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URBAN EXPANSION

RESEARCH

Complexifying urban expansion: an exploratory, gradient-based approach

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ABSTRACT

Opportunities for innovation in urban expansion research abound given the emergence of longitudinal and spatially explicit data. Scholars now use a broad array of data when analyzing expansion, yet the conceptual approach remains limited. Toward this end, this work extends conceptualization of expansion beyond the relatively simple economic approach that emphasizes population growth and income. Instead, insights from social–ecological theory—focusing on the heterogeneous, nonlinear, and hierarchical nature of cities—provide a pathway for specifying urban expansion gradients. The paper demonstrates how a spatial gradient model that considers urban, periphery, and exurban subregions complexifies the urban regional phenomenon, yielding crucial insights into the processes that drive expansion. Exploratory quantitative analysis of the National Land Cover Database (NLCD) provides a prototype implementation, testing the utility of the gradient-based approach for all urban regions in the contiguous United States. Modeling covers both the full study period, 2001–16, and as separate 2001–11 and 2011–16 panels, assessing how relationships change over time. Results show that social–demographics, land use and transportation, regional economics, and physical drivers exhibit diverse impacts across the expansion gradient and over time. This work concludes with a call for scholars to deepen the approach presented here before conducting predictive or confirmatory modeling.

POLICY RELEVANCE

Urban expansion takes many forms and understanding those different forms can benefit decision-makers. Rather than a policy framework that treats urban growth as a regional phenomenon, a gradient-based approach is necessary, one that targets how expansion processes operate differently in urban, peripheral, and exurban subregions. By disaggregating the region, this research provides new insights into expansion dynamics

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such as how higher incomes and GDP growth tie to infill development; concentration of immigrants coincides with reduced land consumption across the gradient; age-based locational preferences yield compact growth; regions with greater natural resource economies and warmer temperatures have more exurban expansion; and steep slopes and open water constrict peripheral expansion. This kind of information allows for different institutions—from regional planning authorities to urban municipal governments to small town mayors—to address the drivers of expansion through more targeted and differentiated policy mechanisms, while also having more information to consider unintended consequences.

1. INTRODUCTION

The study of urban expansion in the United States (US) has seen remarkable progress since the first systematic survey of rural and urban land in 1958. Early research involved land surveys with independent, unique data collection procedures; however, there were often substantive methodological difference between studies, compromising longitudinal analysis of urban land area (Fischel 1982; Alig & Healy 1987). The emergence of the National Resource Inventory (NRI) in 1982, and its subsequent reproduction every five years, began a new phase of true *expansion* research. Data interoperability empowered comparison of urban area *over time* and the measurement of expansion, not just urban area. Several studies came to analyze the NRI (Fulton *et al.* 2001; Alig *et al.* 2004; Wear 2011; Lawler *et al.* 2014). Yet, later attempts to forecast expansion using the first 15 years of NRI data grossly overpredicted actual expansion, which experienced a marked decline after 1997. By 2015, the annual rate of expansion dropped nearly 80% from the peak in 1997 (Richter 2020).

Despite progress in data collection and analytical tools, the models used to make these predictions remained limited by their conceptualization of urban expansion as a predictable economic phenomenon. Instead, urban regions are complex, social–ecological systems (Alberti *et al.* 2003; McPhearson *et al.* 2022) with diverse and heterogeneous components, nonlinear interactions, and hierarchal organization (Wu & David 2002). Crucial to the urban ecological research is the tendency for patterns and processes, such as urban expansion, to operate across an urban-to-rural gradient (McDonnell & Pickett 1990; Haase & Nuissl 2010).

The emergence of the spatially explicit, medium resolution (30 m) National Land Cover Database (NLCD) (Vogelmann *et al.* 2001), and its subsequent reproduction every few years, provides urban expansion researchers an even greater opportunity than does the NRI; the latest iteration includes data for the period 2001–16 (Homer *et al.* 2020). Scholars have begun to leverage this new capability into another round of longitudinal expansion studies (*e.g.* Richter 2020; Vogler & Vukomanovic 2021), but these remain limited. There is a gap between complex, urban ecological conceptualization and existing empirical research on expansion. In particular, large-scale studies in the US have not embraced the concept of the urban-to-rural gradient.

