Patterns of landscape change in a rapidly urbanizing mountain region

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Évolution des paysages d'une région de montagne sous forte pression urbaine

Clémence Vannier, Jérémie Lefebvre, Pierre-Yves Longaretti and Sandra Lavorel

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Introduction

1 Land system changes have broad consequences on human well-being through their impacts on agricultural production, air quality, the provision of drinking water, etc. Understanding land changes depends on the understanding of the role and feedbacks of human activities (GLP, 2005). Since the early 2000's Land Change Science has emerged as an interdisciplinary research field where Land Use and Cover Change (LUCC) is a central process (Turner et al., 2007 ; Millenium Ecosystem Assessment, 2005 ; Omenn, 2006). Turner et al., (2007) highlighted four main research priorities for Land Change Science : 1- observation and monitoring of land changes, 2- understanding these changes as a coupled human-environment system, 3- spatially explicit modeling of land change, 4- assessment of system outcomes, such as vulnerability, resilience or sustainability. Building on these initial objectives, Rounsevell et al. (2012) identified a main challenge for Land Change Science to provide a better understanding of decision-making processes in land management at different scales. Meeting these challenges depends on innovative methods to combine not only social and natural sciences, but also qualitative and quantitative approaches: qualitative information about land management and quantitative data and spatial information.

2 In this study we addressed the first of these research priorities in the context of a mountain and plain landscape characteristic of the central French Alps. Mountain regions cover around 27% of the earth land surface (Blyth et al., 2002) and are currently undergoing rapid and often profound modifications of their socio-ecosystems (Körner and Ohsawa, 2005). The European Alps contain a large variety of landscapes, species and cultures reflecting their very diverse topography, climate and vegetation (Tappeiner et al., 2008). This socio-ecological diversity makes them a hotspot of biodiversity (Brooks et al., 2006) and ecosystem services (Crouzat et al., 2015; Körner and Spehn, 2002). However, the remaining large areas of natural and semi-natural landscapes which are important assets for biodiversity conservation are threatened by an increasing pressure from agriculture and tourism and by the impacts of climate change (Haida et al., 2015; Körner and Ohsawa, 2005; Pauli et al., 2003; Rüdisser et al., 2015; Tasser and Tappeiner, 2002; Zimmermann et al., 2010). Describing and understanding landscape changes in these regions is essential to understand their environmental impacts and to guide future landscape management. This however poses a real challenge due to the magnitude and fine grain structure in the variability of landscape configurations in mountain regions (topography, aspect, local climate, soils, etc.).

3 Observation and monitoring tools have allowed major progress in LUCC analysis and characterization for the last two decades. Based on existing GIS databases of LUCC and/or remote sensing data, they are now routinely applied given their capacity to produce consistent long-term Earth observation data from local to global scales (Giri et al., 2013 ; Hansen and Loveland, 2012 ; Hubert-Moy et al., 2012 ; Smith and Wyatt, 2007 ; Strahler et al., 2006). One of the main challenges of space observation of LUCC change is to perform time series observation (i) to optimize the analysis at different scales (local, regional, global) (Lambin and Geist, 2008), (ii) to explore landscape dynamics and to highlight the main drivers of changes (Bürgi et al., 2004) (iii) to investigate current and future trends and to produce decision-support tools for policy makers (Vacquié, 2015 ; Dodane et al., 2014 ; Lakes and Kim, 2012; Houet et al., 2010; Antrop, 2005, 2004). Moreover remote-sensing observations and monitoring of LUCC (using GIS databases) are now more routinely used for ecological assessment in environmental science, including biodiversity or conservation questions (Ayanu et al., 2012; Nagendra, 2001; Turner et al., 2003; Wang et al., 2010).

4 The starting point of a LUCC study using observation and monitoring tools is to define typology, grain, and data relevant to the focal research question and landscape, subject to constraints of data availability (Bousquet et al., 2013). Existing data on LUCC are based on targeted methodological choices such as the typology used for a specific study and geographical scales (Balestrat et al., 2011). Our focus on a mountain region requires fine resolution mapping due to the diversity and grain of the landscape. Therefore, the use of CORINE Land Cover database, with a 25 ha grain resolution, was not appropriate for our study to capture landscape heterogeneity. In the present study, the production of a fine-grain LUCC database was required, and particular attention was needed regarding the adequacy between existing data and our objectives (Bousquet et al., 2013). For example, at a fine grain resolution, the BD Topo (IGN) is the most exhaustive database covering the whole French national territory ; the Urban Atlas was developed to study the density of urban areas, with a very fine resolution of grain and typology for urban areas around the main European cities ; the "Registre Parcellaire Graphique" (national parcel data base) in agricultural areas reports crops in homogeneous group of fields, and has been updated

yearly since 2002 but is not spatially exhaustive. The types of geographic objects presented in these different LUCC databases are not necessarily consistent with each other (not the same scale of analysis or the same grain of elements). In addition, the territories covered are not necessarily continuous nor complete. For all these reasons, the use of these LUCC databases which provide heterogeneous information requires a merging exercise to ensure consistency between the indicated information and to provide a coherent database. In addition, to complement and refine information available from existing GIS data we used very high spatial resolution remote sensing data. The main challenge in creating our own database by a multi-source merging method (existing GIS data and remote sensing data) lies in the consistency of spatial scales / temporal scales / territory element contents (Warnock and Griffiths, 2015 ; Mathian et al., 2014 ; Hubert-Moy et al., 2012 ; Vannier, 2011 ; Marceau and Hay, 1999 ; Robin, 1995).

5 With this background in mind, the present study focused on developing an appropriate land cover typology and in adopting grain and spatial extent relevant for the time scale of interest, i.e. the last two decades. More specifically, we addressed the following three issues :

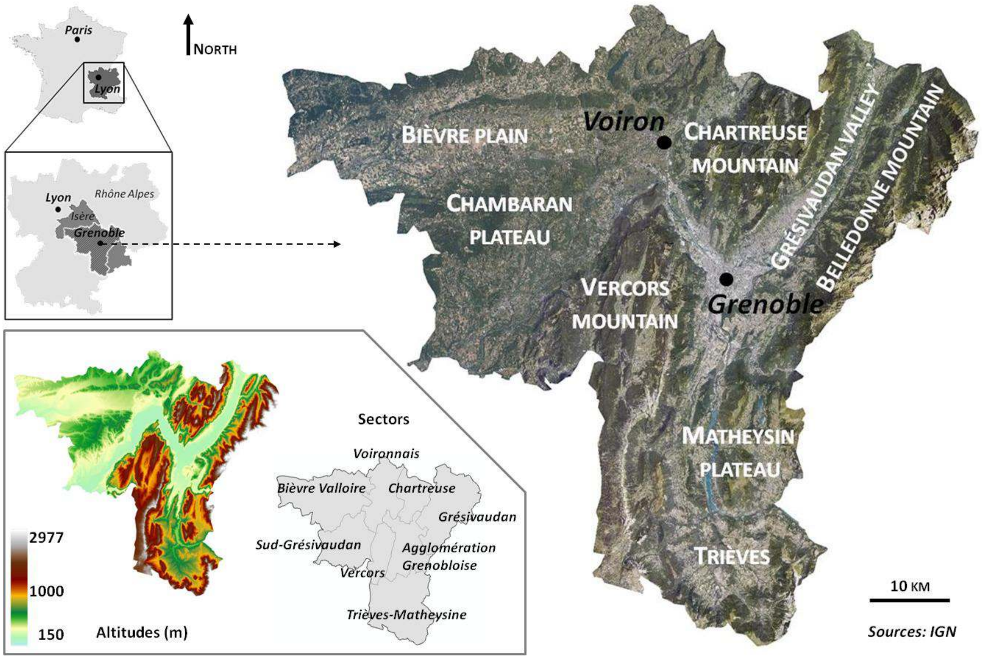
- Producing a cartographic database to characterize the land cover dynamics of the Grenoble urban region. We produced detailed maps for the years 1998, 2003 and 2009 by combining existing a high resolution remote sensing dataset and public information available under Geographic Information System (GIS).
- Analyzing the observed changes over the 1998-2009 period, with particular emphasis on trajectories, frequencies and intensities of changes.
- Defining a typology of land cover change at the municipality scale, designed to provide scientists and decision-makers with a synthetic view and an overall understanding of the main land cover features and trends across the region.

