'a été repris qu'une fois afin que les résultats ne soient pas biaisés par la productivité des auteurs. Des définitions annoncées comme telles ont été prises en compte, mais également des descriptions plus complètes disséminées dans les documents sans être explicitement dénommées « définitions ».

Les caractéristiques ont ensuite été classées, pour chaque zone, selon leur type (ensemble de caractéristiques similaires) et selon leur fréquence de citation, *via* le calcul d'un indice de citation *If* (%) (Équation 1) dont les valeurs oscillent entre 0 (lorsque la caractéristique n'est jamais citée) et 100 (lorsque la caractéristique est la seule à être citée pour décrire la zone en question) :

$$If_{iz} = 100 \times \frac{f_{iz}}{n_c} \qquad \text{Équation 1}$$

avec i la caractéristique pour laquelle l'indice est calculé, z le type de zone, f_{iz} la fréquence de citation de la caractéristique i dans la zone z et n_c le nombre total de caractéristiques utilisées pour décrire la zone. L'ensemble des types de caractéristiques et caractéristiques utilisés lors du classement se trouve en **annexe 2**. Après ce classement, une sélection des caractéristiques principales a été effectuée pour chaque zone en observant successivement deux règles :

- afin d'éliminer les caractéristiques trop anecdotiques, peu souvent citées, seules les caractéristiques dont la fréquence de citation était égale ou supérieure à deux ont été sélectionnées,
- ensuite, afin de ne pas retenir un trop grand nombre de caractéristiques,
  - si leur nombre était inférieur ou égal à dix, toutes ces caractéristiques ont été sélectionnées,
  - si le nombre de caractéristiques sélectionnées était supérieur à dix, toutes celles dont la fréquence était supérieure ou égale à la fréquence de la dixième ont été retenues.

Afin de compiler les informations pour l'ensemble du gradient d'urbanisation, un indice de fréquence relatif *Ifr* a ensuite été calculé pour chaque caractéristique (Équation 2). Ses valeurs sont comprises entre 0 (lorsque la caractéristique n'est jamais citée) et 100 (lorsque la caractéristique est la plus citée pour décrire les zones composant le gradient d'urbanisation en question) :

$$Ifr_i = \frac{\sum_z If_{iz}}{\left(\sum_z If_{iz}\right)_{\max}} \qquad \text{Équation 2}$$

Ensuite, un classement général a été effectué par ordre décroissant de Ifr_i. Le **tableau 1** présente le résultat de ce dernier pour les zones retenues. Enfin, afin d'évaluer la façon dont sont décrites les différentes zones, trois indicateurs supplémentaires ont été calculés par zone : le nombre de types de caractéristiques retenues (n_1), le nombre de caractéristiques retenues (n_2) et le rapport entre ces deux derniers qui représente le nombre moyen de caractéristiques par type. Ces derniers résultats sont représentés, par zone, dans le **tableau 2**.

On remarque que dans le cas des zones urbaines, sept types de caractéristiques dominent, à savoir (les types de caractéristiques sont suivis, entre crochets, du nombre de caractéristiques qu'ils comprennent) : morphologique [5], démographique [2], énergétique [1], environnemental [1], institutionnel [1], administratif et juridique [1] et biodiversité [1]. Dans le cas des zones de banlieue, seuls deux types de caractéristiques décrivent la zone selon nos critères : morphologique [3] et démographique [1]. Les zones périurbaines sont différenciées selon cinq types de caractéristiques : morphologique [6], démographique [2], fonctionnel [1], dynamique [1] et économique [1]. Les zones exurbaines sont définies par trois types de caractéristiques : morphologique [4], démographique [1] et fonctionnel [1]. Les zones d'étalement urbain sont décrites par quatre types de caractéristiques : morphologique [7], fonctionnel [3], démographique [2] et dynamique [1]. Les zones rurales sont, elles, décrites selon deux types de caractéristiques : morphologique [3] et démographique [2].

Comme le montre le **tableau 2**, ce sont les zones urbaines qui sont décrites avec le plus de types de caractéristiques et les zones d'étalement urbain par le plus de caractéristiques. Ce sont aussi ces dernières zones pour lesquelles le ratio n_1/n_2 est le plus élevé ; chaque type de caractéristique qui les décrit contient donc proportionnellement davantage de caractéristiques.

De manière générale et pour l'ensemble des zones (**Tableau 1**), sur les 12 types de caractéristiques, 10 (83 %) ont été retenus à l'issue de la procédure de sélection décrite plus haut. Concernant les caractéristiques, seules 23 des 72 ont été sélectionnées, soit 32 %. Parmi les 23 sélectionnées, 9 (39 %) concernent la morphologie du paysage, 3 (13 %) portent sur la démographie et la fonctionnalité, 2 (9 %) sur la dynamique et tous les autres types de caractéristiques (économie, environnement, énergie, institutionnel, administration, biodiversité) ne sont représentés que par une seule caractéristique, soit 4 % pour chacun. Ajoutons encore que le type de caractéristique « morphologique » arrive en tête du classement puisqu'il correspond à 7 des 10 premières caractéristiques. La première citée est la position de la zone dans un gradient s'éloignant

Tableau 1. Classement des caractéristiques et types de caractéristiques utilisés pour définir les différentes zones situées dans le gradient urbain-rural selon leur indice de citation *If* (%), sur base d'une analyse bibliographique. *Ifr* (%) est l'indice de fréquence relatif — *Classification of characteristics and types of characteristics used to define the different zones within the urban-rural gradient according to their citation index* If *(%), based on a literature review.* Ifr *(%) is the index of relative frequencies.*

Caractéristique	**Type de caractéristique**	**Indice de citation *If*, par zone** (%)						**Somme des *If* pour l'ensemble des zones** (%)	***Ifr*** **(%)**
		Urbain	**Banlieue**	**Péri-sub-urbain**	**Exurbain**	**Étalement urbain**	**Rural**		
Position dans un gradient s'éloignant du centre-ville	Morphologique	3	11	8	33	3	26	84	100
Composition du paysage	Morphologique	18	11	12	11	6	15	73	87
Densité de population	Démographique	13	11	4	7	9	15	59	70
Densité de constructions	Morphologique	7		4	7	10	11	39	46
Organisation de l'espace : dispersion de l'habitat	Morphologique	6	17	4		11		38	45
Nombre de personnes	Démographique	9					15	24	29
Distance à l'agglomération	Morphologique			4	7	3		14	17
Navette vers l'agglomération	Fonctionnel/mobilité			4	7			11	13
Organisation de l'espace : mixité des utilisations du sol ; disposition, uniformité et type de constructions dans l'espace résidentiel	Morphologique					9		9	11
Indices paysagers	Morphologique					8		8	10
Mode de déplacement	Fonctionnel/mobilité					7		7	8
Vitesse de changement	Dynamique			3		3		6	7
Croissance de population	Démographique			3		3		6	7
Maisons unifamiliales	Morphologique			4				4	5
Déchets	Environnemental	4						4	5
Énergie	Énergétique	4						4	5
Type de développement	Dynamique					4		4	5
Marché foncier	Économique			3				3	4
Allure des maisons	Morphologique	3						3	4
Accessibilité	Fonctionnel/mobilité					3		3	4
Structure de pouvoir	Institutionnel	2						2	2
Relation aux limites administratives	Administratif et juridique	2						2	2
Composition et richesse en espèces	Biodiversité	2						2	2

Tableau 2. Nombre de types de caractéristiques retenues (n_1), nombre de caractéristiques (n_2) et rapport entre les deux pour décrire chaque zone rencontrée dans le gradient d'urbanisation, sur base d'une analyse bibliographique — *Number of selected types of characteristics* (n_1)*, of characteristics* (n_2) *and the ratio between them to describe each zone encountered in the urbanization gradient, based on a literature review.*

	Urbain	Banlieue	Péri-sub-urbain	Exurbain	Étalement urbain	Rural
n_1	7	2	5	3	4	2
n_2	12	4	11	6	13	5
n_2/n_1	1,7	2,0	2,2	2,0	3,3	2,5

du centre-ville, la deuxième est la composition du paysage et la troisième est la densité de population. Ces trois caractéristiques sont utilisées pour décrire toutes les zones. La densité de constructions apparait en quatrième position ; elle sert à décrire toutes les zones, sauf la banlieue. La dispersion de l'habitat est classée en cinquième position ; elle caractérise toutes les zones sauf les zones exurbaines et rurales. Toutes les autres caractéristiques décrivent entre une et trois zones.

3. ÉVALUATION DES PRINCIPALES CARACTÉRISTIQUES EXISTANTES

Dans cette étude, afin d'évaluer les caractéristiques principales permettant de définir les zones présentes dans le gradient urbain-rural, cinq types de propriétés ont été choisies, à savoir :

– la possibilité de quantifier la caractéristique et, partant, d'en fixer un (des) seuil(s) ;
– le caractère intégratif ou le fait que la caractéristique représente un grand nombre de paramètres ;
– la présence d'un consensus global que nous avons considéré comme acquis lorsque l'indice *Ifr* était supérieur à 50 % ;
– le caractère discriminant, c'est-à-dire le fait que la caractéristique se base sur un paramètre présentant une gamme limitée de valeurs ;
– la facilité d'application sur le terrain lorsque l'obtention de la donnée ne nécessite pas de données brutes de type statistique ou issues de la télédétection.

La caractéristique idéale est supposée quantifiable, intégrative, faisant l'objet d'un consensus, discriminante et facile à appliquer sur le terrain. Les résultats de cette évaluation sont présentés dans le **tableau 3**.

À nouveau, les caractéristiques de type morphologique se distinguent ici en représentant quatre des cinq caractéristiques comptabilisant au moins trois propriétés attendues. Il s'agit des caractéristiques « position dans un gradient s'éloignant du centre-ville », « composition du paysage », « dispersion de l'habitat » et « organisation de l'espace : mixité des utilisations du sol ; disposition, uniformité et type de constructions dans l'espace résidentiel », la cinquième étant la caractéristique « mode de déplacement » (type « fonctionnel/mobilité »). Aucune de ces cinq caractéristiques n'a toutefois la qualité d'être intégrative. Cette qualité, ainsi que celle de faire l'objet d'un consensus global, sont rarement rencontrées (respectivement 2 et 3 fois sur 23).