This paper begins to fill this gap through an exploratory gradient-based model of expansion. After first developing this model, quantitative analysis of NLCD data provides an initial prototype, testing the implementation of gradient-based expansion for all urban regions in the contiguous US. In doing so, this work leverages the data-rich landscape in the US to progress conceptualization and operationalization of urban expansion and is applicable to rapidly urbanizing regions the world over.

1.1 CONCEPTUALIZING EXPANSION: FOUNDATIONS AND OPPORTUNITIES

The theoretical basis for urban expansion comes from economics, which posits that:

> urban land cover will increase with population and income, as well as with a reduction in transport costs.
>
> (Angel *et al.* 2011: 57)

Scholars have elaborated on this foundation in a variety of ways. It is common to recognize the agricultural economy, whether in the form of product values (Alig *et al.* 2004), arable land per capita (Angel *et al.* 2011), and soil type (Lawler *et al.* 2014). Studies apply a variety of social–demographic variables beyond population growth and income, such as household size (Alig *et al.* 2004) and immigrant population (Fulton *et al.* 2001). Geographic differentiation is another theme. Alig *et al.* (2004) use a simple dummy variable, while Saiz's (2010) study of urban growth and housing prices implements regional physiography—the presence of open water, wetlands, and steep slopes—into a measure of land scarcity.

Despite the use of social and ecological variables, the expansion literature has not fully embraced an integrated social–ecological conceptual approach. One hurdle has been the traditional focus in US studies on agriculture and natural resources (Fischel 1982; Alig & Healy 1987; Alig *et al.* 2004; Wear 2011; Lawler *et al.* 2014). Urban expansion is clearly an important threat to productive ecosystems and ecosystem services, but the emphasis on nonurban outcomes does little to deepen understanding of the largely urban drivers and processes of expansion.

Instead, it is necessary to examine urban land change as a process of urbanization that simultaneously involves many 'teleconnected' places (Seto *et al.* 2012; Güneralp *et al.* 2013). This is not to suggest there is a dearth of literature on urban systems in the US. There is an expansive body of literature, but integration of many important research areas with the myriad processes driving expansion remains nascent. Important opportunities include research on land use and transportation (LUT), an evolving social landscape (demographics, inequality, *etc.*), and structural shifts in urban and rural economies.

There is abundant research on 'urban form' or 'sprawl' with high relevance to expansion. These studies often emphasize the integrated nature of LUT (*e.g.* Galster *et al.* 2001; Ewing & Hamidi 2016), but the focus on the entire urban landscape, not just recent change, obfuscated the rapid decline of expansion in the US (Richter 2021). Thus, it is unclear how multimodal transport systems or increasing housing density contribute to expansion. That a region with a robust transit system and considerable urban density—Chicago, IL—remains highly consumptive of land suggests the processes linking LUT and expansion are indeed complex.

The housing sector provides two clear examples of how expansion processes operate through teleconnections across the urban-to-rural gradient. Saiz (2010) demonstrates how the presence of steep slopes and open water *outside* an urban region led to supply inelasticity, affecting housing prices *within*. Such interactions can be rural to urban, or vice versa. For example, increasing unaffordability in the urban core, sometimes stimulated by development eschewing sustainable values such as transit-oriented development, often displaces lower income residents to the land-intensive development along the suburban fringe (Kneebone & Garr 2010: 24; Oden 2016).

Complementing LUT are important social–demographic trends. As described above, rising inequality can stimulate expansion far from the urban core where land is cheapest. And the rapid growth of young adult and older households without children (*i.e.* millennials and baby boomers, respectively), coupled with shifting locational preferences, has stimulated demand for compact forms of development in the core (Nelson 2013; Myers 2016). Whether such trends operate at sufficient scale to affect expansion rates through increased infill and densification is an important empirical question.

Another important consideration for contemporary expansion research is the transformation of work due to technology. From 2000 to 2014, 2.4 million people began working from home (Kane & Tomer 2015). And similar improvements in communications technologies stimulated the rapid expansion of e-commerce and the requisite warehousing. In both cases, the impact on land use and expansion remains unstudied.

Of course, regional economics need not be technology driven to affect expansion. Some sectors of the economy, especially manufacturing, are space intensive, even with limited overall employment (Nelson 2013). Recreational economies in amenity-rich rural areas, particularly in warmer regions, stimulate economic growth (and expansion) (Irwin *et al.* 2009). And the Great Recession that began in 2008 affected economies throughout the US (Martin 2011).