Materials and methods

Study area

6 Grenoble is the center of one of the very active and dynamic French metropolitan areas. With an extent of 4450 km^2, the Grenoble urban area was the home of around 800,000 inhabitants, and offered around 500,000 jobs to its population in 2012 according to INSEE (Institut National de la Statistique et des Etudes Economiques). We incorporated in our study the entire extent of the economic influence area of Grenoble. All significant landscape units typical of an Alpine region are represented in the resulting study area (plains, plateaus, mountains) (Figure 1). This area also presents a large variety of physical and natural characteristics, resulting in contrasted heterogeneous landscapes. The region is structured by three mountain ranges: Vercors, Chartreuse and Belledonne, culminating at 2977m. The valleys of the Drac and Isère rivers favor urban sprawl, as well as the Bièvres plain, to a lesser extent. The mountain areas benefit from a wide range of protection measures through the existence of 2 natural parks and several conservation areas. There are 311 municipalities within 50 km of Grenoble itself, most of them are integral part of the Grenoble SCoT[1] planning area (Schéma de Cohérence Territorial). The study area is divided into eight main administrative sectors (corresponding to the EPCI "Etablissement Public de Coopération Intercommunale") where municipalities are grouped for their land planning (Figure 1).

Figure 1 – Grenoble catchment area : location map, sectors and physical geography.



Typology and scales

7 We designed a specific land cover typology with three nested levels comprising 5 classes at level 1, 16 classes at level 2 and 23 classes at level 3 (Table 1). This typology was established both from the existing literature (Kias and Demel, 2003; Rameau et al., 1997) and from expert knowledge of existing national databases (Institut Géographique National, BDTOPO Version 2.1, BD ORTHO, Institut Forestier National, BD Foret). The maps produced can be used at the 1:15,000 scale, with a minimal area unit of 0.01 ha (100 m^2), although interpretation should be restricted to 0.2 ha for homogeneity across classes over the entire study area and because the location accuracy ranges from 5 to 10 m. These maps were produced at three dates, 1998, 2003 and 2009, to cover 11 years of landscape change, depending on available IGN data.

Table 1 - Typology of land cover classes

Level 1 (5 classes)	**Level 2 (16 classes)**	**Level 3 (23 classes)**
1 - Aquatic areas	**12** - Water and associated area	**121** - As for 12

2 - Built-up areas	**21** - Urban area **22** - Communication networks and associated areas **23** - Other artificialised areas	**211** - Housing area **212** - Isolated housing area **213** - Industrial, Commercial, Cultural and Sports area (ICCS) **221** - Primary road network **222** - Secondary road network **223** - Railway network **224** - Airport and associated area **231** - As for 23
3 - Agricultural areas	**31** - Crop **32** - Grassland **33** - Poplar **34** - Hedgerow	**311** - Annual crop **312** - Market gardening ; Horticulture **313** - Permanent crop (orchard ; vine) **321** - As for 32 **331** - As for 33 **341** - As for 34
4 - Forest areas	**41** - Hardwood forest **42** - Coniferous forest **43** - Mixed forest **44** - Wood **45** - Clearcut	**411** - As for 41 **421** - As for 42 **431** - As for 43 **441** - As for 44 **451** - As for 45
5 - Semi-natural areas	**51** - Moor wood **52** - Open areas with short or no vegetation **53** - Glacier	**511** - As for 51 **521** - As for 52 **531** - As for 53

Data

8 The dataset we used to produce land cover maps was based on existing vector and raster data (Table 2 and 3):

- BD ortho (orthophotoplan): produced by IGN (French National Geographic Institute), is composed of orthorectified and mosaic aerial photos;
- Digital Elevation Model (DEM): produced by IGN at 25 meters spatial resolution, and 5 to 10 meters elevation resolution;
- RapidEye 2010 satellite images: provided by the GEOSUD program (http://geosud.teledetection.fr/);
- BD Topo: produced by IGN, it is composed of LUCC vector information like roads, buildings, rivers, forests, etc. (http://professionnels.ign.fr/bdtopo);
- Parcel Graphic Register (Registre Parcellaire Graphique - RPG): produced by "Agence de Services et de Paiement" (ASP), it gathers agricultural fields/plots information about 28 crop types per year since 2002;

- Urban Atlas: provides pan-European comparable land use and land cover data for Large Urban Zones with more than 100,000 inhabitants as defined by the Urban Audit.

Table 2 - Raster dataset

Data type	**BDOrtho®**		**RapidEye satellite images**		**DEM BDTopo®**	
Dataset distribution	IGN		"EQUIPEX-GEOSUD" project From : RapidEye AG - GEOSYS		IGN	
Date	Summers 2009-2003-1998		May-October 2010		Version 2	
Dataset characteristics	*Spatial resolution*	0.5 cm	*Spatial resolution*	5 m	*Spatial resolution*	25 m
	Spectral resolution	Blue Green Red	*Spectral resolution*	Red Green Blue + Near-Infrared	*Spectral resolution*	Altitude matrix
	Projection	Lambert-93	*Projection*	Lambert-93	*Projection*	Lambert-93
	Corrections - Other None		*Corrections - Other* Geometric correction: Ortho cubic Convolution IGN Radiometric correction: None Compatible product RGE IGN®		*Corrections - Other* Calculated from the altimetric database, containing curved sides and points of the BDTopo®, completed with the BDAlti® data.	
Spatial extent	Isère department (038)		77-77 km		Isère department (038)	

Table 3 - Vector dataset

Data type	**BDTopo®**	**"Registre Parcellaire Graphique" (RPG)**	**Urban Atlas**
Dataset distribution	IGN	"Agence de Services et de Paiement" (ASP)	Environment European Agency
Date	2009, 2003, 1998	2006,2007,2008,2009,2010	2006