4. SYNTHÈSE DES CONCEPTS : NOUVELLES DÉFINITIONS

Suite à cette étude bibliographique, de nouvelles définitions sont proposées à la **figure 1**. Elles sont basées sur les caractéristiques possédant le plus de propriétés sur les cinq proposées précédemment et, en tout état de cause, en possédant au moins deux. Ces définitions ne reprennent donc pas l'ensemble des caractéristiques de chaque zone. Les critères relatifs à la dominance de surface bâtie, à l'utilisation résidentielle du sol ou au fait que le sol est occupé et utilisé principalement à des fins agricoles, rurales ou forestières découlent de la caractéristique « composition du paysage ». Le critère relatif à la présence de bâti continu concerne la caractéristique « dispersion de l'habitat », celui relatif à la zonation explicite des utilisations du sol provient de la caractéristique « organisation de l'espace : mixité des utilisations du sol ; disposition, uniformité et type de constructions dans l'espace résidentiel » et enfin, le critère se basant sur la présence de navettes quotidiennes des travailleurs de la zone vers l'agglomération correspond à la caractéristique « navette vers l'agglomération ». Le critère relatif à la région d'étude est un critère additionnel provenant de notre analyse qui permet d'affiner encore nos définitions. L'organigramme de la **figure 1** se lit de haut en bas, en répondant par « oui » ou « non ou non précisé » à chacune des propositions. Lorsque deux caractéristiques sont mentionnées au même niveau décisionnel, les deux doivent être rencontrées pour pouvoir répondre « oui ». Une zone déterminée est ainsi définie par les caractéristiques discriminantes

Tableau 3. Évaluation des caractéristiques principales permettant de définir les zones présentes dans le gradient urbain-rural (issues d'une analyse bibliographique) selon cinq types de propriétés — *Evaluation of the main features used to define the zones present in the urban-rural gradient (from a literature review) according to five types of properties.*

Caractéristique	Quantitatif	Caractère intégratif	Consensus global	Caractère discriminant	Facilité d'application sur le terrain
Position relative dans un gradient s'éloignant du centre-ville			x	x	x
Composition du paysage	x		x	x	x
Densité de population	x		x		
Densité de constructions	x				
Organisation de l'espace : dispersion de l'habitat	x			x	x
Nombre de personnes	x				
Distance à l'agglomération	x				
Navette vers l'agglomération	x			x	
Organisation de l'espace : mixité des utilisations du sol ; disposition, uniformité et type de constructions dans l'espace résidentiel	x			x	x
Indices paysagers	x				
Mode de déplacement	x			x	x
Vitesse de changement	x				
Croissance de population	x				
Maisons unifamiliales				x	
Déchets	x	x			
Énergie	x	x			
Type de développement	x				
Marché foncier	x				
Allure des maisons				x	x
Accessibilité	x				
Structure de pouvoir				x	
Relation aux limites administratives				x	
Composition et richesse en espèces	x				

découlant des choix logiques observés. Lorsque l'organigramme est appliqué à une zone précise, il faut considérer un carré dont l'observateur serait le centre et dont le côté a une longueur supérieure à la longueur moyenne des parcelles environnantes. L'échelle d'analyse est donc supraparcellaire, mais inférieure au kilomètre carré. À cette échelle, la zone périurbaine ne peut être différenciée de la ville diffuse (Grosjean, 2010). Ainsi, une zone périurbaine est définie de la façon suivante : une zone où les surfaces bâties ne dominent pas ou où le bâti est discontinu, où il n'y a pas de zonation explicite des utilisations du sol, où l'occupation et l'utilisation du sol ne sont pas quasiment exclusivement agricole et/ou forestière et située dans un pays francophone.

5. DISCUSSION, PERSPECTIVES ET CONCLUSION

Plusieurs facteurs peuvent expliquer la diversité de définitions et caractéristiques trouvées pour chaque terme. En effet, les sources consultées portaient sur des objets différents : patron ou processus d'urbanisation, causes ou conséquences (Jaeger et al., 2010). D'autre part, les techniques mises en œuvre pour répondre à

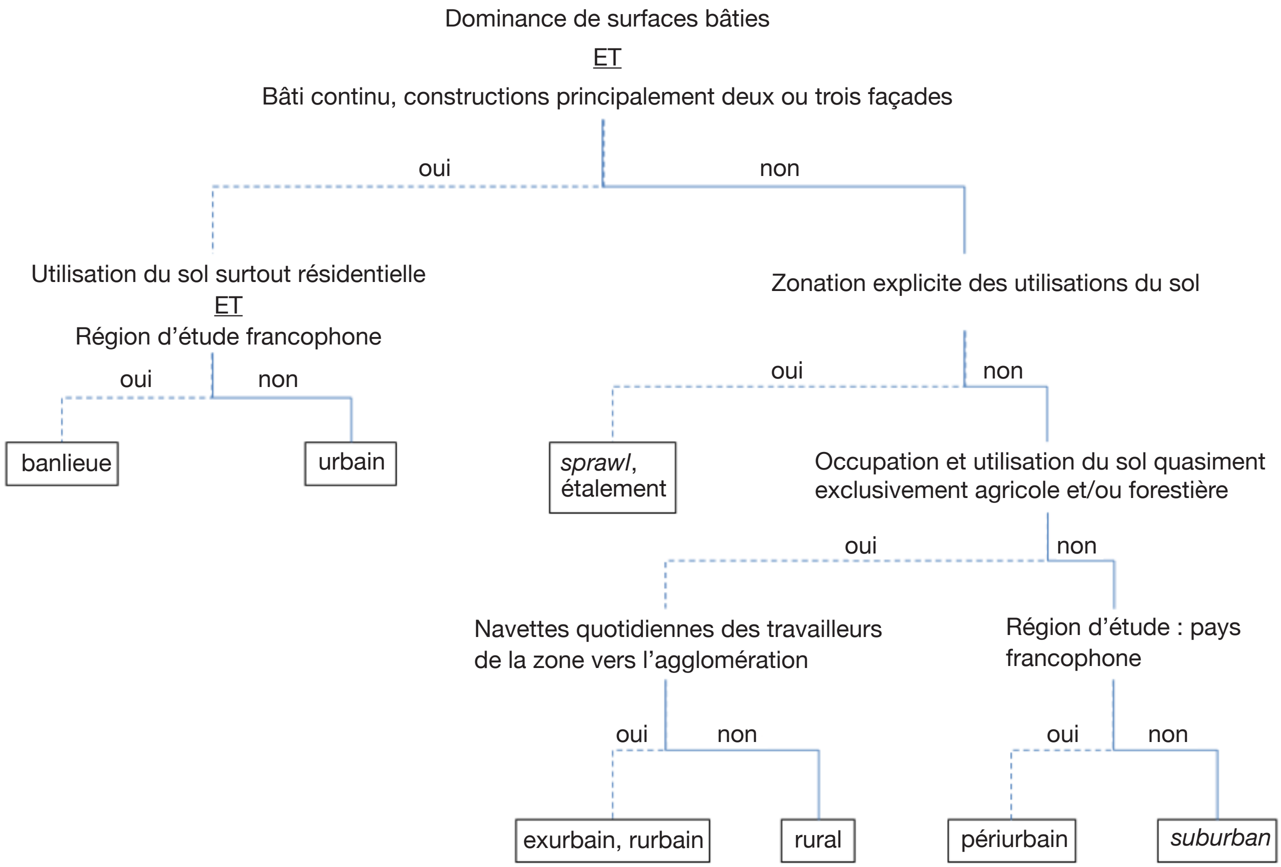

Figure 1. Organigramme des définitions des zones présentes dans le gradient urbain-rural — *Decision tree of the definitions of the zones present in the urban-rural gradient.*

Les flèches en trait discontinu indiquent une réponse «oui» et les flèches en trait continu une réponse « non » ou « non précisé» à au moins un des critères — *Discontinuous arrows indicate a "yes" answer and continuous ones a "no" or "not stated" to at least one criteria.*

la question de recherche variaient, de même que les préoccupations et objectifs, en fonction du domaine d'étude de l'auteur (Grimm et al., 2003 ; Hürriyet, 2010). Enfin, le contexte (date de l'étude, aspects démographique, socio-économique, politique, environnemental, géographique, juridique) a également influencé les caractéristiques et le nombre de zones ainsi que les seuils de séparabilité entre types de zones (Weber, 2001 ; Nilon et al., 2003 ; Simon et al., 2004 ; Van Hecke et al., 2009 ; Gaston, 2010). Cette diversité se traduit aussi par une hétérogénéité et un degré d'abstraction variable des caractéristiques utilisées par les auteurs pour décrire les zones.

Certains auteurs ont mis en garde contre la confusion régulière entre les caractéristiques des zones, les causes qui ont été à leur origine et les conséquences de leur présence (Jaeger et al., 2010). Toutefois, cette confusion est parfois inévitable. Par exemple, dans la catégorie « fonctionnel », Wolman et al. (2005) et Van Hecke et al. (2009) décrivent la zone périurbaine comme une zone où les travailleurs font des navettes en direction de la ville-centre pour les besoins de leur travail. Mais cela n'est-il pas la conséquence de ce patron paysager décentré qui ne fournit pas de lieux de travail à ses habitants, mais principalement des logements?

Une validation des définitions proposées dans cette contribution sera nécessaire *via* leur application au gradient urbain-rural de différentes villes, en vue de l'identification des zones présentes. L'utilisation d'images satellitaires et d'observations *in situ* permettront de renseigner sur les caractéristiques morphologiques, caractéristiques sur lesquelles les définitions proposées se basent principalement. Ces caractéristiques pourraient correspondre aux indices spatiaux développés en écologie du paysage (Hargis et al., 1997). En effet, l'étude de la dynamique des paysages est un des objectifs de cette discipline qui semble dès lors constituer un angle de vue particulièrement approprié (Turner et al., 1988). Une traduction des caractéristiques morphologiques vers les indices correspondant devra donc être effectuée préalablement. Il s'agira également d'évaluer la possibilité de fixer des seuils permettant de discriminer les différentes zones.

En conclusion, cette recherche bibliographique a permis d'identifier puis d'évaluer l'importance relative des caractéristiques et types de caractéristiques utilisés dans la littérature pour décrire les différentes zones du gradient urbain-rural, à savoir les zones urbaines, de banlieue, périurbaines, exurbaines, d'étalement urbain et rurales. En effet, aucune liste exhaustive de définitions n'a été trouvée. L'importance relative des caractéristiques et types de caractéristiques a été jugée sur base de leur fréquence de citation. Les caractéristiques principales ont ensuite été évaluées ; la caractéristique idéale étant supposée quantifiable, intégrative, faisant l'objet d'un consensus, discriminante et facile à appliquer sur le terrain. Les caractéristiques finalement retenues ont ensuite servi à proposer de nouvelles définitions pour les différentes zones du gradient. Le type de caractéristiques qui semble le plus pertinent est le type morphologique ; il est suggéré que son utilisation préférentielle, *via* l'utilisation d'indices d'écologie du paysage, pourrait aider à identifier les différentes zones du gradient urbain-rural.

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Annexe 2. Types de caractéristiques et caractéristiques utilisés par les auteurs pour décrire les zones présentes dans le gradient urbain-rural.

Type de caractéristique	Caractéristique
Démographique	Densité de population
	Localisation de la population
	Nombre de personnes
	Croissance de population
	Rajeunissement de la population
	Revenus de la commune
	Migration provenant de l'agglomération
	Émigration vers la ville centrale
Fonctionnel/mobilité	Navette vers l'agglomération
	Navette scolaire des étudiants
	Achats en ville
	Services en ville
	Temps de trajet entre la zone périurbaine et le centre urbain
	Fonctionnalité urbaine
	Accessibilité
	Mode de déplacement
Morphologique	Composition du paysage
	Taille des parcelles, des zones
	Indices paysagers
	Organisation de l'espace : dispersion de l'habitat
	Organisation de l'espace : mixité des utilisations du sol ; disposition, uniformité et type de constructions dans l'espace résidentiel
	Matériaux
	Âge du bâti
	Proportion d'habitat neuf
	% habitat < 45 m²
	Maisons unifamiliales
	Allure des maisons
	Nombre de constructions
	Densité de constructions
	Nombre de routes
	Densité des routes
	Taille des routes
	Infrastructures
	Espaces « vides »
	Distance à l'agglomération
	Position dans un gradient s'éloignant du centre-ville
	Taille relative de la zone

