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Research article

Multi-temporal monitoring of a regional riparian buffer network (>12,000 km) with LiDAR and photogrammetric point clouds

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ABSTRACT

Riparian buffers are of major concern for land and water resource managers despite their relatively low spatial coverage. In Europe, this concern has been acknowledged by different environmental directives which recommend multi-scale monitoring (from local to regional scales). Remote sensing methods could be a cost-effective alternative to field-based monitoring, to build replicable "wall-to-wall" monitoring strategies of large river networks and associated riparian buffers. The main goal of our study is to extract and analyze various parameters of the riparian buffers of up to 12,000 km of river in southern Belgium (Wallonia) from three-dimensional (3D) point clouds based on LiDAR and photogrammetric surveys to i) map riparian buffers parameters on different scales, ii) interpret the regional patterns of the riparian buffers and iii) propose new riparian buffer management indicators. We propose different strategies to synthesize and visualize relevant information at different spatial scales ranging from local (<10 km) to regional scale (>12,000 km). Our results showed that the selected parameters had a clear regional pattern. The reaches of Ardenne ecoregion have channels with the highest flow widths and shallowest depths. In contrast, the reaches of the Loam ecoregion have the narrowest and deepest flow channels. Regional variability in channel width and depth is used to locate management units potentially affected by human impact. Riparian forest of the Loam ecoregion is characterized by the lowest longitudinal continuity and mean tree height, underlining significant human disturbance. As the availability of 3D point clouds at the regional scale is constantly growing, our study proposes reproducible methods which can be integrated into regional monitoring by land managers. With LiDAR still being relatively expensive to acquire, the use of photogrammetric point clouds combined with LiDAR data is a cost-effective means to update the characterization of the riparian forest conditions.

1. Introduction

Riparian buffers are fundamental landscape features supporting numerous ecosystem services: stream bank stabilization, reduction of sediment and nutrient contamination, aquatic and terrestrial habitat improvement, and recreational and educational opportunities (Naiman et al., 2005). In terms of biodiversity, riparian buffers are exceptionally rich. They form ecotones, located at the intersection of land and water, and present higher (bio)diversity than the two ecosystems considered separately (Naiman and Décamps, 1997). As ecological corridors, they provide crucial aquatic and terrestrial habitats for migrating birds and terrestrial animals (Darveau et al., 2001; Decamps et al., 1987), as well as for plants (Johansson et al., 1996). For all these reasons, riparian buffers represent a major concern for land and water resource managers despite their relatively low area of coverage.

In Europe, the major importance of riparian buffers has been acknowledged by the Habitats Directive and the Water Framework Directive (WFD) (European Council, 2000). These European directives involve multi-scale monitoring activities (local to regional scales) in order to assess the success of previous management actions or existing policies and to target restoration activities when needed (Birk et al., 2012). Monitoring is based on measurable attributes describing the conditions of riparian buffers conditions and the ability to carry out their functions (Innis et al., 2000). For the WFD, monitoring combines observable physical, chemical, and biological attributes which are the indicators of the ecological state of waterbodies (Hering et al., 2010).

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Because of the linear shape of riparian buffers, field-based monitoring involves high manpower costs and time-consuming travel which decrease the sampling intensity and thus the accuracy of results (Debruxelles et al., 2009; Munné et al., 2003; Myers, 1989). Remote sensing methods can help to build cost-effective and replicable “wall-to-wall” monitoring strategies, notably based on land use/cover proxies (Apan et al., 2002; Lalande et al., 2014). Remote sensing approaches are especially effective when the scale is regional (>200 km of river) (Johansen et al., 2007). The increasing availability of very high resolution satellite imagery (IKONOS, QuickBird, GeoEye-1, Pléiades) and aerial LiDAR data can be used for a detailed description of the environment at the regional scale (Alexander et al., 2014). In the case of riparian buffers, the development of regional approaches must integrate adapted geomatics procedures in order to take into account the connectivity between the elements of the network (Alber and Piégay, 2011; Roux et al., 2014; Van Looy et al., 2013).

High-density point clouds (>10 points/m^2) of LiDAR data can provide a three-dimensional (3D) view of riparian buffers. With this 3D information, it is possible to extract and map important physical characteristics of riparian buffers such as water surface, valley bottom, or near-stream topography (Demarchi et al., 2016; Michez et al., 2013). LiDAR data can also provide important information about the riparian forests, notably through the use of very high resolution Canopy Height Models (CHM, < 1 m GSD) (Johansen et al., 2010; Michez et al., 2013; Lallias-Tacon et al., 2016). CHMs are usually stored as raster data describing the height of the forest potentially over a large area. Although previous studies have demonstrated the potential of high-density LiDAR data, such surveys are relatively high-cost and associated with small-scale studies.

High-density photogrammetric point clouds can be a cost-effective alternative to LiDAR data for the generation of high-resolution CHM. They can be derived from stereo-aerial images acquired for regional orthophoto coverage (relatively frequent in Europe) and thus provide 3D data with no supplementary acquisition cost. Considering that the ground topography is constant for the period of analysis, a high-quality LiDAR Digital Terrain Model (DTM) can be used to normalize photogrammetric Digital Surface Models (DSM) derived from more recent surveys. The subtraction of a LiDAR DTM from a more recent photogrammetric DSM allows building ‘hybrid’ CHMs with half or one-third the cost of a LiDAR survey (White et al., 2013).

Michez et al. (2014) described the use of such hybrid CHM (photogrammetric DSM - LiDAR DTM) analyzed simultaneously with the low-density LiDAR DTM data to characterize the physical parameters and forest conditions of riparian buffers. That first case study focused on the development of the methods for an automated characterization of riparian buffers of ca. 500 km of river network. Building upon that study, the present study intends to characterize the riparian buffers associated with the entire river network of Wallonia (southern Belgium) managed by public administration. The main goal is to provide accurate information about the physical parameters (mainly the channel width and emerged depth) and forest conditions (height, longitudinal continuity, water accessibility) of riparian buffer to highlight their regional variability and explore the factors controlling it. More specifically, our study intends to i) map riparian buffer parameters on a regional and a local scale (e.g. single waterbody of the Water Frame Directive), ii) interpret the regional patterns of the riparian buffers in the light of potential human activities and iii) propose new riparian buffer management indicators.

This first overview of the conditions of the riparian buffers at the regional scale (>12,000 km of river length) can be used by public administrators (in particular river managers) in Wallonia to plan and target river and riparian buffer management. As Wallonia is implementing a six-year regional action plan starting in 2016, this study will provide monitoring tools for mid-term and end-of-term evaluations of the efficiency of the action plan.

2. Material and methods

2.1. Study site

The study site is the publicly managed river network in southern Belgium (Wallonia). Wallonia covers an area of 16,902 km^2 (ca. 55% of Belgium's area) with a river network of 12,054 km (drainage area >1 km^2). The study site was chosen due to the availability of concomitant high quality remote sensing data.

Wallonia has contrasted landscapes and can be divided into five natural ecoregions (Fig. 1A and B, Table 1). These five ecoregions have been delimited according to pedological, botanical, and agro-ecological criteria by Noirfalise (1988). The Loam and the Condroz ecoregions include intensive agricultural and industrial activities combined with high human population density. The Ardenne ecoregion is characterized by mostly forested landscapes with relatively low population density. In contrast, the Belgian Lorraine and the Famenne ecoregions have a rural landscape.

