Historical anthropization of a wetland: steady encroachment by buildings and roads versus back and forth trends in demography

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A R T I C L E   I N F O

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A B S T R A C T

Coastal wetlands have been deeply modified by humans over the last centuries. The assessment of such changes has been mainly documented through traditional Land-Use or Land-Cover (LULC) change studies, basically mapping changes in the composition of the main habitats. Through the example of the second largest wetland in France (the Marais Poitevin, 1000 km²), our aim was to test whether only taking into account changes in habitat composition is sufficient to assess the anthropization of a wetland. For the first time at such a temporal and spatial scale and at such a spatial resolution, we documented the historical evolution of human demography, buildings and roads over the three last centuries in this area. These data were then compared with historical changes in habitat composition. We found that backward and forward temporal trends in habitat composition were linked with the evolution of human demography but that building and road density increased steadily over time. Consequently, remote areas far from human artifacts (buildings and roads) have become increasingly scarce. Our results suggest that to assess the anthropization of a wetland, not only changes in habitat composition should be taken into account but also every human artifact that can dramatically change a landscape.

1. Introduction

Wetlands are among the most productive ecosystems in the world (Dugan, 1993; Keddy, 2014) and provide habitats for the survival of a disproportionately high percentage of endangered and threatened species (Mitsch & Gosselink, 2015). However, since 1900, unprecedented loss of wetlands has occurred all over the world for several reasons such as coastal erosion (Cellone, Carol, & Tosi, 2016), coastal subsidence (Rizzetto & Tosi, 2011), land use changes (Margono, Potapov, Turubanova, Stolle, & Hansen, 2014) and they have become increasingly rare and limited in size (for a review, see Nivet & Frazier, 2004 and reference therein). 87% of wetlands may have disappeared since 1700, and 64–71% of the area they covered in 1900 was lost in the 20th century (Davidson, 2014). To monitor these changes, Dixon et al. (2016) constructed a global index of the change in natural wetland extent (Wetland Extent Change) based on a meta-analysis. At local scales, a number of studies have quantified the loss of particular habitats within wetlands such as saltmarshes (e.g., Baily & Inkpen, 2013; Godet, Pournet, Joyeux, & Verger, 2015; Puissant, Lefèvre, Desguée, & Levoy, 2008). Other studies have focused on land cover changes in wetlands either over short-term periods (e.g., recent decades) using remote-sensing methods (Dewan & Yamaguchi, 2009; Dingle Robertson, King, & Davies, 2015; Isunju & Kemp, 2016) or during historical time, but on study sites of small spatial extent (Cousins, 2001; Gustavsson, Lennartsson, & Emanuelsson, 2007; Johansson et al., 2008; Skalol et al., 2011).

As well as habitat loss or conversion, human demography, building and road development are other facets of landscape anthropization, sometimes even recognized as a primary cause of anthropogenic landscapes (Hammer, Stewart, Winkler, Radeloff, & Voss, 2004). These three indicators are usually used together at a large spatial scale to quantify global indices of human pressure at a given time, e.g., the human footprint (Sanderson et al., 2002). They are also used to assess their impact on biodiversity (Chen & Roberts, 2008; Pidgeon et al., 2004; Stritcholt & Dellasala, 2001) or on landscape fragmentation (Hawbaker, Radeloff, Clayton, Hammer, & Gonzalez-Abraham, 2006; McGarigal, Romme, Crist, & Roworth, 2001). While several studies have assessed urbanization within wetlands or at their periphery (e.g., Ancog & Ruzol, 2015; Lee et al., 2006), explicit quantification and mapping of the long-term spatio-temporal extent of demography, buildings and roads in wetlands have not received much attention. Moreover, wetland anthropization assessment has focused on either habitat losses and changes or some indicators of human encroachment but has failed to test whether they follow the same trends.
In this study, we propose to quantify and map the evolution of three facets of anthropization: demography, buildings and roads over 300 years using high-resolution historical records and to compare it with habitat cover changes in a large wetland of 100,000 ha. We selected the Marais Poitevin (MP) as a model for several reasons. First, because it is one of the largest wetlands in Western Europe. Also because a preliminary study was conducted on the temporal evolution of demography and the dynamics of building but only on a restricted area of the western MP (Pouzet, Creach, & Godet, 2015). Finally, the habitat loss and conversion of this wetland are well known and documented. Croplands and grasslands have followed backward and forward temporal trends and, as in many other wetlands, the most natural habitats such as marshes, saltmarshes and other marine habitats have faced a massive decline (Godet & Thomas, 2013). In the MP, the recognition of these losses and changes in natural habitats in the 1970s led to the establishment of a policy (e.g., the creation of natural reserves) to maintain saltmarshes and grasslands, considered the last remaining ‘natural’ habitats. However, because of a lack of knowledge about human encroachment, such as building or road development, there were no conservation policies to manage or control such processes.