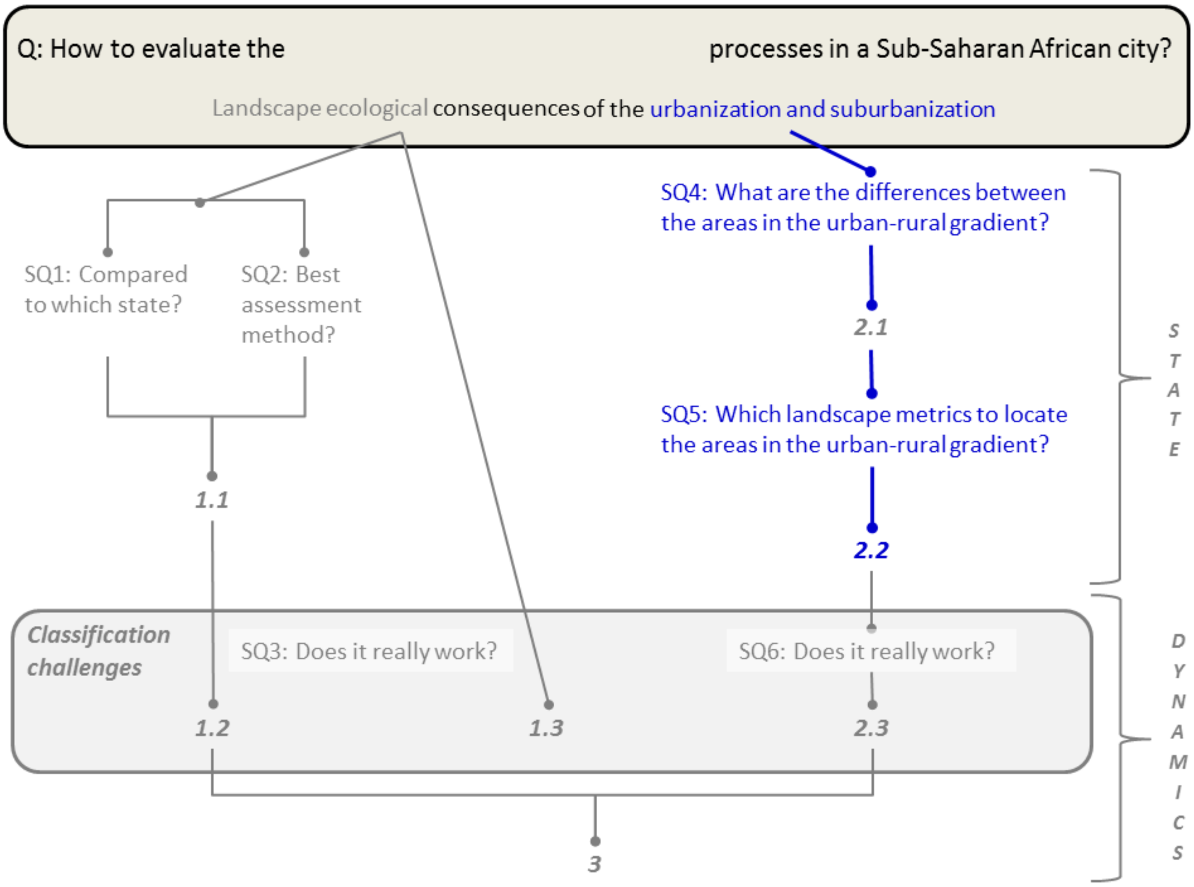
./..

Annexe 2 (suite). Types de caractéristiques et caractéristiques utilisés par les auteurs pour décrire les zones présentes dans le gradient urbain-rural.

Type de caractéristique	Caractéristique
Institutionnel	Types de services étatiques
	Structure de pouvoir
Administratif et juridique	Relation aux limites administratives
	Autres
Économique	Orientation de la production
	Marché foncier
	Taux d'emploi par secteur
	Taux de reprise des exploitations agricoles
	Statuts économiques des communautés
	Activités extractives et productives fortement dépendantes des ressources naturelles et de l'agriculture
Environnemental	Dégradation
	Déchets
	Pollution
Biodiversité	Type d'espèces
	Maintien de stages précoces de succession
	Formation d'un effet d'îlot thermique urbain
	Modification du régime d'humidité du sol
	Apport important d'éléments nutritifs
	Productivité
	Grande disponibilité de nourriture pour les animaux
	Piétinnement
	Fragmentation des espaces ouverts
	Proportion d'espèces introduites
	Composition et richesse en espèces
Énergétique, sociologique et culturel	Stratégies suivies des acteurs
	Hétérogénéité des acteurs
	Diffusion de nouveaux modèles socio-culturels (consommation et mode de vie)
	Ethnicité
	Diversification socio-professionnelle
Dynamique	Type de développement
	Vitesse de changement
Indéterminé	Densité faible
	Diversité faible
	Influence de la ville-centre

Publication 2.2

Vers une définition unique des zones périurbaines? L'apport de l'écologie du paysage pour la segmentation du gradient urbain-rural



VERS UNE DEFINITION UNIQUE DES ZONES PERIURBAINES? L'APPORT DE L'ECOLOGIE DU PAYSAGE POUR LA SEGMENTATION DU GRADIENT URBAIN-RURAL

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Résumé : Cette étude présente une méthode de segmentation du gradient urbain-rural qui s'appuie sur des éléments et indices paysagers décrivant la composition et la structure paysagères. Ces indices illustrent sous forme quantifiable les caractéristiques morphologiques les plus couramment citées pour décrire les différentes zones situées dans le gradient.

Mots-clés : gradient urbain-rural, indices de structure spatiale, morphologie, patron paysager, sémantique

1 INTRODUCTION

Depuis la sédentarisation de l'homme et l'avènement de l'agriculture, l'homme n'a cessé d'augmenter son emprise sur les ressources naturelles (Mazoyer et Roudart, 1997). L'augmentation continue des rendements agricoles, le passage progressif d'une société de production à une société de services dans de nombreuses régions du monde ont contribué à la création des villes puis à leur extension suite à l'afflux de populations venues de la campagne, ce dernier phénomène étant mieux connu sous le nom d' "exode rural" (World Bank, 1984; FAO, 2002). Il n'existe pas de réel consensus concernant l'existence ou non d'un potentiel "exode urbain", phénomène aussi connu sous les noms de "rurbanisation" ou de "contre-urbanisation", qui désigne le retour des citadins vers les zones rurales (Hervoët, 2001). En effet, certains auteurs préfèrent parler d'une simple redistribution de la population urbaine à l'intérieur du "système urbain" (Hervoët, 2001). Toujours est-il que cette (re)colonisation, caractérisée par une expansion diffuse de la ville dans un milieu mitoyen gardant son caractère rural, porte un nom: la périurbanisation (Hervoët, 2001; Fisher, 2003). L'agriculture, la déforestation et la (péri)urbanisation sont donc les trois phénomènes principaux de dynamique paysagère conduisant à l'anthropisation des paysages (Rudel, 2009). Cette contribution se concentre sur le troisième des trois phénomènes. De l'an 100 à 1850, la proportion de population mondiale vivant dans un environnement urbain n'a probablement jamais dépassé 6% (World Bank, 1984). En 1920, cette proportion est passée à 14% puis à 40% en 1980 avant d'atteindre 50% en 2000 (Rodiek, 1995). Aujourd'hui, le nombre de personnes vivant dans ce qu'on désigne sous le terme de "ville" a dépassé celui des personnes vivant en dehors; il est attendu qu'il augmente à près de 70% en 2050 (United Nations, 2007). Cette dominance de population urbaine se vérifie depuis quelques dizaines d'années dans les pays industrialisés alors que dans les pays non industrialisés, cela devrait être le cas dans les années à venir (World Bank, 1984; United Nations, 2007). L'extension des villes n'est pas sans effet; il convient donc d'étudier en profondeur les conséquences que ce phénomène amène et de les quantifier (Trefon et Cogels; Larcher, 1998; Briggs et Mwamfupe, 2001; Brück, 2002; ULB-GEPAC, 2006; Alberti, 2008; Marco, 2008; Jaeger *et al.*, 2010; Rutherford, 2010). Pour cela, il est nécessaire de commencer par délimiter les contours de chacune des zones que l'on peut rencontrer dans un gradient urbain-rural (Grimm *et al.*, 2003).

Une récente étude présentant les résultats d'une synthèse bibliographique sur le sujet démontre qu'il n'existe pas de consensus sur le nombre de zones rencontrées dans ce gradient ni sur les définitions et caractéristiques de chacune de ces zones (André *et al.*, en préparation). Cet article identifie dans la littérature, à l'aide de deux indices, I_c (Indice de citation) et I_a (Indice de caractéristique), chacune des zones les plus couramment citées (à savoir les zones urbaines, de banlieue, périurbaines et rurales) ainsi que les caractéristiques qui sont utilisées pour les définir (André *et al.*, en préparation). Celles-ci sont de type morphologique (types d'occupation et d'utilisation du sol dominant, densité de constructions, continuité du bâti, position dans un gradient s'éloignant du centre-ville, proportion de maisons unifamiliales, distance à la ville centre, dispersion de l'habitat et évolution de la surface bâtie), démographique (densité de population, nombre de personnes total dans la zone, croissance de la population), énergétique (comparaison de la consommation énergétique et de matériaux et de leur production), environnemental (comparaison de la production de déchets et son assimilation), institutionnel (présence d'un gouvernement/d'une autorité propre), de mobilité (navettes des travailleurs vers l'agglomération, accessibilité) et lexical (définition par un autre mot) (André *et al.*, en préparation). L'article conclu qu'en vue d'une identification spatiale des zones à l'aide de la télédétection, il est préférable d'utiliser préférentiellement les caractéristiques morphologiques qu'il convient de traduire sous forme d'indices de structure spatiale permettant l'implémentation pratique des définitions données aux zones (André *et al.*, en préparation).

2 L'APPORT DE L'ECOLOGIE DU PAYSAGE

La présente étude propose une méthode qui permet d'identifier les différentes zones du gradient urbain-rural sur des données référencées comme des cartes numériques ou des images satellites. Pour ce faire, elle se base sur les indicateurs quantitatifs que sont les indices de structure spatiale. Ces indices sont couramment utilisés en écologie du paysage afin de quantifier le patron paysager (McGarigal, 2002; Herold *et al.*, 2003). Ce dernier peut être modélisé selon le paradigme *"patch-corridor-matrix"* qui subdivise le paysage en unités fonctionnelles aussi appelées "taches" présentant des conditions environnementales homogènes (Forman et Godron, 1986; Burel et Baudry, 2000). La "classe" représente l'ensemble des taches ayant des caractéristiques similaires. La "matrice" est le type de tache le plus répandu et le moins fragmenté; en quelque sorte, c'est l'arrière plan du paysage dans lequel viennent s'inscrire les autres éléments (Iorgulescu et Schlaepfer, 2002). Lorsqu'aucune matrice ne peut être mise en évidence, on parle de "mosaïque". Les "corridors" représentent un type de tache particulier car ayant une forme linéaire. Le patron paysager peut être décrit par sa composition et/ou sa configuration. La première concerne la présence et le nombre de taches issues de différentes classes au sein du paysage; la seconde, se rapporte à la distribution spatiale, la forme et la variabilité des aires de ces taches (Alberti, 2008). La description du patron paysager est importante car selon l'hypothèse centrale de la discipline, le "*pattern-process paradigm*", les processus écologiques découlent des structures caractéristiques des paysages et vice versa (Coulson *et al.*, 1999; Bogaert *et al.*, 2004).

3 SEGMENTATION PAYSAGERE

Les tableaux 1 à 4 présentent les résultats de la mise en correspondance entre les caractéristiques morphologiques issues de la synthèse bibliographique de André *et al.* (en préparation) et les indices de structure paysagère pour chaque zone dans un gradient urbain-rural, soit respectivement pour les zones urbaine, de banlieue, périurbaine et rurale. Les caractéristiques morphologiques proviennent indifféremment de définitions ou de descriptions des zones. La première colonne énonce lesdites caractéristiques morphologiques, la seconde présente l'interprétation des caractéristiques morphologiques par les différents auteurs, la troisième montre l'élément paysager quantifiable qui correspond, enfin, la dernière présente les indices paysagers correspondants disponibles dans la littérature. Dans ces tableaux, la notion d'"occupation du sol" se réfère aux caractéristiques de la surface, que celle-ci soit naturelle ou artificielle, et découle d'observations directes alors que celle d'"utilisation du sol" se base à la fois sur l'occupation du sol et sur une interprétation socio-économique des activités qui prennent place sur cette surface (Anderson *et al.*, 1976; Fisher *et al.*, 2005). Les équations qui permettent de calculer les différents indices sont données en annexe 1.