The study area mainly drains into two major rivers: the Meuse and the Escaut rivers. The Escaut basin is relatively homogeneous and located in the Loam ecoregion, with an open landscape dominated by agricultural activities. The Meuse basin is more heterogeneous and its rivers flow over the 5 ecoregions of the study area.

2.2. Remote sensing data

We combined LiDAR and photogrammetric point clouds to characterize the riparian buffers in Wallonia. More specifically, we computed two reference CHMs at the regional scale to delineate the riparian forest.

Small footprint airborne LiDAR data was captured with an average point density of 0.8 points/m^2 (Table 2). The survey was conducted during leaf-off conditions, from December 12, 2012 to April 21, 2013 and from December 20, 2013 to March 9, 2014. The main goal of this survey was to cover the study area with a regional Digital Terrain Model (1 m GSD, Ground Sampling Distance). The data provider also computed a Digital Surface Model (DSM) at the same resolution.

We used raw images (VEXCEL UCX camera) from two regional orthophoto datasets of the study area to generate two high-density photogrammetric point clouds. The first survey flights occurred between April and September in 2009 and 2010 (side and front overlap: 33% and 66%). The second regional survey took place at the same time window in 2012 and 2013 (same overlap as 2009–2010 survey). The mean resolution of the two final orthophoto coverages (which were not used in this study) was 0.25 m GSD.

2.3. Processing remote sensing data

2.3.1. Computing two reference Canopy Height Models

We estimated the riparian forest height for a 3-year interval (2009–2012) using two reference CHMs, based on LiDAR and photogrammetric point clouds.

We used Agisoft PhotoScan (http://www.agisoft.com/) to compute photogrammetric point clouds from raw aerial images initially captured for two regional orthophoto coverages of Wallonia. The dense matching was run on tiled projects (4 km^2), computing the dense cloud at the ‘high’ level of quality.

The density of the regional LiDAR survey was too low in one-

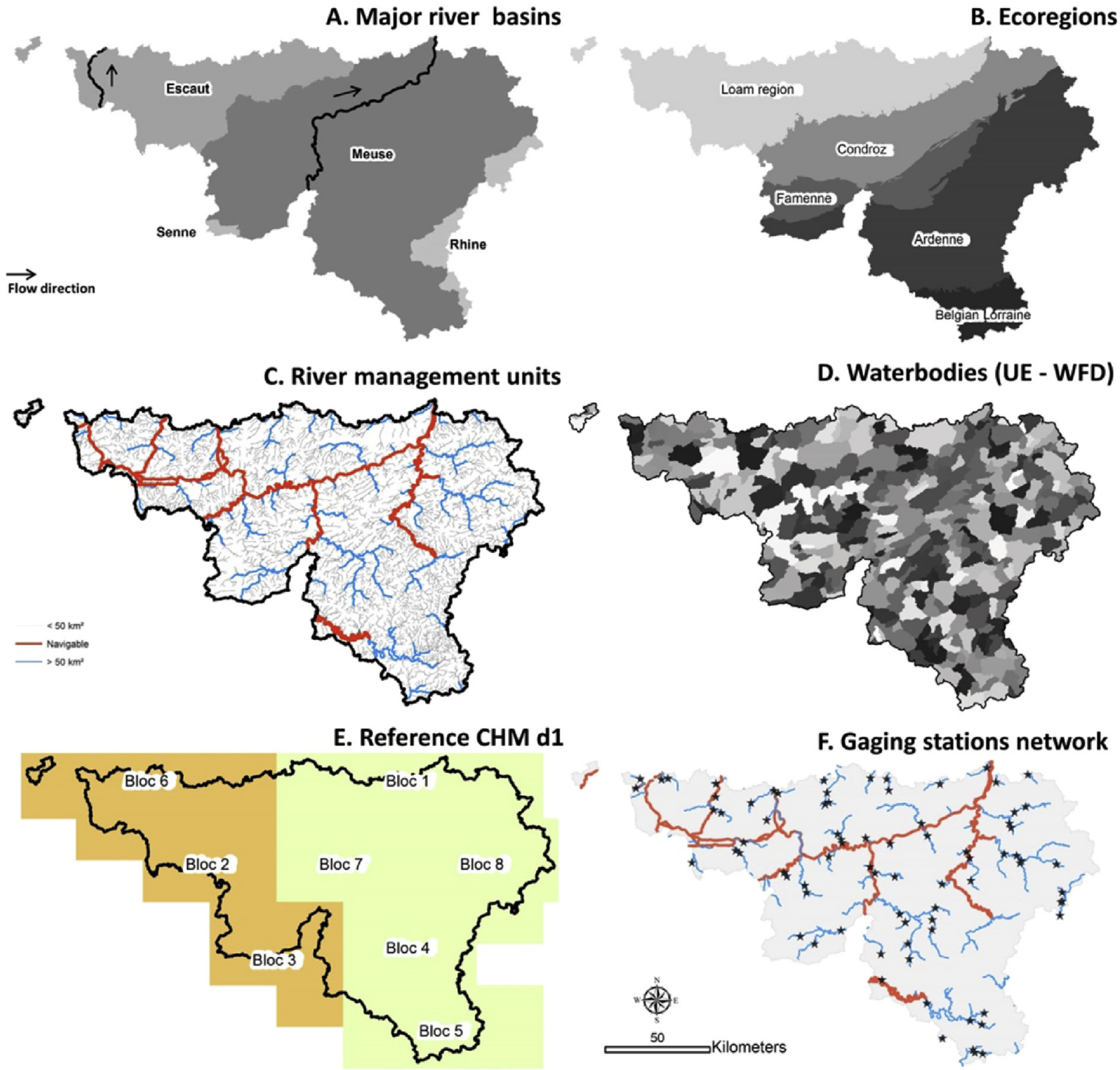

Fig. 1. Key information maps about the study area. A. Major river basins: the Escaut and the Meuse rivers are the two most important rivers of the study site; B. The study area was divided by Noirefalise (1988) in 5 ecoregions; C. The publically managed rivers network has been divided in 6085 river managements units (mean length: 2 km); D. The study area has been divided in 354 Water Frame Directive waterbodies with a mean river length of ca. 35 km; E. The hybrid reference CHM d1 is a combination of hybrid (photogrammetry DSM – LiDAR DTM) and LiDAR CHM (LiDAR DSM – LiDAR DTM). The hybrid component of the CHM 2012–2013 represents 32% of the regional area and is based on data acquired in 2012 (darker grey); F. Gaging stations network used to validate the LiDAR channel width.

Table 1
Key characteristics of Wallonia and its ecoregions.

	River (km)	Area (km^2)	Rainfall (mm/year)	Mean altitude (m)	Mean slope (%)	Agr. (%)	Art. (%)	For. (%)	Wat. (%)	Mean density (hab/km^2)
Ardenne	4545	5741	1140	425	11	37	5	57	<1	44
Condroz	2391	3546	956	214	9.8	56	23	20	1	344
Famenne	964	1555	898	227	9.3	53	8	38	<1	74
Belgian Lorraine	603	843	934	322	9.1	55	7	38	<1	107
Loam region	3551	5218	825	103	4.8	70	23	6	<1	320
Wallonia	12,054	16,902	971	258	8.5	54	15	31	<1	208

Land cover data derived from the CORINE land cover project (http://www.eea.europa.eu/publications/COR0-landcover). Agr.: % of agricultural area; Art.: % of artificial area; For.: % of forested area; Wat.: % of wetlands and waterbodies areas.

third of the study area; therefore, we used photogrammetric point clouds to compute a hybrid CHM for the corresponding time period. The hybrid CHM is composed of contemporary LiDAR ground points from the LiDAR point cloud and the photogrammetric point cloud. We used LASTools suite to implement the CHM computation at the regional scale and to compute two reference CHMs for the entire study area (1 m Ground Sampling Distance, GSD).

