Article

Changes in land cover and urban sprawl in Ireland in comparative perspective over 1990-2012

Achim Ahrens [1,*] and Seán Lyons [1,2]

[1] The Economic and Social Research Institute, Dublin, Ireland
[2] Trinity College Dublin, Ireland
* Correspondence: achim.ahrens@esri.ie; Tel.: +353 1 8632023

Received: date; Accepted: date; Published: date

Abstract: An extensive literature suggests that spatial development patterns characterised by sprawl are inefficient from an economic and environmental perspective. Specifically, sprawl has been associated with adverse effects on health, increased commuting times, and negative environmental consequences due to pollution and greenhouse gas emissions. In this article, we first summarise trends of land use changes and urbanisation in Ireland since 1990 using data from the Corine Land Cover program. In doing so, we compare the developments in Ireland with other European countries. Second, we formally test for the presence of sprawl using conditional and unconditional convergence tests. The two-part empirical analysis allows us to establish that Ireland has experienced substantial loss of non-urban land over the last decades. Furthermore, a significant share of urban areas have been created in remote areas, thereby exacerbating sprawl.

Keywords: urban sprawl; land use; land cover change; urban expansion

---

1. Introduction

An extensive but often theoretical literature shows that spatial development patterns are not necessarily efficient from an economic and environmental perspective and that market failures are pervasive. While this is a key rationale for effective spatial planning, current planning practices may not always overcome these market failures.

There is relatively little research on quantifying the effects of inefficient spatial development patterns both from an environmental and economic perspective. Furthermore, the specific market failures that create these inefficient patterns have not been analysed and tested empirically. However, efficient policy to address the market failures can only be devised with a better understanding of their nature, and quantification of the scale of impacts will provide a strong rationale for policymakers to address the issues. In particular, spatial development patterns characterised by sprawl and low density can have important environmental consequences in terms of transport patterns and related emissions. Other impacts include landscape changes, loss of habitat and higher energy consumption.

What is sprawl, and how does it relate to urbanisation? Economic development is associated with changes in land use, typically transformations from natural green spaces to artificial areas. The expansion of urban space is a common trend across Europe, despite low or stagnant population growth. Indeed, as shown in Figure 1, the growth rate of urban expansion, as measured by the area classified as urban, exceeds population growth in almost all European countries between 2000 and 2012. Rather, income growth and the associated rise in demand for single-family detached housing in sub-urban areas are discussed to be leading drivers of sprawl [1,2]. The trend towards urbanisation of land is especially pronounced in Ireland. With an annual growth rate of 3.1% (2.5%) over 1990-2012 (2000-2012), urban land expansion in Ireland is among the highest in Europe. For comparison, the average rate in other European countries is 1.4% (1.1%) over the same period.

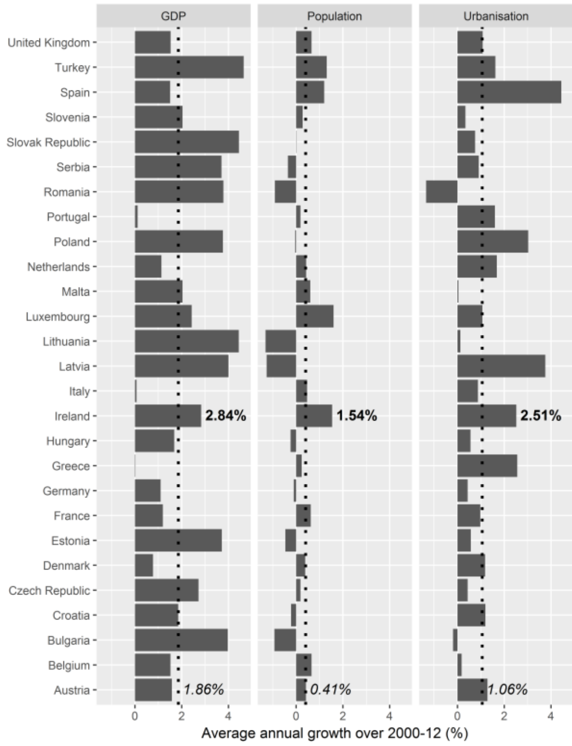


Figure 1. GDP growth, population growth and rate of urbanisation. Dotted lines indicate average annual growth for all countries excluding Ireland (average rates shown in italics). Growth rates in bold are for Ireland. (*Data source:* Authors' calculations using IMF, Corine Land Cover.)

Urban expansion may take place in a dense form, where new urban areas are located adjacent to or nearby existing urban structures. On the other extreme, urbanisation can be accompanied by sprawl. Sprawl is a multi-dimensional, ambiguous concept, which can refer to both a state and a process [3]. Due to the complexity of sprawl, there is a large and ongoing literature devoted to developing methods to quantify sprawl [4-8]. For the purpose of this article, we conceptualise the state of sprawl broadly as a land-intensive, low-density and scattered use of land. Similarly, the process of sprawl refers to transformation of green spaces to artificial areas resulting in a dispersed population structure and built environment.

Sprawl and the consumption of green spaces can have various adverse effects, including negative impacts on health, commuting times, energy use and the environment. Ewing et al. [9] find that measures of sprawl, derived from principal component analysis, are negatively related to physical activity, and thus contribute to obesity and hypertension. In a meta-study involving thirty-five articles, Lee and Maheswaran [10] show that there is evidence, albeit only weak, that accessibility and quality of green spaces affect physical activity. However, in terms of social interactions, according to Brueckner and Largey [11], population density seems to impair, rather than facilitate, social connections.