Caractéristiques morphologiques	Interprétation	Eléments paysagers quantifiables	Indices paysagers correspondant
Continuité du bâti	Bâti continu	Taches de surfaces bâties	Densité de taches (ρ) Distance bord à bord au plus proche voisin (z) Indice d'agrégation (R) Indice de proximité (PX)
Densité de constructions	Plus élevée que celle des autres zones	Taches de surfaces bâties	Densité de taches (ρ)
Type d'occupation du sol dominant	Surfaces bâties	Matrice paysagère	Indice de dominance (D)

Tableau 1 Caractéristiques morphologiques et leurs interprétations, éléments paysagers quantifiables et indices paysagers pour les zones urbaines

Caractéristiques morphologiques	Interprétation	Eléments paysagers quantifiables	Indices paysagers correspondant
Continuité du bâti	Bâti continu	Taches de surfaces bâties	Densité de taches (*ρ*) Distance bord à bord au plus proche voisin (*z*) Indice d'agrégation (*R*) Indice de proximité (*PX*)
Densité de constructions	Plus faible que la densité urbaine mais plus élevée que celle des autres zones	Taches de surfaces bâties	Densité de taches (*ρ*)
Types d'occupation et d'utilisation du sol dominants	Dominance du type d'occupation du sol "surfaces bâties" et du type d'utilisation du sol "résidentiel"	Matrice paysagère	Indice de dominance (*D*)

Tableau 2 Caractéristiques morphologiques et leurs interprétations, éléments paysagers quantifiables et indices paysagers pour les zones de banlieue

Caractéristiques morphologiques	Interprétation	Eléments paysagers quantifiables	Indices paysagers correspondant
Continuité du bâti	Bâti discontinu	Taches de surfaces bâties	Densité de taches (*ρ*) Distance bord à bord au plus proche voisin (*z*) Indice d'agrégation (*R*) Indice de proximité (*PX*)
Densité de constructions	Densité faible	Taches de surfaces bâties	Densité de taches (*ρ*)
Dispersion du bâti	Bâti dispersé	Taches de surfaces bâties	Indice d'agrégation (*R*) Indice de proximité (*PX*)
Evolution de la surface bâtie	Evolution rapide	Taches de surfaces bâties	Différence de surface bâtie entre les temps t1 et t2.
Types d'occupation et d'utilisation du sol dominants	Dominance du type d'occupation du sol "agricole" et des types d'utilisation du sol "rural", parfois mosaïque de différentes utilisations	Matrice paysagère	Indice de dominance (*D*)

Tableau 3 Caractéristiques morphologiques et leurs interprétations, éléments paysagers quantifiables et indices paysagers pour les zones périurbaines

Caractéristiques morphologiques	Interprétation	Eléments paysagers quantifiables	Indices paysagers correspondant
Types d'occupation et d'utilisation du sol dominants	Utilisation et occupation principale du sol: agricole ou forestière	Matrice paysagère	Indice de dominance (*D*)

Tableau 4 Caractéristiques morphologiques et leurs interprétations, éléments paysagers quantifiables et indices paysagers pour les zones rurales

4 DISCUSSION

Les résultats des tableaux 1 à 4 montrent qu'il existe un ou plusieurs indice(s) paysager(s) correspondant à chacune des caractéristiques morphologiques; il semble possible de définir les limites des différentes zones à partir de quelques indices paysagers qui existent déjà. Par ailleurs, l'examen des tableaux fait apparaître les éléments suivants:

- Aucun des indices paysagers ne se base sur l'élément "corridor". Ce type d'interprétation fonctionnelle de la connectivité du paysage n'est pas pertinente dans ce cas-ci.
- La littérature ne mentionne pas l'utilisation du sol dominante pour décrire la zone urbaine mais plutôt l'occupation du sol. Cela peut être dû au fait qu'à l'occupation du sol "surfaces bâties" peut correspondre un très grand nombre d'utilisations dans cette zone; cet inconvénient a rendu ce critère non pertinent pour la majorité des auteurs.
- La notion de "continuité" n'est pas à comprendre au sens propre du terme mais plutôt au sens de "proximité".
- Certains indices comme la densité de taches, l'indice d'agrégation et l'indice de proximité ont l'avantage de permettre la définition plusieurs caractéristiques morphologiques.

- L'indice de dominance est utilisé dans tous les cas, c'est donc un indice de référence pour la segmentation. Dans le cas de la zone rurale, il est le seul indice permettant de définir les limites de la zone. Cela peut être un avantage en terme de simplicité, pour autant que cet indice soit suffisant, ce que seule la mise en pratique des indices paysagers pourra confirmer.
- C'est principalement la classification bâti/non-bâti qui est à la base du calcul des différents indices. Cela rejoint le constat d'autres auteurs comme Kasanko *et al.* (2006) ou Herold *et al.* (2003).

Certaines notions mises en évidence par André *et al.* (en préparation) ne sont pas reprises dans cette contribution, bien qu'il s'agisse de caractéristiques morphologiques. Ainsi la "proportion de maisons unifamiliales" n'est pas reprise car cette notion, correspondant à la proportion de pavillons quatre façades, est impossible à mettre en évidence en pratique dans une analyse cartographique. La notion de "distance à la ville centre" n'est pas non plus retenue car elle suppose un modèle de ville concentrique, ce qui n'est pas toujours le cas. Les indices retenus sont tous indépendants de la structure de la ville. La notion de "position dans un gradient s'éloignant du centre-ville" n'est pas non plus considérée. En effet, cette caractéristique n'est pas indépendante car elle se repose sur la définition des limites des autres zones. Elle n'est donc pas pertinente.

A propos des indices retenus, les commentaires suivants peuvent être formulés:

- Une attention particulière a été portée sur le fait d'éviter l'utilisation d'indices corrélés. En effet, la corrélation statistique entre indices de structure spatiale amène à une redondance d'informations et complique l'interprétation du patron paysager; elle doit donc être évitée (Bogaert et Hong, 2004). Une manière d'éviter ce problème est d'utiliser un nombre limité d'indices se rapportant aux composantes de base de la structure spatiale (Li et Reynolds, 1994; Bogaert *et al.*, 2004).
- Pour le calcul de la distance au plus proche voisin, de l'indice d'agrégation et de l'indice de proximité, c'est la distance bord à bord entre taches qui est considérée et pas la distance entre les points les plus éloignés ou la distance centre à centre. En effet, la considération des deux derniers types de distance pourrait introduire un biais dû à la taille du bâti. Ainsi, deux bâtiments de grande taille situés à égale distance bord à bord l'un de l'autre que deux autres bâtiments de plus petite taille sont considérés comme situés à égale distance, moins éloignés ou plus éloignés l'un de l'autre selon que la première, la deuxième ou la troisième distance est considérée (Bogaert, comm. pers.).
- Les indices paysagers proposés correspondent aux caractéristiques le plus couramment citées par les auteurs selon André *et al.* (en préparation). Toutefois, ces caractéristiques peuvent se révéler non pertinentes ou insuffisantes. Si cela s'avère être le cas, il conviendra de compléter le panel d'indices paysagers permettant la segmentation du gradient urbain-rural.
- On peut se demander si la notion de "continuité de bâti" n'est pas redondante avec celles de "densité de constructions" ou de "dispersion du bâti". En effet, ce sont les mêmes indices de structure spatiale qui permettent de les mettre en évidence. L'utilisation du nombre le plus limité possible d'indices pour la segmentation du gradient est souhaitée dans un souci d'efficacité lors, par exemple, du traitement d'un grand nombre d'images satellitaires.
- Au contraire, les notions de "densité de taches" et de "dispersion spatiale des taches" se rattachent à des notions différentes, comme illustré à la Figure 1.

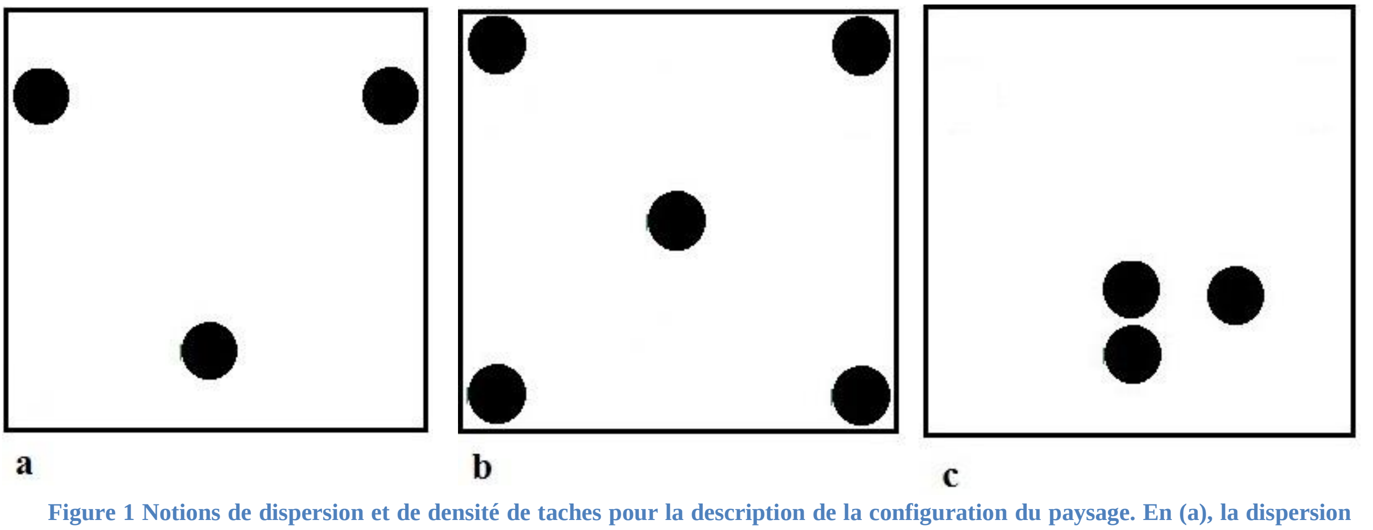

Figure 1 Notions de dispersion et de densité de taches pour la description de la configuration du paysage. En (a), la dispersion des taches est maximale et la densité est de trois taches. En (b), la dispersion est toujours maximale mais la densité est de 5 taches. En (c), la dispersion n'est plus maximale mais la densité de taches vaut de nouveau trois.

Afin de calculer la valeur des indices paysagers, il est important de disposer d'une cartographie des villes (au sens large du terme) suffisamment précise pour mettre en évidence les taches de surface bâtie. Cela dépendra en grande partie de la résolution des images satellitaires sur lesquelles se basera cette cartographie.

La présente contribution se distingue d'autre études similaires par son objectif de segmentation spatiale du gradient. En effet, la plupart des études existant sur le sujet proposent des indices qui permettent d'évaluer le degré de *sprawl* d'une ou plusieurs villes dans un but de comparaison diachronique d'une même ville ou en vue de comparer plusieurs villes entre elles. Toutefois, ces études ne permettent pas une localisation exacte des différentes zones au sein d'une ville (Razin et Rosentraub, 2000; Galster *et al.*, 2001; Davis et Schaub, 2005; Theobald, 2005).

Enfin, il est important de tester les indices dans la réalité afin de vérifier leur pertinence, leur efficacité et la faisabilité de leur mise en œuvre. Suite à ces tests, des seuils critiques pourront être déterminés. Ces seuils permettront de tracer les limites des différentes zones et d'apprécier la gamme des valeurs prises par les seuils pour différents types de villes.