We computed a regional CHM for the years 2012 and 2013,

Table 2
Key features of the regional LiDAR survey.

Parameter	Value
Scanner	Riegl Litemapper 6800i
Flight altitude	1500 m
Speed	75 m s^{-1}
Lateral overlapping	30%
Pulse frequency	150 kHz
Scan angle	60°
Number of echoes	4
Z precision	0.12 m
XY precision	<1 m

which will be referred to as "*CHM d1*" in this study, based on a combination of LiDAR and photogrammetric point clouds. Sixty-eight percent of the study area was fully covered with a LiDAR CHM (LiDAR DSM - LiDAR DTM), the rest of the study area (Fig. 1E) was covered with hybrid CHM (photogrammetric DSM - LiDAR DTM).

To assess the evolution of riparian forest, we computed a hybrid CHM with the photogrammetric point clouds computed from the regional survey of aerial imagery acquired in 2009 and 2010, considering that the topography did not change significantly at the regional scale between the two aerial surveys. This hybrid regional CHM will be referred to as "*CHM d2*" in this study.

We masked the two reference CHMs with zero values for pixels located within the 'building' polygons of a reference land cover dataset provided by the Belgian Geographic Institute (TOP10VGIS product, www.ngi.be for details).

2.3.2. Extraction of attributes characterizing the riparian buffers

We used a single automated workflow to characterize the riparian buffers related to the 12,054 km of the regional river network (see Supplementary material 1). The majority of the attributes (Table 3) are related to the entire river network (drainage area >1 km^2), except for two attributes that were only calculated for major rivers (drainage area >50 km^2) representing a total length of 2,307 km.

We exploited the attributes which can be directly linked to the ecological indicators based on the previous studies involving high-density LiDAR point clouds (see Michez et al. (2013) for further details about the construction of the indicators). Beside the information provided from the thematic river network data, the attributes completely rely on LiDAR and photogrammetric point clouds.

2.3.2.1. Physical parameters of riparian buffers. To extract the emerged channel depth (floodplain height above water level), we used the minimum altitude within each 50 m long floodplain sample of the disaggregation process to define a reference altitude assumed to be the water level. This reference altitude was then subtracted from the absolute DTM to produce a relative DTM regarding the channel elevation at each point along the stream network. A mean value was computed at the re-aggregated scale and was used to study the topography of the riparian buffers. The mean value can be considered as the mean floodplain height above the channel (or emerged channel depth), and is important for understanding geomorphic patterns related to the channel size and geology as well as potential human impacts on the channel form (e.g. dredging/incision). It is also a critical parameter for riparian vegetation as it provides information about the nearness of the groundwater. This proximity is associated with the riparian status of the buffers. We performed the evaluation of these attributes within two buffers (river +6 m and +12 m).

We extracted a LiDAR derived channel width for the river management units with a catchment area over 50 km^2 or considered as navigable by the administrators. The high absorption of near-infrared LiDAR signal by the wetted channel locally results in very low point densities. Our methodology takes advantage of those very low density areas in the LiDAR point cloud by localizing them through the use of point cloud density raster (see Supplementary material 1) using an Object Based Image Analysis (OBIA) approach (Blaschke, 2010). This approach allows us to extract a water surface polygon even under the riparian tree crowns and for small river reaches (<5 m channel width). The resulting water surface polygon was cleaned by an operator based on contemporary regional aerial orthophoto and ancillary vector data. For each river management unit, channel width was extracted for every floodplain sample generated during the disaggregation process. The median of these widths was computed and applied to the river management unit. This variable is useful for avoiding the effect of the river size on different lateral scales of analysis. Its regional pattern also provides information on geomorphic and hydroclimatic conditions, and potential human impacts.

Sinuosity of the wetted channel was computed following the classical approach which is the ratio of the river length and the length of the valley axis (mean axis of the meander band) within each of the aggregated scales. Its regional pattern provides potential information on human impacts (e.g., straightening).

2.3.2.2. Riparian forest attributes. We identified riparian forest patches at the reference periods related to the CHM d1 and CHM d2 using a minimum height threshold of 2 m. Within the identified

Table 3
Ecological attributes of the riparian buffers.

Riparian buffers attributes	Considered river network (km)		Indicator of ecological function[a]
	Entire river network	Major river network (DA > 50 km^2)	
Emerged channel depth	x	x	Flooding frequency of riparian buffers, central habitat attribute for typical riparian species, proxy of human impacts on channel depth/deepening
Channel width		x	Habitats and migration corridors for riparian species communities; needed to estimate relative overhanging, proxy of human impacts on channel pattern/lower value due to regulation
Channel sinuosity	x	x	Channel heterogeneity, diversity of aquatic habitats, proxy of human impacts on channel pattern
Riparian forest continuity	x	x	Corridors for plant dispersal; habitats and migration corridors for birds and mammals
Riparian forest mean height	x	x	Mature stand localization (mean height)
Riparian forest degree of canopy overhang		x	Shading effect and water temperature regulation services. Habitat and organic input to benthic fauna

Four attributes are extracted for the entire river network of the study area (12,054 km) whereas the channel width and the degree of canopy overhang are extracted for management units with a drainage area above 50 km^2 (2307 km) or referred as navigable.
[a] See Michez et al. (2013) for further details on the indicators.

patches, a mean riparian forest height was computed based on the forest pixel, with no minimal width threshold. The riparian forest patch was identified within two buffers (river +6 m and +12 m).

We computed a riparian forest longitudinal continuity index which can be defined as the continuity of the presence of riparian forests along a given stream network. We performed the evaluation of this attribute within two buffers (river +6 m and +12 m). We defined the continuity index for each of the 50-m long sampling segments in order to explore the upstream-downstream pattern:

$$Continuity\ index(Xi) = 1 - \frac{Riparian\ forest\ area(sample\ Xi)}{Total\ area(sample\ Xi)} \quad (1)$$

We evaluated the canopy overhang of the riparian forest in order to assess the shading effect and water temperature regulation services provided by the riparian forest. The study of the canopy overhang also evaluates its added value as the habitat and provider of organic input to benthic fauna (Barton et al., 1985; Beschat et al., 1987; Shirvell, 1990). For the river management units with a catchment area over 50 km^2 or considered as navigable by the administrators (*i.e.* 2307 km network), the canopy overhang of the riparian forest was computed using the ratio between the area of the riparian forest that directly overlays the water surface patch and the area of the water surface itself. The overhanging forest area was computed with a classical 'intersect' geomatics procedure between the riparian forest patches and the water surface area previously extracted.

$$Degree\ of\ canopy\ overhang(Xi) = \frac{Canopy\ overhang\ of\ riparian\ forest(sample\ Xi)}{Water\ surface\ area(sample\ Xi)} \quad (2)$$

2.3.3. Scales of analysis and sampling units

Based on a disaggregation procedure described by Alber and Piégay (2011), we extracted different key attributes (Table 3) of the riparian buffers on 50-m long floodplain segments distributed regularly (at 50-m intervals) along the smoothed centerline of the river floodplain. For the riparian forest attributes and the emerged channel depth, we calculated the attributes within two buffers (river +6 m and +12 m). The +6 m and +12 m buffers were chosen because these distances represent the average width of one and two riparian tree crowns. They also correspond legal minimal distances (depending the administrative status of the riparian area) for planting non-native tree species (e.g. Spruce (*Picea abies*) or hybrid poplars (*Populus* sp.)).