With regard to commuting behaviour, Cervero and Murakami [12] show that there is a negative correlation between population density and distances travelled by car for the US. Specifically, a 1% reduction in population density is associated with a 0.6% increase in vehicle miles travelled per capita. In an analysis of Italian municipalities, Travisi, Camagni, and Nijkamp [13] also find that measures of sprawl are linked with commuting intensity, suggesting that sprawl contributes to the rise in commuting times in Italy. In a similar study for Germany, Keller and Vance [14] establish a statistical association between two measures of sprawl—the share of open green spaces and diversity of land use—with distances driven.

The increased use of vehicles for commuting and transport has naturally implications for greenhouse-gas emissions and pollution, as shown by Niemeier, Bai, and Handy [15] and Kim and Brownstone [16], among others. Ewing and Rong [17] point out that, because residents in rural areas are more likely to live in detached single-family houses, sprawl results in higher residential energy use, which again has consequences for the environment. Glaeser and Kahn [18] link sprawl directly to green-house gas emissions and conclude that, using US household data, emissions could be reduced if more people move to cities and locations with high population density. The results are confirmed by Jones and Kammen [19], also for the US, and Grazi, van den Bergh, and Ommeren [20] for the Netherlands. On the other hand, Minx et al. [21] argue that greenhouse gas emissions are predominantly driven by socio-economic factors rather than factors of the built environment.

Next to the literature on measuring sprawl and the cost of sprawl, a third strand asks which underlying factors cause sprawl. Burchfield et al. [22] show that sprawl is more severe in cities with a lack of public transport and with availability of undeveloped land within the municipality. In a panel study of 282 European cities covering 1990, 2000 and 2006, Oueslati, Alvanides, and Garrod [2] find that the extent of artificial area is increasing in population and income per capita, whereas agricultural productivity at urban fringes alleviate sprawl. Pirotte and Madre [1] establish that household incomes are positively associated with sprawl for the French cities Paris, Lyon, Marseille and Lille over 1985-98.

Despite the large literature devoted to sprawl and its impacts, there is no recent analysis examining trends of land use and sprawl for Ireland. This is although, as we will point out, Ireland has experienced substantial changes in the use of land since the start of the Celtic Tiger period. Understanding trends of urbanisation is especially important since, empirically, urbanisation is only rarely reversed, presumably due to the absence of economic incentives. In this article, we summarise changes of land use changes for Ireland while comparing trends to other European countries. To this end, we analyse Corine Land Cover maps. Furthermore, we propose a formal test for the presence of sprawl in Ireland, which draws on convergence tests from the economic growth literature, and apply the test to a data set of Irish Electoral Divisions.

This article proceeds as follows. In Section 2, we summarise trends of land cover and use for Ireland with a special focus on urbanisation. In doing so, we use other European countries as a point of comparison. Section 3 tests for the presence of sprawl in Ireland. Section 4 provides a discussion of the results and conclusion.

2. Trends of Land Cover Change

2.1. CORINE Land Cover data and methodology

The source for the first part of the empirical analysis of land cover flows is the Corine Land Cover (CLC) programme, which is administered by the European Environment Agency (EEA). Based on satellite images, CLC examines shape, size, colour, texture and pattern of landscape area in order to classify land into types of cover.

The Corine nomenclature distinguishes between 44 classes of land cover over three aggregation levels. Table 1 lists the first and second level of the Corine nomenclature. The primary purpose of Corine is to classify land by land cover types rather than by land use. Land cover refers to the physical characteristics of land, while land use refers to the purpose of land for humans. However, the CLC classification also provides some insights into the use of land. For example, the distinction between artificial and agricultural land indicates whether land is predominantly used for residences and for commercial and industrial activities, or whether the primary purpose is the production of agricultural goods.

CLC (level 1)	CLC (level 2)
1 Artificial surfaces	1.1 Urban fabric
	1.2 Industrial, commercial and transport units
	1.3 Mine, dump and construction sites
	1.4 Artificial, non-agricultural vegetated areas
2 Agricultural areas	2.1 Arable land
	2.2 Permanent crops
	2.3 Pastures
	2.4 Heterogeneous agricultural areas
3 Forests & semi-natural areas	3.1 Forests
	3.3 Open spaces with little or no vegetation
	3.2 Shrub and/or herbaceous vegetation associations
4 Wetlands	4.1 Inland wetlands
	4.2 Coastal wetlands
5 Water bodies	5.1 Continental waters
	5.2 Marine waters

Table 1. Corine Land Cover classification (level 1 and level 2)

For most of the analysis, we consider the second level of aggregation. To summarise trends, we adopt the framework of Feranec et al. [23], who classify land cover flows (LCF) into seven categories. These categories are as follows:

- *Urbanisation* (LCF1) refers to transformation of land, predominantly but not exclusive agricultural land and forests, into artificial surfaces. These artificial surfaces include area destined for buildings, industrial facilities and infrastructure, but also artificial green spaces (e.g. parks).
- *Intensification of agriculture* (LCF2) refers to transition of land from low-intensity agricultural use (pastures [2.3] and heterogeneous agricultural areas [2.4]) to high intensity use (arable land [2.1] and permanent crops [2.2]). High intensity use is thereby understood as being associated with a higher use of artificial fertilizers, weed killers, fungicides and pesticides, as well as the use of modern machinery and techniques such as irrigation and drainage.
- *Extensification of agriculture* (LCF3) is the converse of intensification (LCF2). Hence, LCF3 refers to the transition from high to low-intensity forms of agriculture.
- *Afforestation* (LCF4) is the re-creation of forest land naturally or by planting.
- *Deforestation* (LCF5) is the transition of forest land into non-forest land.
- *Water bodies construction and management* (LCF6) refers to the creation of water bodies.
- *Other* (LCF7) are other non-classified land change flows.