5 ANNEXE : EQUATIONS DES INDICES PAYSAGERS

- Densité des taches (ρ)

$$\rho = n/E$$

où n est le nombre de taches et E la superficie de la zone d'étude

- Distance bord à bord au plus proche voisin (z): distance du bord d'une tache au bord de la tache la plus proche
- Indice d'agrégation de Clark et Evans (R) (Clark et Evans, 1954)

$$R = \overline{z_i}/\overline{r_a} = 2\overline{z_i}\sqrt{\rho}$$

où $\overline{z_i}$ est la distance bord à bord moyenne de chaque tache à son plus proche voisin, calculée comme suit:

$$\overline{z_i} = \sum_{i=1}^{n} r_i/n$$

et où $\overline{r_a}$ est la distance bord à bord moyenne attendue pour une distribution spatiale aléatoire des taches, calculée via la formule:

$$\overline{r_a} = 1/2\sqrt{\rho}$$

- Indice de proximité de Gustafson (PX) (Gustafson et Parker, 1994)

$$PX = \sum_{i=1}^{n} (S_i/z_i)$$

où S est la surface de la tache considérée

- Indice de dominance de Turner (D) (Turner et Ruscher, 1988)

$$D = Hmax - H$$

où $Hmax = \ln M$
avec M le nombre de classes du paysage
et où H est l'indice d'hétérogénéité de Shannon (Shannon et Weaver, 1949) in (Magurran, 2004)

$$H = -\sum_{i=1}^{m} pi \ln pi$$

où pi est la proportion de la classe i en terme de superficie

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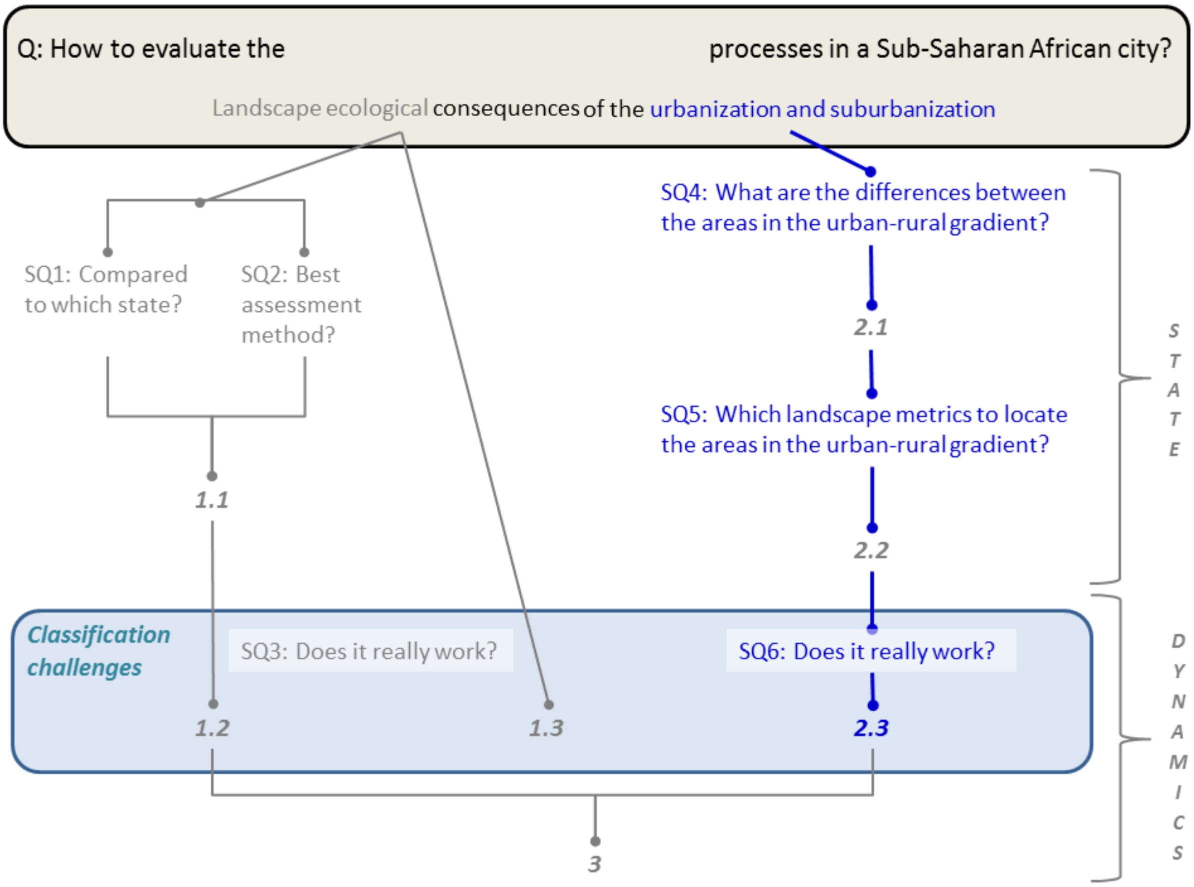
Publication 2.3

How much has that city grown? The case of Lubumbashi (DRC)



Publication 2.3
How much has that city grown? The case of Lubumbashi (DRC)

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Abstract. A precise, quantified and spatially explicit overview of the processes of urbanization and suburbanization as well as of their impact on the adjacent landscapes is critical in order to allow the scientists, landscape architects, urban planners and policy makers to propose the most appropriate responses. Despite this, methodologies to locate accurately the boundaries of the urban, surburban and secondary spatial impact areas (interest areas) are poorly developed. In this study, we evaluate a methodology of delimitation based on polygons adjacencies along with the calculation of the built density metric and its use in a recursive partitioning. We applied it to investigate the effect of a decade of (sub)urban expansion in the region of Lubumbashi (Democratic Republic of Congo), using several classified Landsat images of 2002, 2013 and 2014. The methodology appears promising for the detection of the interest areas. During the decade, the urban area almost quadrupled while the suburban and secondary impact areas increased one and a half time compared to their situation in 2002. However, suburban areas show a highly dynamic comportment with shrinking areas compensating expansion areas. The national road 5 and the relief seem to determine the shape of the secondary spatial impact area while a river strongly slows the urban expansion in the south-west part of the city. The causes and effects of misclassifications, the accuracy of the methodology and the (sub)urban dynamics are then finally discussed.

Keywords. Urban areas; suburban areas; secondary spatial impact areas; spatial footprint; spatial dynamics; Landsat

Introduction

Since human sedentarization coupled with the emergence of agriculture, human impact on natural resources has never ceased to increase (Mazoyer et al., 2002). That impact lead rapidly to the creation then extension and densification of cities through the development of the secondary and tertiary sectors (Mazoyer et al., 2002) coupled to the migration of agricultural populations into the city (Besussi et al., 2010) and eventually demographic self-sustainability (Weeks, 2010). While before 1850, the proportion of the world population living in cities never overtook 6% (World Bank, 1984), nowadays, it is superior to 50% and it is expected that that proportion reaches 66% in 2050 (United Nations, 2015). The distribution of the urban population varies among the world regions but projections show that almost 90% of the rise in the world's urban population by 2050 will take place in the urban areas of Asia (increase by 61%) and Africa (increase by 200%) (United Nations, 2015). Beside the urbanization process, some cities assist to a reverse migration into the countryside (Besussi et al., 2010) leading to the expansion of metropolitan regions through low-density development, phenomenon called suburbanization (Calthorpe, 2011; Hervoët, 2001) or sprawl (Alberti, 2008; Ewing, 1997). These latter are presented as the new model of urban growth (Besussi et al., 2010) and as one of the greatest causes of land-use change of the twentieth century (Forman, 1995; Rudel, 2009).

Beyond the direct impacts of (sub)urbanization, i.e. the space occupied by the human settlements of the city, (sub)urban expansion lead to what will be called in this contribution "secondary spatial impact" on the surrounding rural land cover. The main human activities leading to that secondary spatial impact area are land clearance for agriculture, timber production to satisfy the growing (sub)urban markets demand, wood fuel and charcoal production (that may be a by-product of land clearance or not), mining of materials for building as well as soil pollution resulting from unregulated dumping of urban waste (Clancy, 2008). That secondary spatial impact area could have been called "offsite footprint" (Sonter et al., 2014) but the latest appellation would have been confusing with the broader concept of "footprint" that refers to all the resources consumed and necessary to absorb the waste generated by human societies (Wackernagel et al., 1996).

Furthermore, according to the core hypothesis of landscape ecology, the pattern-process paradigm, the landscape changes part of the urbanization process have undoubtedly consequences on the ecosystems inside the cities as well as in their neighborhood, then in turn on human populations and activities (Bogaert, Ceulemans, et al., 2004; Coulson et al., 1999). The latter direct and mutual relationship between landscape pattern and human activities is conceptualized in the so-called bio-cultural landscape concept (Bogaert et al., 2014; Hong et al., 2014).

In that context, it is essential that scientists, landscape architects, urban planners and policy makers propose the most appropriate responses to the impacts of these urban, suburban and secondary spatial impact areas dynamics (Alberti, 2008; Jaeger et al., 2010b; Ness et al., 2010; Rutherford, 2010). Such a level of relevance is currently difficult to reach due to a lack of precise and quantified overview of the aforementioned processes (Jaeger et al., 2010b). Indeed, if it is of high importance to define and then locate precisely the boundaries of the urban (McIntyre et al., 2000), suburban (Grimm et al., 2003; Macgregor-Fors, 2011, 2010) and secondary spatial impact areas, numerous authors consider such definitions as superfluous and/or implicit (André et al., 2014; McIntyre, 2011). Many authors propose methodologies to describe the urban spatial pattern based on various metrics, often combined. However, none of these methodologies concern the secondary spatial impact area, allow drawing a line between the different areas of the urban-rural gradient, are linked to a specific definition of the areas nor are applied-oriented. Finally, most of them are data demanding, suggest metrics that are correlated and/or depend on spatial resolution (Alberti, 2008; Angel et al., 2007; Batisani et al., 2009; Bhatta et al., 2010; Christensen, 2009; Davis et al., 2005; Feranec et al., 2010; Galster et al., 2001; Glaeser et al., 2001; Hasse, 2004; Jaeger et al., 2010b; Kline, 2000; Martinuzzi et al., 2007; Nelson et al., 1999; Theobald, 2005; Torrens, 2000; Transportation Research Board, 2002). The other few methodologies that avoid these latter pitfalls are either still inadapted to suburban and secondary spatial impact areas (Kasanko et al., 2006) and/or too rigid (Macgregor-Fors, 2010). Both gaps in definitions and localization can result in misinterpretations of the locations of case studies and therefore hamper rigorous comparisons or complementarity between studies (Forstall et al., 2009; Jaeger et al., 2010a; Macgregor-Fors, 2011). The aforementioned problematics are particularly tricky in the poorest countries due to the lack of data and resources to study and monitor the states and dynamics of their cities (Besussi et al., 2010).

A recent review on the characteristics used to define the areas situated in the urban-rural gradient concludes by proposing easily applicable definitions and identifications based upon quantitative-based, integrative, consensual and discriminative criteria or principles (André et al., 2014). Among these criteria, these linked to landscape composition (Turner et al., 2015) are the widest used; they gather the most numerous qualities and contribute to the definition of both urban and suburban areas (André et al., 2014). Use a relevant metric describing the landscape composition and develop adequate thresholds to that metric between the areas of the urban-rural gradient, could therefore represent a consistent way to delineate the urban and suburban areas. Indeed, some authors (André et al., 2014; Weber, 2001) emphasize the fact that when attempting to practically spatially identify these areas at the landscape level, morphological characteristics should be used preferentially through their translation into spatial metrics. Such metrics are commonly used in landscape ecology to quantify the landscape pattern (Herold et al., 2003; McGarigal, 2002); they take advantage of the properties of remote sensing.

Due to the large area coverage and its ability to map inaccessible areas, remote sensing has a tremendous advantage over ground survey methods to provide detailed, accurate, cost-effective and up-to-date information concerning the land use/cover (Congedo et al., 2014; Forkuor et al., 2011; Taubenböck et al., 2009). These characteristics explain why images from earth observation satellites have been gaining always more value to map, monitor and manage earth's resources during the last decades (Forkuor et al., 2011). In the large offer of different satellite images, the Landsat family of satellites offers free archive images since 1972 in combination with a 16 days temporal resolution that allows multi-temporal analysis (Forkuor et al., 2011). These sensors are of particular interest in data-poor regions facing a lack in recent and reliable spatial information (Pham et al., 2011) like countries preparing to face a tremendous urbanization process in the coming years.

In that context, the objectives of this study were (a) to develop a methodology to locate the extent of the different interest areas (urban, suburban, secondary spatial impact area) in a Sub-Saharan landscape, based on morphological characteristics, (b) to evaluate the decadal dynamic of every area and (c) to evaluate the drivers of that dynamic.