Depending on the objective being pursued, the information at the 50-m long floodplain segments is re-aggregated into various sampling units to provide different visualization perspectives. In this study, we considered three sampling units within which re-aggregation was performed: river management units > WFD waterbodies > ecoregions.

The river management units of Wallonia are homogenous river reaches which have been delimited by expert operators. About 6085 river management units were defined (Fig. 1C), with a mean length of 2.0 km (+/− S.D. 2.6 km) (Burton et al., 2011). These units cover the whole river network of Wallonia managed by public administrations (drainage area >1 km^2). The WFD waterbodies are the WFD fundamental management units. In Wallonia, the implementation of the directive identified 354 waterbodies which cover the entire study area (Fig. 1D). The average river length in the WFD waterbodies is 35.0 km (+/S.D. 35.5 km). The five ecoregions at the study site represent a homogeneous area in terms of geology, climate, land-use, and a river network varying from 603 to 4545 km (see Table 1 for details).

2.4. Validation

We performed a validation of the reference datasets (channel width and CHMs d1 & d2) which were used to compute the attributes of the riparian buffers.

The channel width was validated through field measurements. The field measurements of the channel width were extracted from recent (after 2010) field calibration campaigns of 79 gaging stations covering the entire study area (Fig. 1F). The field measurements of the river widths were selected based on their similarity in terms of water discharge (±10% of discharge during the LiDAR survey). This reference dataset covers the entire study area and various discharge conditions. The field calibration campaigns are not performed at the station itself, but in an undisturbed section close to the station. The LiDAR derived channel width was computed by the median of the channel widths for every 50-m long segment from a 1-km long river reach centered at the gaging station. The river reach can slightly be shifted when a modification of the river section is detected (tributary, river engineering).

The reference CHM d1 & d2 were validated with field tree height measurements provided by the Walloon permanent forest inventory (http://environnement.wallonie.be/dnf/inventaire/). We used the dominant height as a measure of the forest height to be compared with the forest height extracted from the reference CHM d1 & d2. The dominant height is extracted from the height of the tallest trees (100 trees/acre) in the forest inventory plots. This height was chosen over the individual tree height because its lower spatial variability better suits the quality of the georeferencing of the ground measurements of the height data. As pointed out by Dedry et al. (2016), LiDAR CHM can provide highly accurate estimations of the dominant height (coefficient of determination > 0.95 with LiDAR CHM).

2.5. Mapping the attributes of riparian buffers

We analyzed riparian buffer parameters at various scales considering different sampling units: the river management units and the WFD water bodies. The mapping of the riparian buffer attributes was performed at the scale of the whole study area, further referred to as the regional scale. The information can be mapped on the hydrographic network (Fig. 1C, case of river management units) and also on spatial units (Fig. 1D, case of the WFD waterbodies). The mapping of the riparian buffer attributes was also attempted at local scale: the river management units within a single WFD waterbody.

2.6. Interpreting the regional patterns of riparian buffers

2.6.1. Modeling physical parameters and size-dependency effect

In order to interpret the regional patterns of the physical parameters, we modeled the channel width and the emerged channel depth with the related drainage area. This analysis allowed us to highlight the spatial variation in the entire study area and five ecoregions. The modeling (power law) was performed using the *'nls'* function of the *'stats'* package of R (https://cran.r-project.org/) to determine the nonlinear least-squares estimates of the parameters of the power law:

$$FE = a{*}Drainage\ Area^{\ b} \quad (3)$$

$$Channel\ width = a{*}Drainage\ Area^{\ b} \quad (4)$$

We selected 418 river management units (1535 km) that had no major regulations (dams, openings, other navigation works) to build a reference dataset. We studied the fitted models for the five ecoregions at the study site, assuming that they were homogeneous in terms of physical characteristics (climate, topography, geology). A residual analysis of the fitted model (e.g. observed LiDAR channel width versus predicted channel width) was explored to highlight the river reaches potentially disturbed by human activities.

As the channel width and the emerged channel depth are directly impacted by the river size, we used the parameters of the fitted model to minimize the size-dependency effect. A weighting by the drainage area was performed by dividing the parameter by the associated drainage area exponent ‘b’, following the method proposed by Piégay et al. (2009). The ‘b’ parameter was extracted from the power law model linking the drainage area and the physical parameters of riparian buffers. The weighting by the drainage area was undertaken because of its simplicity and ability to be computed over all selected management units.

2.6.2. Typology of riparian buffers

We also conducted a cluster analysis in order to group five classes of riparian buffers strictly based on the six riparian buffer attributes of the same selection of lowly disturbed management units (418 units, 1535 km) used for the removal of the size dependency effect. We built a dendrogram using ward clusters extracted from a distance matrix computed on the six riparian attributes (analysis performed with CRAN R). The sinuosity, the weighted channel width, and emerged channel depth were log-transformed to enhance the normality of their distributions. The six parameters were centered and scaled (mean of 0 and standard deviation of 1) before the computation of the distance matrix.

3. Results

3.1. Validation results

The LiDAR derived channel widths are strongly correlated ($r^2 > 0.9$) with the field measurements (see Supplementary material 2). The LiDAR method slightly underestimates the river width (median residual: −0.79 m), in accordance with the previous results that used high-density LiDAR point cloud (Michez et al. (2013)). Among the 79 gaging stations used for the validation, only four stations located on small river reaches (mean width and depth were below 3 and 0.15 m, respectively) could not be compared to a LiDAR derived surface width. The stations which could not be characterized by the method are associated with smallest river beds of the reference dataset (see Supplementary material 3).

The linear relationships between the field measurements of the forest height (dominant height) and the estimated height with CHM d1 & d2 also provide fairly good results (Supplementary material 2). The values of the root mean square error (<3 m) and the coefficient of determination ($r^2 = 0.85$) are comparable to those obtained with a LiDAR CHM by Dedry et al. (2016). These positive results allow for the use of the two reference CHMs to evaluate the attributes related to riparian forest height.

3.2. Mapping the attributes of riparian buffers

3.2.1. Regional scale

The map of the channel width highlights the major rivers of Wallonia (>50 km^2 network, 2307 km) (Fig. 2A) and provides a preliminary visualization of the hierarchical organization of the network. On the other hand, the channel sinuosity (Fig. 2B) draws attention to smaller streams exhibiting higher values of sinuosity.

The re-aggregation of attributes of the riparian forest conditions from the river management units to the WFD water bodies for two lateral buffers (river +6 m and +12 m) provides another geovisualization of information by surface areas (Fig. 3). The regional map highlights the regional pattern of the forest continuity and the mean height of the riparian forest which can be linked to the intensity of the agricultural practices. Although the riparian forests on the western part of the entire study area and the eastern Ardenne ecoregion display a fairly discontinuous pattern, the central part of the region has more continuous forests. This regional contrast is also observed for the mean tree height. These patterns are highlighted for the two buffer widths studied (+6 or +12 m).

