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The effects of land use planning on housing spread: A case study in the region of Brest, France

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ABSTRACT

This work provides a long-term study of housing development in the Brest region (France). Its main objective is to test the efficiency of the French laws and of urban planning bylaws to control housing development in the coastal zone. Based on the yearly status of available plots, a panel longitudinal analysis (1968–2009) is developed. It combines survival analyses with spatial-temporal diffusion indices, to assess their joint effects on the urban form evolution considering accessibility, proximity, spatial contiguity, temporal continuity, edge waves versus leapfrog growth, etc. That allows testing hypotheses about the diffusion processes, and the achievement of sustainable urbanism to increase density, promote adjacency and avoid urban sprawl and its detrimental effects on the environment and climate. The main finding is that national laws need land planning to deploy locally and that municipalities and stakeholders still prefer economic development over environmental conservation. That is putting emphasis on a restricted (short term) view of sustainable development.

1. Introduction

In developed countries, increasing income, longer leisure time, and greater mobility concur to diversify families' housing and professional choices (Krišjāne et al., 2014; Stimson and Minnery, 1998; Ullmann, 1954). This phenomenon is particularly visible in coastal areas where landscapes and environmental amenities attract tourists, retired people, and workers (Bohnet and Moore, 2011; Gurran et al., 2007). Mostly based on detached housing, this trend favours diffuse urbanization which occurs in several stages (Gonzalo Malvarez et al., 2000): 1) unorganized dissemination of detached houses according to land supply, household income, and amenities which drives land prices and potentially fuels social segregation; 2) large-scale urbanization of rural spaces by developers (housing and tourism), leading to competition with agriculture, artificial landscapes, increasing traffic, and land speculation (Cooper and Alonso, 2006; European Environment Agency, 2006); 3) enactment of bylaws to protect natural and historic areas, rationalize urbanization, and ensure the space needed to sustain maritime and industrial activities (Brody and Highfield, 2005; Daligaux, 2003). Conflict of interest between stakeholders, alignment is-

sues between different planning scales (from local to national), and competition between local jurisdictions (Byun et al., 2005) often impede the effectiveness of bylaws.

The purpose of our research is to provide a long-term study of housing development in the Brest region (France). This article presents and discusses an approach to assess the marginal effect of land-planning bylaws on the diffusion of new housing. Emphasis is put on their impact on the changes in urban development. Considering the laws and bylaws that were enacted locally at various points in time, our analysis uses a longitudinal survival model (available unbuilt lots) using spatial process indicators (Hägerstrand, 1967) and the control of accessibility to urban amenities.

The main objective is to test the effectiveness of urban planning bylaws in regulating housing development and limiting urban sprawl, as well as the effectiveness of the French Coastal Law to control housing construction within 100 m from the shore. Considering the yearly status of available lots, a longitudinal panel data analysis (1968–2009) used five spatial-temporal indicators to approximate and compare the marginal effects (hazard ratios) of spatial processes on development where bylaws applied. The process indicators pertained to den-

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sity, proximity to the nearest neighbour, contiguity of the urban fabric, and growth and sprawl trends. The survival model followed the event history of 194,345 available lots (100–2500 square metres), starting in 1968, extending over a 42-year period, yielding 66,284 failures (a house was built), and giving more than 6 million observations (lots-years).

The hypotheses are: 1) The Coastal Law (CL, enacted in January 1986) lowers the risk of housing build-up in the 100-metre coastal band strip; 2) Successive bylaws enacted at the municipal level under the Land Use Law (LUL in December 1967) and the Solidarity and Urban Renewal Law (SURL in December 2000) effectively enhanced urban development and promoted its sustainability. Comparison criteria used net residential density, proximity (as opposed to isolation), spatial contiguity, and urban extension trends (edge extension versus leapfrog dissemination—diffusion mode; urban consolidation versus sprawl—temporal continuity).

The remainder of the article comprises five sections: 2) literature review; 3) study design (conceptual framework, study area, data, and methodology); 4) results and main findings; 5) discussion, perspectives, and future research avenues; and 6) conclusion.

2. Literature review

Starting in the 19th century, but mostly after the mid 20th century, coastal regions were developed as leisure and resort areas. Indeed, housing development has boomed in these areas during the last few decades (Bruyelle, 1998; Gonzalo Malvarez et al., 2000; Merckelbagh, 2009). However, due to their interface of marine and terrestrial environments, these regions are fragile and sensitive to land use intensification (Agardy and Alder, 2005; Carter, 1988; Masselink and Gehrels, 2014). All of this has led to the need for regulation (Deboudt et al., 2008).

2.1. Progressive enactment of planning laws and bylaws

For a long time in France, the dominant trend was non-interventionism, leading to unbridled urbanization influenced by real estate markets, proximity of amenities, and access to services and transportation networks (Martignac et al., 2011; Le Berre et al., 2017). The first laws aimed at environmental conservation, including nature, wildlife, landscape, and heritage (Deboudt et al., 2008). They used zoning to protect small places from urbanization.

In the 1970s, natural parks were created to protect quality of life and enhance the economic development of declining regions. These policies needed complementary land planning to handle several issues related to infrastructure, control of urbanization, land use arbitration, natural resources conservation, and farmland protection. Urbanization involves intensive transformation and often means perennial change of land use, whereas land is a non-renewable resource. Land-taking must thus be regulated accordingly (European Environment Agency, 2006; Zoppi and Lai, 2014). This is the case in France where the planning laws require local communities to assess their consumption of natural, agricultural, and forest land ten years before the approval of a land use plan or after the last modification of bylaws.

Above and beyond the regulatory framework, urban planning schemes are often political projects, carried out at various levels. In France, local authorities develop and implement their land use projects, defining development objectives, infrastructure linkage, and technical implementation objectives (Prévost and Robert, 2016).

2.2. Land planning objectives

In a high-mobility, high-living-standard society with free time, the issue of the living environment is central to residential choices (Allain, 2004). Wealthy households tend to favour detached housing (

Kestens et al., 2008; Mercier, 2006; Paül and Tonts, 2005), which results in scattering and sprawl.

Nevertheless, residential dispersal is often considered in planning policies as an “expensive” urban form (Pouyanne, 2014). It consumes and fragments agricultural lands and natural areas (Zoppi and Lai, 2014), which alters the functioning of farms and ecosystems (Irwin and Bockstael, 2007; Munroe et al., 2005). It increases mobility (Charmes, 2007), which raises greenhouse gas emissions and the demand for infrastructure (Des Rosiers et al., 2017). And it can likewise exacerbate social segregation (Charmes, 2007; European Environment Agency, 2006; Ewing, 2008; Paül and Tonts, 2005).

Conversely, continuity with previous urbanization is considered more rational. It responds to the demand for accessible and central housing, while optimizing the use of existing local services and infrastructure that need only to be expanded (Delattre et al., 2012). Thus, fostering the continuity/contiguity of built areas is a major objective for dealing with multifaceted issues with functional (transportation and sustainable city), economic (support for agricultural productivity), and environmental (protection of ecosystems) (Salvati et al., 2012) facets.

2.3. Urban density

Building densification slows urban sprawl, conserves landscapes and reduces transportation needs, while making infrastructure profitable (Delattre et al., 2012). Urbanized areas often include undeveloped interstitial spaces linked to low-density urban forms (suburban spaces on large parcels) or to lots left vacant (“missing teeth”) by the land market (Reux, 2017). These parcels constitute a land reserve, even if their use is difficult to optimize because of their dispersal. Their development is based on small-scale operations involving households and small- or medium-sized businesses. These can however be promoted and coordinated by communities. For instance, these interstices (e.g., brownfields) may result from the closure of industrial and commercial enterprises (Sieber, 1991). On the coast, they come mainly from the old port areas (Chaline, 1992). The lots are consequently more extensive, allowing a large-scale urban renewal.

Land is frequently used to control residential construction (Byun et al., 2005; Carrion-Flores and Irwin, 2004; Gottlieb et al., 2012) using land-use coefficients (built-up portion of the lot). With single-family dwellings, lot sizes define net density and set the land cost. This implies two alternative policy options: 1) favouring diffuse urbanization on large lots, which aims to preserve the landscape and/or living environment of the residents by keeping a “rural” (garden city) character. This strategy is used to limit population growth (and sometimes its socio-economic status) and public spending (Delattre et al., 2012); 2) densifying urban areas on small lots, which protects the current uses of the territory and the integrity of natural or agricultural areas (Daligaux, 2003). This also makes it possible to renew the population with lower land costs, to maintain and develop services, and to favour social diversity (Delattre et al., 2012). These principles are applied through zoning.

2.4. Zoning and controlled urbanization

Zoning makes it possible to control land use through arbitration. Zones can be quite compelling when mapped in urban planning documents (Prévost and Robert, 2016). For example, they can protect residential areas from nuisance and potential risks by defining the location of industrial zones and by regulating housing development in risk-prone areas. They distinguish urban areas, which are intended to be developed, from non-urban areas (agricultural and natural), which are meant to be excluded.

Even when the regulations are respected (Alfasi et al., 2012; Loh, 2011), these distinctions are not always clear. Although natural ar-

areas are often subject to strict protections, agricultural areas may be the subject of public-interest constructions (e.g., infrastructure) or related to agricultural activities. Agricultural areas are often seen as land reserves that can be developed later, especially when they are close to urbanized areas. Indeed, zoning evolves. It can be revised from one project to another, usually to extend the areas to be urbanized. Sometimes, zoning is defined initially as broadly as possible to meet the objectives set by proactive policies (Mercier, 2006). Areas of urbanization can be highly overestimated in terms of real demographic and economic trends. They are however rarely reduced, so as not to hinder future development projects (Paül and Tonts, 2005).

2.5. Urbanization processes and spatial diffusion

Urbanization can take many forms (Renard, 1984). Regulations tend to favour the continuous extension of existing urban spaces. New development can be built however if it is not *ex nihilo* and starts at least from hamlets and small villages. In low-density areas with high dispersion, legislation can favour consolidation by urbanizing interstices (the filling in of “missing teeth”). Finally, in the urban fronts, outlying settlements occur in a dispersed distribution. They are later joined by new settlements in a diffusion process leading to coalescence. These trends ultimately result in a consolidation of more coherent urban forms. Urban development then continues by scaling up, initiating a new cycle of dispersion and diffusion (Dietzel et al., 2005). These processes operate like the waves of innovation described by Hägerstrand (1967).

2.6. Efficiency of planning bylaws

Regulations related to residential urbanization are a topic of hot debate. Do they respond correctly to the issues of territories and populations? Are they effective? Are they right? Are they well applied? The debates are very intense on the coast.

Legislation is often adopted to favour economic development and the exploitation of the environment rather than its protection (Abrantes et al., 2016; Goiffon, 2003; Norton, 2005), leading to the criticism of these political projects.

Criticism also focuses on institutional failures. Norton (2005) regrettably notes that urban planning is based on standardized plans to meet the wishes of land developers rather than based on a rational analysis of the land’s capabilities. These plans are thus designed with sectoral and local needs (natural risk management, sanitation), rather than integrated and regional ones (Norton, 2005). Concerns differ across administrative levels, leading to institutional competition (Prévost and Robert, 2016). Often, the multiplicity of stakeholders (Nakhli, 2010; Jauze, 2013) and the weakness of coordination structures (Abrantes et al., 2016; Merckelbagh, 2009; Meur-Férec, 2007) result in inconsistencies in the regulations, causing block-

ages (Bernardie-Tahir and El-Mahaboubi, 2001). These malfunctions can even lead to the bypassing of regulations (Burak et al., 2004). Finally, considering the fast and largely spontaneous dynamics of coastal urbanization, the slow or late implementation of regulations (Abrantes et al., 2016; Gonzalo Malvarez et al., 2000; Renard, 1984) produces obsolescent and inefficient planning systems and objectives (Alfasi et al., 2012; Loh, 2011).