The traditional economic approach to expansion is both quintessential and limited. It does little to explain the 60% reduction in the US from 2001 to 2016, or the vast regional disparities in expansion (Richter 2020). A renewed focus on the processes of expansion necessitates further data integration targeting a diversity of phenomena, such as those described above. However, innovation requires more than augmenting existing methods with new variables. Instead, a richer operationalization is necessary to comprehend how interacting phenomena affect expansion across the urban-to-rural gradient.

1.2 TOWARD A GRADIENT-BASED APPROACH

The phrase 'urban expansion' can be misleading in its oversimplification of development patterns. It suggests that outward growth along the urban fringe is the primary measure; however, studies that leverage the NRI and NLCD include much more. They often leverage units of analysis that extend well beyond the urbanized area (*e.g.* Fulton *et al.* 2001; Richter 2020). This means that development far beyond the urban fringe counts, as does infill closer to central areas or development in and around smaller satellite settlements (towns, villages, *etc.*). How much development is in which part of the region varies across the US and by method of delineation; however, the proportion of 'expansion' located within or beyond the periphery is often significant.

The regional strategy is driven in part by practicality. There are considerably more data available at larger geographies (counties and metropolitan regions) than at the urbanized region (called 'urban areas' (UA) by the US Census). But regionalization also aligns with the evolution of urban systems over the last century. Early in the 20th century, discrete urban settlements grew rapidly, joining together to form 'conurbations' (Geddes 1915). As communication and transport technology improved, urban systems extended outward, initiating a transition to what urban historian Martin Melosi calls the 'Metropolitan Era' (Melosi 1990). New forms of transport induced different patterns of growth, with post-war development occurring more continuously across space, loosely guided by interstate highways (Muller 2017) or sometimes in amenity-rich rural areas that had been difficult to access (Irwin *et al.* 2009). Limiting analysis too close to the urbanized core could omit the extended impact of urbanization and discount teleconnections and interdependence between urban and rural areas (Irwin *et al.* 2009).

Given contemporary data and analytics and integrative theory, the metropolitan region has become an effective scale for transdisciplinary research and practice (Bixler *et al.* 2019) and is therefore central to expansion research. Thus, the aforementioned studies did not err in applying the coarser, regional unit of analysis; however, there remains considerable opportunity in transitioning from a simple, regional approach to one capable of capturing more complex processes.

To begin that process, this study proposes a spatial conceptual model that identifies three discrete sub-geographies: urban, periphery, and exurban (Figure 1). This approach describes an urban

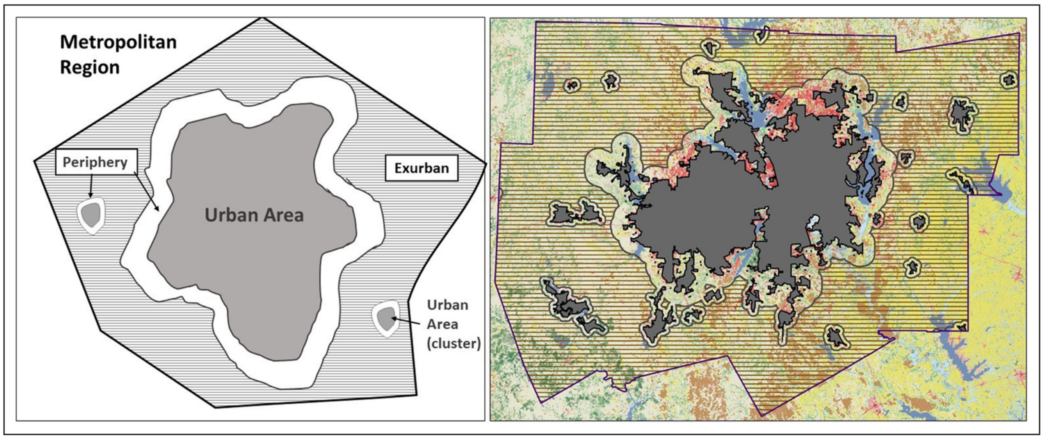

Figure 1: Gradient-based measurement concept (left) and geographic information system (GIS) implementation for the Dallas–Ft Worth–Arlington metropolitan statistical area (MSA) (right) with 2016 National Land Cover Database (NLCD) in the background.

ecological gradient within the larger metropolitan region, albeit relatively simple and discrete. The model transects the pre-existing, centralized developed area, sometimes called an 'urban footprint' (*e.g.* Angel *et al.* 2021b), into areas beyond. Moreover, it distinguishes the region close to the urban footprint (periphery) from that more distant (exurban). This is especially important given the latter has seen rapid population growth since 2000 (Berube *et al.* 2006), and development occurring closer to the urban fringe exhibits significantly different characteristics than that further beyond (Clark *et al.* 2009). This spatial conceptual approach therefore distinguishes three key geographies within the broader metropolitan region and provides the foundation for the subsequent analysis.