3.2.2. Local scale: single WFD waterbody

The visualization of riparian buffer attributes associated with river management units is also possible at a single WFD waterbody scale so as to catch all the local variability of river management units within a given waterbody. Fig. 4 shows an example of such visualization. It highlights the contrast between an upstream tributary located in a steep and forested area (‘Lhomme 097’) and a management unit located downstream, in a relatively open, flat, and inhabited area (‘Lhomme 106’). As the management unit ‘Lhomme 097’ is mainly located in a forest landscape, it has higher values of riparian forest height and continuity than the ‘Lhomme 106’ river management unit (Fig. 4).

3.3. Regional patterns of riparian buffers

After mapping the attributes of the riparian buffers and their geographic patterns, we interpreted these regional patterns in relation to land cover and specific characteristics of the five ecoregion (see Fig. 1B).

3.3.1. Physical parameters of riparian buffers

The channel width regional model (see Supplementary material 4) presents the best relationship with the associated drainage area ($r^2 = 0.81$). The value of r^2 at the ecoregion scale exceeds the r^2 value of the regional model. The model at the regional scale highlights a significant relationship (*p value* < 2e-16) between the emerged channel depth and drainage area. However, its regional pattern is much more disturbed ($r^2 = 0.20$) than the channel width regional model. At the ecoregion scale (see Supplementary material 5), the relationship between the emerged channel depth and drainage area still shows high variability for Condroz, Ardenne, and Famenne ecoregions. Belgian Lorraine and Loam region do not show any pattern. The deepest reaches are observed in the Loam region and the Condroz. These results support the use of the drainage area to weight the channel width and the emerged channel depth for lowering the impact of the stream size and for the aggregation of information at the scale of the ecoregions.

The statistical distribution (boxplot) of the three physical attributes of the Loam region shows evidence of significant alterations with deeper channels and lower sinuosity values (Fig. 5A). It also highlights the lower connectivity with water resources of the riparian buffers in this ecoregion.

3.3.2. Riparian forest conditions at the regional scale (period 2012/2013)

The study of the riparian forest continuity at the re-aggregated scale of the five ecoregions confirms the poor condition of the riparian buffers in the Loam ecoregion. The riparian forests of this ecoregion have the lowest continuity and mean tree height (see Fig. 5B). The higher values of the emerged channel depth for this ecoregion (see Fig. 5A) suggest a lower access to the water resources, confirming the trend of terrestralization of the riparian buffers in the Loam region.

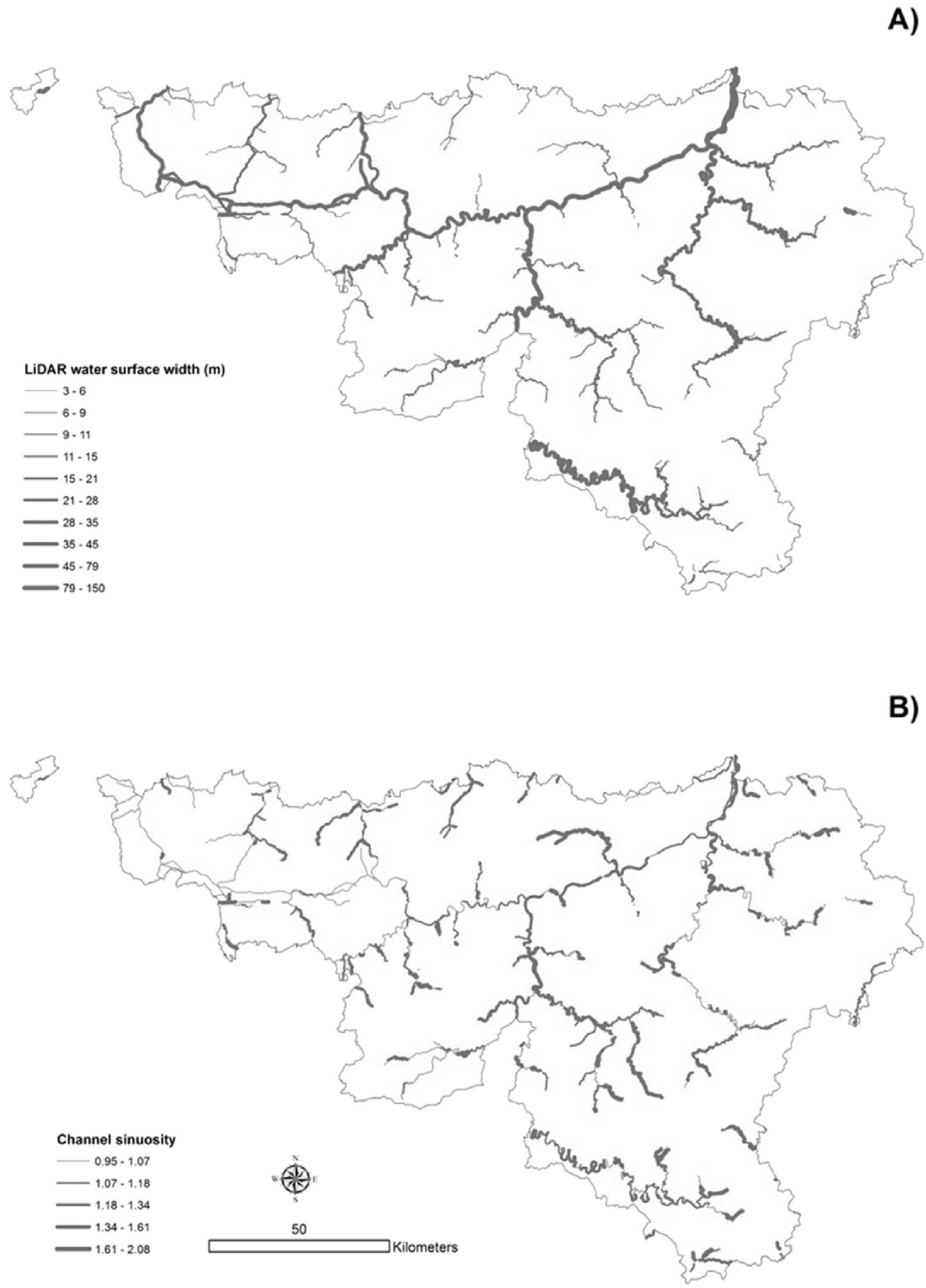

Fig. 2. Mapping of the physical attributes of the riparian buffers at the regional scale (2307 km network): channel width and channel sinuosity.

3.3.3. Relation between the land cover and the riparian forest continuity

In order to identify the potential drivers of the riparian forest conditions, we studied the correlation between riparian forest continuity and land cover information (TOP10VGIS product, see www.ngi.be for details) of the WFD waterbodies (Table 4). The area dominated by agricultural and artificial land cover classes in those water bodies are negatively correlated with the continuity of the riparian forests while the average slope is positively correlated. This result has implications for the pressure potentially exerted on regional riparian forest conditions. It also confirms the importance of targeting the management actions that maintain or even develop riparian forests in agricultural areas.

3.3.4. Typology of riparian buffers

Following the analysis focused on *a priori* assemblage (five ecoregions of the study area), we conducted a cluster analysis in order to group five classes of riparian buffers strictly based on the six riparian buffer attributes for a selection of lowly disturbed management units (1535 km).