Our primary hypothesis is that the evolution of demography, buildings and roads shows trends other than those of habitat cover. This provides complementary approaches to assess and monitor the anthropization of wetlands.

The specific aims of our study are (i) to quantify three indicators of human encroachment, i.e. demography, buildings, roads, over 300 years and compare the temporal trends in these indicators with those in grassland and cropland cover; (ii) to map the spatio-temporal evolution of buildings and roads in terms of both densification and sprawl.

2. Materials & methods

2.1. Study site

The Marais Poitevin (MP) is the largest Atlantic wetland in France and covers approximately 100,000 ha (Verger, 2009). In this study, we applied a 500-m buffer zone around the official perimeter of the MP (Forum des Marais Atlantiques & Conservatoire du Littoral, 1999, p. 62) in order to assess the temporal evolution of the buildings and road network inside and at the edge of the wetland. This buffer radius allows including the coastline in the analysis. The total area considered in this work thus encompasses 140,542 ha (Fig. 1).

2.2. Demography assessment

Because the demographic census was recorded within each municipality which does not match with the exact perimeter of the study site, only municipalities totally included within the study site were selected (outlined in black in Fig. 1). The area covered by these municipalities represents 75% of the total area of the study site. For each of these 31 municipalities, all the 33 years, with intervals of 5–6 years, of the demographic census from 1801 to 2012 were used to assess the evolution of demography.

2.3. Building and road data processing and mapping

Four datasets were used to assess the temporal evolution of building and road networks from 1705 to 2014 (see a sampling example of the data sources used and a step by step workflow of the data processing in Fig. 2). In order to compare the temporal trend in building and road distribution with changes in the two main land covers assessed by Godet and Thomas (2013), we reused the 3 same original documents dated 1705, 1820 and 1950. The first is composed of 7 historical maps drawn by the French engineer Claude Masse dated 1705 (scale 1:28,000); the second is the ‘Etat-Major’ historical maps dated 1820 which have a resolution of 1:40,000 and the third is composed of panchromatic aerial photographs of 1950 taken by the French National Geographic Institute (IGN) at a scale of 1:26,000. For detailed information about scanning, georeferencing and orthorectification process of these 3 documents, see Godet and Thomas (2013), pp. 134–136. Finally, the most recent dataset comes from a vector database (BD-TOPO) also produced by the IGN in 2014.

With help of a Geographical Information System (GIS), all roads were vectorized as lines and buildings as polygons, using the same 1:1000 zoom scale for the Claude Masse and Etat-Major maps. Photo-interpretation of the 1950 aerial photographs and their vectorization were performed using the same zoom scale. Finally, the 2014 BD-TOPO dataset was used as the most recent year known. For the 1705, 1820, and 1950 datasets, 871 km of roads and 45,184 buildings, which represent 2024 ha, were manually vectorized.

The density of both roads and buildings was calculated and mapped for each of the 4 selected years. The Kernel density was used for points and lines of the spatial analyst toolbox in ArcGis 10.2 to calculate a magnitude per unit area from point/polyline features that fall within a neighborhood around each cell. The kernel function is based on the
Fig. 2. Diagram of image and data processing in a sampling example (2 × 2 km, located in Fig. 1) for each of the four years with (A) the original documents used, (B) the digitalization process of roads and buildings, (C) the calculation of densities of roads and buildings and (D) the calculation of the distance from roads and buildings.
quartic kernel function described by Silverman (1986). The density
calculation for roads was performed in a radius of a 1000-m circle
(314.16 ha). Road density maps are expressed in kilometers of road per
square kilometer. For building analysis, every building was firstly
converted in point in order to then compute the calculation of kernel
density of building points in a radius of 500 m (78.54 ha).

The radiuses of density calculations were chosen by an empirical
method. We first tested three distances of radius (500 m, 1 km and
2 km) and kept the best compromise between visual representation and
the normal distribution of the resulting data. The sprawl of roads and
buildings was assessed by calculating and mapping the remoteness.
Remoteness can be defined geographically as the distance from the
nearest point of access to a road or a building. It was performed with
ArcGis Spatial Analyst, using the Euclidean distance tool to calculate for
each cell the Euclidean nearest distance to any road or building. It
describes each cell’s relationship to a set of sources based on the
straight-line distance. For both raster layers, variables were then catego-
rized into 5 classes as follows [0–200]; [200–500]; [500–1000];
[1000–1500]; > 1500 m. In a further step, road and building layers
were summed to obtain a single map of distance from human settle-
ment. The resolution chosen for the raster data process was a pixel of
5 m which is a trade-off between accuracy and the final size of the raster
data.