From / *To*	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	5.1	5.2
1.1	0	7	7	7	8	8	8	8	8	8	8	7	7	7	7
1.2	7	0	7	7	8	8	8	8	8	8	8	7	7	7	7
1.3	7	7	0	7	8	8	8	8	8	8	8	7	7	6	7
1.4	7	7	7	0	8	8	8	8	8	8	8	7	7	6	7
2.1	1	1	1	1	0	2	3	3	4	4	7	7	7	6	7
2.2	1	1	1	1	3	0	3	3	4	4	7	7	7	6	7
2.3	1	1	1	1	2	2	0	2	4	4	7	7	7	6	7
2.4	1	1	1	1	2	2	3	0	4	4	7	7	7	6	7
3.1	1	1	1	1	5	5	5	5	0	5	5	5	7	6	7
3.2	1	1	1	1	2	2	2	2	4	0	5	7	7	6	7
3.3	1	1	1	1	2	2	2	2	4	4	0	7	7	6	7
4.1	1	1	1	1	2	2	2	2	4	4	7	0	7	6	7
4.2	1	1	1	1	2	2	2	2	4	4	7	7	0	6	7
5.1	1	1	1	1	7	7	7	7	4	4	7	7	7	0	7
5.2	1	1	1	1	7	7	7	7	4	4	7	7	7	7	0

LCF codes: 1 – urbanisation, 2 – intensification of agriculture, 3 – extensification of agriculture, 4 – afforestation, 5 – deforestation, 6 – water bodies construction & management, 7 – other, 8 – de-urbanisation.

Table 2. Classification of land cover flows (LCF) based on Feranec et al. (2010)

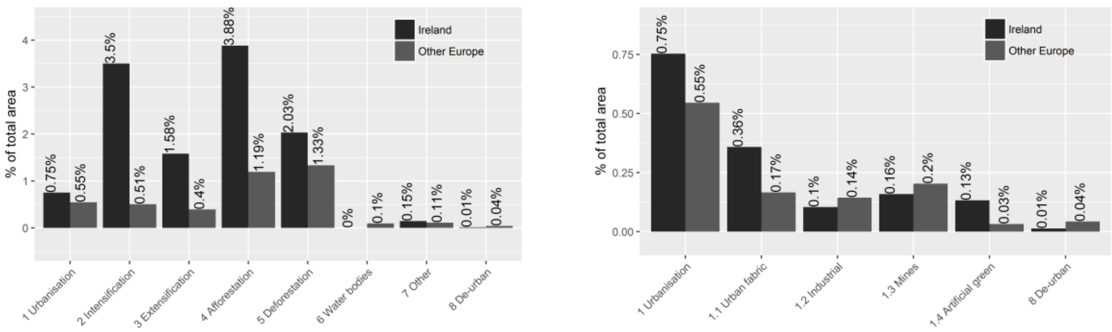
Since we focus on urbanisation, we add another category, de-urbanisation (LCF8), which is the regeneration of artificial areas into agricultural, semi-natural or natural areas (i.e. 2.1 to 3.3). The LCF classification is summarised in Table 2.

2.2. Land cover trends in Ireland

In this section, we discuss trends in land cover changes for Ireland based on Figures 2-3 and Table 3. All tables and figures were compiled using data from the CLC programme. Figure 2(a) shows land transformations by LCF class over the period 1990 to 2012 as a share of total land area, while Figure 2(b) displays only urban-related formations.

The bar diagrams in Figure 2 show that Ireland experienced overall a higher degree of land conversions relative to other European countries across all LCF classes except LCF6 (water body construction) and LCF8 (de-urbanisation). In total, 11.9% of land was transformed between 1990 and 2012, compared to 4.2% in Other Europe[1]. The gap between the intensity of transformations is especially pronounced for afforestation, intensification and extensification. For example, the proportion of land converted to forests is more than three times as high in Ireland compared to Other Europe (3.9% versus 1.2%).

With 32.6% of transformed area, afforestation accounts for the largest share of land transformations in Ireland over the 1990-2012 period, exceeding deforestation (17.1%). In terms of total area, de-forestation amounts to 2.0%. For comparison, the rest of Europe experienced a small reduction in forest area.



(**a**) (**b**)

Figure 2. Land transformation in Ireland over 1990 to 2012.

Table 3 provides a detailed break-down by period for Ireland and Other Europe. These data show that afforestation slowed down over the three periods from 143.1km^2 in 1990-2000 to 69.2km^2 per year in 2006-12, but exceeded deforestation in each period. In relative terms, forest-related flows were especially pronounced in 2000-6 when afforestation and deforestation accounted jointly for more than 80% of all transformations.

The flow diagrams in Figure 3 illustrate origin-destination flows across all LCF categories (left panel, referred to as 3a) and for urbanisation (right panel, referred to as 3b) split by sub-period for Ireland. These diagrams reveal that afforestation was partially due to the conversion of wetlands (4.1) into forests. Intensification of agriculture is the second largest LCF class, with most of the intensification taking place in the 1990s. Figure 3(a) shows that in that period more than 2,000km^2 of pastures (2.3) were transformed into arable land (2.1), see top-left diagram. In 2006-2012, 358.6km^2 of

[1] In this section, Other Europe includes the following countries (using iso3 codes): AUT, BEL, BGR, CZE, DEU, DNK, ESP, EST, FRA, GBR, GRC, HRV, HUN, IRL, ITA, LTU, LVA, NLD, POL, PRT, ROU, SRB, SVK, SVN, TUR.

new pastures were formed, which however did not compensate for the loss in pastures over 1990-2000.