The effects of regulations are mixed. On the one hand, their role is not necessarily to slow down residential development. It can indeed favour it. In the eyes of political and economic actors, urban development is as commendable as the protection of the environment and agricultural land. On the other hand, the amenities provided by protected natural and agricultural areas, and the guarantee of their protection, are very attractive for housing. Paradoxically, the relative scarcity of land near these amenities can lead to an increase in urbanization in their vicinity. In addition, when amenities are highly valued, as in the case of the coastline, urbanization can be pushed to back-shore areas (Byun et al., 2005; Gottlieb et al., 2012), sometimes far away (Larrosa Rocamora, 2003).

Therefore, the impact of regulation on land consumption and changes therein seems limited and difficult to establish (Alfasi et al., 2012; Colantoni et al., 2016). In fact, whatever the policy pursued, the role of regulation is more to structure urban development than to limit it. It is this structuring effect of land planning on the evolution of urban form that this study aims to evaluate.

2.7. Assessing the effects of planning bylaws

Many studies have discussed the effects of urban planning (Brody and Highfield, 2005; Loh, 2011). The effectiveness of zoning depends on the degree of urbanization (Onsted and Chowdhury, 2014), and land planning is most effective when urban pressure is high (Mimet et al., 2013; Prévost and Robert, 2016).

However, the analysis of urban planning effects entails certain difficulties. Residential development is naturally driven by several factors (Table 1) that combine or offset each other. In addition to these factors, land planning distinguishes areas that are suitable for urbanization or not. It is thereby used to distribute infrastructure investments, which in turn have a major influence on residential built-up. Multi-criteria analysis methods must therefore be used to disentangle the cross-effects. Everything evolves: the influence factors, land use, and regulations; these require using spatiotemporal methods in order to handle their joint evolution. The effects of regulations are progressive and/or deferred over time. Legislation requires time to be applied, since there is often reluctance and opposition. The materialization of the effects comes after its effective application. Thus, when it exists and is respected, a regulation’s impact is harder to measure than that of economic and geographic factors (Le Berre et al., 2017; Norton, 2005).

Table 1
Exogenous influence factors of housing development location.

Factor/Variable	Process	Influence	Reference
Proximity/similitude	Spatial organization	Closest places tend to be similar (cross-sectional view; first law of geography)	Tobler, 1970
Centrality	Bid rent	Bid rent theory/competition for better centrality (Ricardo, Von Thünen)	Alonzo, 1964
Accessibility	Mobility/commuting	Configuration/efficiency of transportation networks and access to labour/urban amenities	Hansen, 1959
Diffusion	Imitation/innovation	Spatial-temporal component of diffusion either in proximity (oil stain) or in leapfrog	Hägerstrand, 1967
Land price	Behaviour/markets	House choices are driven by hedonism seeking for positive externalities and by inconvenience avoidance	Rosen, 1974
Public policy	Local choices	Spatial segmentation and grouping according to socio-economic profiles through residential choice	Tiebout, 1956
Physical constraints	Feasibility/suitability	Morphological and physical attributes of land may constrain construction costs/feasibility	Grether and Mieszkowski, 1974
Negative externalities	Noise/hazards	Huge infrastructure (e.g., airport, industrial plant) may cause noise and risks that repel housing development	Hunt and Watkiss, 2011

Among modelling methods, survival analysis allows time-varying variables to be used to measure their cumulative effects on the probabilities of change in land use (Bell and Irwin, 2002; Wang et al., 2013). It can unravel complex spatial-temporal processes, integrating event-based dynamics to assess the odds and time elapsed before change occurs, while controlling for competing risks (An and Brown, 2008). It has proved appropriate to analyze the evolution of housing development by taking into consideration a gradual implementation of regulatory controls (Le Berre et al., 2017). The effect of regulations is complex and evolutionary. Assessing urban planning's effectiveness in controlling urbanization requires that elements of the spatial diffusion theory (Hägerstrand, 1967) be integrated into survival analysis. That is the object of this research.

3. Research design

3.1. Conceptual framework

As stated above (Table 1), urban planning objectives are multifaceted. Policy assessment criteria to balance socio-economic development and the effectiveness/relevance of land consumption are thus complex. Nevertheless, urban development leads to spatial-temporal diffusion processes that require explicit definitions to permit statistical modelling. The main principle is that suitable lots are at risk of being developed soon or later. To analyze these processes, we need a survival model to relate lot failure (it is built) with successive events over time and space. The purpose is two-fold: 1) identify lots with higher hazards (knowing the outcome is a rare event) and 2) measure their survival expectancy (time at risk before they fail). Events are related to three broad categories: 1) policies applied to specific lots (e.g., environmental conservation), (lowering or cancelling the hazard); 2) decisions of stakeholders to develop given available lots in the vicinity (increasing risk); 3) land use planning specifying principles and rules (altering risk). The first two classes of events are driven by exogenous forces and relate to policies and actions related to societal expectations (e.g., conservation) and markets (e.g., economic growth). They form intertwined phenomena that are to be controlled for (or censored) to measure the effects of land planning on changes to the urban form. In this research, we use "risk" and "hazard" concepts with their statistical meanings and link them to land development. This must be distinguished from natural and industrial hazards which are not addressed due to lack of data and low risks in this coastal region.

Land planning objectives and principles lead to regulations (e.g., zoning bylaws) that are enacted (or modified) by a community (e.g., municipality) at a given time (event). These regulations are complex, which impedes their detailed specification in a model. They aim to restrict the development process and to control urban growth so as to reach four broad goals: 1) increase density to generate economies of scale; 2) favour proximity to and spatial contiguity with existing built areas to optimize use of infrastructure and lower public expenses; 3) target spatial-temporal continuity of urban space spread to lower urban sprawl and transportation costs; 4) avoid anarchic dispersion of urban areas to protect other land uses. Fig. 1 shows spatial diffusion process indicators to assess the achievement of these goals.

If we want to arrive at better urban development with minimum land consumption and lower costs, the targets are: 1) a higher density; 2) a contiguous and compact urban form (i.e., consolidation followed by growth at the edges). In most cases, scattering, leapfrog diffusion and urban sprawl should be avoided as they are less efficient. Growth processes do however evolve. If land planning is working, the hazard of a lot grows when its neighbours are built. Diffusion indicators and associated hazards are therefore time-varying; they are not only consecutive of events but also based on previous effects they had in each lot's spatial-temporal vicinity. The effect can however be delayed, which yields random noise. This is the case in Hägerstrand's (1967) spa-

tial diffusion theory, where adoption of an innovation (build a lot) spreads continuously, with possible leap frogs until saturation (growth slowdown or redevelopment).

3.2. Study area, period, and land planning regulation

The case study presented here focused on Brest, a medium-sized city (200,000 inhabitants) in north-western France, and its metropolitan area (400,000 inhabitants) called Pays de Brest. Despite its relatively small size, Brest counts as one of the 21 French metropolises. Its population growth (+30% from 1954 to 2007) and its economic vitality (70% of the jobs of the metropolitan region are located in the agglomeration) have produced significant land use changes (4.5% of its natural and agricultural land has been developed from 1984 to 2005) driven by various residential dynamics. The urban population increase from 1950 to 1975 (about 2% per year) triggered urban expansion and sprawl. The population of the City of Brest then steadily declined until 2009, but mainly for the benefit of its metropolitan area (90% of the people who left the city stayed in the Pays de Brest), and the natural balance of the population of the Pays de Brest remained globally positive (+1200 inhabitants/year from 1985 to 2008). This led to suburbanization and scattered development, which was fostered by a preference for detached housing, the desire to live close to environmental amenities (e.g., landscapes, beaches, and nautical leisure), and the deployment of road infrastructure.

Since the 1960s, the dynamics of residential development have been in line with national trends, in relation to the economic cycles and political orientations of French spatial planning (see Fig. 3, Le Berre et al., 2016). In addition, despite a relatively high residential density, the coast of the Pays de Brest is not yet saturated by urbanization, unlike the French Mediterranean coast, for example. Sequentially, land planning regulation is thus likely to have contributed to structuring and moderating its residential development. Finally, the Pays de Brest includes sizeable agricultural and natural areas. The regulatory protection of the latter (Marine National Park, Biosphere Reserve, land reserves, etc.) provides supplemental tools to control the coastal urbanization.

In France, three laws were enacted to regulate land planning at the national and local levels (Le Berre et al., 2016): 1) the Land Use Law (LUL, December 30, 1967—to establish urban and local planning); 2) the Coastal Law (CL, January 3, 1986—to regulate coastal development); 3) the Solidarity and Urban Renewal Law (SURL, December 13, 2000—to enhance urban and local planning and to promote sustainable development principles). At the municipal level, the LUL and the SURL were eventually complemented with local plans and bylaws with the obligation to stay compatible with the previous laws. According to Le Berre et al. (2017), the main types of plan are: 1) land use plans (LUP); 2) urban development plans (UDP); 3) land use schemas (LUS). Planning tasks take place at the municipal level. Municipalities adopt plans at their convenience, meaning that the regulation status varies over time and among municipalities. Lot development (building permits) is thus regulated at the municipal level.

At the national level, the Coastal Law is intended to develop and to protect the coastal area. The control of coastal urbanization is based on several principles (Bordereaux, 2014), namely: 1) coastline protection against urbanization (building is restricted inside the 100 m coastal strip); 2) off-the-coast developments (perpendicular and inland development must be encouraged); 3) urbanization contiguity (new extensions must be developed close—at less than 200 m—to existing settlements); 4) green corridors (non-urbanized—i.e. agricultural or natural—areas must be preserved between settlements). These principles are common in national legislations designed to control coastal urbanization (Gibson, 1999; Christie, 2013; Norton, 2005; Gurran et al., 2007; Deboudt et al., 2008).