2.4. Changes in habitat composition

We directly used the data of Godet and Thomas (2013) related to
land cover changes in the MP from 1705 to 2008, for a comparison
purpose with the temporal evolution of the demography, building and
road distribution. We specifically extracted from Godet and Thomas
(2013) the temporal evolution of the area covered by the two main
habitats: croplands and grasslands.

3. Results

3.1. Evolution of demography, roads and buildings over 300 years

3.1.1. Demography

In the 31 municipalities, the population trend followed three dif-
cent steps (Fig. 3). Firstly, the population increased from 1800 to
1866 from 27,924 to 41,911 (linear model + 232.27 inhabitants per
year ( ± 15.66 s.d.), $R^2 = 0.95$, $P < 0.0001$). Then, between 1866 and
1946, the population decreased from 41,911 to 30,425 inhabitants
(linear model –155.4 inhabitants per year ( ± 16.34 s.d.), $R^2 = 0.86$,
$P < 0.0001$). Finally, the population increased from 1946 to 2009 to
reach 39,151 inhabitants in 2009 (linear model + 120.92 inhabitants
per year ( ± 23.57 s.d.), $R^2 = 0.76$, $P < 0.0001$).

3.1.2. Buildings and roads

Over the study period, the total area of buildings and the total road
length steadily increased (Fig. 3). Only 1820, 1950 and 2014 data
covered the entire study site, so the year 1705 was excluded from the
comparison of building area and road length over the whole study site.
From 1820 to 1950, the road network increased from 188 to 220 km
and the number of buildings increased from 12,002 to 27,167
(+87.72 ha). Then, between 1950 and 2014, the trend grew, with 144
additional kilometers of roads (from 220 to 364 km) and 61,931 addi-
tional buildings (from 27,167 to 89,098) which represent 465 ha.

3.1.3. Comparison of the trends in demography, road length, building area
and habitat changes

The cropland/grassland ratio on the study site (taken from Godet &
Thomas, 2013, Fig. 4, p137) showed back and forth temporal trends,
which can be compared with the temporal trend in the demography
(Fig. 3). The high number of inhabitants corresponded to a high pro-
portion of croplands. However, both the area covered by buildings and
the road network length showed a steady increase, with no back and
forth trend (Fig. 3).

3.2. Maps of the spatio-temporal evolution of buildings and roads in terms of
both densification and sprawl

3.2.1. Densification

Between 1705 and 2014, there was a significant densification of
both roads and buildings (Fig. 4). The mean building density increased
from 4.59 buildings per km² ( ± 11.73 s.d.) in 1705 to 58.50 buildings
per km² ( ± 157.95 s.d.) in 2014. In the same way, the mean density of
roads increased from 0.80 km/km² ( ± 0.95 s.d.) in 1705 to 2.52 km/
km² ( ± 1.79 s.d.) in 2014. Over the whole period, the road and
building densities steadily increased with an acceleration from 1950.

However, the densification of roads and building was not dis-
tributed homogeneously throughout the study site (Fig. 4). From 1705
and then 1820, the highest densities of buildings and roads were lo-
cated in the highest topographic areas (see Fig. 1 to locate the highest
area, and Fig. 4 to locate the evolution of buildings and roads). The
eastern part of the wetland also had higher densities of buildings and
roads that the western part. From 1950, the initially densest areas
continued to become denser. There was also a sprawl and some dense
areas merged together.

Finally, in the western part of the study site, precisely on the
coastline, located to the west of the Bay of Aiguillon, a new extremely
dense area of roads and buildings appeared. Whereas in 1705 and 1820
this area had very low densities of roads and buildings, it became the
densest area in 2014.

3.2.2. Remoteness

The average distance from roads and buildings (Table 1) and the
extent of the remote area (Table 2) decreased steadily over the study
period.

Between 1705 and 1820, the average distance from a road de-
creased from 1148 to 611 m and from a building, from 807 to 515 m. In
1950, the average distance from a road was 376 m and from a building
484 m. Over the last period, the trend remained the same. In 2014, the
average distance from a road was 247 m and from a building 356 m.