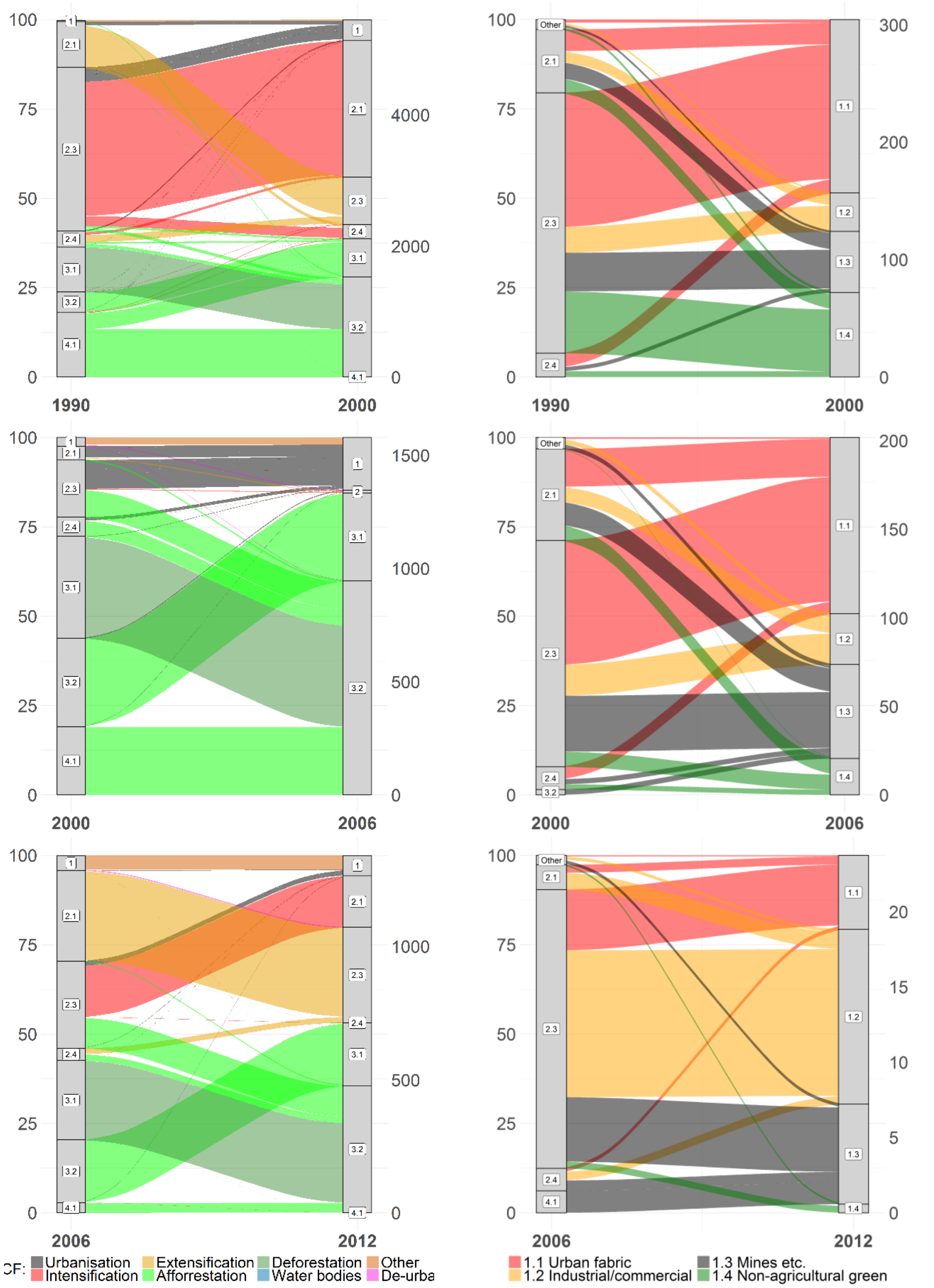
	Ireland				*Other Europe*			
	1990-2000	*2000-2006*	*2006-2012*	*1990-2012*	*1990-2000*	*2000-2006*	*2006-2012*	*1990-2012*
Share of transformed (%)								
Urbanisation (LCF 1)	5.58	12.79	1.77	6.32	12.43	14.30	12.62	12.91
of which	2.70	6.30	0.37	3.01	5.31	3.30	1.69	3.93
Industrial (1.2)	0.60	1.82	0.86	0.87	3.25	3.48	3.66	3.41
Mines, etc. (1.3)	0.95	3.36	0.49	1.33	3.01	6.68	6.75	4.80
Artifical green (1.4)	1.32	1.30	0.04	1.11	0.86	0.84	0.52	0.77
Intensification (LCF 2)	41.50	0.25	14.45	29.39	14.03	10.00	9.56	11.97
Extensification (LCF 3)	13.80	0.25	26.44	13.27	12.86	3.60	7.43	9.36
Afforestation (LCF 4)	26.20	56.06	30.90	32.58	31.65	22.50	26.58	28.26
Deforestation (LCF 5)	12.57	28.28	22.16	17.07	23.97	43.17	36.60	31.58
Water bodies (LCF 6)	0.03	0.00	0.00	0.02	2.54	1.80	2.22	2.29
Other (LCF 7)	0.32	2.03	3.98	1.23	1.59	3.42	3.99	2.62
De-urbanisation (LCF 8)	0.00	0.34	0.30	0.11	0.93	1.21	1.01	1.01
Transformed								
Area (km^2)	5,459.60	1,579.48	1,343.18	8,382.25	95,532.21	42,382.14	46,939.74	184,854.09
Area/year	545.96	263.25	223.86	381.01	9,553.22	7,063.69	7,823.29	8,402.46
Share of total (%)	7.76	2.24	1.91	11.91	2.18	0.97	1.07	4.23
Urbanisation								
Area (km^2)	304.44	201.97	23.75	530.17	11,874.89	6,059.65	5,922.39	23,856.93
Area/year	30.44	33.66	3.96	24.10	1,187.49	1,009.94	987.07	1,084.41
Share of total (%)	0.43	0.29	0.03	0.75	0.27	0.14	0.14	0.55
Total area (km^2)			70,366.7				4,373,315.7	