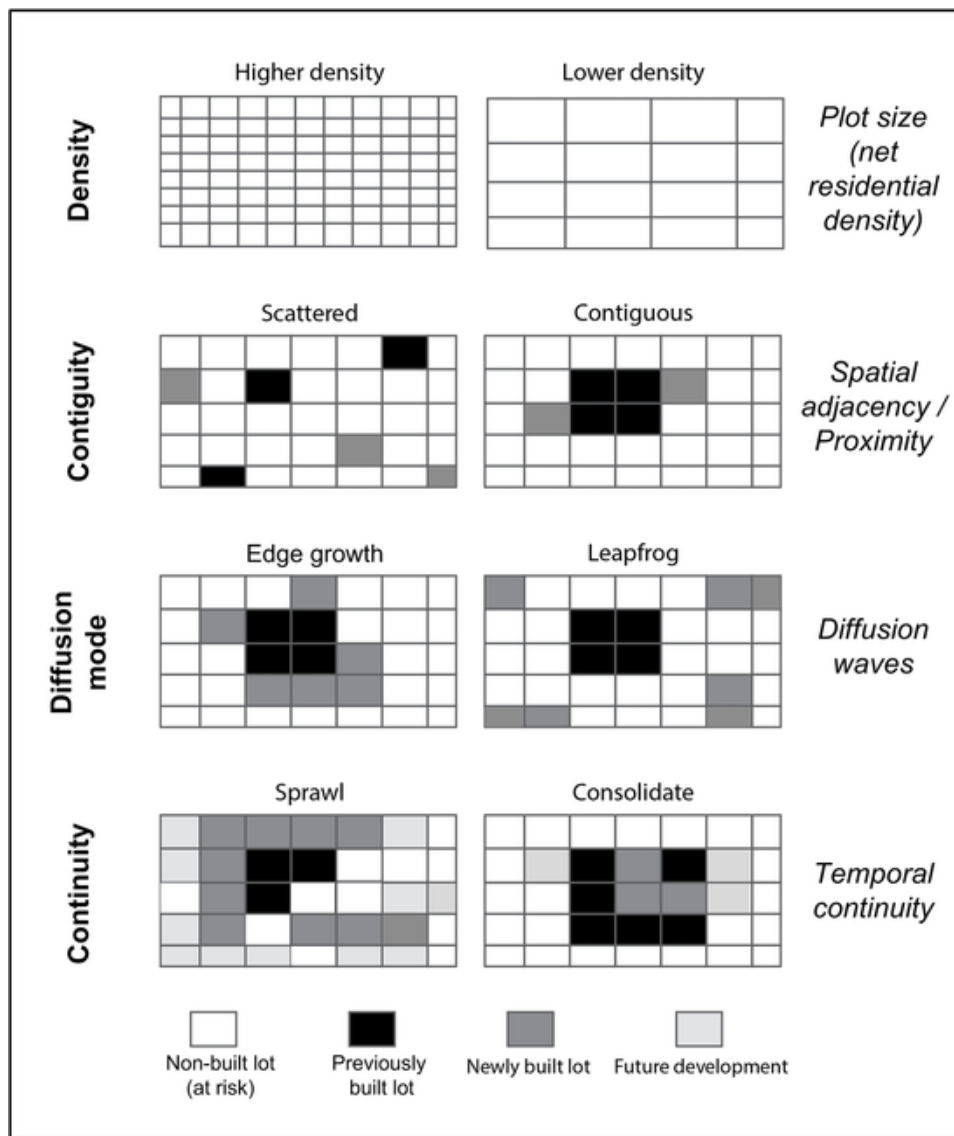


Fig. 1. Spatial diffusion shapes/patterns of housing build-up.

The French Coastal Law is a framework law that is part of a complex regulatory system (Eymery, 2014) with several components: a) environmental conservation, the only bulwark against development; b) urban planning, which is being increasingly asked to enforce the principles of the CL; and, c) the framework law on urbanism which sets unified rules across the country. The law thus sets general objectives and leaves the specific choices of how to do so to local decision makers who have acquired a major role in urban planning after devolution laws were enacted (Miossec, 2004; Prévost and Robert, 2016). The meaning of the CL “is based on the kind of coastal zone you want” (Herviaux and Bizet, 2014). It deliberately contains imprecise notions that must be specified by taking unique local qualities into consideration. There is therefore a divergence between the national goal and its local implementation (Prévost and Robert, 2016), as evidenced by the diversity of coastal development modes. This is the result of regional diversity, disparate natural environments, plurality of community projects leading to distinct trajectories of local development, environmental conservation, and urbanism. Another cause is the high degree of decision-making occurring at the local level, which has been reinforced by the devolution laws of 1982-83. The mayor both defines urban planning projects and grants building permits. So, if

the policies are national, the strategies are mostly local (Prévost and Robert, 2016).

The CL’s regulatory framework has also gradually become more specific, which explains its lagging implementation (Eymery, 2014). Its full integration into urban plans became mandatory in the 1990s (Dalignaux, 2003). This compliance could therefore happen early (or be delayed) depending on the community projects, and a town’s willingness to protect the coast. It also depends on the power balance between private and public stakeholders. This can limit the effectiveness of regulation by seeking a compromise between the stakeholders’ respective interests, whether private or collective (Adolphson, 2008; Bimonte and Stabile, 2015).

These factors explain the recurrent debates about the Coastal Law (CL) and the frequency with which it is questioned (Merckelbagh, 2009), which shows the difficulty of assessing its effects.

The case study uses a dataset developed by Le Berre et al. (2016) for the Brest metropolitan area which provides a detailed status of 415,436 land lots on a yearly basis. Table 2 presents available lots and built-up of houses according to four combinations of law and by-law statuses: A) without (before the CL and without a local plan); B) CL only (coastal law without local plan); C) a local plan in a municipal-

Table 2
Observed residential build up on available lots (100–2500 sq. m.) from 1968 to 2009 according to the regulations (number of lot-years).

Regulations	Hazard	1968–1975	1976–1982	1983–1990	1991–1999	2000–2009
A: Without	At risk	1,373,900	1,025,471	337,505	103,798	76,283
	Built up	13,025	12,481	5,058	857	974
	Rate ^a	9.48	12.17	14.99	8.26	12.77
B: CL only	At risk			205,752	163,351	45,034
	Built up			1,310	1,167	318
	Rate ^a			6.37	7.14	7.06
C: UDP/LUP/LUS	At risk	128,714	162,720	261,301	138,817	156,006
	Built up	2,556	2,559	3,218	1,647	3,885
	Rate ^a	19.86	15.73	12.32	11.86	24.90
D: CL + LUP/LUS	At risk			374,918	842,016	976,093
	Built up			1,607	4,842	10,780
	Rate ^a			4.29	5.75	11.04
Overall	Rate^a	10.37	12.66	9.49	6.82	12.73

CL: the Coastal Law; UDP: urban development plan; LUP: land use plan; LUS: land use schema.

^a Rate is the number of houses built per 1000 lots at risk.

ity that is not subject to the CL, either before it was enacted or after for inland municipalities (UDP/LUP/LUS); D) the combination of the CL and a local plan (CL + LUP/LUS). Statuses A and C apply to inland municipalities while B and D are for coastal municipalities or before the CL. Construction rates give an indication of house building outcomes for five periods. However, effects are not conclusive as variation over time is high. Other effects (e.g., accessibility to amenities) must be controlled to measure the marginal impact of laws and bylaws on housing development diffusion.

The choice of five periods is based on that of a previous study (Le Berre et al., 2017). It aims to satisfy the proportional hazard (PH) assumption for building the survival model using Cox regression. It uses population census dates rather than law enactment dates. The actual effect of land planning laws is often delayed until the adoption of planning bylaws at the local level; the four categories (A to D) presented above are thereby used to test the significance of law enforcement in municipalities.

3.3. Data transformation

All lots already built in 1967 were excluded (left-censored) from the statistical analysis but kept in the GIS (geographical information system) to generate spatial and temporal indicators for their neighbours. From 1968 to 2009, each lot was characterized on a yearly basis to record the building of a house (the studied phenomenon), alternate events (e.g., lot purchase for environmental conservation—right-censoring), and activation of land-use laws and bylaws (risk modifiers set at the municipal level). This yielded a long-format database describing each lot (when at risk) to model its survival (number of years) as an unbuilt lot.

For the needs of the analyses, 194,345 at risk lots with an area between 100–2500 square metres were retained. With 66,284 failures (houses built), 12,144 right-censored lots (devoted to alternate uses), and 115,917 lots still at risk in 2010, there was a total of 6,371,679 plot-years for risk assessment. Table 2 shows their distribution over time. As reported by Le Berre et al. (2017), the pool of available lots left without planning shrank as plans were gradually enacted by municipalities. Moreover, the CL was a major event because it uniformly applied to shore municipalities and restricted development in the first 100-metre band from the seashore.

Previous experiments in modelling the probability for building lots (Le Berre et al., 2016, 2017) show significant differences in coefficients over time. Survival models thus imply a proportional hazard (PH) assumption that is not met over the 42-year period. Therefore,

the analysis had to be segmented into five periods which were delimited by six population censuses (1968, 1975, 1982, 1990, 1999, and 2008).

As stated in the literature review, housing development is influenced by several factors. The most important are accessibility to work and to urban amenities, which has a strong impact on land prices and real estate costs. This must be controlled for when assessing the marginal effect of planning. Unfortunately, the variation of land prices is not available before 2000, inhibiting its inclusion in the analysis. Nevertheless, we argue that accessibility is a good proxy for house values and land prices (Thériault et al., 2005; Dubé et al., 2013).

Table 3 presents the variables used in the survival model. Some are static, but most are time-varying so as to be able to consider the cumulative effects of previous development on the spatial variation of risk. The first four variables measure various aspects of accessibility: 1) to the seashore (DS) measuring the impact of the CL and bylaws on the protection of the shore band; 2) to main cities (Brest and Centre—DB, DC) using simulated car travel time to the main and second-third order work and service centres; 3) walk distance to the nearest school (SL) to account for an important local amenity. The road network structure was rather stable during the 42 years. Therefore, car travel time is modelled as static over time. This is far more relevant than using Euclidean distance since the region has a highly indented seashore (large bays and peninsulas) that implies road detours.

The next five variables are indicators used to operationalize the diffusion shapes/patterns shown in Fig. 1. Most are obtained by spatial analysis in the GIS by considering neighbours in space and previous distribution of housing units. Each year, Euclidean distances are computed based on the lot centroid using buffers to select previously built houses at given radii. Only the lot area is static (PA), as it is used to assess the net residential density. The other indicators are time-varying: 1) the proximity to the nearest neighbour (NN); 2) the spatial contiguity (SC) that is approximated by the proportion of built lots in a 100-metre radius 3 years earlier; 3) the diffusion mode (DM); 4) the temporal continuity (TC).

Finally, two variables indicate the planning (PS) and built-up (BU) statuses for each combination of lot and year. Each variable is then eventually expanded with two indexes: 1) i to identify each lot among the N (194,345) lots under observation ($i \in 1..N$); and 2) t to identify the observation year (1968–2009; $T = 42$; $t \in 1..T$). Static variables are identified by subscript i (DS_i , DB_i , DC_i , PA_i), while time-varying covariates have both subscripts i and t (SL_{it} , NN_{it} , SC_{it} , DM_{it} , TC_{it} , PS_{it} , BU_{it}). Indicator variables are split into categories, eventually leaving the reference category out of the model to set a baseline hazard. For example, the planning status is split into four dummies: PS_{itA} ; PS_{itB} ; PS_{itC}

Table 3
Survival model variables.

Name	Variable	Specification	Temporal
Shore (DS)	Location/Accessibility Lot inside the 100-metre seashore band	Dummy (reference is outside the band)	Static
Brest (DB)	Car travel time to Brest CBD (minutes)	< 8; 8.1–12; 12.1–16; 16.1–20; 20.1–24; 24.1–28; 28.1–32; > 32 (reference)	Static
Centre (DC)	Car travel time to the nearest 2 nd /3 rd order service centre (minutes)	< 2; 2.1–4; 4.1–6; 6.1–8; 8.1–10; > 10 (reference)	Static
School (SL)	Walking distance to the nearest school (metres)	< 500; 501–1000; 1001–1500; 1501–2000; > 2000 (reference)	Time-varying
Lot area (PA)	Urban density Lot size (square metres) as an indicator of net residential density	Continuous 4 th order polynomial	Static
Proximity to neighbour (NN)	Proximity to nearest neighbour Distance to the nearest neighbour 1 year before the risk is assessed	Less than 100 metres (reference); 100–200 metres; > 200 metres	Time-varying
Scattered vs. Contiguous (SC)	Spatial contiguity Proportion of built lots in a 100-metre radius, 3 years earlier	logarithm; 2 nd order polynomial	Time-varying
Edge growth vs. Leapfrog (DM)	Diffusion mode Ratio of proportions of built lots in 100-versus 300-metre radii, 3 years earlier.	logarithm; 4 th order polynomial	Time-varying
Consolidate vs. Sprawl (TC)	Temporal continuity Proportion of houses older than 5 years in a 300-metre radius, 1 year earlier	Continuous 4 th order polynomial	Time-varying
PS	Lot statuses Planning status (treatment)	A: without regulation B: CL only C: bylaws only D: CL and bylaws	Time-varying
BU	Lot is built (failure)	Dummy (reference is not built—stay available)	Time-varying

and PS_{itD} . Considering an observation duration of 42 years, which yields a maximum of $M = N T$ observations, which in this case totals 6,371,679 due to right censoring (lots no longer at risk). This is the basis for populating the data matrix ($X_{it,k}$) made of M rows and K columns for covariates (in this case $K = 9$).