By taking into account both roads and buildings together (hereafter

Fig. 3. Evolution of the population (in number of inhabitants), densities of roads and
buildings (in base 100) and ratio of cropland and grassland from 1705 to 2014 taken from
Godet and Thomas (2013).
Fig. 4. Maps of the density of (A) roads in km per km² and (B) buildings in number of buildings per km² for 1705, 1820, 1950 and 2014.
The percentage of wetland area located at less than 200 m from human artifacts decreased from 10.54% to 1.36% of the total area. Conversely, proportion of the wetland located at more than 1500 m from human artifacts in 1705, and this proportion called “human artifacts”), almost 40% of the wetland was located at more than 500 m from human artifacts in 1705, and this proportion decreased from 10.54% to 1.36% of the total area. Conversely, the percentage of wetland area located at less than 200 m from human artifacts increased from 31.30% in 1705 to 62.87% in 2014 (see Fig. 5).

4. Discussion

4.1. A steady growth of human encroachment over three centuries in the largest French Atlantic wetland

The first main result of this study is that contrary to cropland - grassland cover changes (assessed by Godet & Thomas, 2013) and demography, which followed similar back and forth trends over three centuries, buildings and roads grew steadily over the same period.

It is generally accepted that population growth must be expected to play a major role in explanations of land cover change but there is a combination of factors that determines the direction and extent of these changes (Lambin & Geist, 2006). In the MP, we have shown that demography can be considered a powerful driver of land cover changes over 300 years, particularly concerning the evolution of the relative area covered by grassland and cropland. Godet and Thomas (2013) have shown how in the MP the exceptional increase in grassland and decrease in cropland from the end of the 19th century to the 1950s can be partly explained by the decrease in the population between the 1860s and 1950s described at a national scale by Dupâquier (1989). Our results, based on the assessment of population evolution at a municipality scale, confirm that demography may play an important role in the evolution of grassland and cropland cover in the MP over the study period.

More surprising is the absence of an obvious link between the temporal trend in demography on the one hand, and the temporal trend in building density and road network length on the other hand. This result differs from another study, which observed a strong relationship between road densification and population growth in an urban area (Strano, Nicosia, Latora, Porta, & Barbiélyem, 2012). However, these overall trends can hide stagnation in building and road development during the period of population decline that we cannot detect in our study because of the difference in the temporal extent analyzed between population and roads and buildings. In the MP, over the four years of the study, both buildings and roads followed a significant and constant growth. The total area covered by buildings tripled and the road length doubled, between 1820 and 2014. Even during the period of a decrease in demography, the growth of buildings and roads remained steady. These results highlight an incremental phenomenon of human encroachment, as demonstrated for human intrusion since 1870 in the Highlands of Scotland (Carver & Wrighnam, 2007).

Moreover, the significant development of coastal tourism since the 1950s has promoted the development of roads and buildings on the coastline as we showed to the west of the Bay of Aiguillon, and as demonstrated in several parts of European coastlines (European Environment Agency, 2006). This densification of roads and buildings is also found in the highest parts of the MP in the borders of the MP and in the former islands when the area was still a marine gulf and where first human settlements were recorded as early as the middle Neolithic period (Large, 1998), and, long time after, in the Middle-Ages (Clouzot, 1904).

To date, many studies have focused on the evolution of roads and buildings but mainly in recent decades and in urban areas. Our study shows that the phenomenon of human encroachment is ancient and does not only apply to urban areas. Processes of “densification and expansion” (Broitman & Koomen, 2015) or “densification and exploration” (Strano et al., 2012) already identified in urban contexts also occurred in more natural areas such as wetlands. This result highlights the need for buildings and roads control to preserve remote areas from human encroachment.

4.2. New insights into wetland anthropization assessment

Our study also highlights the importance of taking into account the evolution of roads and buildings in the assessment of land cover changes in wetlands. Usually, land cover is defined by “the attributes of the Earth’s land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human (mainly built-up) structures” (Lambin & Geist, 2006). Taking examples of studies related to land cover changes in wetlands, most of the authors took into account changes in the extent of the wetland itself (e.g., Yu et al., 2017), in the conversion of (semi) natural habitats into croplands (e.g., Schleupner & Link, 2008; Wu, Gao, Wang, & Xu, 2015), or in hydrological conditions (e.g., Carol, Braga, Kruse, & Tosi, 2014). Theoretically, the study of land cover changes may include roads and buildings but in fact, most studies do not quantify their evolution. This is mainly due to both the scarcity of accurate historical maps for long-term analyses and the low resolution of satellite imagery, which does not allow the mapping of individual buildings. Furthermore, the digitalization of buildings and roads at such a spatial extent and resolution is highly time-consuming because there is no satisfactory automatic method when original data are as diverse as in this study (different sets of old maps and old aerial photographs).