Table 3. Land conversion in Ireland and other European countries over 1990-2012.

Compared to forest-related and agricultural transformations, urbanisation (LCF1) makes up only a small share of total land transformations, accounting for 6.3% and 12.9% of total transformations in Ireland and Other Europe, respectively. The speed of urbanisation slowed down from 30.4km² and 33.5km² per year in 1990-2000 and 2000-06 to only 4.0km² over 2006-12. For comparison, the annualised rate remained more stable in Other Europe where it decreased from 1187.5km² in 1990-2000 to 987.1km² in 2006-2012. While the slowdown is more noticeable in Ireland, the impact of urban expansion was generally more pronounced compared to rest of Europe, where only 0.55% of the total was urbanised (see Figure 2).

Table 3 also reveals that de-urbanisation occurs only rarely. Only 0.1% of total land transformations in Ireland and 1.0% in rest of Europe are classified as de-urbanisation (LCF8). This insight stresses the importance of tracking the process of urbanisation due to its lasting impact on the environment.

On the formation side, the creation of urban fabric (1.1) decreased as a share of total urbanisation. While urban fabric accounted for almost 50% of new land formation over 1990-2000, the share dropped to 25% over 2006-2012. Similarly, the formation of non-agricultural green spaces fell from 25% to less than 5%. On the other hand, the share of new land area for industrial purposes increased from less than 10% to 50%. On the consumption side, pastures experienced the largest losses due to urbanisation across all three sub-periods, followed by arable land, whereas only a negligible share of urbanisation involved forests and wetlands.



(**a**) (**b**)

Figure 3. Land use flows in Ireland over 1990-2012. Left scale is in % and right scale is in 000km².

2.3. Sparseness of new artificial areas

In the previous section, we have focused on the quantity of newly generated urban land. However, not all formation of urban land is qualitatively the same. New urban areas may be developed adjacent to existing urban areas or in remote locations yielding a scattered, sparse structure of land use. Dense urban structures tend to be more efficient from a land planning perspective; for example, dense structures are associated with lower travel times and thus minimise environmental impact [12,18]. To assess how Ireland compares to other European countries in this regard, we have calculated the distances from new artificial areas (i.e., Corine class 1) to existing artificial areas, where each area corresponds to a contiguous polygon in the Corine data set. All other things equal, higher distances to existing areas suggest that urban expansion takes place in an unplanned manner, resulting in disperse urban structures, and inefficient economic and environmental outcomes. Summary statistics are shown in Table 4 for Ireland and Other Europe[2]. The proportion of new artificial areas created between 1990 and 2012 that are adjacent to existing structures is slightly lower in Ireland compared to other European countries, with 63.5% versus 64.6%. On the extreme end, 13.3% of new artificial areas are created at least 2km from existing artificial structures, while the same proportion for Other Europe is only 7.8%. The average distance amounts to 761.1m, which is considerably higher than in Other Europe (516.9m). The median distance of nonadjacent artificial areas is 1,172.1m, implying that more than half of new non-adjacent artificial structures are created more than 1.1km away from existing artificial areas.

	Period	*All*	*Adjacent*		*Distance above (in %)*			*Average*	*Median*
		Count	*Count*	*in %*	*20m*	*200m*	*2km*	*All*	*Non-adjacent*
Ireland	1990-2000	1,137	686	60.33	39.40	34.12	14.86	837.99	1,146.38
	2000-2006	1,564	944	60.36	38.43	33.12	15.03	845.97	1,359.54
	2006-2012	473	384	81.18	17.97	16.28	3.81	295.39	702.71
	Total	3,174	2014	63.45	35.73	30.97	13.30	761.06	1,172.13
Other Europe	1990-2000	43,431	31844	73.32	25.78	22.01	5.54	389.70	775.76
	2000-2006	42,470	25688	60.49	36.71	30.97	9.15	606.50	755.59
	2006-2012	43,263	25904	59.88	38.54	31.98	8.71	556.76	732.43
	Total	129,164	83436	64.60	33.65	28.30	7.79	516.94	753.47

Table 4. Distance of new artificial areas to existing artificial structures for Ireland and Other Europe for 1990-2012

The insight that the process of urban expansion in Ireland is characterised by the formation of scattered, remote urban structures is confirmed by Figure 4, which shows two density curves; one for Ireland (solid line) and one for Other Europe (dashed). The curves are generated using kernel density algorithms and approximate the underlying distribution of distances for Ireland and Other Europe. Compared to Other Europe, Ireland has a lower share of distances below around 1.75km, while the right tail of the distribution is more pronounced for Ireland indicating a higher share of artificial formations far away from existing structures.