3.4. Survival model specification

The survival model estimates time to events (hazard ratio and survival time) considering treatments (combination of bylaws) and controlling for influence factors (e.g., accessibility). The Cox proportional hazard (PH) model is a semi-parametric specification of the survival model that can be used when the theoretical distribution of failure is unknown (Klein and Moeschberger, 2003; Box-Steffensmeier and Jones, 2004). This research uses the single spell Cox PH specification because the database structure cannot handle the redevelopment (e.g., densification) of built lots. A failure is assumed to be unrecoverable and definitive.

In the Cox PH model, the ordered survival times are parametrized using a set of covariates:

$$h_i(t) = h_0(t) \exp(X_{it,k} \beta_k) \quad (1)$$

where $h_i(t)$ is the PH of lot i being built on at time t , $h_0(t)$ is the baseline hazard of the reference lots to be built at time t , $X_{it,k}$ is the long-format matrix of time-varying and static lot attributes, and β_k is a column vector of parameters to estimate. β_k has K rows. For the sake of simplicity, static variables are indexed with t and fed with constant values for each lot.

That being said, this specification is valid only when the PH assumption holds. Unfortunately, the PH test fails when considering the overall 42 years. Hence the need to divide it into the five periods ($J = 5; j \in 1..J$) as set by Le Berre et al. (2017):

$$h_i(t) = h_0(t) \exp(X_{it,kj} \beta_{kj}) \quad (2)$$

where $j = 1$ if $t < 1976$; $j = 2$ if $t > 1975$ and $t < 1983$; $j = 3$ if $t > 1982$ and $t < 1991$, etc. In this specification, the data matrix is extended to $K J$ columns (9 variables split into five periods; $K J = 45$, where irrelevant cells — t is outside the j thresholds — are set to zero). The parameter vector has $K J$ rows.

The model aims at the comparison of four ($P = 4; p \in 1..P$) time-varying planning statuses (PS_{itA} to PS_{itD}) as treatments (dummies) that must be introduced into the specification to define treatments:

$$h_i(t) = h_0(t) \exp(X_{it,kjp} \beta_{kjp}) \quad (3)$$

where $X_{it,kjp}$ is a matrix of all feasible scalar interactions between the $K J$ attributes and the P treatments; it has $K J P$ columns, which actually yield 176 variables because treatments B and D do not exist prior to 1986 (CL enactment). In each case, irrelevant cells are set to zero.

The Eq. (3) specification is suitable for handling single variables, either dummies (e.g., distance to the shore: DS_i), static numerical values like the lot size (PA_i), and time-varying covariates (e.g., spatial contiguity: SC_{it}). However, it cannot handle indicator variables (DB, DC, SL, NN) and complex functional forms needed to better assess the non-linear effects of PA, SC, DM, and TC. This requires value vectors $f(X_{it,jpc})$ to handle ($C; c \in 1..C$) category indicators or transformed continuous variables to adjust polynomials.

For this application, the data matrix merges components of the nine attributes:

$$X_{it,kjpc} = \{f(DS_{it,jpc}), f(DB_{it,jpc}), f(DC_{it,jpc}), f(SL_{it,jpc}), f(PA_{it,jpc}), f(NN_{it,jpc})\}$$

where c stands for the transformed variables needed to implement the functional forms specified in Table 3. Each functional form was tested using the link (Pregibon, 1980) and PH (Grambsch and Therneau, 1994) tests. Finally,

$$h_i(t) = h_0(t) \exp(X_{it,kjpc} \beta_{xjpc}) \quad (5)$$

where β_{xjpc} is a vector of parameters assessing hazard ratios for independent variables using indicators or polynomial terms (c) from $X_{it,kjpc}$ considering separate periods and treatments.

This gives 340 parameters related to 9 independent variables with 5 periods and 4 planning treatments, which yields 16 combinations (or cells), as shown in Table 2. They assess the marginal hazard (likelihood to build) of the lot considering time at risk. As the effect of most variables involves many parameters ($C > 1$), Wald tests are later used to assess the global significance of differences between treatments ($p_1 \neq p_2$), periods ($j_1 \neq j_2$), and their evolution from one period to the next. Statistical analysis was done with Stata, release 14.

4. Results

The survival model is presented in the appendix. Overall, it is highly significant (χ^2 : 111341; df: 340) and departure from the proportional hazard assumption is non-significant (χ^2 : 127; df: 340). While significant, the link test seems generally appropriate (95 % confidence intervals – hat: .9971–1.0107; hat²: .0152–.0217). For each cell, with a combination of period and planning statuses, model parameters estimate the marginal effect of each variable on the risk of building on a lot considering time at risk, location, lot size, and the recent changes in nearby lots. Most parameters vary according to periods and treatments while categories or polynomial terms are used for independent variables. Interpretation at the coefficient level can be difficult (see Appendix) and curves are needed to compare hazard relationships. The following sections present and summarize the results.

4.1. Controls for accessibility

The Cox PH model uses a baseline control group of lots. The independent variables are: situated away from the sea by more than 100 m, a travel time to Brest by car of more than 32 min, a travel time to the nearest 2nd or 3rd level service centre of more than 10 min, and a distance to school of more than 2 km. Differences in these location factors are used in the model to control for accessibility. Results of controls are shown in Table 4 and, as expected, are highly significant for each period (see Wald tests). However, the hazard ratio patterns change over periods to account for the decreasing availability of lots in the most accessible locations.

As stated previously, access to the seashore is a high demand amenity. Thus, the CL was enacted to protect the first 100-metre band. Using survival models, Le Berre et al. (2017) show that this is a multidimensional issue that needs several indicators. Nevertheless, it is worthwhile to assess the cross effectiveness of the CL and planning by-

laws using a dummy variable (DS). Results in Table 4 indicate that before 1975, lots located in the first band were significantly more likely to be built. After 1975, the difference was non-significant, except for municipalities combining the CL with planning bylaws, meaning that the CL only was not enough. Moreover, the combination reduces the likelihood of building by 30–40 %. It does not completely prohibit housing development, since it is still allowed in previously urbanized areas.

4.2. Proximity to the nearest neighbour

As it provides easier access to infrastructure, immediate proximity to the nearest neighbour (NN) lowers the cost of new housing. Table 5 presents the impact according to periods and land planning statuses with a 100-metre threshold. The actual numbers of built houses and times at risk are reported in Table 2 for each cell (period x planning status: 16 cells). Each coefficient is computed separately in a simultaneous model, taking into consideration three classes of distance to the nearest neighbour, leading to 48 subsamples. The references are locations at less than 100 m from the nearest neighbour in each cell. Wald tests report on the significance of the decrease within each cell. The decrease is sharp and highly significant irrespective of land planning, laws, and periods. A continuous specification could have revealed a more precise relationship but was not feasible with this database. Furthermore, buildings at more than 200 m from the nearest neighbour are deemed isolated in the French urban planning code.

4.3. Residential density

Fig. 2 shows the impact (hazard ratios) of regulation on urban density from 1983 to 2009: $f(PA_{it,jpc}) = \{PA_i^1, PA_i^2, PA_i^3, PA_i^4\}$ as split into periods and treatments; irrelevant cells are set to zero. For the purpose of this article, the last three periods (after the CL) are retained

Table 4
Impact of accessibility in the survival model according to periods (hazard ratios of lot development).

Variable	Regulation/Access	1968–1975	1976–1982	1983–1990	1991–1999	2000–2009
Shore (dummy)	A: Without	1.26 ***	0.91			
	B: CL only			0.87	0.88	No failure
	C: UDP/LUP/LUS	1.85 **	0.84			
	D: CL + LUP/LUS			0.64 **	0.71 ***	0.60 ***
Brest (minutes)	0–8	1.63 ***	0.60 ***	0.77 *	0.66 **	0.29 ***
	8.1–12	3.75 ***	1.68 ***	2.04 ***	1.30 ***	0.75 ***
	12.1–16	2.45 ***	1.79 ***	2.37 ***	1.70 ***	1.45 ***
	16.1–20	1.94 ***	1.63 ***	1.52 ***	1.59 ***	1.40 ***
	20.1–24	1.60 ***	1.55 ***	1.58 ***	1.58 ***	1.26 ***
	24.1–28	1.29 ***	1.50 ***	1.47 ***	1.44 ***	1.10 ***
	28.1–32	1.30 ***	1.39 ***	1.28 ***	1.39 ***	1.17 ***
	> 32 (reference)	1.00	1.00	1.00	1.00	1.00
	Wald tests (χ^2)	1131 ***	633 ***	655 ***	302 ***	309 ***
	Center (minutes)	0–2	1.02	0.93	0.61 ***	1.05
2.1–4		1.30 ***	1.27 ***	1.04	0.95	1.49 ***
4.1–6		1.63 ***	1.43 ***	1.06	1.02	1.34 ***
6.1–8		0.97	1.22 ***	1.00	1.18 ***	1.26 ***
8.1–10		1.02	1.14 ***	0.85 ***	1.05	1.09 **
> 10 (reference)		1.00	1.00	1.00	1.00	1.00
Wald tests (χ^2)		248 ***	165 ***	71 ***	21 ***	254 ***
School (meters)		0–500	2.01 ***	1.76 ***	1.43 ***	1.39 ***
	501–1000	2.04 ***	1.75 ***	1.57 ***	1.51 ***	1.75 ***
	1001–1500	1.58 ***	1.80 ***	1.35 ***	1.33 ***	1.52 ***
	1501–2000	1.24 ***	1.20 ***	1.32 ***	1.19 ***	1.29 ***
	> 2000 (reference)	1.00	1.00	1.00	1.00	1.00
	Wald tests (χ^2)	822 ***	645 ***	195 ***	133 ***	445 ***

Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 5
Impact of proximity to the nearest neighbour in the survival model according to regulation status by periods (hazard ratios).

Distance (metres)	1968–1975	1976–1982	1983–1990	1991–1999	2000–2009
A: Without < 100 (reference)	1.00	1.00	1.00	1.00	1.00
100–200	0.18 ***	0.15 ***	0.10 ***	0.08 ***	0.10 ***
> 200	0.06 ***	0.04 ***	0.03 ***	0.08 ***	0.03 ***
B: CL Only < 100 (reference)			1.00	1.00	1.00
100–200			0.11 ***	0.19 ***	0.06 ***
> 200			0.01 ***	0.08 ***	0.05 ***
C: UDP/LUP/LUS < 100 (reference)	1.00	1.00	1.00	1.00	1.00
100–200	0.23 ***	0.12 ***	0.12 ***	0.14 ***	0.18 ***
> 200	0.07 ***	0.04 ***	0.02 ***	0.08 ***	0.03 ***
D: CL + LUP/LUS < 100 (reference)			1.00	1.00	1.00
100–200			0.04 ***	0.18 ***	0.14 ***
> 200			0.01 ***	0.04 ***	0.03 ***
Wald tests (χ^2)	(df = 2)	(df = 2)	(df = 4)	(df = 4)	(df = 4)
Without	3374 ***	618 ***	866 ***	87 ***	232 ***
CL only			173 ***	43 ***	49 ***
UDP/LUP/LUS	541 ***	269 ***	520 ***	129 ***	408 ***
CL + LUP/LUS			311 ***	168 ***	644 ***

Significance: * p < 0.05; ** p < 0.01; *** p < 0.001.

for analysis because they involve the four planning statuses. Results for periods prior to 1983 are in the model but not presented. Wald tests indicate the overall significance of each curve, most being at the 0.1 % significance level, with one exception at the 5 % level (D in 1983–90). It is noteworthy that in all the figures, the curves cross at 1000 square metres (10 houses per hectare) with an odds ratio of one. This reference was not specified in the model but emerges as a regional constant and is indicative of a rather low residential density for reference lots.