2. DATA AND METHODS

2.1 SPATIAL DEFINITIONS

The first step toward implementation of the spatial conceptual model is defining the urban, periphery, and exurban geographies. When designing urban land research, it is essential to align measurement with the desired outcomes (Richter 2021). In this study, the primary goal is the differentiation of metropolitan expansion into subregional geographies to examine how expansion processes differ across an urban-to-rural gradient. The metropolitan region is defined using the 2017 US Census metropolitan statistical area (MSA) delineation and is constituted of groups of counties with shared economic trends and commuting patterns.

The definition of urban aligns with that of the 'urban footprint' concept via the 2000 US census UA geographies. The intention is to identify a perimeter that encompasses the pre-existing urban landscape. UAs are conurbation, not individual political districts (*e.g.* municipalities), and they include smaller satellite settlements called an 'urban cluster.' The intention of the periphery is to capture recent growth outward from the urban. An ideal implementation would be precise, applying similar rules to that of the urban but at the end of the study (*e.g.* Angel 2018). There is no 2016 UA, and the 2010 version applies different rules than those used to delineate the urban (Ratcliffe 2015). Considering this limitation, the periphery extends as a 3-mile buffer beyond UAs, though only 1 mile beyond slower growing clusters. The buffer lengths were selected using visual inspection of fast-growing areas and are intentionally inclusive. Any area within the metropolitan region (*i.e.* MSAs), but beyond the urban or periphery, is defined as exurban. This differs from other definitions of exurban, which sometimes extend beyond a given metropolitan region using commuting data at the census tract scale (Berube *et al.* 2006), and are immediately adjacent to the urban (Clark *et al.* 2009), or are diffuse and dependent on residential density (Irwin *et al.* 2009).

There is a variety of alternative implementations than those described above, *e.g.* through the use of US Census tracts. However, tracts contain roughly the same number of residents despite vast differences in population density, leading to the modifying areal unit problem (MAUP) (Wong 2009). Of particular concern is the tendency for tracts to become large along the periphery, often crossing from urban to periphery to exurban, as implemented in this study. The application of tracts, though potentially increasing the explanatory power of statistical analysis, could decrease the conceptual clarity of expansion. This work prioritizes the latter.

Applying the spatial model to understand expansion trends immediately demonstrates its value (Table 1). Annual rates of expansion in metropolitan regions drop 54% by the 2011–16 interval. The periphery experiences a similar decline (51%), but the reduction in urban is even greater (75%). The exurbs, which contain contain 15% of all 2001–16 expansion, show little variability.

	2001–16	2001–11	2011–16	2001–11 AND 2011–16 CHANGE (%)
Urban	135	180	45	–75%
Periphery	189	227	112	–51%
Exurban	55	54	55	1%
Metropolitan	378	462	212	–54%

Table 1: National rate of expansion in acres (thousands) per year by sub-geography.

2.2 EXPLORATORY HYPOTHESIS, DATA VARIABLES, AND MODEL SELECTION

Complex interactions between social and ecological systems (Alberti *et al.* 2003; McPhearson *et al.* 2022), both within and across regions via teleconnections (Seto *et al.* 2012; Güneralp *et al.* 2013), make hypothesizing about individual variables challenging. For example, dense central development is widely considered necessary to reduce expansion; however, the concurrent displacement of low-income residents to land-intensive peripheral or exurban developments (Kneebone & Garr 2010: 24; Oden 2016) demonstrates how urban–rural interdependence (Irwin *et al.* 2009) complicates the processes of expansion. Therefore, expansion researchers need a system of measurement sensitive to such dynamics.