Dataset characteristics	*Definition* Vector database describing the land cover elements (Habitat, Vegetation, etc.) and infrastructures. Metric resolution.	*Definition* Anonymous database allowing the agricultural field identification. Device used for the management of EU aid linked to the CAP.	*Definition* Land Use database in 21 classes for cities more than 100,000 habitant in Europe.
	Elements of typology used Road and railway network Industrial areas Wood vegetation (hardwood, coniferous, mixed forest, wood, orchard, poplar, hedgerow, moor)	*Elements of typology used* Crops (all types grouped) Grasslands Orchard Vine Gardening Horticulture	*Elements of typology used* Continuous urban area Discontinuous urban area Isolated urban area Construction sites Mineral extraction
	Projection Lambert-93	*Projection* Before 2008: Lambert 2 extended After 2008: Lambert-93	*Projection* ETRS89-LAEA
	Update: Every 2 years	*Update:* Every years	*Update:* Every 3 years
	Spatial resolution: 1:10,000	*Spatial resolution*: 1:5000	*Spatial resolution*: 1:10,000
Spatial extent	Isère department (038)	Isère department (038)	Grenoble urban area (INSEE)

Mapping procedure

9 In order to produce multi-timescale maps of land cover at the 1 : 15,000 scale, we developed an object-oriented, semi-automatic, multi-source procedure which was applied for the year 2009, because the full raster and vector dataset was only available for this date.

10 Because the study area is far too extensive for a complete manual digitizing process to be practical at the required resolution (Hengl et Rossiter 2003), we used existing LUCC databases presented in table 3. By combining these databases, all the requested types of land cover classes we wanted to map were informed (elements of typology used, table 3), but the databases are not spatially exhaustive. Consequently, we chose to merge all the relevant landscape elements for our study from existing LUCC databases and to complete the database using remote sensing data classification and finally photo-interpretation to complete and validate the analysis. The processing flow-chart is illustrated in Figure 2 and can be summarised as follows.

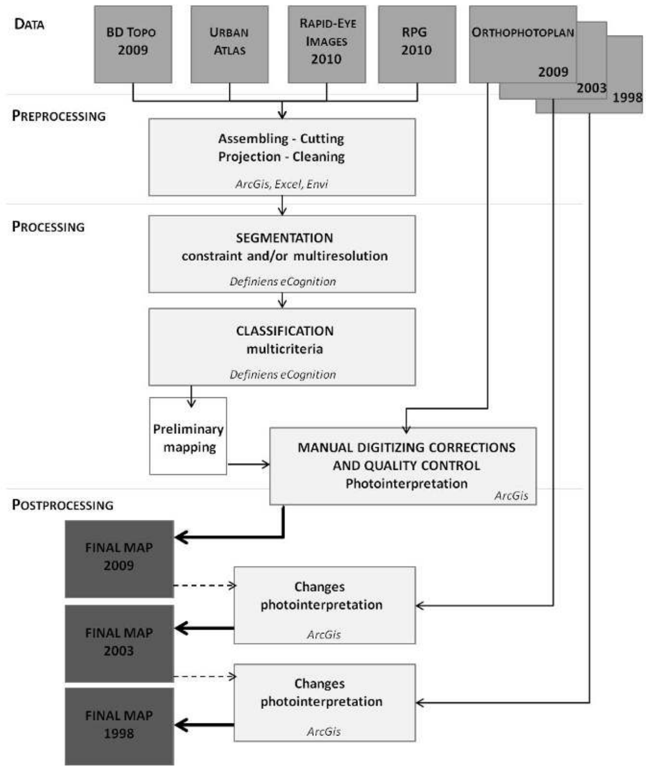
11 First, we collected, assembled, cut, projected and cleaned the heterogeneous dataset that proposes different spatial, temporal and qualitative information (i.e. preprocessing, figure 2). Second, we processed through segmentation and classification of 2010 RapidEye satellite images and of the vector dataset (which was previously normalized and merged). Third, we conducted a manual photo-interpretation of the 2009 orthophotoplan to refine and correct the classification.

12 Segmentation and classification processing was performed using the eCognition Developer 8.7© software (Baatz M. et al., 2004). Object edges were identified from vector data input (Table 3). Then a multi-resolution segmentation was based on spectral, texture and context-dependent criteria; this allowed us to capture objects that were not identified in the first phase (Baatz and Schäpe, 2000 ; Benz et al., 2004). This process produces precise polygons that were classified according to spectral differences to match the typological classification presented in table 1. At the end of this semi-automatic extraction process, a photo-interpretation and manual digitize correction was performed to ensure a precise matching between the map produced and the IGN orthophotoplan dataset.

13 This process was initially conducted for the 2009 data. The 2003 and 1998 land cover maps were then produced by identifying changes, which were manually digitized using IGN orthophotoplans of 2003 and 1998. From the 2009 final map, we identified the changes that occurred over the 2003-2009 period by photo-interpretation of the 2003 orthophotoplan and thus obtained the 2003 final map through this backwards updating process. We repeated the same process to obtain the 1998 land cover map. The use of the BD Topo database by 1998 and 2003 (Table 3) helped us in the photo-interpretation process. All types of changes were taken into account. The photo-interpretation process for detecting and updating land cover changes was conducted at a 1:10,000 resolution.

14 Lastly, all three maps were independently assessed by a photo-interpreter who had not been involved in initial map production (Bariou, 1978; Bie and Beckett, 1973). For all specific details about the mapping procedure please refer to Lefebvre (2014). The final map is evaluated with a Global Precision mapping higher than 95%.

Figure 2 - Processing flowchart for Land Cover mapping in 1998, 2003 and 2009, using an object-oriented, semi-automatic, multi-source approach.



Landscape dynamics analysis

We analyzed resulting maps in three steps:

- First we analyzed area and percentage of land cover change between 1998 and 2009, per landscape type (at the three levels of the typology), per study site sector. The analysis was conducted by analyzing the GIS database using the ArcGis (version 10.2, ESRI Inc.) software.
- Second, we then designed a dynamic typology of municipalities to produce a synthetic map of land cover changes, aggregating fine-scale patterns to a scale more relevant to stakeholders and decision-makers. This classification step aimed to determine the dominant land cover types for all municipalities in 1998 and the major trends observed over the 1998-2009 period. We quantified for each municipality the land cover transitions over the 1998-2009 period using the GIS database in ArcGis (version 10.2, ESRI Inc.) software.
- Third, the landscape dynamics analysis identified some characteristic trends of changes across the study area. We analyzed it for a selection of seven municipalities that represent an overview of land cover change types and dynamics in different parts of the study site. We refined the major trends changes in spatial patterns of land cover using two main landscape metrics (table 4): the Landscape Shape Index (LSI) and the Shannon Diversity Index (SHDI). LSI and SHDI provide a good representation of landscape configuration and diversity (Cushman et al., 2008; Sheeren et al., 2014). Of the multiple landscape metrics tested, we chose to present these two which adequately capture landscape patterns and their changes over the observation period. We computed the LSI and SHDI metrics using the Fragstats software (McGarigal et al., 2012).