A second set of Wald tests assesses the difference between pairs of curves within periods. Coastal municipalities with only the CL (B) are similar to inland municipalities without land planning (A). Land planning alone (C) or combined with the CL (D) is different from low regulation statuses (A and B) except in 2000–09 where the CL only (B) locations are the same. Finally, combining the CL with planning bylaws made a difference (C ≠ D), especially after 2000. Table 6 presents a third set of Wald tests to compare curves between periods. It shows significant evolution in the impact of planning statuses from 1983–90 to 1991–99, and from 1991–99 to 2000–09.

Globally, Fig. 2 shows a notable and constant decrease in the likelihood of developing smaller lots from 1983 to 2009. Smaller lots (e.g., 500 sq. m.) were developed into housing in the eighties; the likelihood decreased in the nineties and, after 2000, it decreases on both sides of the 1000 sq. m. reference. After 2000, the main differences are a slightly higher probability of developing smaller lots (land scarcity) when the CL combines with bylaws (D) and a lower probability of developing larger lots in inland municipalities (densification) with planning bylaws (C). Thus, the CL and planning bylaws slightly increase the urban density in this region. The trend is significant but could be enhanced by reducing the reference lot size, which is not the case here.

4.4. Spatial contiguity

Fig. 3 present curves for the spatial contiguity, that is the logarithm of the proportion of built lots within a 100-metre radius three years earlier ($BP_{it-3, \Delta 100}$): $f(SC_{it,jpc}) = \{ln(SC_{it,jp}^1), ln(SC_{it,jp}^2)\}$, where $SC_{it,jp} = BP_{it-3, \Delta 100}$ as split into periods (j) and treatments (p); otherwise zero. Wald tests indicate highly significant curves in every period. The hazard ratio increases with the proportion of built lots within 100 m 3 years earlier. The growth is very strong (hazard ratios from 0 to 300) and continues to strengthen after 1990. Within periods, all curves are significantly different, except between unplanned coastal municipalities (B) and inland municipalities with land planning (D). Table 6 reports a significant increase in the spatial contiguity in planned municipalities (C and D) from the eighties to the nineties and from the nineties to 2000–09 in coastal planned municipalities (D).

The increasing differences between planned and unplanned municipalities indicate considerable success in both avoiding scattering and developing locations at the margin of existing neighbourhoods. This feature involves building in proximity to the nearest neighbour to increase coherence in territorial development. After 2000, it is noteworthy that unplanned coastal municipalities increased the likelihood of developing spatial contiguity. Does this mean that the CL is enough to guarantee contiguity? Or is contiguity related to lower development pressure in unplanned communities?

4.5. Diffusion mode

Fig. 4 shows hazard-ratio curves for the diffusion mode (DM). It is based on the ratio between proportions of lots already built within a radius of 100 m versus 300 m three years earlier: $f(DM_{it,jpc}) = \{ln(DM_{it,jp}^1), ln(DM_{it,jp}^2), ln(DM_{it,jp}^3), ln(DM_{it,jp}^4)\}$ where $DM_{it,jp} = PB_{it-3, \Delta 100} / PB_{it-3, \Delta 300}$, and $PB_{it-3, \Delta 100}$, $PB_{it-3, \Delta 300}$ are the proportion of built lots within a 100-m and 300-m radii three years earlier as split into periods and treatments.

All curves are highly significant, meaning that the probability of observing leapfrog diffusion increases when the 100-metre proportions are higher than in the 300-metre buffer. This is not a scattering diffusion (as reported by SC) because a large proportion of nearby lots are built and there is a relative gap with other developed areas at more than 300 m. A DM value below one means that the proportion is lower in the 100-m range (edge growth) while a value above one indicates a higher concentration of built lots within a 100-m radius (leapfrog). The significance in the differences between the curves changes slightly over time, but unplanned municipalities (A and B) are more prone to leapfrog style growth than are planned ones (C and D). Table 6 reports no significant change from the eighties to the nineties, but significant change afterwards.

In the eighties, inland municipalities with land planning (C) showed a far larger propensity to experience leapfrog diffusion. They were joined by unplanned inland municipalities (A) in the nineties. After 2000, leapfrog diffusion occurred mostly in unplanned inland municipalities (A). During the three periods, coastal municipalities (B and D) had a lower probability of leapfrog expansion, with a light advantage to municipalities with CL and LUP or LUS (D).

4.6. Temporal continuity

Temporal continuity is modelled using the proportion of houses older than 5 years within a 300-m radius, 1 year earlier ($PH_{it-1, \Delta 300}$): $f(TC_{it,jpc}) = \{TC_{it,jp}^1, TC_{it,jp}^2, TC_{it,jp}^3, TC_{it,jp}^4\}$, where $TC_{it,jp} = PH_{it-1, \Delta 300}$ as split into periods and treatments. This indicator considers only built lots to assess the recent rate of housing growth rel-

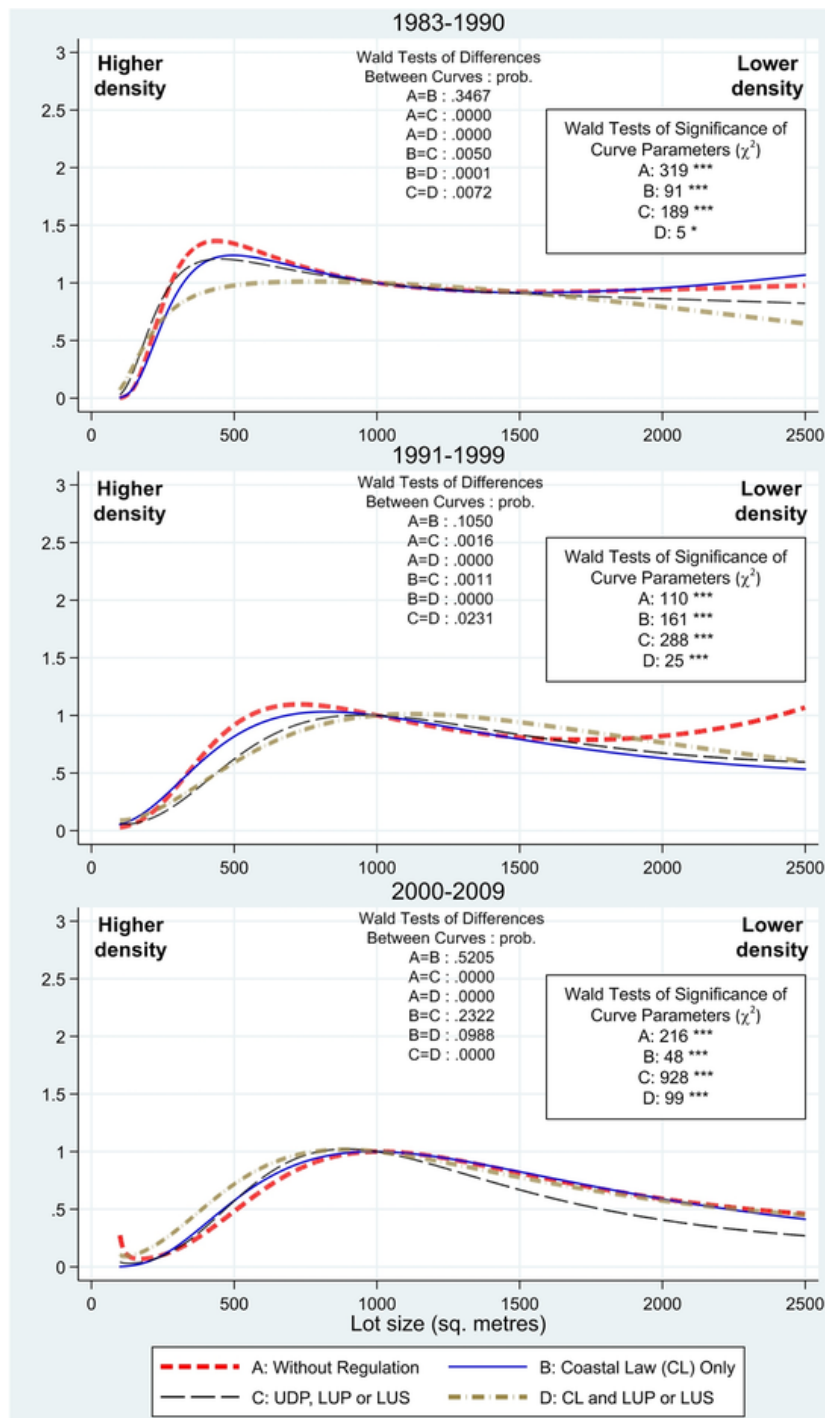


Fig. 2. Hazard ratios of residential density development from 1983 to 2009. Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

ative to previous urbanization. A lower proportion of older houses is related to urban sprawl, while a higher proportion indicates consolidation of older neighbourhoods.

The curves are shown in Fig. 5. They display the growth of the hazard ratio (from 1) in newly built neighbourhoods to a maximum that depends on the planning statuses, then a steady decrease as one moves towards older neighbourhoods where the hazard ratio is again close to one. All the curves are highly significant, which confirms the relevance of the indicator. Most differences between planning statuses are significant with a few exceptions. The tests in Table 6 indicate that

most changes in shape occurred between the eighties and the nineties and became more stable afterwards.

In the eighties, urban sprawl was prevalent in planned inland municipalities (C) with a peak of 20 % of houses older than 5 years around newly built houses. The risk of urban sprawl was far lower in coastal municipalities (B and D). The relative absence of variation in unplanned coastal municipalities (B) is likely related to a lower demand for housing in remote places. The hazard ratios are higher after 1990 and the curves display more contrasting situations. The curves for planned municipalities (C and D) show a high rate of urban