Study area

Lubumbashi and its hinterland were chosen as the study area. Indeed, the city's numerous challenges are representative for those currently faced or encountered in a near future respectively by other big cities or developing cities in Sub-Saharan Africa. Lubumbashi is the second economic (Ravelosoa et al., 2009) and the second most populated (United Nations, 2015) city of the Democratic Republic of the Congo. It is situated in the Haut-Katanga province in the Southern part of the country (Fig). The administrative area of the city is 747 km² (Bruneau et al., 1990) for a population of 1,769,400 inhabitants in 2014 (unpublished data from Lubumbashi's Town Hall). Since the beginning of the 20th century, Lubumbashi has developed along with its flourishing mining sector, due to its ideal localization in the Katangese copper belt (Bruneau et al., 1990; Chapelier, 1957). Historically densely built (Bruneau et al., 1990), it is nowadays rapidly growing in an unplanned way. That extensive (sub)urbanization (Groupe Huit, 2009), along with atmospheric deposits of non-ferrous metal particles and associated substances (Vranken et al., 2013) as well as with anthropogenic fire practices

(Malaisse, 2010), lead to landscape anthropisation of the city hinterland. Before its recent anthropisation, the studied landscape was mainly composed of woodland (Malaisse, 2010) as well as, to a lesser extend, of wetlands (Sys, 1960), natural grassland (Sys, 1960; White, 1983) and copper hills (Duvigneaud et al., 1963). Today, the composition of the landscape ranges from continuous built in the most urbanized areas to woodland in the most remote one, passing by bare ground, crops and all the types of anthropogenic savannahs (Malaisse, 2010).

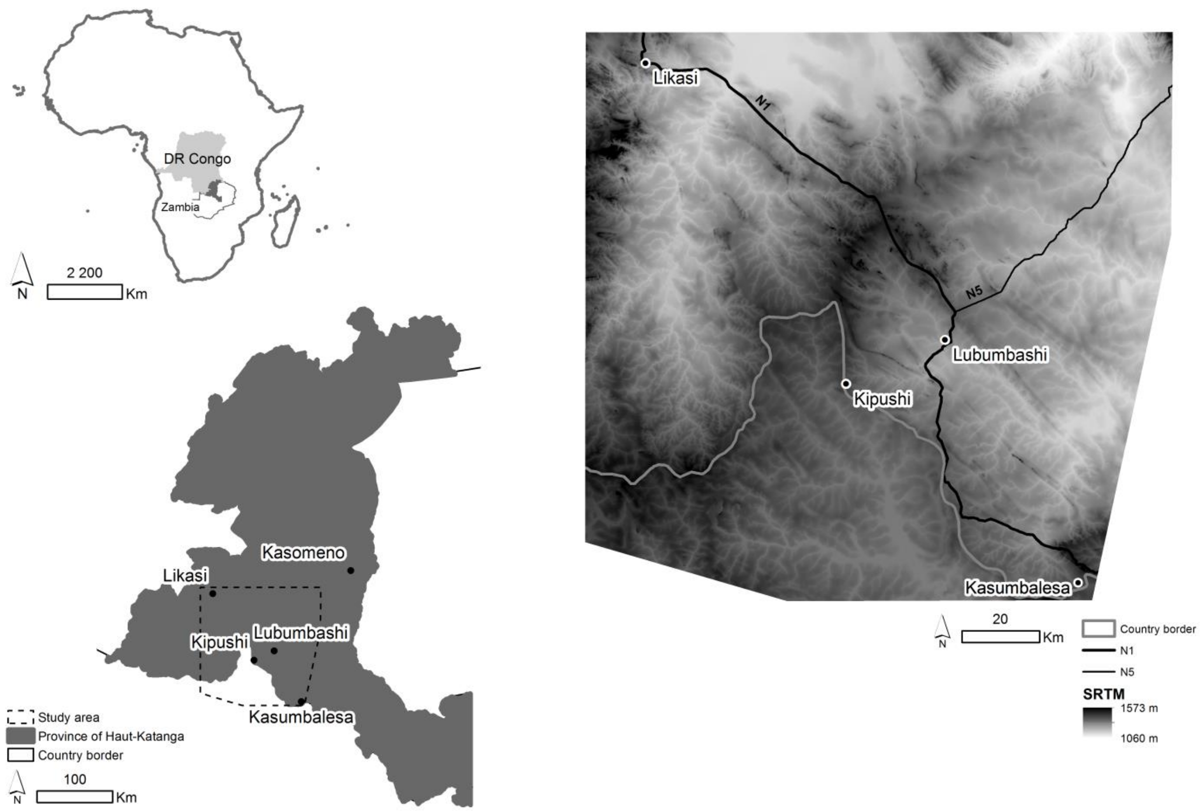

Fig 1. Situation map of the study area: Lubumbashi, its hinterland and the neighbor cities (Province of Haut-Katanga, DRC). The study area corresponds to the intersection of the eight Landsat images used in the study.

Material and methods

Classification of the Landsat images

Our methodology relies on free Landsat ETM+ and OLI multispectral images as well as a free digital elevation model from Shuttle Radar Topography Mission (SRTM) image, all with a 30m spatial resolution (U.S. Geological Survey, 2014a, 2014b). The Landsat images (path = 173, row = 068) were acquired on 2002.05.04, 2002.07.07, 2002.08.08, 2002.10.11, 2013.06.27, 2013.07.13, 2013.08.30 and 2014.11.05. They were radiometrically calibrated and pan-sharped to 15m spatial resolution with the software ENVI 5.0. In order to remove the burned areas on the 2002 and 2013 images, a new composite near infrared (NIR) band was composed from the maximum value of each pixel for the same year. We then recomposed multidate 2002 and 2013 images taking the images of 2002.07.07 and 2013.07.13 as a basis and replacing their NIR band by the maximum filter–originating one.

Once after having operated the pretreatments on the Landsat images, the topographic position index (TPI) measuring the difference between the elevation of each raster cell and the mean elevation (Guisan et al., 1999) within its 1000m radius circular neighborhood was calculated. That index helps highlighting fine topographic differences and was used as a complement to the SRTM layer.

In order to conduct thereafter an object-oriented classification, a segmentation was performed using the Blue, Green, Red, NIR, SWIR 1 and SWIR 2 bands of the Landsat images, the SRTM and TPI of the studied area. A supervised classification based on the nearest sample neighbors (Trimble Documentation, 2013) was then conducted on, on the one hand, the multidate 2002 image with the two topographic layers and, on the other hand, the multidate 2013 image, the 2014 image and the two topographic layers. Both operations were performed using the eCognition© software. That first land cover classification lead to 7 land use/cover classes (LULCC) (Table 1) and was refined with proximity rules to display more information on the hemeroby level of certain classes (Vranken et al., n.d.). First, wetland objects were assumed to be potentially cultivated, at least occasionally, if they shared a part of their border with anthropogenic ones and were in that case assimilated to "anthropogenic herbaceous vegetation". The other were called "natural wetlands". Concerning the "water" class, the objects sharing 20% or more of their borders with other water segments were labeled as "reservoirs" while the others were assigned as "streams". The result of these refinements was a final result of 8 LULCC (Table 1). An hemeroby level was then attributed to each of the final classes to express the measure of the difference between the postulated reference natural state and the current anthropised state in every place of the study area (André et al., n.d.). Due to constraints in their discrimination during the classification process, "woodland, wooded savannah and old fallow" would be a hybrid between the "near-natural" and "semi-natural" hemeroby levels and "savannah, bushland, fallow and anthropogenic herbaceous vegetation" would be a hybrid between the "altered" and "cultural" levels (André et al., n.d.; Rüdisser et al., 2012; Vranken et al., n.d.).

135 training sample points per year were extracted from GoogleEarth© to check the precision of the classification through the evaluation of the Kappa coefficient (Congalton, 1991).

Table 1. Primary and secondary classification of the land use and land cover classes of Lubumbashi and its hinterland (DRC), hemeroby levels corresponding to the classification II.

Classification I	**Classification II**	**Classification II : hemeroby levels**
Natural grasslands and wetlands	Natural grasslands and natural wetlands	Natural
Water		
	Streams	Near-natural
Woodland, wooded savannah and old fallow	Woodland, wooded savannah and old fallow	Near/semi-natural
Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Altered/cultural
	Reservoir	Cultural
Discontinuous built-up and bare ground	Discontinuous built-up and bare ground	Artificial with natural elements
Slag heap	Slag heap	Artificial
Continuous built-up	Continuous built-up	Artificial

Adjustment of the built density thresholds between urban, suburban and rural areas

Among all the landscape metrics proposed to describe the pattern of the urban-rural gradient (André et al., 2012; Bhatta et al., 2010; Brown et al., 2006; Christensen, 2009; Ewing et al., 2002; Forman et al., 1986; Galster et al., 2001; Gustafson et al., 1992; Hasse, 2002; Herold et al., 2003; Parker et al., 2004; Riitters et al., 1996; Sudhira et al., 2007; Whitcomb et al., 1981; Xiulan et al., 2010), we chose to evaluate the efficiency of the "built density" metric (Angel et al., 2007; Hasse, 2002; Kasanko et al., 2006). That landscape composition index represents the percentage of built (i.e. impervious) surface for a given area. As the spatial resolution of our images did not allow for the distinction of individual houses, we hypothetized that continuous and discontinuous built pixels represented respectively an average of 75% and 25% built surface. These values represent, respectively, the middle value of a class ranging from 50% to 100% and from 0% to 50% built surface. The built density of other landscape classes was set to 0%. A built density map was derived using the ArcGIS© software zonal statistics tool with which every pixel in the map was attributed a value corresponding to the mean built density of its 100m radius circular neighborhood.

Alongside this, 799 GPS points were acquired during a field mission in November and December 2012. They identified the urban, suburban and rural areas of the urban-rural gradient according to the decision tree of André et al. (2014) (Bogaert et al., 2015), evaluating its land-use and land-cover composition characteristics in a 100m radius neighborhood. The rurban area could not be identified due to a lack of data on commuting comportments. The definition of the sprawl area was practically difficult to implement and was therefore omitted. Concerning the terms "dominate" and "not exclusively" used in the definitions, 1) a situation of domination was identified when the proportion of the built surface exceeded 50% and 2) "not exclusively" was interpreted as inferior to 75%. 132 GPS points (17%) were acquired in urban areas, 98 (12%) in suburban areas and 569 (71%) in rural areas.

Ten recursive partitionings (Breiman, 1984) were completed using the R© software, rpart package (Therneau, Atkinson, & Ripley, 2015), Gini rule for splitting (Therneau, Atkinson, & Mayo Foundation, 2015), to match the built densities of 2013/14 and the GPS points, in order to adjust the built density thresholds between the urban, suburban and rural areas in the urban-rural gradient. Alike the evaluation of the classification, the precision of each of the recursive partitioning was evaluated through the calculation of the Kappa coefficient (Congalton, 1991). The set of built density thresholds corresponding to the Kappa maximum was retained. If that set corresponded to different Kappa, an average Kappa was calculated. The set of built density thresholds of 2013/14 was then applied to the built density map of 2002.

Delimitation of the secondary spatial impact, suburban and urban areas of Lubumbashi

First, the anthropised neighbourhood of Lubumbashi has been identified as the aggregation of the adjacent polygons centered on Lubumbashi corresponding to the classes associated with the "altered", "cultural", "artificial with natural elements" and "artificial" hemeroby levels.

Secondly, the urban and suburban areas of other peripheral cities than Lubumbashi, such as Likasi and Kasumbalesa, have been excluded from the analysis by only considering the extent of the secondary spatial impact area centred on Lubumbashi.

Finally, the secondary spatial impact area of Lubumbashi has been deduced as its anthropised neighbourhood net of its urban and suburban areas.

Results

The Kappa coefficients obtained for the classification of 2002 and 2013/14 are respectively 0.73 and 0.63 (see Appendix); those for the recursive segmentation are 0.68 (max. value) and 0.51 (average value for that set of thresholds). All these values are referred as "good" by Landis and Koch (1977), except the average value of the recursive partitioning which was referred as "moderate". The recursive segmentation showed that the rural, suburban and urban areas are characterized respectively by a built density threshold inferior to 21.1%, between 21.1% (included) and 49.7% (excluded) and superior to 49.7%.