Table 4 - Description of landscape metrics using Fragstats (Cushman et al., 2008).

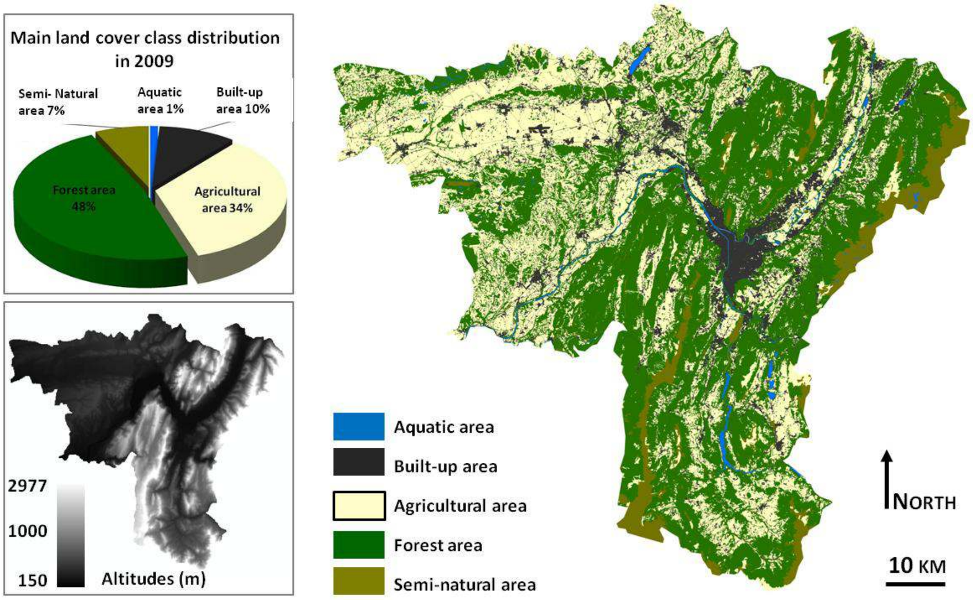
Metric	Name, description	Category	Level
LSI	**Landscape Shape Index** equals the total length of edge (or perimeter) involving the corresponding class, given in number of cell surfaces, divided by the minimum length of class edge (or perimeter) possible for a maximally aggregated class, also given in number of cell surfaces, which is achieved when the class is maximally clumped into a single, compact patch. LSI ≥ 1, without limit. LSI = 1 when the landscape consists of a single square or maximally compact patch of the corresponding type; LSI increases without limit as the patch type becomes more disaggregated.	Perimeter (Landscape configuration)	Class
SHDI	**Shannon Diversity Index** equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion. SHDI ≥ 0, without limit. SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SHDI increases as the number of different patch types (i.e., patch richness) increases and/or the proportional distribution of area among patch types becomes more equitable (Shannon and Weaver, 1964).	Diversity	Landscape

3. Results

Landscape dynamic analysis between 1998 and 2009

16 In 2009, built-up surfaces represented 466 km², i.e. 10 % of the study area; the respective figures are 1497 km² (34 %) for agriculture, 2153 km² (48 %) for forests, 293 km² (7 %) for semi-natural areas and 41 km² (1 %) for aquatic surfaces (Figure 3).

Figure 3 - Main land cover distribution on the Grenoble region in 2009.

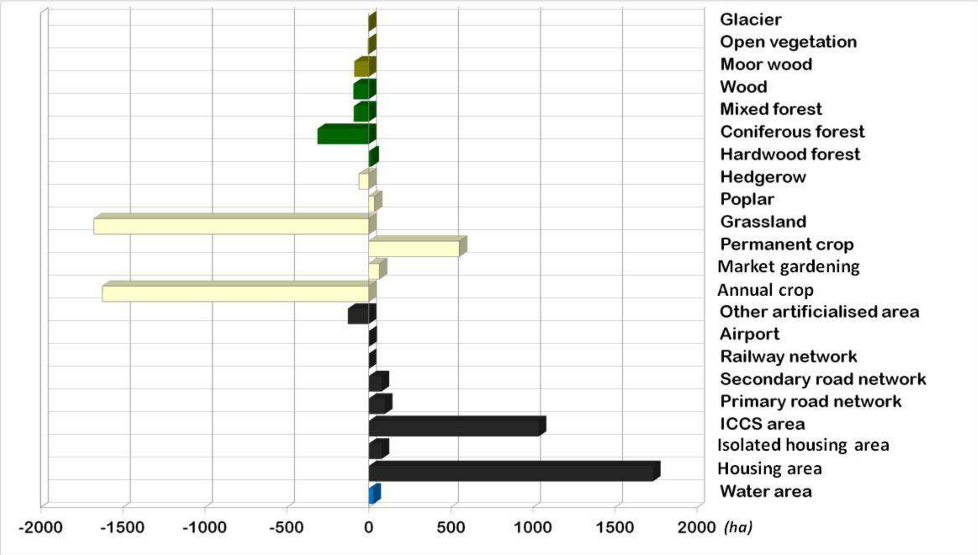


17 The observed land cover evolution between 1998 and 2009 for all classes of our detailed typology (level 3) is shown on figure 4. The most significant trends concern built-up areas.

18 Between 1998 and 2003, artificialization increased by 14.2 km² (+3.3 %), while agricultural surfaces decreased by 13.6 km² (-0.9 %). Forests and semi-natural areas showed very limited change, 0.05 km² and 0.8 km² respectively. Finally aquatic areas increased by 0.1 km². During the next period (2003-2009), net gains of built-up areas of 14.7 km² (+3.3%) at the expense of agriculture (13.5 km², - 0.9 %) were still significant, and consistent with the previous period; trends in water bodies (0.2 km², + 0.4 %), forests (-1.2 km²) and semi-natural areas (-0.1 km²) were also steady.

19 This first analysis points out a significant dynamics primarily of both built-up and agricultural areas, where most of the 28.9 km² gained by urban areas between 1998 and 2009 were taken from agriculture for 90% (seasonal crops 52%, grasslands 33%, permanent crops 3%) and 10 % from forest or semi-natural areas (hardwood forests and wood 4.9%, open vegetation 2.5%, moor wood 2%). The total agricultural area (SAU, “Surface Agricole Utile”) decreased by 27 km² while forests and semi-natural areas decreased by 2.1 km². The remainder of this discussion is therefore centered on the dynamics of built-up areas, whose fast growth raises a number of environmental and planning issues.

Figure 4 - Land cover evolution between 1998 and 2009 (typology level 3).



20 In 1998, the urban area was mostly concentrated in the Grenoble 'Y' (at the confluence of the rivers Isère and Drac): this encompasses the Grenoble metropolitan area per se, the North-East Gresivaudan valley and the area around the town of Voiron in the North-West. This was the largest residential area, and most commercial and industrial activities were also concentrated there. The southern part of the region (Matheysin plateau, Trièves) had a more rural character, with a small fringe of economic activity located at the border of the city of La Mure. In the Vercors range, residences and activities were located in the four main towns of Lans-en-Vercors, Villard-de-Lans, Méaudre and Autrans. In the Bièvres sector, mostly residential areas were to be found, with business areas limited to specific zones such as the Grenoble-Isère airport. Finally, in the South Gresivaudan valley both businesses and residential zones were mostly found in the two main local towns of Saint-Marcellin and Tullins. The other (usually small) urbanized patches of the study area correspond to villages and isolated farms.