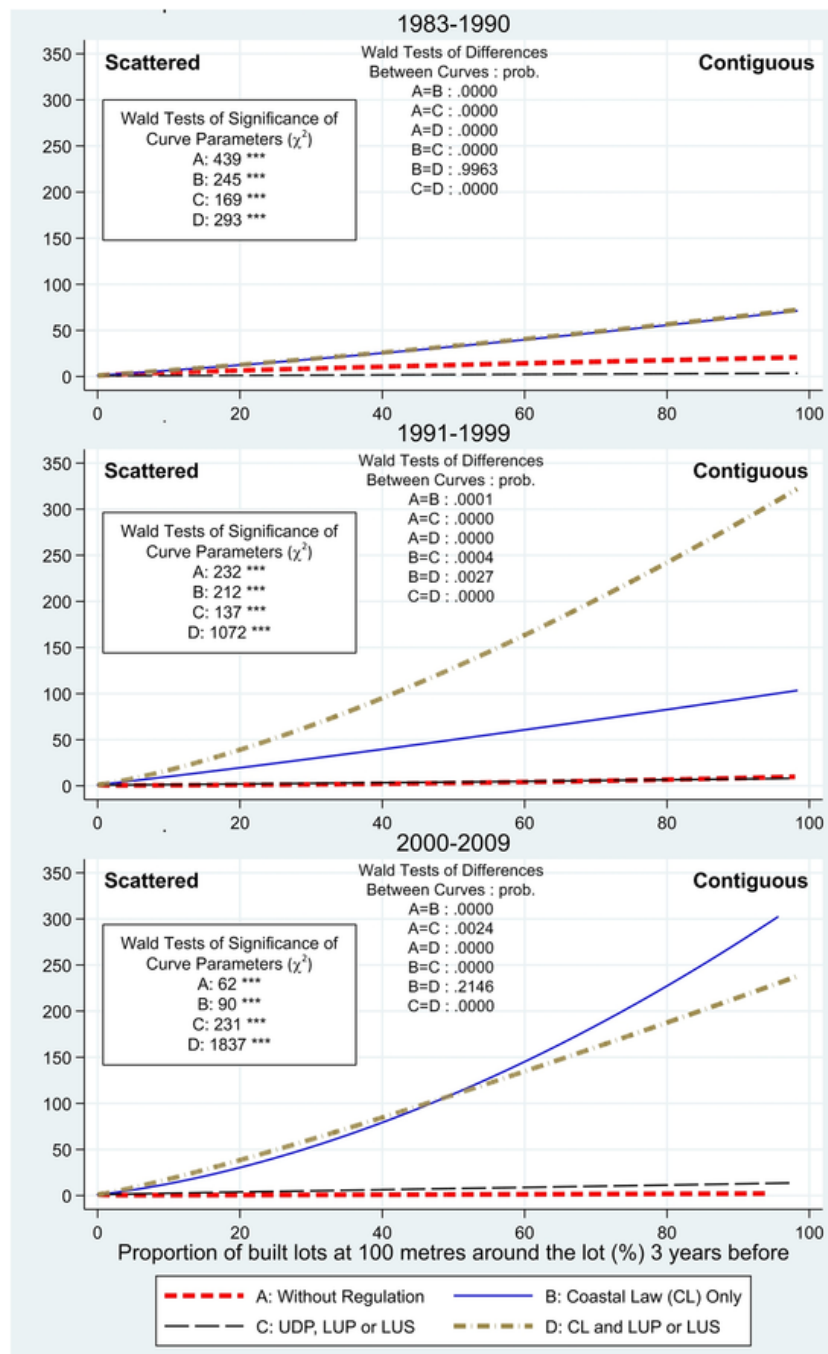


Fig. 3. Hazard ratios of spatial contiguity in housing development from 1983 to 2009. Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

sprawl linked to fast development, while the trend in unplanned municipalities is towards consolidation close to older settlements.

4.7. Summary of findings

Particularly noteworthy is the high contrast between the temporal continuity (TC) results and the findings for spatial contiguity (SC), where the reverse is observed. The objective of land planning is thus not to slow down housing growth and urban sprawl (TC), but rather to optimize the use of existing infrastructure, thereby maximizing closeness to existing settlements (SC) while avoiding unnecessary leaps in space (DM). These trends are becoming stronger as time goes by. Moreover, densification of the urban fabric (PA) is not on the plan-

ning agenda in the Brest region, as indicated by the prevalence of 1000 sq. m. lots and a decreasing likelihood to build on smaller lots (Fig. 2). Finally, while the CL is marginally effective in lowering the risk of building houses in the first 100-meter strip along the coast (Table 4), it does not prohibit it. In France, land planning encourages new housing in urban zones (with services), whereas it is more restrictive in rural areas.

To complement the LR test (likelihood ratio) which is highly significant, Fig. 6 shows box lots of hazard ratio distribution according to periods and planning statuses. The distribution of lots built during the observation year (at time t) displays values higher than lots that remain undeveloped. In general, the lower quartile of built lots is closely equivalent to the higher quartile of lots still available at the end of the year. This is an indication that both false positives and false nega-

Table 6
Wald tests of change between hazard functions by regulation status from 1983 to 2009 (χ^2).

Variable	Regulation	1991–1999 vs. 1983–1990	2000–2009 vs. 1991–1999
Density (lot size)	B: CL only	39.91 ***	10.54 *
	C: UDP/LUP/ LUS	174.32 ***	31.21 ***
	D: CL + LUP/ LUS	163.46 ***	74.74 ***
Spatial contiguity Scattered/Contiguous	B: CL only	0.56	4.99
	C: UDP/LUP/ LUS	6.15 *	2.87
	D: CL + LUP/ LUS	14.90 ***	10.56 **
Diffusion mode Edge growth/ Leapfrog	B: CL only	6.59	21.91 ***
	C: UDP/LUP/ LUS	8.42	45.70 ***
	D: CL + LUP/ LUS	1.03	19.96 ***
Temporal continuity Sprawl/Consolidate	B: CL only	51.33 ***	5.37
	C: UDP/LUP/ LUS	30.95 ***	8.68
	D: CL + LUP/ LUS	21.69 ***	0.32

Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

tives are the exception. Moreover, the discriminant power of the model slightly increases after 1990 (no overlap between quartiles). However, model performance can be improved as is indicated by the log likelihood of the null model (-791,555) compared to the fit model (-735,885). This indicates that relevant factors (e.g., local policies, demographics, and real estate indicators) are needed to improve predictive performance.

5. Discussion, limitations, and research perspectives

Our main results can be summarized as shown in Fig. 7. Residential construction is further away from the shoreline. Until 1975, lots located in the 100-metre coastal strip had the highest propensity to be built. After this date, the probability of construction was reduced by 30–40% in coastal municipalities with urban planning (Table 4). The coherence of residential construction has increased. Whatever the type of municipality (coastal or not) and the status (planning or not), the probability of construction has greatly decreased away from built-up areas. In addition, the influence of spatial contiguity increased considerably after 1990. This occurred initially in municipalities with urban planning and, from 2000 on, in those without urban planning (Table 5). The diffusion mode of urbanization has also become more coherent. Before the 1990s, inland municipalities with planning were the most prone to leapfrog development, but this became much less likely as of the 1990s, and especially in the 2000s. The propensity for leapfrog development is lower in coastal than in inland municipalities (Fig. 4). The density of built-up areas has not increased significantly (Fig. 2). Along the shore, a steady reduction in the probability of building the smallest lots ($< 500 \text{ m}^2$) has been observed since the 1980s, while the probability of building larger lots has decreased since the 1990s, especially in inland municipalities without planning. Therefore, a constant lot size of 1000 m^2 emerges from the models, indicating a low residential density (10 houses per ha) in the region. Finally, temporal continuity analysis (Fig. 5) shows a greater propensity for spreading in municipalities with urban planning than without, especially inland.

Therefore, the effects of the CL appear to be ambivalent. While it does not prohibit the construction in the 100-metre band, where the restriction only applies to undeveloped areas, it does seem to have a moderating effect. Conversely, beyond the 100-metre coastal strip,

the CL favours urban development, especially when associated with urban planning. Fig. 5 shows that the CL associated with urban planning tends to favour urban sprawl, whereas the absence of regulation has resulted in a merge of already built spaces.

How can this apparent paradox be explained? Until 1999, urban plans allowed building to occur far from developed areas. In the absence of local plans, the National Planning Regulation (NPR) applied. The NPR is restrictive and prevents urban sprawl outside urbanized areas as defined by criteria of building contiguity, density and convenience. On the contrary, by designating areas to be urbanized, planning allows and promotes urban expansion. However, this expansion is structured by the 200-metre agglomeration distance between buildings as defined by the National Planning Code. As early as 1983–90, the CL, with or without planning, strongly moderated the risk of dispersed building whatever the density and scale (Fig. 4). Urban expansion has thus been well controlled, which explains why the proximity criterion appears to so effectively structure modelling whatever the regulatory system applied (Table 5). However, even though urbanization is more consistent, land consumption is not always moderated. Indeed, urban sprawl seems to be preferred to other forms of development: scattered urbanization, which is now prohibited; leapfrog development, which continues only marginally in inland small municipalities; and densification, which remains limited when considering the size of the lots built during a given period.

Although it is a major objective, the protection of coastal land is jeopardized by the difference in the status of natural and agricultural areas. On the one hand, natural areas enjoy a high level of protection due to their regulatory status and their recognized heritage value, which allows them to be safeguarded from development (right censorship as seen in Le Berre et al., 2017). On the other hand, the protection of agricultural areas is weaker. It lacks a strong and legitimate status which stems from low interest among stakeholders, including farmers because of the rent they could derive from their land (Minvielle, 2006). This partly explains why the strengthening of regulation does not necessarily translate into a reduction in land consumption, but rather a more coherent urbanism. It increases the probability that residual lands in dense zones will be built, favouring better land use (notably by filling in “missing teeth”). In turn, it reduces the probability of development of large lots away from the coast (Fig. 2).

All these facts combine to show that the CL and land planning do not restrict urbanization but rather help to ease and control it. This complicates the assessment of their effects, especially in a sustainable development perspective. In the Brest region, residential density has not risen in the last thirty years and the marginal likelihood of building on smaller lots is lower now than it was in the past. Moreover, urban sprawl increases over time in planned municipalities while smaller ones, without urban plans, are forced to consolidate due to lower demand for housing. This suggests that land planning is often seen as a tool for increasing development profitability. Therefore, hypothesis 1 (CL lowers the risk of housing build-up in the 100-metre coastal band) is partly supported by our findings but is highly dependent on the local context, as explained above. Findings support the first part of hypothesis 2 (planning bylaws are effective in enhancing urban development), but the second part (promotion of sustainability) is highly dubious, if not rejected. It would appear that economic development competes with sustainability (e.g., increasing urban sprawl and associated GHG emissions). However, socio-economic sustainability is likely achieved thanks to more effective urban management. That being said, the environmental aspect would seem to be neglected.

This research was limited by data availability, by the characteristics of the Brest region, as well as by modelling constraints, particularly those related to the need to control the number of variables.

Thus, despite their interest, some data are not available for the study area, or for the entire time span of the analysis. 1) Property val-

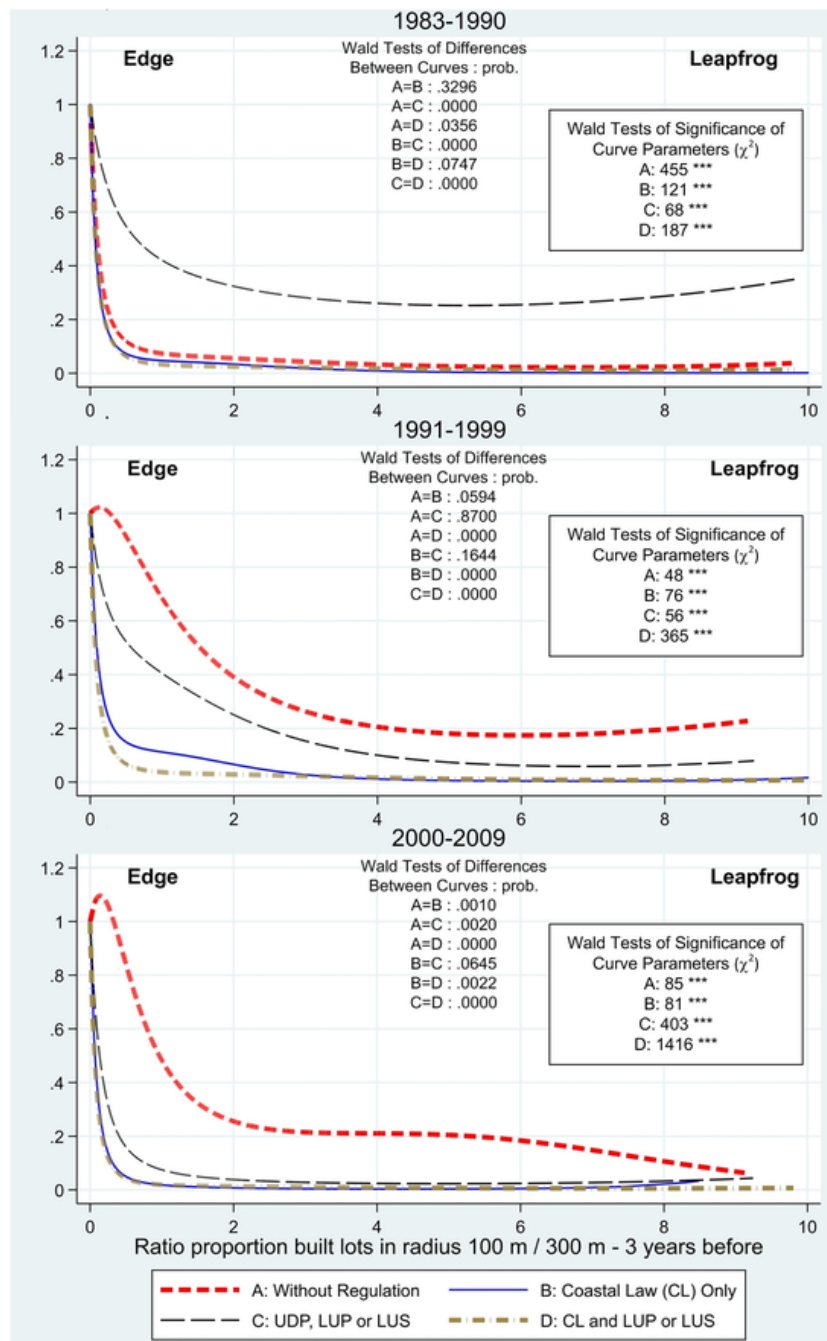


Fig. 4. Hazard ratios of diffusion mode in housing development from 1983 to 2009. Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