The results showed that the riparian buffers of group 1 and group 2 constitute an important sub-group (49% of total length) which is mainly characterized by the presence of large rivers at the selected units (Fig. 6A). Both groups have lower sinuosity values

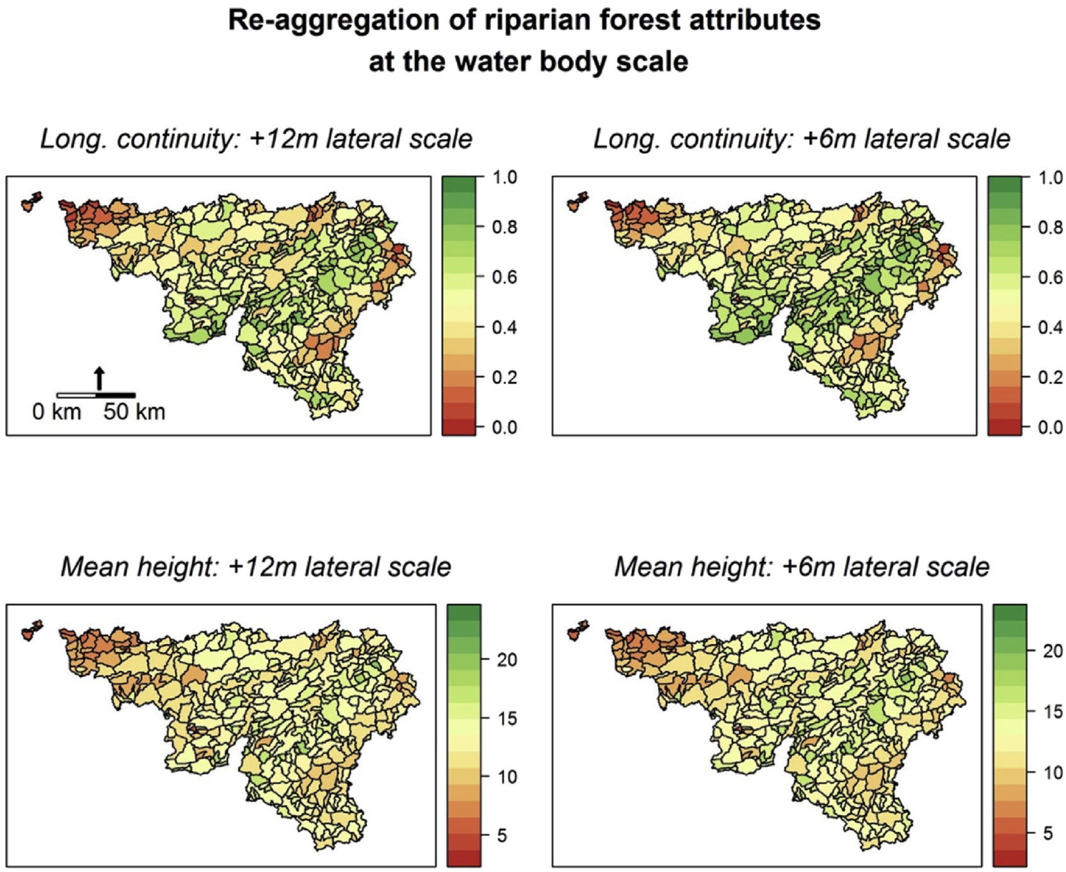

Fig. 3. Regional mapping of the riparian forest attributes: forest continuity index [0–1] for date 1 (2012–2013) and mean riparian forest height (m). Results are aggregated from the river management units to the WFD water bodies through weighting by river length.

and a lowly developed riparian forest (Fig. 6B1 and B2). Group 2 is almost exclusively composed of rivers from the Ardenne region with high channel width values and low emerged channel depth and riparian forest continuity values.

The second subgroup is composed of groups 3 to 5. It is associated with smaller streams and more developed riparian forest. The sinuosity of group 3 is more pronounced and associated with small units mostly located in the lowly disturbed ecoregion, Ardenne. It is likely the group with the healthiest conditions (low emerged channel depth values, high channel sinuosity, higher riparian forest continuity and degree of canopy overhang). Group 4 regroups the river management units from across Wallonia. It has the highest riparian forest continuity values. Group 5 is characterized by low channel width values because the majority of the river management units is located in the Loam ecoregion which has the lowest channel width values (see Fig. 5A).

3.4. From regional patterns to indicators of impacts/quality

3.4.1. Using fitted model to localize potentially impacted reaches

High quality fitted models linking the channel width and drainage area allow for the identification of locations of human alteration and drainage areas. At the regional scale (see Supplementary material 6A), the model linking the drainage area and the LiDAR channel width reveals positive residuals for management units located in the Ardenne ecoregion. At the intermediate scale (see Supplementary material 6B), the model of the Ardenne ecoregion on the upper Ourthe valley allows for locating the reaches that have negative residuals and positive residuals related to the presence of a dam (Nisramont dam).

3.4.2. Multitemporal monitoring of riparian buffers

The multitemporal remote sensing data is used for monitoring the evolution of the riparian buffers. It is also used for the evaluation of management policies and improved planning of future management activities. Using the results of the regional CHMs covering two distinct time frame (2009–2010 and 2012–2013), we can detect major changes in the riparian forest conditions at the management unit scale (Supplementary material 7). The nature of the changes within riparian forests must be related to the vertical accuracy of the reference CHMs (Root Mean Square Error (RMSE) > 2 m, Supplementary material 2). However, the method can be used to monitor forest cuttings in the riparian buffers (Supplementary material 7A), even spatially limited ones such as the management cuts in urban areas (Supplementary material 7B). The relatively small time period between the two CHMs combined with the vertical accuracy of the reference CHM prohibits their use for finer scale monitoring such as the detection of riparian forest growth or plantation.

4. Discussion and conclusion

4.1. Interpreting the regional patterns of riparian buffers

The quality of the physical parameters models is comparable with the quality obtained by Petit et al. (2005) for the Ardenne ecoregion (0.92 versus 0.88 in our results) with a strict field based approach for the width measurement.