In addition, our study shows that the assessment of building and road evolution requires specific spatial analyses as calculation and mapping of densities and remoteness and cannot be quantified only in terms of spatial extent as for other land cover types. The first reason is

<table>
<thead>
<tr>
<th>Class of remoteness from roads and buildings</th>
<th>1705</th>
<th>1820</th>
<th>1950</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>In ha</td>
<td>In %</td>
<td>In ha</td>
<td>In %</td>
<td>In ha</td>
</tr>
<tr>
<td>[0–200]</td>
<td>36,748</td>
<td>31.30%</td>
<td>64,770</td>
<td>46.10%</td>
</tr>
<tr>
<td>[200–500]</td>
<td>33,666</td>
<td>28.68%</td>
<td>45,694</td>
<td>32.52%</td>
</tr>
<tr>
<td>[1000–1500]</td>
<td>9,683</td>
<td>7.74%</td>
<td>4,107</td>
<td>2.92%</td>
</tr>
<tr>
<td>[1500– &gt; 1500]</td>
<td>12,375</td>
<td>10.54%</td>
<td>4,675</td>
<td>3.33%</td>
</tr>
</tbody>
</table>
that at a regional scale, the areas covered by roads and buildings represent a very small proportion of the total area of any study site. For example, in the MP, the building land cover increased from 0.37% in 1820 to 0.93% in 2014 of the total area, which appears almost insignificant compared to other land cover changes. This simple quantitative approach hides a real increase in building number over this period. The second reason is that the mapping of buildings and roads can only reasonably be carried out in most cases in terms of points (buildings) and lines (roads), which does not allow any real quantification of surface areas.

To achieve this, the use of remoteness analysis appears to be a very useful method to map the spatial extent of the impact of the evolution of roads and buildings. Generally used to assess the wilderness character of a landscape (Carver, Tricker, & Landres, 2013) or to identify the

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**Fig. 5.** Remoteness (in meters) from (A) buildings, (B) roads, (C) buildings and roads pooled together, categorized into five classes, in 1705, 1820, 1950, 2014 and represented in relative areas covered by each of the 5 classes (D).
wilder parts in a country (e.g., Müller, Bacher, & Svenning, 2015) the average distance from any roads or buildings is a good index of the evolution of human encroachement in a wetland. For example, over the period 1820–2014, we have shown that the average distance from the closest building decreased from 515 m to 388 m, which highlights a massive loss of the most remote areas. Moreover, the distance-effect from roads and buildings has both a real meaning for the perception of the naturalness of a landscape (Scottish Natural Heritage, 2012), especially in open landscapes such as wetlands where human features are visible and audible from a long distance, and strong impacts on several components of biodiversity (e.g., Forman & Alexander, 1998).

Thus, over three centuries of land cover changes in the MP, the loss of remote areas due to human settlement is probably a conservation issue similar to the conversion of grasslands to croplands. Studying the evolution of roads and buildings at a suitable spatial resolution scale with appropriate spatial analysis seems to be a complementary approach to the traditional analysis of land cover changes.

5. Conclusion
The different facets of the anthropization of wetlands (e.g., reduction of their spatial extent, changes in habitat composition, urbanization, changes in their hydrological conditions, etc.) are sometimes mixed together to assess the influence of humans activities on these fragile ecosystems. By comparing three major facets of landscape anthropization (human demography, and the distribution of buildings and roads) with changes in habitat composition over a long period and at a fine spatial resolution, we found that their trends may evolve differently. In the Marais Poitevin, trends in population are linked with back and forth trends in habitat composition.

On the other hand, over the same period, we found a steady increase in buildings and in roads. Remote areas, far from roads and buildings, became therefore increasingly rare. In addition to changes in habitat composition, this study highlights the importance to better take into account the spatiotemporal dynamics of buildings and roads when assessing the anthropization of a wetland. More specifically, both the increase in road/building densities and the decrease in remoteness from them should be considered. Habitat composition changes only document one aspect of landscape fragmentation: the habitat loss. However, landscape fragmentation also includes the breaking up of habitats (see Fahrig et al., 2011 for a review) what is highlighted by the decrease in the areas far from human artifacts such as roads and buildings, which play the role of barriers in these landscapes.

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