The Fig 2 shows the urban, suburban and "secondary spatial impact" areas in the neighborhood of Lubumbashi in 2002 and 2013/14. It appears that from the beginning of the study period, the city of Kipushi, situated in the south-west neighborhood of Lubumbashi, is part of the secondary spatial impact area of Lubumbashi. However, during the last decade, it has unquestionably gained importance, with the emergence of a new proper urban area. Concerning the shape characterizing the expansion of the different interest areas, the one of the secondary spatial impact area seems determined by the recently asphalted (2009-2011) national road 5 leading to Kasomeno. Those of the suburban and urban areas behave in an approximatively concentric way, except in the south-west part of the city where their expansion is strongly limited.

The examination of the net areas increases (Table 2) shows that urban area was 26.3 km² in 2002 and 100 km² in 2013/14, representing a net increase of 280% regarding its surface in 2002. Suburban areas represented 115.2 km² in 2002 and 191.9 km² in 2013/14, a net increase of 67% compared to 2002. Secondary spatial impact areas increase from 1293.3 km² to 2009.5 km² in 2013/14, a net increase of 55% compared to 2002. Urban areas appear therefore to grow four to five times faster than the other areas which have similar growth rates. The ratio between urban and suburban areas more than doubled, growing from 0.23 in 2002 to 0.52 in 2013/14. It should be noted that if the secondary spatial impact areas and suburban areas have similar net increases, their dynamics are different. Secondary spatial impact areas show the highest unchanged rate (26%) while the high expansion rate of the suburban areas (58%) is compensated by their significant shrinking rate (29%) (Table 3). Finally, 45% of the increase of urban areas took place in previous suburban areas and the remaining 55% in previous rural areas.

Table 2. Net surface increases between 2002 and 2013/14, compared to the surfaces in 2002, of the different areas (urban, suburban, secondary spatial impact) corresponding to the city of Lubumbashi (DRC).

	Area 2002 (km²)	**Area 2013/14 (km²)**	**Net increase (km²)**	**Net increase (% 2002)**
Urban	26.3	100.0	73.7	280
Suburban	115.2	191.9	76.7	67
Secondary spatial impact	1293.3	2009.5	716.3	55

Table 3. Dynamics between 2002 and 2013/14, compared to the surfaces in 2002, of the different areas (urban, suburban, secondary spatial impact) corresponding to the city of Lubumbashi (DRC).

	Gained (%)	Unchanged (%)	Lost (%)
Urban	75.6	17.2	7.2
Suburban	57.5	13.2	29.2
Secondary spatial impact	50.7	25.8	23.5

Figure 3. Fig 2. Urban, suburban and “secondary spatial impact” areas in the neighborhood of the city of Lubumbashi (DRC) in 2002 (to the left) and in 2013/14 (to the right).

Discussion

Concerning the discrimination on the field between the suburban and rural areas, few borderline situations were encountered; land cover and/or use were in most case clearly dedicated to agriculture, forestry or nature, or not at all.

Four factors have been very challenging in the classification process: the medium spatial resolution, the context of urban areas aggravated by the necessity of the identification of the discontinuous built-up class as well as the context of developing country. These factors have lead to several practical issues: firstly, the medium spatial resolution of the images induces a generalization within each pixel and therefore a loss of information, the pixels may no longer be representative of the whole pixel area (issue also known as the "mixel" problem) (Pham et al., 2011). That issue is exacerbated when trying to classify the heterogeneous continuous built class, and even more problematic when dealing with low built density discontinuous built: in that latter case, classification algorithms assimilate the discontinuous built to the landscape background, ranging from bare ground to herbaceous vegetation. For that reason, bare ground has a very similar spectral signature to built-up areas (Congedo et al., 2012). On the other hand, there exists a correlation between spatial and temporal scales and the medium spatial resolution appears most appropriate for the extent and temporality of this study (Burel et al., 1999). Increasing spatial resolution may also lead to a rise of the noise in the data complicating the interpretations (Mesev, 2003). Secondly, African spatial structure is loose compared to the one of Northern countries: land cover/use patches are less clearly delimited likely because of different land planning practices, adjacent one may be confounded (Vranken et al., 2013). Moreover, land cover/use represents often transition states in a regressive or progressive process. Therefore, analysts and the classification algorithms may determine differently the thresholds between borderline land covers, leading to virtual misclassifications (André et al., n.d.). On the other hand, the modification of the NIR band could also have induced a loss of spectral information for the classes dominated by vegetation.

In particular, the mutual confusion between the classes "savannah, bushland, young fallow and anthropogenic herbaceous vegetation" and "woodland, wooded savannah and old fallow" (see Appendix) may have led to a secondary spatial impact shape slightly different from the real one. On the other hand, the "continuous built" land cover seems to have been somewhat overestimated in 2013/14 to the detriment of the "discontinuous built and bare ground" class (Appendix). The latter confusion may in turn have led to an overestimation of the built densities thresholds separating the different interest areas. Most authors working in the same context bypass that issue by regrouping the continuous and discontinuous built classes (Zhang et al., 2011) or even sometimes the bare ground (Griffiths et al., 2010; Toyi et al., n.d.) in one single class. The global accuracies obtained in this study are slightly lower (Forkuor et al., 2011) or higher (Congedo et al., 2012) than accuracies obtained by other authors working in a very similar context and highlighting the discontinuous built class.

Concerning the recursive segmentation, the accuracy would probably have risen if the sampling effort would have been more uniformly distributed between the different areas. The choice of assuming that built densities separating the different interest areas were equal in 2002 and 2013/14 should also be kept in mind when considering the results, especially given the upper considerations on the continuous built class overestimation in 2013/14. The built densities thresholds characterizing the different areas of interest correspond to the thresholds sometimes detailed in the literature (Angel et al., 2007; Kazmierczak et al., 2010; Macgregor-Fors, 2010; Marzluff et al., 2001; McKinney, 2008). Nevertheless, in view of the aforementioned frequent dependence of metrics on the spatial resolution (Bhatta et al., 2010), a sensitivity study of the thresholds to different spatial resolutions of images could prove useful. Among all the landscape metrics available, the choice of the built density appears to be an efficient choice for that kind of data. However, the combination of built density with a configuration (Turner et al., 2015) metric could correspond better to the definition of the urban areas given by André et al. (2014) and therefore increase the accuracy of the identification of these areas.

The shape of the secondary spatial impact area may significantly change when some key pixels convert from “altered”, “cultural”, “artificial with natural elements” and “artificial” hemeroby levels to “natural”, “near-natural” or “semi-natural”. Indeed, our methodology is based on polygons adjacency. That consideration, along with the confusion between the classes “savannah, bushland, young fallow and anthropogenic herbaceous vegetation” and “woodland, wooded savannah and old fallow” could explain why this study did not evidence an expansion of the secondary spatial impact of the city more in the north-west direction, along the national road 1 leading to the city of Likasi. Indeed, the latter transportation axis is of major importance for the mining economy sector of Lubumbashi (Bruneau et al., 1990). Another explanation may be the less favorable topography (higher elevations) in the Northwestern area around the city (Fig).

The results of this study show anyway an important influence of the national road 5, on the secondary urbanization dynamics of Lubumbashi. That result is consistent with the study of Vranken et al. (2011) which highlighted a high level of deforestation rate on the Northeast axis. That behavior corresponds to the linear/transport-corridors development model (Forman, 2008), similarly to urbanization patterns in U.S. and European cities (Brück, 2002; Ewing, 2008; Grosjean, 2010). Specific impact of road system development is well known as an important driver of anthropogenic pattern change (Bamba et al., 2010; Forman, 1995; Vranken et al., 2011). The urbanization and suburbanization dynamics seem rather to correspond to a concentric-rings model (Forman, 2008) except in the south-west where an affluent of the Kafubu river and its corresponding wetland areas have till now prevented the expansion of the urban area. If the important increase rate of the urban area seems to indicate a spatial densification of Lubumbashi's city center, these results should be put into perspective of 1) the appearance of an urban area in the city of Kipushi (the results show that the global densification corresponds partly to an increase of building density and partly to dense new built areas) and 2) the comparison between the growth rate of the urban and suburban area (+ 116.34%) and of the population (+ 55%) both for the administrative entity of Lubumbashi, which indicates a population dedensification of the city.

The methodology proposed here highlighted secondary spatial impact of (sub)urbanization, but does not provide a complete picture of the anthropogenic processes in the area. Indeed, perforation, dissection, fragmentation, shrinkage and attrition processes are linked to land-cover degradation (Bogaert, Ceulemans, et al., 2004) and may affect the area of the natural, near-natural and semi-natural landscape classes but may not lead to a change in the shape of the secondary spatial impact area.

In any case, the methodology proposed here is based on consistent, quantitative-based, consensual and discriminative-based definitions of the interest areas (André et al., 2014). It allows the detection of the urban, suburban and secondary spatial impact areas and appears to be a promising, non expensive way of monitoring and comparing the evolution of cities in countries suffering from a lack of data and means. Our methodology is based on the reality on the ground and jibes probably more with the spatial reality than other inflexible methodologies (Macgregor-Fors, 2010). This is of particular importance in the context of urban spread which can expand on important surfaces in unexpected ways (Besussi et al., 2010).

However, an in-depth understanding of the (sub)urbanization drivers and processes that could lead to the most appropriate responses from planners and decision makers would require a complement of spatially explicit socioeconomic data (Besussi et al., 2010; McIntyre, 2011).

Conclusion

A methodology was proposed to locate the extent of the urban, suburban and secondary impact area of the city of Lubumbashi and showed good results. The rural, suburban and urban areas are characterized respectively by a built density threshold inferior to 21.1%, between 21.1% (included) and 49.7% (excluded) and superior to 49.7%. During the last decade, the dynamics of the secondary spatial impact seems to have been determined by the national road 5 leading to Kasomeno and a favorable relief. The suburban and urban areas of Lubumbashi have grown in an approximatively concentric way except in the south-west direction where a river and the associated wetland areas have prevented the expansion of the city. The urban area has grown four to five times faster than the other areas, mainly due to a densification of the city centers of Lubumbashi and Kipushi. The secondary spatial impact area and the suburban area have similar growth rates but the suburban area shows a highly changing comportment. The methodology to highlight the secondary spatial impact area is though highly dependent on the precision of the classification.

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List of abbreviations

DRC: Democratic Republic of the Congo

ETM+: Enhanced Thematic Mapper Plus

LULCC: land use/cover classes

NIR: near infrared

OLI: Operational Land Imager

SRTM: shuttle radar topography mission

SWIR: short-wave infrared

TPI: topographic position index

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Appendix

Table 4. Confusion matrix for the classification of the 2002 Landsat image of Lubumbashi (DRC)