21 On average urban growth in the study area was stable and high, above 4 % over the two periods. Out of the nearly 28.9 km² of urban areas gained in the 1998-2009, period, about 70% of the increase observed in 1998-2003 and 60% in 2003-2009, were concentrated in two sectors: the North-Gresivaudan valley and Bièvres-Voiron. However their respective dynamics differs in details, indicating a significant shift in the urban sprawl dynamics with a decrease across the two periods from 7 % to 3.5 % for Grésivaudan, in contrast to a stable rate or a slight increase from 7 % to 8 % in Bièvres-Voiron. Most of this growth is due to residential areas (2/3), the rest being accounted for by business areas (1/3). Finally, most of it (3/4) is located in valleys, with hillsides and other areas representing the remainder.

Synthetic overview of changes

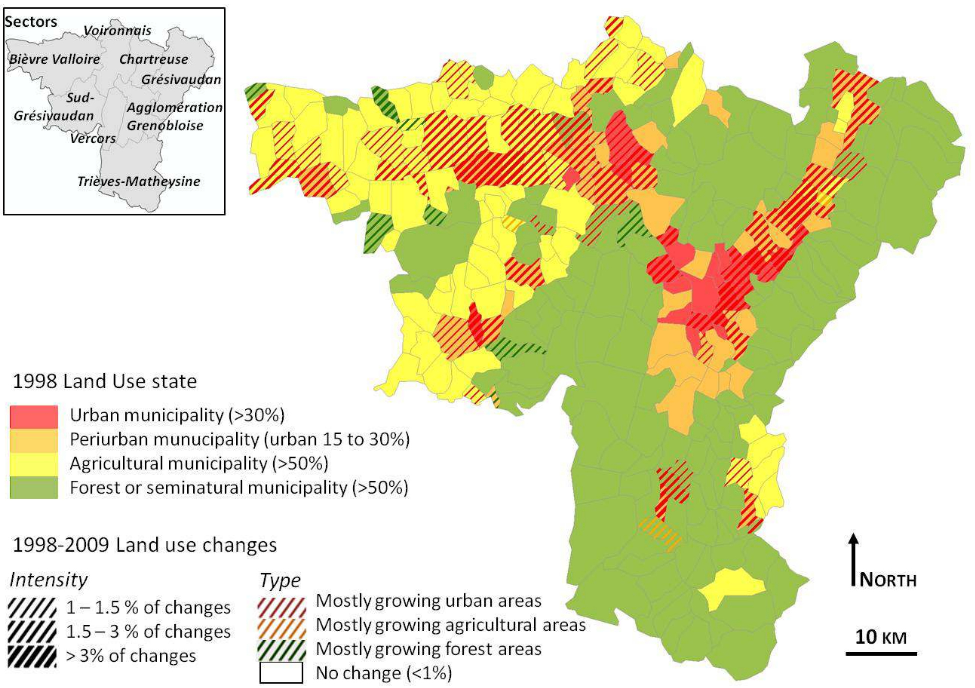
22 The dynamic topology of municipalities in the Grenoble catchment area allowed us to characterize in a synthetic way the prominent features embedded in our typological classification of land cover. Figure 5 shows, per municipality, 1- a typology of land cover state in 1998 and 2- the most salient changes during the 1998-2009 period. First, we

defined four types of land cover states in 1998 : urban, periurban, agricultural, forest or semi-natural municipalities, representign the prevalent land cover type in a municipality. Second, we quantified the percentage of changes in land cover types to define the more salient change per municipality, yielding four types: mostly growing urban areas, agricultural areas, forest areas and no changes (less than 1%). Figure 5 maps the 1998 state, the 1998-2009 changes per types of change, and takes into account the intensity of the change.

23 The resulting qualitative map highlights the same type of dynamic at the municipality scale than at the finest grain : the urban/peri-urban dominance of the Grenoble 'Y' ("Agglomération Grenobloise", "Grésivaudan", "Sud-Grésivaudan" sectors, figure 5), although agricultural areas are not negligible there, as well as forested areas, to a lesser extent. Probably the most significant characteristic displayed on this map is the prominence of newly built-up areas in the 1998-2009 period, not only in the valleys of the Grenoble 'Y', but also in the Bièvre and Voiron plains. The second most important feature to note is the significant abandonment of farmland in more rural municipalities resulting in encroachment, or conversely a gain in areas devoted to agriculture; however such changes remain less extensive than the generalized tendency towards artificialization. Most "Forest or Semi-natural municipalities" were very stable during the period.

24 This analysis also shows that the study area can be divided into two major zones of contrasted characteristics. Mountain massifs and valleys represent 2/3 of the total area, at the East and South of the region, where most forested areas are located, and urban development confined in valleys. The last 1/3, at the North-West, is made up by Bièvre and South-Grésivaudan, with a dominant plain and low plateau type of landscape, where agriculture and peri-urban growth constitute the salient features.

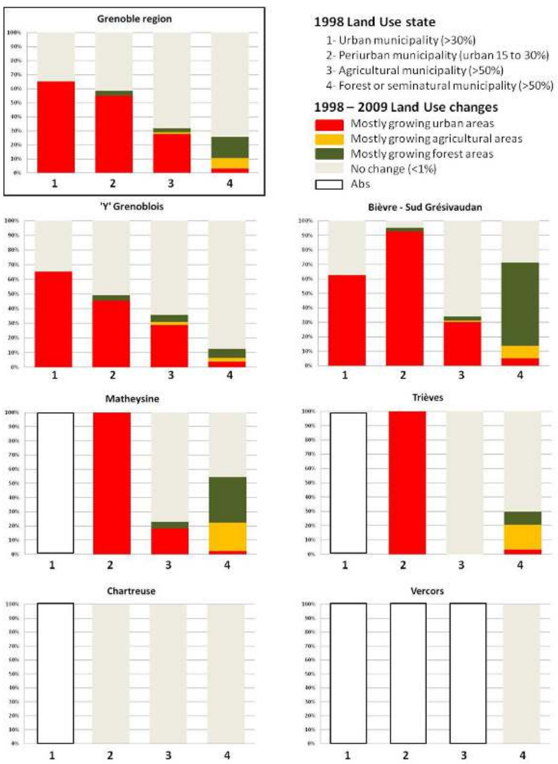
Figure 5 – Typology of municipalities of the Grenoble catchment area in 2009. The dominant type of land cover in 1998 is shown, with the dominant type of change of land cover in the 1998-2009 period superposed.



25 Figure 6 presents a more quantitative but less spatially explicit statistical analysis of this dynamic typology. This analysis was performed per sector (by aggregation of municipalities' statistics) of the study area and for the whole study area in order to compare the changes between sectors and according to the general trend. The dynamic typology represented is the same as in figure 5: for each sector the four major land cover types present in 1998 are represented by one bar for each type; and the percentage of changes that occurred between 1998 and 2009 is represented for each type of 1998 land cover.