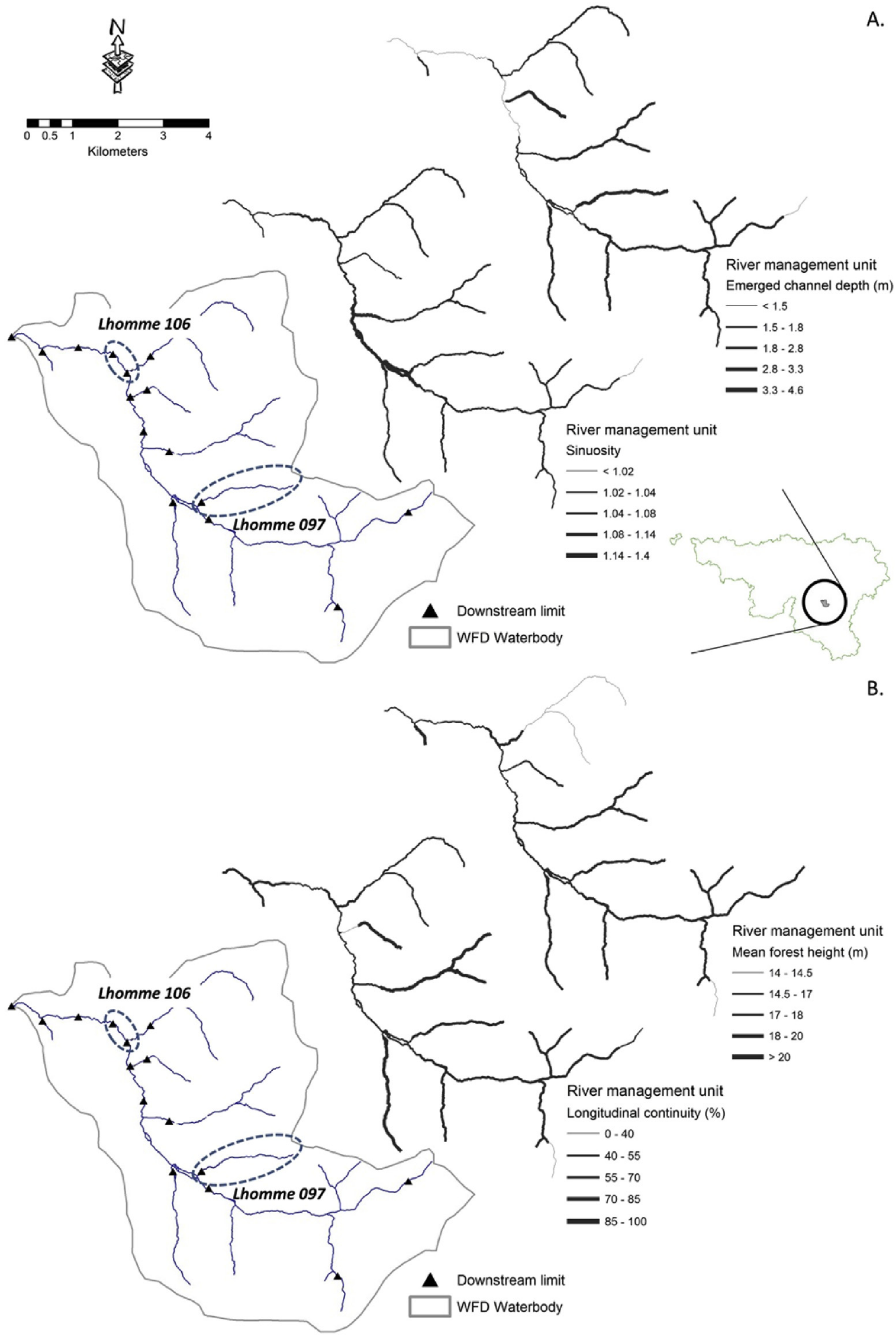

Fig. 4. Spatial and synthetic visualization of the physical (A) and forest attributes (B) extracted for the management units of the waterbody 'LE14R'.

Fig. 5A shows higher channel width values of the gravel-bed rivers in the Ardenne ecoregion which could be due to the larger size of the bedload in this ecoregion combined with an impermeable river bed substrate (Petit et al., 2005). This ecoregion also gets higher rainfall than the others which could partially explain these wider channels. In contrast, the Loam ecoregion has the lowest channel width values which may be linked to the smaller size of sediments and loamy streambanks with higher cohesion and resistance. Besides geomorphological features, significant alterations in the Loam ecoregion (Fig. 5A) can be explained by a disturbed river network that had been intensively dredged and rectified by human activities (mostly agricultural). The river engineering was facilitated by the low slopes and the loamy soil texture which also lowered the ability of the stream to recover the original

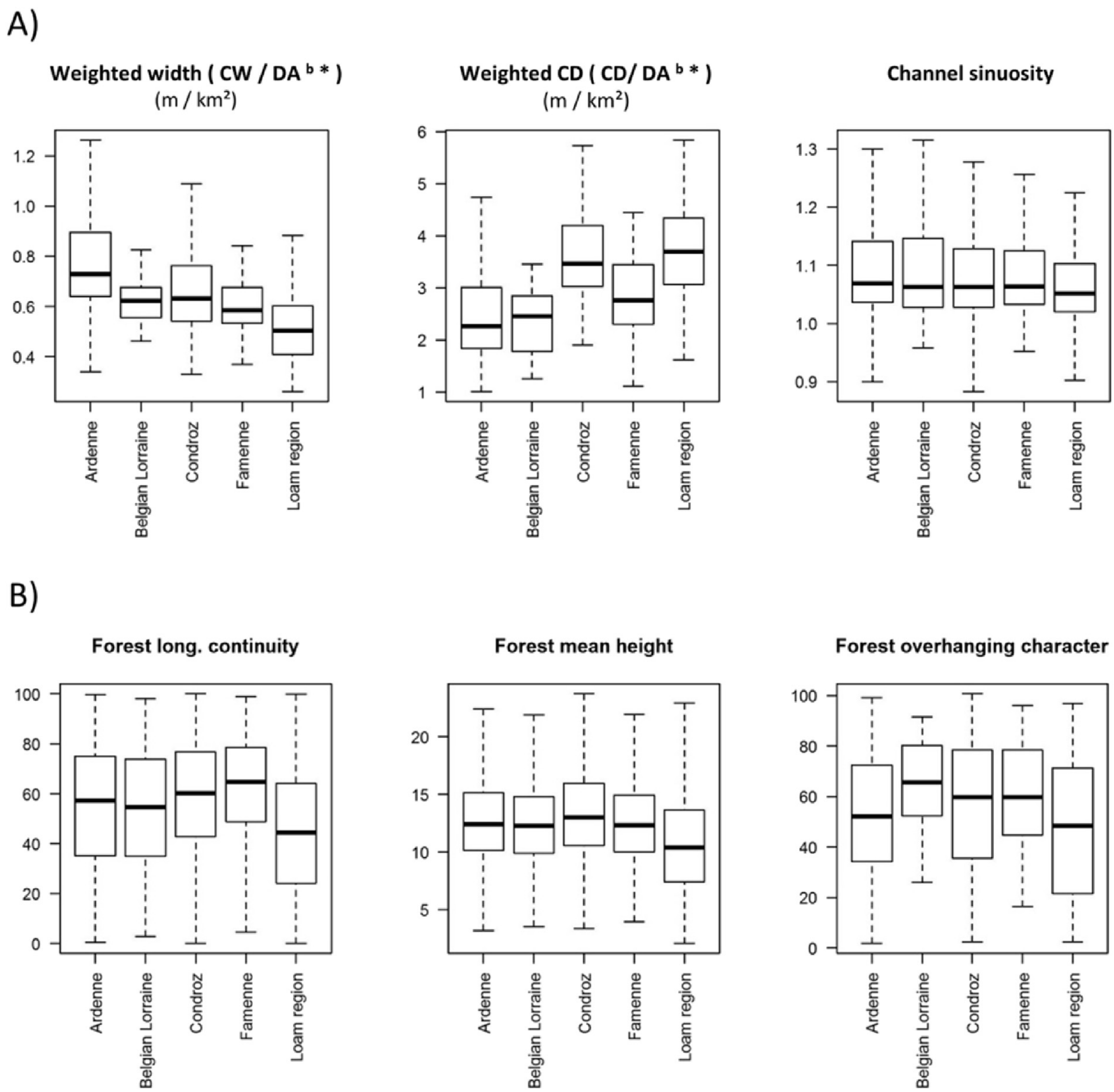

Fig. 5. A) Attributes of the physical conditions of the riparian buffers synthesized by ecoregion. The channel width (CW) and the emerged channel depth (CD) are computed within the 2307-km network (>50 km^2) and are weighted by the drainage area. For the 3 attributes, the Loam region presents values which highlight the highest anthropic pressures. B) Riparian forest conditions (+12 m lateral scale of analysis) of the management units of the study site synthesized by ecoregion. The condition of the riparian forest in the Loam region clearly stands out negatively. The degree of canopy overhang is computed within the 2307-km network (>50 km^2).