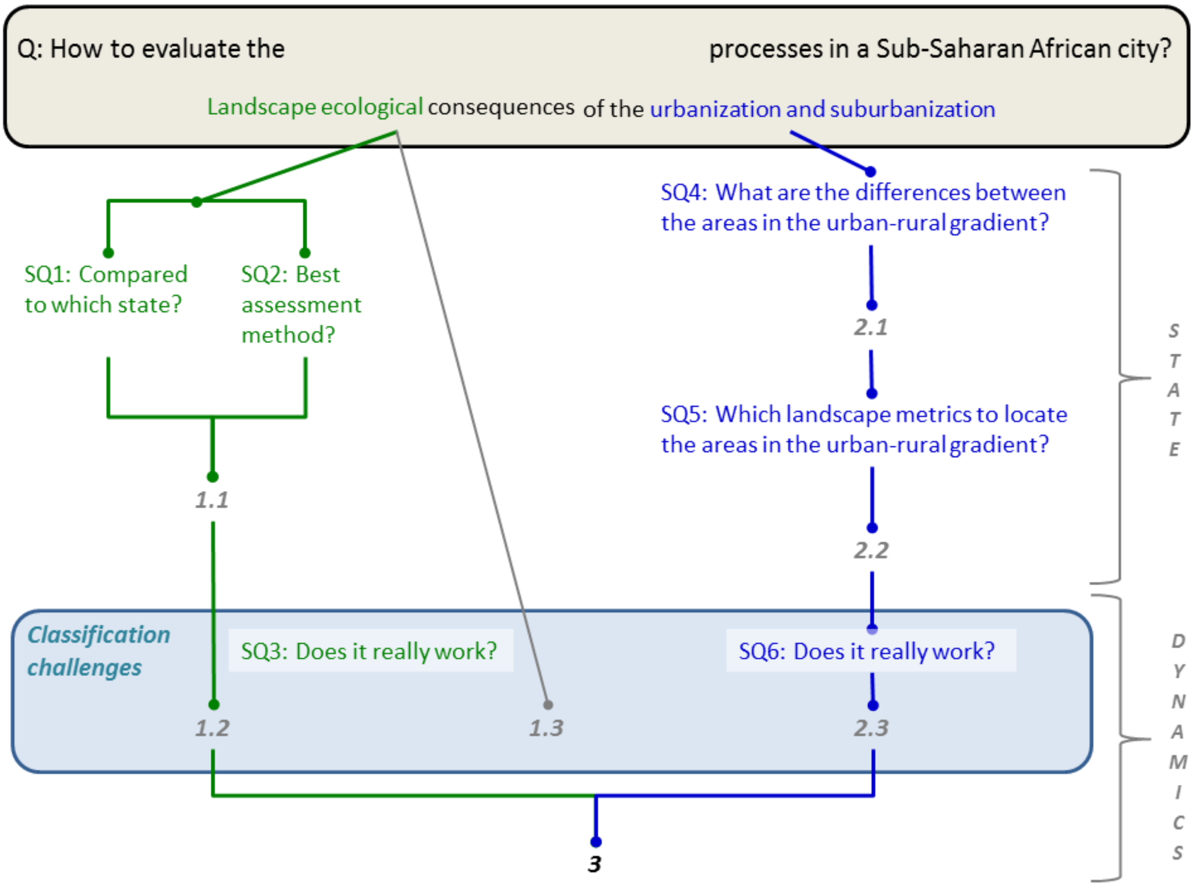
Classified data	Reference data						User's accuracy (%)
	Continuous built-up	Discontinuous built-up and bare ground	Natural grasslands and wetlands	Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Water	Woodland, wooded savannah and old fallow	
Continuous built-up	10						100.0
Discontinuous built-up and bare ground	3	24					88.9
Natural grasslands and wetlands		2	21	2			84.0
Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	1	2	5	9	1	3	42.9
Water					14		100.0
Woodland, wooded savannah and old fallow	1	2	4	4		27	71.1
Producer's accuracy (%)	66.7	80.0	70.0	60.0	93.3	90.0	
Overall accuracy: 77,8%; Kappa statistic: 0,73							

Table 5. Confusion matrix for the classification of the 2013/14 Landsat image of Lubumbashi (DRC)

Classified data	Reference data						User's accuracy (%)
	Continuous built-up	Discontinuous built-up and bare ground	Natural grasslands and wetlands	Savannah, bushland, young fallow and anthropogenic herbaceous vegetation	Water	Woodland, wooded savannah and old fallow	
Continuous built-up	12	6	2	1	1		54.5
Discontinuous built-up and bare ground	2	24					92.3
Natural grasslands and wetlands			17	1	1	1	85.0
Savannah, bushland, young fallow and anthropogenic herbaceous vegetation			3	7	2	4	43.8
Water			1		9		90.0
Woodland, wooded savannah and old fallow	1		7	6	2	25	22.0
Producer's accuracy (%)	80.0	80.0	56.7	46.7	60.0	83.3	
Overall accuracy: 69,6%; Kappa statistic: 0,63							

Publication 3

Le patron urbain, un facteur influençant l'impact de l'urbanisation sur les écosystèmes : les cas de Kisangani et de Lubumbashi (RDC)



Le patron urbain, un facteur influençant l'impact de l'urbanisation sur les écosystèmes : les cas de Kisangani et de Lubumbashi (RDC)

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1. Introduction

La problématique de l'urbanisation en Afrique sub-saharienne

Depuis sa sédentarisation couplée à l'apparition de l'agriculture, puis la création et l'extension des villes, l'homme n'a cessé d'accroître son empreinte sur les ressources naturelles [6]. Alors qu'avant 1850 la proportion de la population mondiale vivant dans un environnement urbain n'avait jamais dépassé 6%, il est attendu que ce pourcentage atteigne 70% en 2050 [9, 8]. La répartition de population urbaine varie selon les régions géographiques mais il est entendu que cet accroissement aura principalement pour origine l'augmentation de la population dans les communautés urbaines les plus pauvres d'Afrique sub-saharienne, d'Asie du Sud et du Moyen Orient. L'étude des espaces qui ceinturent ces villes, le phénomène de leur extension dans les régions rurales ainsi que les schémas conceptuels de leur morphologie et dynamique interne sont dès lors plus que jamais des sujets d'actualité [3].

Objectifs de l'étude

Dans cette étude et dans ce contexte d'urbanisation, nous nous sommes intéressés à la dynamique de deux villes de République Démocratique du Congo (RDC) : Lubumbashi et Kisangani.

Les objectifs de cette étude sont doubles :

1) Cartographier et quantifier la dynamique des différentes zones (rurale, périurbaine et urbaine) constituant le gradient urbain-rural au cours de la dernière décennie.
2) Quantifier l'effet sur les écosystèmes d'une décennie de croissance urbaine et périurbaine.

Notre analyse s'est basée sur l'écologie du paysage ; discipline utilisant des indices de composition spatiale pour décrire le patron paysager en quantifiant la présence et le nombre de taches issues des différentes classes du paysage [1]. Cette étude se distingue donc des autres, subjectives, par son approche quantifiée et objective.

2. Matériel et méthode

Les villes étudiées sont respectivement les deuxième et troisième villes économiques de la RDC. Elles sont contrastées par leur localisation au sein de la RDC, le type de climat qui découle de cette localisation (sud-est pour Lubumbashi avec un climat subtropical humide, nord-est pour Kisangani avec un climat équatorial), le nombre d'habitants (estimé respectivement à 1 800 000 habitants en 2013 pour Lubumbashi et à 1 300 000 en 2011 pour Kisangani) ainsi que le type d'activités économiques (forte présence des secteurs industriel et minier à Lubumbashi).

Pour chacune des deux villes, des images multispectrales SPOT 5 ont été utilisées. Pour la ville de Lubumbashi, les images choisies étaient datées du 16/07/2002, du 18/06/2008, du 17/05/2009 et du 28/05/2009 (ces trois dernières ayant été regroupées sous forme d'une mosaïque afin de couvrir toute la zone d'intérêt). Pour Kisangani, les images choisies étaient datées du 28/12/2002 et du 02/03/2010. Elles ont été calibrées puis classifiées sur base d'une approche orientée-objet à l'aide du logiciel Definiens et d'une classification supervisée [4].

Une série de post-traitements ont ensuite été réalisés à l'aide des logiciels Arcgis, Excel et R afin de localiser précisément les zones rurale, périurbaine et urbaine dans le gradient urbain-rural puis de mettre en évidence les dynamiques des deux villes durant la décennie. Ainsi, la proportion des taches de surface bâtie dans le voisinage de chaque pixel a été établie. Une segmentation récursive entre la densité de bâti et des points de terrain classés par zones (rurale, périurbaine ou urbaine) selon l'arbre à décisions établi par André et al. [2] a permis d'identifier les seuils de densité de bâti séparant les différentes zones, d'établir une carte illustrant ces zones et d'observer les dynamiques opérées au cours de la décennie [7]. Enfin, la répartition des classes d'occupation du sol dans la surface d'expansion des zones urbaine et périurbaine a été examinée afin de mettre en évidence les classes d'occupation du sol les plus impactées par la croissance et la densification de ces deux villes.

Résultats

La segmentation récursive réalisée a montré que les zones rurale, périurbaine et urbaine de Lubumbashi sont caractérisées respectivement par une densité de bâti inférieure à 23 %, comprise entre 23 et 48% et supérieure à 48%. Les valeurs des seuils pour Kisangani sont respectivement de 22% et 57%. On voit donc que le seuil pour définir la zone rurale est presqu'identique pour les deux villes alors que la limite supérieure de densité de bâti de la zone périurbaine est plus élevée à Kisangani.

En termes de surfaces, ces différentes zones couvraient en 2008 pour Lubumbashi, en pourcentage de la totalité de la zone : 94.4% pour la zone rurale, 2.3% pour la zone urbaine et 3.3% pour la zone périurbaine. Ces surfaces correspondent respectivement à une diminution de 2%, une augmentation de 33.6% et une augmentation de 69.1% de ces zones par rapport à leur surface en 2002. Pour Kisangani, les différentes zones couvraient en 2010: 97.5% pour la zone rurale, 1.6% pour la zone urbaine et 0.9% pour la zone périurbaine, ce qui correspond respectivement à une diminution de 0.3%, une augmentation de 22.1% et une diminution de 0.4% de ces zones par rapport à leur surface en 2002. Au cours de la dernière décennie, on remarque que Lubumbashi a connu un phénomène d'extension de sa zone périurbaine et dans une moindre mesure de sa zone urbaine. Dans le cas de Kisangani, l'urbanisation et *a fortiori* la périurbanisation ont été nettement moins marquées.

En ce qui concerne la répartition des classes d'occupation du sol dans la surface d'expansion des zones urbaine et périurbaine (en % de la surface totale d'expansion), pour Lubumbashi, les classes sur lesquelles ces deux zones se sont principalement étendues totalisent 91% de la surface d'expansion et sont : 1) les surfaces soumises au feu, 2) les zones de bâti discontinu et de sol nu, 3) les champs, jeunes jachères, savanes herbacées, arbustives et arborées et 4) les zones de bâti continu. Pour Kisangani, ce sont 1) les zones de champs, jeune jachère et bambous, 2) les zones de bâti continu et 3) les zones de bâti discontinu et de sol nu qui constituent les principales classes impactées par l'extension urbaine et périurbaine en totalisant 87% de la surface d'expansion. On voit que dans les deux cas, les classes les plus impactées sont celles qui étaient déjà fortement anthropisées en 2002.

3. Discussion

Ces résultats mettent pour la première fois en application les définitions de zones présentes dans le gradient urbain-rural proposées par André et al. [2]. Couplée à un travail de terrain, on voit que cette méthode permet de mettre en évidence les différentes zones et d'en suivre l'évolution. Toutefois, comme la méthode se base sur la densité de surface bâtie, afin que les résultats soient satisfaisants, il est important que la classification des surfaces bâties soit de bonne qualité sous peine d'induire des erreurs en chaine. La segmentation récursive nécessite également un nombre suffisant de points de terrain pour identifier avec une précision suffisante les seuils de densité de bâti permettant de différencier les différentes zones. Dans ce cas-ci, la moyenne des précisions utilisateur et producteur pour la mise en évidence des zones de bâti continu et de bâti discontinu est de 78.5 % pour Lubumbashi et de 58.3% pour Kisangani. D'autre part, pour Lubumbashi, la segmentation récursive et son évaluation ont été effectués sur base de 636 points de terrain alors que l'opération sur Kisangani n'a été réalisée qu'à partir de 116 points de terrain. Les résultats concernant Kisangani sont donc à nuancer. Malgré cela, le coefficient Kappa κ (estimateur de précision compris entre 0 –pour une précision minimale- et 1 –pour une précision maximale) relatif à la segmentation récursive indique une précision « très bonne » pour Lubumbashi (κ = 0.83) et « bonne » pour Kisangani (κ = 0.79) si l'on se réfère aux catégories proposées par Landis [5].

4. Conclusion

Les résultats montrent que les seuils permettant de différencier les différentes zones du gradient urbain-rural sont similaires pour les deux villes bien que celles-ci soient fort différentes l'une de l'autre. D'autre part, bien que l'urbanisation et la périurbanisation soient plus fortes à Lubumbashi qu'à Kisangani, les classes impactées par ces deux phénomènes sont similaires pour les deux villes et correspondent à des classes déjà fortement anthropisées.

5. Remerciements

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