26 The resulting aggregation at sector scale highlights a strong dynamics of urban and periurban areas, in the same way as the analysis at the municipality and fine scales. For the whole study site (name Grenoble region in figure 6), 65% of the municipalities classed in "urban > 30%" (type 1) encompass mostly growing urban areas. This percentage is the same for the "Y" Grenoblois, Bièvre and Sud-Grésivaudan, were the dominant sectors where urban growth was very marked in absolute value during the period. Three sectors showed a very marked relative urban growth in peri-urban municipalities, Bièvre and Sud Grésivaudan, Matheysine, Trièves. In these three sectors the changes in forest or semi-natural municipalities were also greated than in the entire study area. This is due to encroachment because of agricultural abandonment or alternatively some resumption of agriculture in some parcels. The Chartreuse and Vercors sectors, the two only entirely mountainous sectors in the study area, were very stable during the period.

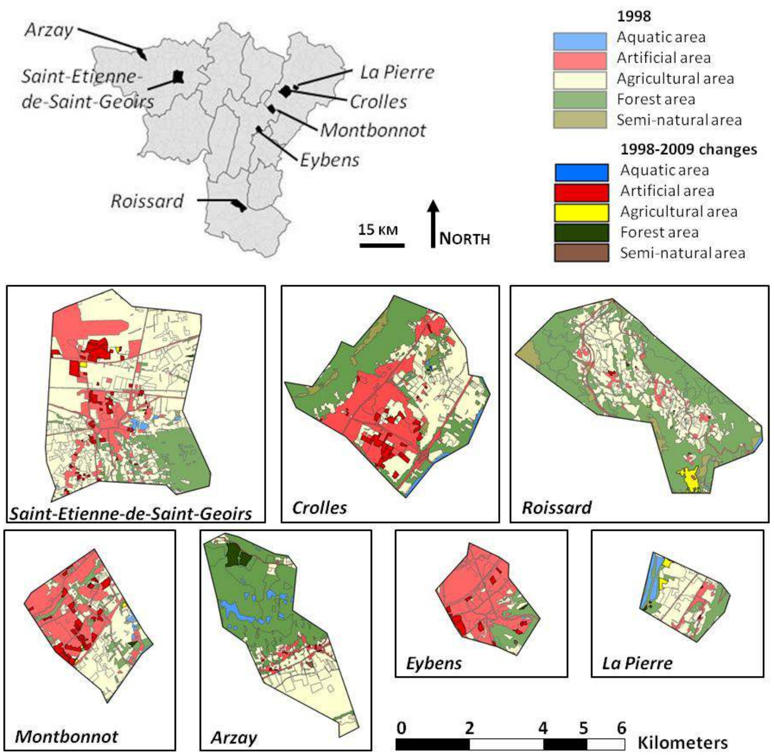
Figure 6 - Statistical analysis of the dynamic typology: land cover states and changes in 1998 and between 1998 and 2009 per sector and for the whole study site.



Changes in spatial patterns of land cover

27 Given the results proposed by the synthetic overview of changes, we chose to apply some landscape metrics analysis in seven municipalities representative of the most salient land change types (Figure 7). They are located in the three most dynamic sectors, 'Y' Grenoblois, Bièvre and Trièves-Matheysine. The Eybens and Montbonnot municipalities were classified as "Urban municipalities" in 1998 and were "mostly growing urban areas" between 1998 and 2009. Crolles and Saint-Etiennes-de-Saint-Geoirs were classified as "Periurban municipalities" in 1998 and were "mostly growing urban areas" between 1998 and 2009. La Pierre was classified as "Agricultural municipality" in 1998 and reflected "mostly growing agricultural areas" between 1998 and 2009. Arzay and Roissard were classified as "Forest or semi-natural municipalities" in 1998 and were "mostly growing forest/agricultural areas" (respectively) between 1998 and 2009.

Figure 7 - Choice of the seven municipalities, representative of the dynamic changes observed, for landscape metrics calculation.



28 The Landscape Shape Index (LSI) decreased for nearly all the land cover classes considered (Figure 8). This is explained by the homogenization of the landscape, with the new urban/agricultural/forest areas appearing most of the time along existing urban/agricultural/forest patches. Figure 8 shows the LSI evolution for the four more dynamic municipalities. In Eybens and Montbonnot, the LSI decreased steadily through the study period, indicating an ongoing homogenization and simplification of the landscape. In Crolles and St Etienne, the LSI of urban class decreased while the LSI of agriculture or forest classes increased or remained stable. This dynamics illustrates that built-up areas grew almost exclusively in the continuity of existing urban areas. Isolating the most

dynamic municipalities makes these trends much clearer and their origin simpler to identify.

29 The Shannon diversity index (SHDI, Figure 9) decreased through the study period for Eybens, Montbonnot, and La Pierre; was stable for Crolles and Roissard and increased for Arzay and St Etienne. These results show that whatever the types of changes, the spatial patterns of all the landscape types induce a better homogeneity and contiguity of the landscape elements.

Figure 8 - Landscape Shape Index calculated at the class scale for the four more dynamic municipalities.

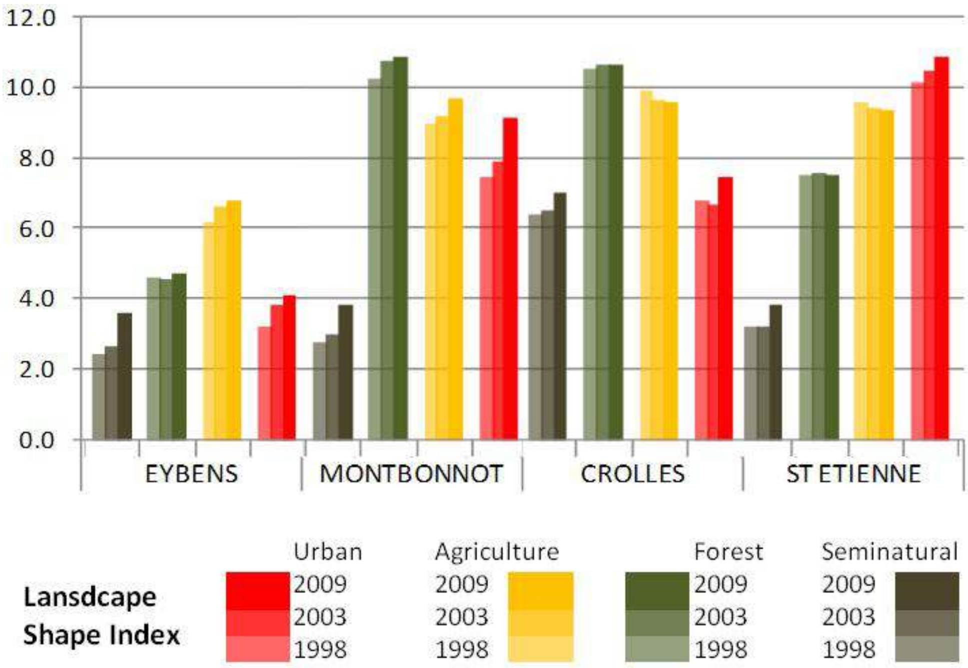
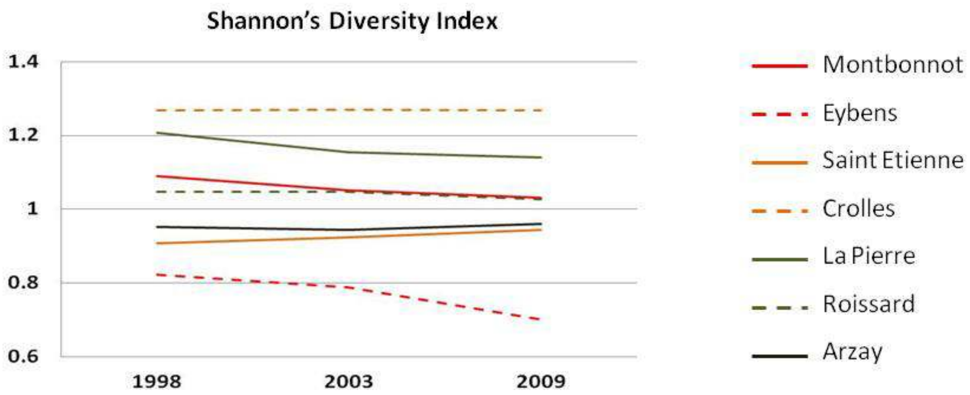