Looking at the break-down by period, the average distance in Ireland dropped from above 800m to 295.4m in 2006-12, while the share of adjacent new areas rose to 81.2% from around 60.3%. Over 2006-12, only 3.8% of new artificial areas were located more than 2km away from existing structures. For comparison, the share of adjacent dropped in Europe from 73.3% to only 59.9%. Certainly, as remote locations become increasingly scarce, a fall in average distances is expected; nevertheless, the drop is considerable, especially in comparison to the rest of Europe.

[2] Due to data constraints, Other Europe uses a reduced sample incuding AUT, BEL, BGR, CZE, DEU, DNK, ESP, FRA, GRC, HRV, HUN, IRL, ITA, LTU, LUX, LVA, NLD, POL, PRT, ROU, SVK.

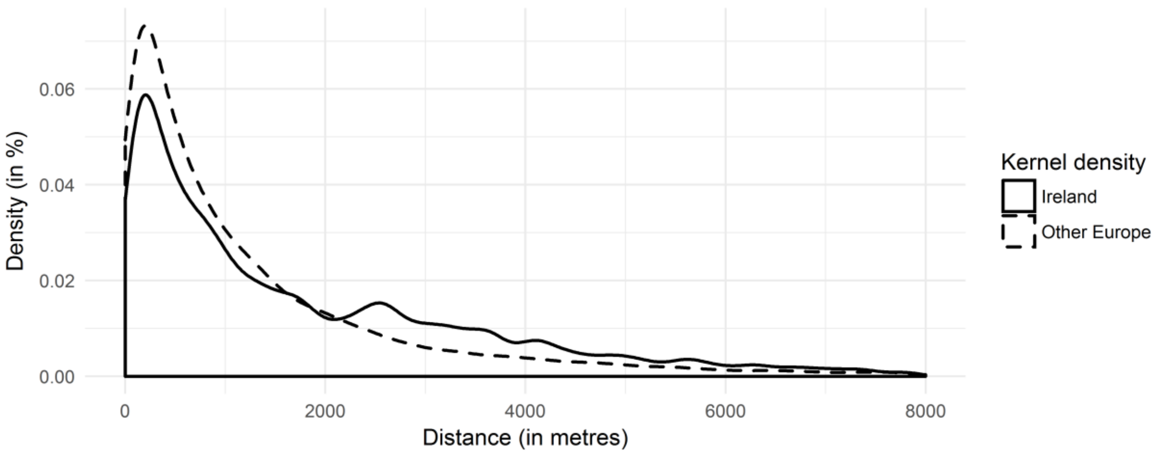


Figure 4. Distance of new artificial areas to existing artificial structures for Ireland and Other Europe for 1990-2012

3. Testing for sprawl

In the second part of the empirical analysis, we develop a formal test for sprawl. For this purpose, we conceptualise sprawl in terms of population and building density. Intuitively, if population and buildings are clustered in a few areas, the level of sprawl is, all other things equal, low. On the other extreme, if population and buildings are distributed uniformly across space, sprawl is at its maximum. Accordingly, sprawl as process is the transition to a state of higher dispersion across space. Sprawl increases over time if low-density areas exhibit higher growth rates in population and building stock than high-density areas. This occurs when people tend to move to low-density areas and when new buildings are constructed in sub-urban areas.

This insight motivates a test of whether growth rates in population and building density are significantly higher in low-density areas. Formally, we consider the model:

$$\varDelta density_{i,t} = \alpha + \beta . density_{i,t-1} + \epsilon_{i,t} \qquad \text{(i)}$$

where $density_{i,t}$ denotes either population density or building stock of area i at time t in logarithmic terms and the left-hand side is the (approximate) percentage change in density between time $t-1$ and time t. $density_{i,t-1}$ is the density in the previous period and α is the intercept. If the parameter β is negative, then areas with low density in the previous period $t-1$ tend to exhibit higher growth rates in density between $t-1$ and t. Thus, a negative β provides evidence for sprawl.

The theoretical framework borrows from the convergence literature in economics, which examines to what extent low-income countries catch up with developed countries [24]. In the convergence literature, a negative β is referred to as absolute or unconditional β-convergence. The model (i) can be extended to include control variables,

$$\varDelta density_{i,t} = \alpha_i + \beta . density_{i,t-1} + \boldsymbol{x}'_{it}\boldsymbol{\delta} + \epsilon_{i,t} \qquad \text{(ii)}$$

where $\boldsymbol{x}'_{it}$ is a vector of control variables and α_i are fixed effects which control for unobservable time-invariant and area-specific characteristics, such as geography. If β is negative in the above model, we say that conditional β-convergence is taking place. That is, the catch-up effect is conditional on control variables.

We estimate different versions of model (i) and (ii) using a panel dataset of Small Area Population Statistics from the Central Statistical Office covering the Census years 2006, 2011 and 2016. The unit of analysis are Electoral Divisions (ED) of which there are 3,409 in the sample. The building stock is taken from the GeoDirectory, which is a registry of buildings in Ireland compiled by the Ordnance Survey Ireland jointly with An Post.