Table 4
Correlation between riparian forest continuity (+12 m lateral scale) of the WFD waterbodies and parameters of land cover and the riparian buffers topography.

Variable	Correlation coefficient
Mean slope	0.61
Forest ratio	0.60
Agricultural ratio	−0.56
Artificial ratio	−0.25
Mean altitude	0.12

The density of agricultural areas impacts negatively the continuity of the riparian forest while the mean slope is positively linked.

section through natural processes.

The regional mapping of the residuals between the fitted and the observed channel widths (see Supplementary material 6) highlighted the positive values for river reaches in the Ardenne ecoregion, especially in the Semois river basin. Petit et al. (2005) also reported frequent positive residuals for this river when modeling the channel width with the drainage area. They interpreted this result as the consequence of a regular contact of the river bed with an impermeable rocky substrate.

4.2. Status of riparian buffers in study area

Our approach highlights the regional differences in riparian buffer alterations and suggests that the Loam ecoregion was the most affected one by the alterations, confirmed by the riparian forest conditions and the physical conditions of the riparian buffers. Our results suggest that the conditions of the riparian forest of this ecoregion can be described as longitudinally interrupted; with a relatively low access to the water resources (see Fig. 5). In terms of

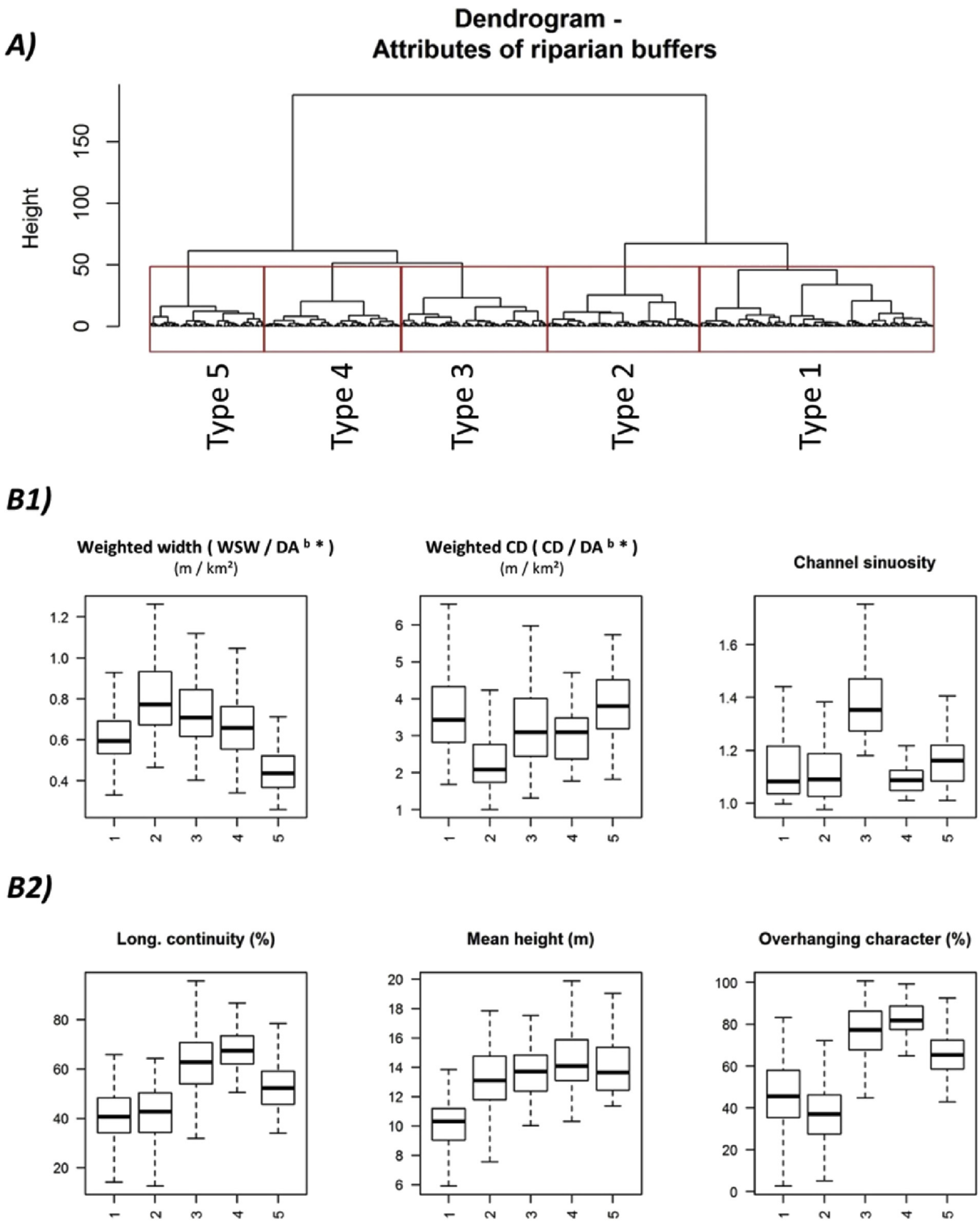

Fig. 6. Summary of the attributes of riparian buffers (+06 m lateral scale of analysis) following a cluster analysis performed on selected management units with a drainage area >50 km^2 (1535 km). A) Hierarchical dendrogram of the grouped management units (Ward clusters). B1) Physical parameters of the riparian buffers: weighted channel width, weighted emerged channel depth, channel sinuosity. B2) Riparian forest conditions: forest continuity, mean height and degree of canopy overhang.

physical conditions, the lower sinuosity reflects the high level of river regulations in the ecoregion combined with low capacities to self-restore natural processes such as erosion and deposition, notably linked to low values of stream power (<15 W/m^2, Petit et al. (2005)).

4.3. Remotely sensed indicators for riparian buffer management?

Our approach can be used to identify the priorities in terms of riparian buffer management from a given river reach to the entire study network. The multitemporal assessment of the longitudinal structure (longitudinal continuity) and vertical structure (mean height) of the riparian forest is used to objectively prioritize and plan riparian forest management efforts. The physical parameters of riparian buffers provide objective and up-to-date information about the local context of the day-to-day river management such as the river size and the river bed morphology. The regional modeling of physical parameters can be used to identify locally disturbed river reaches through a residual analysis.

4.4. Conclusion

As the availability of 3D point clouds at the regional scale is constantly growing, our study proposes reproducible methods that can be integrated into regional monitoring by land managers. Although LiDAR data is still expensive, the use of photogrammetric point clouds combined with LiDAR data is a cost-effective means to update the characterization of riparian forest conditions. On the regional scale, physical conditions of riparian buffers are evolving slower than riparian forests.

The accuracy of the reference CHMs used in this study (RMSE > 2 m) and the short time period between the two reference CHMs (3 years) did not allow us to study the (re)growth of the riparian forest. However, major landscape patterns were detected and can be analyzed to identify potential drivers of riparian buffer conditions. A longer time window between the two acquisitions would provide promising results on major modifications to river management policies in the study area. For example, in 2014, Wallonia has officially implemented an European directive that requires fencing the river banks. The application of this measure should induce natural riparian forest regrowth, which could be identifiable in future surveys. An update of the regional LiDAR coverage of the study site before 2020 would provide a fully multitemporal approach to regional remote sensing monitoring of the ecological conditions of riparian buffers based on physical and forest parameters.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.02.034.

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