Figure 9 - Shannon Diversity Index calculated at the landscape scale for the seven representative municipalities.



30 More generally, the analysis of the two selected indicators of landscape spatial patterns, both at the landscape and class level (for the five main classes at typology level 1), and the cartographic analysis of changes, confirm that most of the changes took place adjacent to similar spaces. This is particularly true for urban growth, where all new built-up areas appeared alongside or less than 50 meters (97.3%) away from existing urban

areas, or by densification within existing urban areas. This induced little or no fragmentation in the landscape and increased the continuity of similar spaces. This explains the steady decrease in the LSI especially for the urban class, and the decrease of the SHDI especially for the urban municipalities.

4. Discussion

Quantifying artificialization at different scales

31 In general, quantitative analyses of landscape dynamics make use of existing cartographic databases. These data sources are either used "as is" or after improvements tailored to fit the needs of the project at hand. In Europe, Corine Land Cover (CLC) from the EEA (2009) is used most frequently as primary data (Díaz-Palacios-Sisternes et al., 2014; Feranec et al., 2010, 2007; Guérois, 2003), or combined with remote sensing data (Tapiador and Casanova, 2003 ; Pekkarinen et al., 2009). The CLC database has already been used to analyze urbanization and its major patterns from European to regional scales, for the years 1990, 2000 and 2006. This general analysis allows us to put our fine scale study and its spatial trends in a larger perspective: Feranec et al. (2010) showed that France is one of countries with the most distinct and extensive urbanizing process (+6.8% during the 1990-2000 period) along with Germany, Spain, the Netherlands, Italy and Portugal. The artificialization process in Europe is marked essentially by residential, industrial and commercial area growth. In France expansion has however started to slow down from +4.8% between 1990 and 2000, to +3% between 2000 and 2006. The same trend is relevant at the regional scale for our study area, where according to CLC artificialization in the Rhône-Alpes NUTS2 region was +3.7% between 1990 to 2000 and +3% for the 2000-2006 period, the latter mostly due to the growth of industrial and commercial areas.

32 A finer database than CLC, around 1 ha resolution, could be necessary to discern patterns of urban sprawl in most French territories (Aguejdad et al., 2009; Laroche et al., 2006). In fact, at NUTS3 scale (Isère department), the artificialization process observed using CLC is +1.57% (1990-2000) and 2.42% (2000-2006). However, our study, located in the southern half of the Isère department (but including 3/4 of the department's population) showed a high and steady increase of +6% for urbanization along the 10 year study period, with even greater rates in valley, plain and plateau areas (+7% to 8%) but lower rates (3.5%) in the mountain areas. At fine scale, in a region dominated by small- to medium-sized urban areas and only small changes around the existing ones, the observed trends appear to exceed interpretation limits of the CLC database. This fully supports the development of a multi-temporal cartographic database for our study.

Changes in landscapes in mountain regions of the Alps

33 Few other studies have mapped and quantified regional-scale land use and land cover dynamics in mountain regions using appropriate data and typology. However, despite differences in data, typology, spatial and temporal resolution, the major trends of landscape pattern dynamics recur across all studies. For example, two main studies at a large spatial and temporal scale took the challenge of the fine-grain analysis of land use and land cover in alpine landscapes. First, Zimmerman et al. (2010) studied LUCC trends for the entire European Alps, using a sample of 35 municipalities in five alpine countries,

representative of landscape diversity across the region, and stratified by ecoregions and topography. Their study was based on historical maps and remote sensing data to determine LUCC trends since the 19th century. The typology of their study was very precise, using 35 land cover classes to estimate plant species richness and temporal dynamics. Second, the OPS program (Swiss Landscape Observation - OFEV, 2010), studied across Switzerland the state and changes of Swiss landscapes, based on national statistical analysis, topographic databases and indicators, since the 1980's. For these two studies, and more generally for analyzing the state and dynamics of a large and complex landscapes, no unique and ideally suited data set can be found. Even remote sensing cannot fulfill all criteria of fine spatial resolution to produce a fine typology relevant over a large area, and covering several decades of retrospective / historical analysis (Kuenzer et al., 2014). This imposes methodological trade-offs, which are particularly acute for built-up land or urban settlements, for which precise data is scant (Antrop, 2004).

34 Despite such methodological trade-offs, but taking into account the main topographic conditions, Zimmerman et al. (2010) distinguished different trajectories, e.g. pointing out contrasts between valley bottoms and slopes for agriculture trends. They found a mean urban sprawl of 16 to 21% since the 19th century, taking place more often in urbanized centers and through a densification process. OFEV (2010) results for Switzerland confirm the same trends: agricultural areas decreased by 2% per decade due to urban pressure; artificialization was rapid, albeit with a recent slowing down (13.3% between 1983-1995, and 9.2% between 1995-2007). Residential areas and roads accounted for most of these trends as a result of population growth as well as increasing urban sprawl, especially in the Swiss plateau region. Antrop (2004) noted the same characteristic patterns of urban sprawl in Europe, with artificialization taking place along roads or due to the development of satellite urban centers with new commercial or industrial activities.

35 These main results, at two different scales, in the Alps region, although produced by very different data and methods concur with the results of our analysis especially concerning artificialization trends despite the different scales of analysis. Such consistency could be explained by the magnitude of the urban sprawl phenomenon. Our study, with a precise mapping for three dates over a bit more than a decade showed that in spite of a restrictive land planning policy, urban sprawl remains high (even if it has slowed down), especially in plain or plateau regions, and logically rather in valley bottoms than at altitude or on slopes. The contribution and originality of our mapping exercise was its fine grain that allowed us to quantify the artificialization process in great detail, distinguishing urban residential areas, roads and industrial/commercial areas. However, such a study was feasible for 4450 km² (half of a French department), but would not be practical for a greater extent (the entire Alps for example), or for a longer time span.