ues play a considerable structuring role on residential development (Dubé et al., 2013). In France however, data on real estate transactions have only recently been released by the tax administration. They thus only offer a historical depth of 5 years, which is too limited to be able to analyze the effects of the CL. 2) Accessibility to daily commodities and environments that enhance quality of living can be included, as they likely drive the demand for specific locations. Daily commodities are integrated into the model through distance to the city centres and schools. These poles are ranked in three classes according to their level of service. Albeit limited, their integration allowed us to control for the effects of the main service points in the region. It would be interesting to consider the redeployment of many services in the urban peripheries, and to improve our understanding of the Pays de Brest's suburbanization dynamics. 3) Given the geographical configuration

of the region, coastal landscapes and accessibility to the coast (beaches, ports, etc.) also structure residential development. They are currently integrated into the modelling through proximity to the coastline and protected natural areas. The integration of a landscape variable could improve the description of the amenity indicators and the estimation of real estate values. This would however require a complex landscape analysis whose benefit would probably be limited (Cavailhès et al., 2008).

Several modelling specifications rely on the region's characteristics. 4) The modelling concentrates on housing development while other land uses are also involved in the urban development process. In particular, the modelling does not look at industrial and commercial developments, except when they generate new centralities. However, although industrial and commercial areas cover, on average, 4 times more

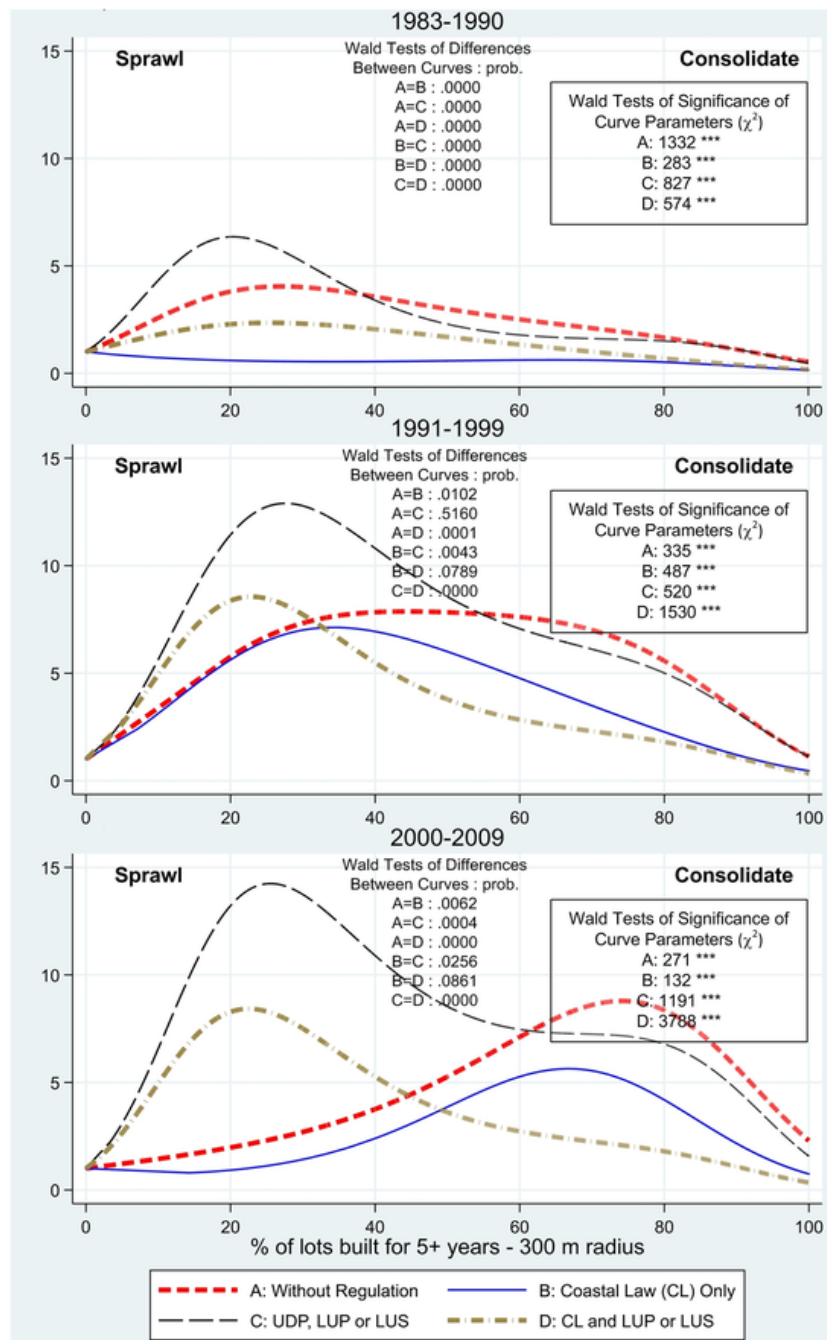


Fig. 5. Hazard ratios of temporal continuity in housing development from 1983 to 2009. Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

space on the coast than on the whole of the French territory, residential occupancy dominates (22.6 % in the 500-metre coastal strip, compared to 3.6 % on the national average). In addition, residential development often stems from individual choices, while that of commercial and industrial activities is purely defined by planning. 5) Our analysis ignores lot redevelopment (increasing density by replacement of a single-family house by larger buildings). Indeed, one particularity of Brest is that it is a rebuilt city (after World War II). Its reconstruction continued until the beginning of the 1970s. Therefore, single-family residential development is still relatively recent, especially on the coast where it really increased from the 1960s on. In these conditions, renovation is more common than redevelopment. The redevelopment of single-family residential space by residential collectives can be observed but remains marginal and limited to the downtown. However, as redevelop-

ment will probably become more popular in time, it should be considered in future modelling. 6) The spatial diffusion indices assume isotropy even though there are likely development axes (e.g., along roads). However, the high density of the road network in the Brest region does not generate a great deal of access inequalities, with the exception of distance to commodities and the coast. The structuring effect of the roads is nonetheless considered in the model, both as a factor of accessibility to land parcels and as a dis-amenity.

Finally, 7) the model specification does not distinguish between types of urban plans and their peculiarities. Urban planning has been implemented gradually, municipality by municipality, and it evolves regularly, according to local political agendas. The planning choices and patterns are therefore highly differentiated and understanding them may be relatively complex. This could therefore be an interest-

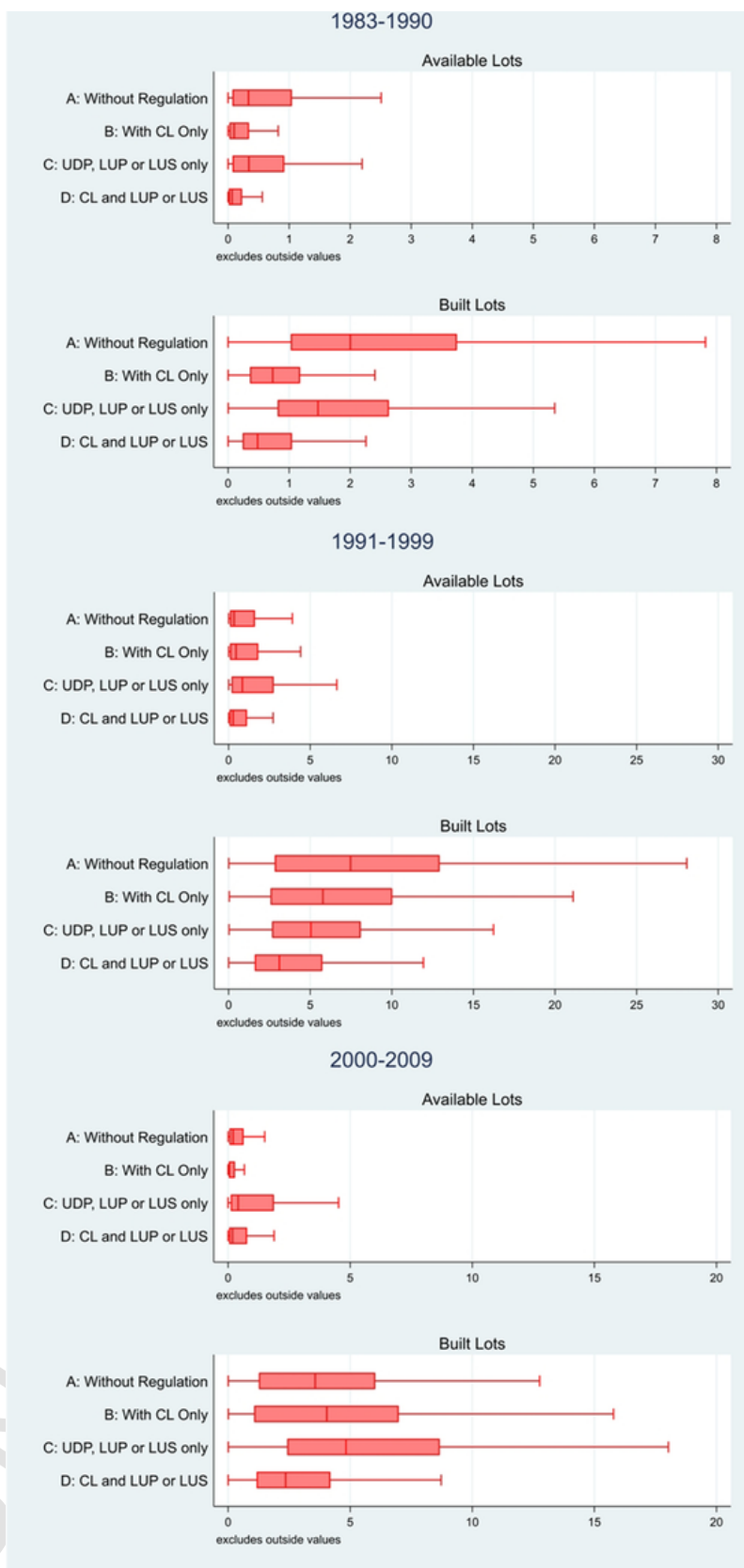


Fig. 6. Distribution of hazard ratios for available versus built-up lots according to regulations from 1983 to 2009.