Table 5 shows the estimation results. Model (1) and (2) correspond to the basic models in equation (i) with population density and number of buildings per ED, respectively. The β coefficient estimates are significantly negative for both population and buildings at the 0.1% level, providing evidence for unconditional β-convergence across EDs, which in our context is evidence for sprawl. However, while highly significant, both coefficient estimates are small in absolute size.

	(1)	(2)	(3)	(4)	(5)	(6)
			Dependent variable: Change in			
	Population	Buildings	Population	Buildings	Population	Buildings
Lagged level	-0.00277***	-0.106***	-0.845***	-0.855***	-0.879***	-0.950***
	(0.000673)	(0.00390)	(0.0140)	(0.00529)	(0.0171)	(0.00599)
$\mathrm{Commute}_{i,t-1}$			-0.100***	0.00213	-0.110***	0.00171
			(0.0154)	(0.00912)	(0.0154)	(0.00836)
$\mathrm{Motorway}_{i,t-1}$			-0.00674***	-0.0123***	-0.00291	-0.00117
			(0.00176)	(0.000948)	(0.00191)	(0.000934)
$\mathrm{Unemployment}_{i,t-1}$					-0.0784**	-0.00475
					(0.0257)	(0.0132)
$\mathrm{Broadband}_{i,t-1}$					0.0348***	0.0672***
					(0.00708)	(0.00365)
$\mathrm{Foreign}_{i,t-1}$					0.243	-0.171***
					(0.187)	(0.0514)
Observations	6805	6882	6728	6728	6728	6728
Fixed effects	No	No	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses are robust to within-ED clustering. * p < 0.05, ** p < 0.01, *** p < 0.001. Constant in Model (1) and (2) omitted.

Table 5. Testing for sprawl

Models (3) to (6) add fixed effects and additional control variables and thus test for conditional β-convergence. Model (3) and (4) include average commuting times in minutes ($Commute_{i,t-1}$) and motorway access ($Motorway_{i,t-1}$) to the model. Motorway access is approximated by the road distance from the EDs centroid to the nearest motorway junction.[3] Both variables are included in logarithmic terms and lagged, i.e., for time $t-1$, to avoid simultaneity bias. When controlling for these transport variables, the β coefficients increases in absolute size, suggesting that the process of sprawl is more severe once we control for commuting times and access to motorways. This in line with theoretical expectations, as it is to be expected that people prefer to migrate to EDs with good motorway access and close to business districts to avoid long commuting times. In other words, low-density areas which are more attractive for migrants are driving sprawl. The coefficients of −0.845 and −0.855 imply that a 1% decrease in density is associated with an increase in the growth rate by approximately 0.85 percentage points. Motorway accessibility only has a negligible effect on population density growth, but a larger effect on building construction.

Lastly, we consider a more general model with unemployment rate ($Unemployment_{i,t-1}$), percentage non-Irish residence ($Foreign_{i,t-1}$) and percentage of households with broadband ($Broadband_{i,t-1}$), as a proxy of broadband availability, to the model. The addition of further regressors confirms the presence of conditional β-convergence, and thus sprawl. Broadband availability is shown to be a strong predictor of both population growth and growth in the housing stock. Areas with high

[3] We thank Edgar Morgenroth for providing these estimates to us.

unemployment rates experience lower population growth rates, presumably because they provide fewer employment opportunities, whereas there is no significant effect of unemployment in the previous period on the rate of building construction. The share of foreign-born persons does not appear statistically associated with population growth, whereas it is negatively correlated with building growth.

As noted earlier, sprawl is a multi-dimensional phenomenon. Population density and building stock alone do not capture the full complexity of sprawl. However, even when taking these limitations into account, the analysis provides strong statistical evidence supporting the hypothesis that sprawl is occurring in Ireland. Furthermore, the results reveal that population growth rates and construction of buildings on the level of Electoral Divisions is affected by infrastructure and socio-economic variables. When controlling for these factors, sprawl is shown to be more severe.

4. Conclusions

In this article we show that Ireland has experienced substantial changes in land cover and land use since 1990. Two trends stand out in particular: first, the expansion of area classified as urban has increased at a higher rate than in the rest of Europe. The process of urbanisation has slowed down in the 2006-12 period; yet, the changes are likely to be lasting. Since de-urbanisation occurs only rarely, transformations of green spaces to urban areas tend to be permanent. Second, relative to other European countries, urban areas are created in more remote locations, resulting in sprawl. Sprawl has been associated with a wide range of adverse effects for the economy and the environment, including increased emissions due to commuting and inefficient residential energy use. To address these adverse effects requires appropriate policies that can alleviate sprawl.

Furthermore, we carry out a formal statistical test for sprawl and provide some insights into the drivers of sprawl. Using a panel data set of Irish EDs, we find robust evidence that low-density areas exhibit higher growth in population density and building stock, implying that the population structure is becoming more dispersed over time. The results are more pronounced when controlling for ED-level characteristics. Consistent with theory, population growth and building construction are associated with employment opportunities, broadband availability and motorway access.