Limits of decadal landscape observation

36 Although the time span of our analysis is quite appropriate for the analysis of recent urban sprawl and of current spatial patterns, our study holds some limitations. Our 11 year time period, with three evenly spaced maps, does not match the temporal scale needed to quantify some changes like forest encroachment or agricultural system transformations. Rutherford et al. (2008) showed that one of the predominant processes of land cover change in the European Alps over the last 150 years has been the abandonment of agricultural land and the subsequent regeneration of forest. Zimmerman

et al. (2010) and Tasser et al. (2007) showed that using a multi-decadal temporal depth, some major agricultural trends can be highlighted. They showed major grassland abandonment, natural reforestation processes or changes in cropping systems (introduction of permanent crops like vineyards or orchards) thanks to this longer time span. However, in the Rhône-Alpes region and particularly in the Grenoble area such an agricultural abandonment process at the benefit of reforestation cannot be observed in our data. Forest boundaries have been very stable for several decades. Some local colonization can however be observed along forest edges in steep and closed landscapes resulting from agricultural abandonment, or in the plain, pending an urbanization process. Our study database allowed us to detect these two processes at specific locations but can be only partially validated because of the lack of externa precise spatial data for encroachment. While our database is not appropriate for describing the dynamics of cropping systems (lack of precise typology and monitoring), these can be observed using remote sensing data even in mountain region (Atzberger 2013; Ayanu et al., 2012; Kuenzer et al., 2014).

37 Finally the urban densification process, which is the main strategy to reduce urban sprawl, is one of the gaps in our database. While we were able to quantify urban sprawl precisely, observing the densification of existing urban areas proved to be impossible at this spatial scale. Quantifying and mapping urban densification over time needs multi-temporal and high or very-high spatial resolution remote sensing data (Bhatta et al., 2010; Wurm et al., 2010; Banzhaf and Hofer, 2008; Rashed, 2008). The Urban Atlas (from the European Environment Agency - EEA) could allow us to quantify urban sprawl. This database, created using remote sensing classification and photo-interpretation, maps precisely land cover and urban density for all large urban zones with more than 100,000 inhabitants in Europe. Unfortunately, for the Grenoble region, the data is delivered only for year 2006 (and not yet for year 2012).

Landscape analysis for ecosystem services assessments and land planning

38 This study was developed in partnership with local stakeholders of the Grenoble region. The ultimate aim for this database was to produce spatially-explicit and exhaustive knowledge for the whole Grenoble area at three dates. The spatial scale, map typology and indicators of landscape dynamic analysis were developed according to the needs of stakeholders, as identified during dedicated workshops. This participatory experience allowed us to develop a database and targeted indicators such as the synthetic map (presented in section 3.2.) that could be useful for stakeholders and public dissemination. This synthetic map represents trajectories of changes at the municipality scale. It displays in compact visual form the nature of changes and highlights the importance of urbanization as the dominant driver of change in the study area during the 1998-2009 period. Typologies, such as the one we developed, are a common tool to cluster spaces with similar characteristics and possibly similar policy needs (Davis and Hansen, 2011; Verburg et al., 2010). Therefore, we believe that the synthetic map we proposed at municipality scale should help managers, decision makers and land use planners in their decision exercises by providing information on land use trajectories.

39 Furthermore the whole database will be used for supporting ecosystem services mapping taking into account and addressing stakeholders main concerns. Indeed, the ecosystem

services concept is increasingly incorporated into land planning (Ahern et al., 2014; Cowell and Lennon, 2014; Egoh et al., 2008; Gill et al., 2008). Developing such studies in direct interaction with stakeholders is a fundamental challenge to mainstream ecosystems services into land planning exercises (de Groot et al., 2010; Opdam et al., 2015).

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NOTES

1. The SCoT, Territorial Coherence Scheme is a French planning document that determines, for groups of municipalities, common objectives for urban planning, housing, transport, and business and retail areas.
http://www.region-grenoble.org/index.php

ABSTRACTS

We describe landscape changes in the context of a rapidly urbanizing mountain region, around the city of Grenoble in the French Alps. By combining a multi-source merging method and aerial photo-interpretation, we analyzed land cover dynamics during the 1998-2009 period. The analysis across 3 dates of the cartographic database for the 4450km² at 1:15,000 scale, with of 23 land cover types, showed a rapid and steady urban growth at the expense of agricultural areas, with an expansion greater than 6% during the ten-year period. A synthetic overview of changes at municipality scale showed the prominence of newly artificialized areas not only in the valleys around Grenoble but also in the main, predominantly agricultural plain areas of Bièvre and Voiron. Most of the changes are contiguous to already urbanized areas. Therefore they induce limited landscape fragmentation, as new built-up areas are emerging alongside existing ones or within existing ones as part of a densification process.
The results obtained for this area illustrate an emerging major preoccupation in the Western European Alps (Switzerland, Italy, Austria...), namely that the present rate of urbanization is not sustainable in the longer run in fragile Alpine valleys. In this respect, our cartographic database will provide baseline information for a participatory prospective exercise performed with local stakeholders of the Grenoble region, aiming to support sustainable land management and planning.

Cet article présente l'analyse de l'évolution du paysage en région de montagne, dans les Alpes françaises autour de la ville de Grenoble où l'étalement urbain joue un rôle important. Nous avons analysé la dynamique de l'occupation des sols au cours de la période 1998-2009, à partir de

la fusion de données spatiales multi-sources et de l'interprétation de photographies aériennes. Cette analyse, sur trois dates, à partir d'une base de données de 4450 km² au 1:15000ème comportant 23 classes d'occupation des sols, a permis de montrer la croissance urbaine rapide et régulière, supérieure à 6% le long des onze années de la période étudiée, ayant lieu pour l'essentiel au détriment des espaces agricoles. Une carte de synthèse des changements observés, présentée à l'échelle communale, montre l'importance des zones nouvellement artificialisées non seulement dans le fond de la vallée autour de Grenoble, mais également dans les principales zones de plaines agricoles de la Bièvre et du Voironnais. La plupart des changements d'occupation des sols s'effectuent dans la continuité des espaces similaires existants. Ils induisent une fragmentation limitée du paysage, comme c'est le cas des espaces nouvellement urbanisés apparaissant dans la continuité de la tache urbaine existante.
Les résultats obtenus dans cette étude illustrent une des préoccupations majeures des Alpes d'Europe occidentale (Suisse, Italie, Autriche…), à savoir que le taux actuel d'urbanisation n'est pas soutenable à long terme dans des vallées alpines fragilisées. A cet égard, notre base de données cartographique fournit une information de base pour un exercice prospectif participatif effectué avec les acteurs locaux de la région de Grenoble dans le but de soutenir une gestion territoriale et une planification locale durables.

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