Variable	Status								Construction trend conclusions
	Inland without regulation		Inland with land planning		Coastal without regulation		Coastal with land planning		
	Small	Large	Small	Large	Small	Large	Small	Large	
Lot Size	↗	↘	↗	↘	↗	↘	→	→	Residential density remains low
Spatial contiguity	→	→	→	→	↗	↗	↗	↗	More coherent development
Leapfrog devt	↗	↘	↘	↘	→	→	→	→	
Sprawl	↘	↘	↗	↗	↘	↘	↗	↗	Spreading is more probable with urban planning
Proximity to shoreline	↘	↘	↘	↘	↘	↘	→	→	Construction away from the shoreline

Fig. 7. Overall impact of spatial diffusion trends on housing development.

ing research prospect, which could aim to establish a typology of development agendas carried out in urban planning. In particular, it would allow us to distinguish those municipalities planning a strong development from those opting for a moderate development, and thereby better understand the influence of political orientations on urbanization processes (Prévost and Robert, 2016; Onsted and Chowdhury, 2014).

Even though our findings must be interpreted with caution, this study has shown the feasibility of a comparative analysis of planning policies over a large diverse area. The effects are compared between the five time periods to assess built-up pace and diffusion. The regression equation can be used to calibrate simulation tools (e.g., set rules for cellular automata or multi-agents) to forecast likely development forms in the short term. We could thereby validate its predictive power and perform sensitivity analysis of spatial and temporal distance thresholds. For this study, thresholds were chosen to the best of our knowledge (and experience), though it would have been useful to test the differences obtained based on several specifications. Including land prices and socio-economic data should improve the models by simultaneously considering demand and supply. Moreover, approaches still need to be defined to better specify the nature of local policies and to develop indices for integrating them into the model. Furthermore, considering that the natural hazard issues and vulnerability can improve the choice of criteria for assessing sustainable urban development, the comparison of four regulatory statuses was very restrictive, although useful.

6. Conclusion

This article is the third to use the Brest longitudinal database of residential development. Le Berre et al. (2016) discuss differences in the probability of building a house using five logistic regression models. Le Berre et al. (2017) use a survival model to explore various dimensions of the CL's impact on shore protection. This article goes further, combining the CL and land use planning with spatial-temporal diffusion indices to assess their joint effects on changes in urban form, taking into consideration accessibility, proximity, spatial contiguity, temporal continuity, edge waves versus leapfrog growth, etc. This makes it possible to test hypotheses about diffusion processes and about the achievement of sustainable urbanism in increasing density, promoting adjacency, and avoiding urban sprawl and its detrimental effects on the environment and climate. The main finding is that national laws need land planning to be employed locally and that municipalities and stakeholders still prefer economic development over environmental conservation. This emphasizes a restricted (short term) view of sustainable development.

Our findings are consistent with those obtained by Prévost and Robert (2016) using a different method. They also show the dissonance existing between government regulations and the development projects carried out by the local authorities. This is clearly an effect of the process of decentralization initiated since the beginning of the 1980s in France, and the CL is one of the tools of decentralization. Indeed, this framework law was deliberately defined in an imprecise way, in order to allow a local adaptation in keeping with the development projects envisaged by local authorities.

It would be interesting to test this analysis on other study sites. At the national level, the method is reproducible because it is based on the use of readily available reference data that would allow the configuration of similar databases in other coastal areas. The discordance between general rules designed to answer national issues and their application to differing territories to respond to local issues and projects is not specific to France, as evidenced by several international examples (Abrantes et al., 2016; Brody and Highfield, 2005; Paül and Tonts, 2005). From this point of view, since our method is relatively parsimonious, it should be applicable in other national contexts where detailed geolocated (lot-level) land use data is recorded over time.

To the best of our knowledge, this is the first time the Hägerstrand's (1967) spatial diffusion theory is applied to changes in land use using an autoregressive approach to assess the direct effects of location choice and local-level dynamics. While different in its scope, this study is in line with Dubé et al.'s (2017) proposal to measure both the direct and indirect effects in order to analyze the short- and long-term spatial-temporal relationships in autoregressive models. For spatial processes, such methods are critical to disentangle the complexity of land use evolution. They shed light on the overall consequences of land use policies and on stakeholders' subjacent goals and choices. This type of approach needs further development, as it can be beneficial in other topics where space-time matters.

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Appendix A. Longitudinal (yearly basis) panel survival model of undeveloped lots from 1968 to 2009 – Cox regression (hazard ratios and significance)

Variable	Planning status Category / Polynomial	1968-1975	1976-1982	1983-1990	1991-1999
Distance to shore (0-100 m.) [DS]	A: Without only	1.26 ***	0.91		
	B: CL			0.87	0.88
	C: UDP/LUP/LUS	1.85 **	0.84		
	D:			0.64 **	0.71 **
	CL + LUP/LUS				
Distance to Breast Car travel time (minutes) [DB]	0-8	1.63 ***	0.60 ***	0.77 *	0.66 **
	8.1-12	3.75 ***	1.68 ***	2.04 ***	1.30 **
	12.1-16	2.45 ***	1.79 ***	2.37 ***	1.70 **
	16.1-20	1.94 ***	1.63 ***	1.52 ***	1.59 **
	20.1-24	1.60 ***	1.55 ***	1.58 ***	1.58 **
Distance to urban center (2 nd level) [DC]	24.1-28	1.29 ***	1.50 ***	1.47 ***	1.44 **
	28.1-32	1.30 ***	1.39 ***	1.28 ***	1.39 **
	>32 (reference)	1.00	1.00	1.00	1.00
	0-2	1.02	0.93	0.61 ***	1.05
	2.1-4	1.30 ***	1.27 ***	1.04	0.95
Road distance to the nearest school (metres) [SL]	4.1-6	1.63 ***	1.43 ***	1.06	1.02
	6.1-8	0.97	1.22 ***	1.00	1.18 **
	8.1-10	1.02	1.14 ***	0.85 ***	1.05
	>10 (reference)	1.00	1.00	1.00	1.00
	0-500	2.01 ***	1.76 ***	1.43 ***	1.39 **
Distance to the nearest neighbour 1 year earlier (metres) [NN]	501-1000	2.04 ***	1.75 ***	1.57 ***	1.51 **
	1001-1500	1.58 ***	1.80 ***	1.35 ***	1.33 **
	1501-2000	1.24 ***	1.20 ***	1.32 ***	1.19 **
	>2000 (reference)	1.00	1.00	1.00	1.00
	A: Without				
Distance to the nearest neighbour 1 year earlier (metres) [NN]	<100 (reference)	1.00	1.00	1.00	1.00
	100-200	0.18 ***	0.15 ***	0.10 ***	0.08 **
	>200	0.06 ***	0.04 ***	0.03 ***	0.08 **
	B: CL Only				
	<100 (reference)			1.00	1.00
100-200			0.11 ***	0.19 **	

>200			0.01 ***	0.08 **	
C: UDP/LUP/LUS					
<100 (reference)	1.00	1.00	1.00	1.00	
100-200	0.23 ***	0.12 ***	0.12 ***	0.14 **	
>200	0.07 ***	0.04 ***	0.02 ***	0.08 **	
D: CL + LUP/LUS					
<100 (reference)			1.00	1.00	
100-200			0.04 ***	0.18 **	
>200			0.01 ***	0.04 **	
Residential density	A: Without				
Lot area (metres ²) [PA]	PA	1.19 ***	0.97	0.70 ***	0.60 **
	PA ²	1.54 ***	1.32 ***	1.41 ***	0.64 **
	PA ³	0.93	1.34 ***	1.24	2.45 **
	PA ⁴	0.78 ***	0.91 **	0.81 ***	1.36 *
	B: CL Only				
PA			0.70	0.73	
PA ²			1.25	0.47 **	
PA ³			1.44	1.31	
PA ⁴			0.90	1.14	
C: UDP/LUP/LUS					
PA	0.48 ***	0.55 ***	0.75 ***	0.90	
PA ²	2.51 ***	1.70 ***	1.10	0.36 **	
PA ³	1.93 ***	1.89 ***	1.10	1.42	
PA ⁴	1.00	0.92	0.88 *	1.27 **	
D: CL + LUP/LUS					
PA			0.91	1.22 **	
PA ²			0.81 *	0.42 **	
PA ³			0.89	0.97	
PA ⁴			0.89	1.08	
Spatial contiguity	A: Without				
Built lots in 100 metre buffers 3 years earlier (proportion) [SC]	ln(SC)	1.27 ***	1.06	1.72 ***	0.39 **
	ln(SC) ²	1.05 ***	1.08 ***	1.03	1.37 **
	B: CL Only				
	ln(SC)			1.89 **	2.50 **
	ln(SC) ²			1.07	1.02
C: UDP/LUP/LUS					
ln(SC)	0.76 *	1.34 *	0.70 **	0.82	
ln(SC) ²	1.09 ***	1.08 **	1.15 ***	1.15 **	
D: CL + LUP/LUS					
ln(SC)			1.92 **	3.02 **	
ln(SC) ²			1.06 *	1.03	

Diffusion mode	A: Without				
ln(DM)		0.01 ***	0.01 ***	0.00 ***	1.46
Built lots in 100 metre / 300 metre buffers	ln(DM) ²	515.75 ***	242.16 ***	44475 ***	0.19
	ln(DM) ³	0.04 ***	0.05 ***	0.00 ***	1.59
	ln(DM) ⁴	1.82 ***	1.70 ***	3.28 ***	1.03
	B: CL Only				
3 years earlier [DM]	ln(DM)			0.00 ***	0.00 **
	ln(DM) ²			9.14 ***	2.15 **
	ln(DM) ³			0.00 ***	0.00 **
	ln(DM) ⁴			6.73 ***	10.21 *
	C: UDP/LUP/LUS				
	ln(DM)	0.12 *	0.01 ***	0.14 *	0.07
	ln(DM) ²	11.39	62.95 *	4.66	33.44
	ln(DM) ³	0.20	0.11	0.45	0.06
	ln(DM) ⁴	1.50	1.62	1.19	2.01
	D: CL + LUP/LUS				
	ln(DM)			0.00 ***	0.00 **
	ln(DM) ²			2337 ***	3756 **
	ln(DM) ³			0.00 ***	0.00 **
	ln(DM) ⁴			3.05 ***	3.34 **
Temporal continuity	A: Without				
TC		1.00	1.11 ***	1.14 ***	1.17 **
Built lots in 300 metre buffers	TC ²	1.00	1.00 ***	0.99 ***	0.99 *
	TC ³	1.00	1.00 ***	1.00 ***	1.00
	TC ⁴	1.00	1.00 ***	1.00 ***	1.00 *
Older than 5 years	B: CL Only				
1 year earlier [TC]	TC			0.96	1.16 **
	TC ²			1.00	1.00
	TC ³			1.00	1.00 **
	TC ⁴			1.00	1.00
	C: UDP/LUP/LUS				
	TC	0.93 ***	1.08 ***	1.25 ***	1.27 **
	TC ²	1.00 *	1.00 ***	0.99 ***	0.99 **
	TC ³	1.00	1.00 ***	1.00 ***	1.00 **
	TC ⁴	1.00 *	1.00 ***	1.00 ***	1.00 **
	D: CL + LUP/LUS				
	TC			1.09 *	1.26 **
	TC ²			1.00 *	0.99 **

TC ³	1.00	1.00 **
TC ⁴	1.00	1.00 **

Significance: * p < 0.05; ** p < 0.01; *** p < 0.001.

No. of subjects: 194,345; No. of failures: 66,284; Time at risk 6,371,679 years; LR Chi2 (340): 111,341.

N.B. Coefficients with more digits are needed for estimating polynomials.

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