References

1. Pirotte, A.; Madre, J-L. Determinants of Urban Sprawl in France. Urban Studies **2011**, 48, pp. 2865-2886, https://doi.org/10.1177/0042098010391303.
2. Oueslati, W.; Alvanides, S.; Garrod, G. Determinants of urban sprawl in European cities. *Urban Studies* **2015**, 52, pp. 1594-1614. https://doi.org/10.1177/0042098015577773.
3. Galster, G.; Hanson, R.; Ratcliffe, M.R.; Wolman, H.; Coleman, S.; Freihage, J. Wrestling Sprawl to the Ground: Defining and measuring an elusive concept. *Housing Policy Debate* **2001**, 12, pp. 681-717, https://doi.org/10.1080/10511482.2001.9521426.
4. Frenkel, A.; Ashkenazi M. Measuring urban sprawl: How can we deal with it? *Environment and Planning B* **2008**, 35, pp. 56-79, https://doi.org/10.1068/b32155.
5. Arribas-Bel, D.; Nijkamp, P.; Scholten, H. Multidimensional urban sprawl in Europe: A self-organizing map approach. *Computers, Environment and Urban Systems* **2011**, 35, pp. 263-275, https://doi.org/10.1016/j.compenvurbsys.2010.10.002.
6. Hamidi, S.; Ewing, R.; Preuss, I.; Dodds, A. Measuring Sprawl and Its Impacts: An Update. *Journal of Planning Education and Research* **2015**, 35, pp. 35-50, https://dx.doi.org/10.1177/0739456X14565247.
7. Laidley, T. Measuring Sprawl. *Urban Affairs Review* **2016**, 52, pp. 66-97, https://doi.org/10.1177/1078087414568812.
8. Aurambout, J.-P.; Barranco, R.; Lavalle, C. Towards a Simpler Characterization of Urban Sprawl across Urban Areas in Europe. *Land* **2018**, *7*, 33. https://doi.org/10.3390/land7010033

9. Ewing, R.; Schmid, T.; Killingsworth, R.; Zlot, A.; Raudenbush, S. Relationship Between Urban Sprawl and Physical Activity, Obesity, and Morbidity. American Journal of Health Promotion **2003**, 18, pp. 47-57, https://doi.org/10.4278/0890-1171-18.1.47
10. Lee, A.C.K.; Maheswaran, R. The health benefits of urban green spaces: a review of the evidence. *Journal of Public Health* **2011**, 33, pp. 212-222. https://doi.org/10.1093/pubmed/fdq068.
11. Brueckner, J.K.; Largey, A.G. Social interaction and urban sprawl. *Journal of Urban Economics* **2008**, 64, pp. 18-34, https://doi.org/10.1016/j.jue.2007.08.002.
12. Cervero, R.; Murakami, J. Effects of Built Environments on Vehicle Miles Traveled: Evidence from 370 US Urbanised Areas. Environment and Planning A **2010**, 42, pp. 400-418, https://doi.org/10.1068/a4236.
13. Travisi, C.M.; Camagni R.; Nijkamp, P. Impacts of urban sprawl and commuting: a modelling study for Italy. *Journal of Transport Geography* **2010**, 18, pp. 382–392. https://doi.org/10.1016/j.jtrangeo.2009.08.008.
14. Keller, R.; Vance, C. Landscape pattern and car use: Linking household data with satellite imagery. *Journal of Transport Geography* **2013**, 33, pp. 250-257, https://doi.org/10.1016/j.jtrangeo.2013.07.006.
15. Niemeier, D.; Bai, S.; Handy, S.L. The impact of residential growth patterns on vehicle travel and pollutant emissions. *Journal of Transport and Land Use* **2011**, 4, pp. 65-80, http://dx.doi.org/10.5198/jtlu.v4i3.226.
16. Kim, J.; Brownstone, D. The impact of residential density on vehicle usage and fuel consumption: Evidence from national samples. *Energy Economics* **2013**, 40, pp. 196-206, https://doi.org/10.1016/j.eneco.2013.06.012.
17. Ewing, R.; Rong, F. The impact of urban form on U.S. residential energy use. *Housing Policy Debate* **2008**, 19, pp. 1-30, http://dx.doi.org/10.1080/10511482.2008.9521624.
18. Glaeser, E.L; Kahn, M.E. The greenness of cities: Carbon dioxide emissions and urban development. *Journal of Urban Economics* **2010**, 67, pp. 404-418, https://doi.org/10.1016/j.jue.2009.11.006.
19. Jones, C.; Kammen, D.M. Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanisation Undermines Greenhouse Gas Benefits of Urban Population Density. *Environmental Science & Technology* **2014**, 48, pp. 895-902, https://dx.doi.org/10.1021/es4034364.
20. Grazi, F., van den Bergh, J.C.J.M; van Ommeren, J.N. An Empirical Analysis of Urban Form, Transport, and Global Warming. *The Energy Journal* **2008**, 29, pp. 97-122, https://www.jstor.org/stable/41323183.
21. Minx, J.; Baiocchi, G.; Wiedmann, T.; Barrett, J.; Creutzig, F.; Feng, K.; Förster, M.; Pichler, P.P.; Weisz, H.; Hubacek, K. Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters* **2013**, 8, pp. 1-10, https://doi.org/10.1088/1748-9326/8/3/035039.
22. Burchfield, M.; Overman, H.G.; Puga, D.; Turner, M.A. Causes of Sprawl: A Portrait from Space. *The Quarterly Journal of Economics* **2006**, 121, pp. 587-633, https://doi.org/10.1162/qjec.2006.121.2.587.
23. Feranec, J.; Jaffrain, G.; Soukup, T.; Hazeud, G. Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. *Applied Geography* **2010**, 30, pp. 19-35, https://doi.org/10.1016/j.apgeog.2009.07.003.

Salai-i-Martin, X.X. Regional cohesion: evidence and theories of regional growth and convergence. European Economic Review **1996**, 40, pp. 1325-1352, https://doi.org/10.1016/0014-2921(95)00029-1.