The demand to capture such complexity, combined with the failure of past attempts at confirmatory modeling (Richter 2020), highlights the need for an exploratory approach. Toward this end, the central hypothesis presented here is that variable significance and coefficients will differ across space and over time. Some variables might be significant only in certain portions of a metropolitan region. Others may be significant across the expansion gradient but signify different relationships, in terms of either magnitude or direction. More than the identification of causal theory, this study provides useful guidance about the processes of expansions and the means of understanding them.

The gradient implementation described in section 2.1 is intentionally simple. It yields four dependent variables—at the metropolitan region and the three sub-geographies—achieving a balance between parsimony and spatial analytical refinement. Complementing the different outcome variables is a wide variety of explanatory data (see Table 2 for a summary of all model variables). The review of theoretical expansion drivers in section 1.1 guided the selection of independent variables across four categories: socio-demographics, land use and transportation, regional economics, and physical drivers and constraints. Variables either represent the conditions at the beginning of the study period or factors that change over time. Though NLCD data begin in 2001, data pulled from the US Census begin in 2000 as they do not exist for 2001. For this reason, calculations of percent change are annualized.

Three models test how the relationship between explanatory and dependent variables changes across space and over time. The first applies ordinary least squares (OLS) regression for the full study period (2001–16). The second and third models are longitudinal, attempting to measure how relationships change across time. Though there are four NLCD periods with three intervals of change (2001–06, 2006–11, and 2011–16), the dearth of data for 2006 limits the study to two panels: 2001–11 and 2011–16. The second model adds a dummy variable representing the year, enabling a pooled OLS regression. The third model leverages fixed-effect panel regression to formally test the relationships over time. Data that remain consistent throughout the study period are omitted from panel data to maintain the focus on change over time. For all models, a mean variable inflation factor (VIF) of 2.71 ensures that variables are not collinear, while robust cluster standard errors counteract heteroscedasticity among the explanatory variables.

Each of the three model types uses all four dependent variables, leading to 12 models in total. The goal of this analysis is to understand the relationships between a diverse array of explanatory variables, and urban expansion within the 2001–16 period. The models shown in section 3 are prototypes. They exist to test the usefulness of the spatial conceptual model, not to make predictions about future expansion. Section 4 discusses the success of this effort and gives implications for future research.

3. RESULTS

To facilitate analysis, the type of statistical model organizes the 12 models into three model groupings (OLS, pooled OLS, and panel regression). This allows for easier comparison between the metropolitan region and each subregion. All 12 models highlight significant variables, including several with $p < 0.001$. Tables 3–5 show F, R^2, and Rho (model 3 only) statistics for each individual model, along with normalized variable coefficients and standard errors.[1]

Table 2: Model data with descriptive information and statistics for 2001–16.

Notes: [a] A few regions have no urban, periphery, or exurban portions.

[b] The saturation metric is inspired by a similar metric in Angel (2018). But in this instance, it represents the developed proportion of unconstrained land, not the total extent of urban footprint.

[c] The same logic as used by Saiz (2010) determines constrained land: a combination of land with a slope ≥ 15%, wetlands, and open water. LANDFIRE 2020 data locate slope, while the National Land Cover Database (NLCD) identifies open water and wetlands. GDP = gross domestic product.

Sources: 1 = NLCD; 2 = 2000 US Census; 3 = American Community Survey (ACS) 2009–13; 4 = ACS 2013–18; 5 = US Bureau of Economic Analysis (BEA); 6 = National Oceanic and Atmospheric Administration (NOAA); and 7 = LANDFIRE 2020.

	VARIABLE	DESCRIPTION	UNIT	SOURCE	OBSERVATIONS	MEAN	SD	MINIMUM	MAXIMUM
Dependent variables	*M_EXPAN_01to16*	Metropolitan expansion	Acres	1	379	14,984	27,708	307	245,918
	U_EXPAN_01to16	Expansion within the urban area	Acres	1	378[a]	5,347	10,371	97	98,588
	P_EXPAN_01to16	Expansion within the periphery	Acres	1	378[a]	7,496	14,376	103	142,277
	E_EXPAN_01to16	Expansion within the exurbs	Acres	1	375[a]	2,184	4,460	0.2	47,379
Socio-demographics	*POP_00*	Initial population	Residents	2–4	379	621,000	1,479,000	52,000	18,900,000
	MEDINC_00	Initial median income	2018 US$	2–4	379	US$59,955	US$10,075	US$37,589	US$111,602
	FORBORN_00_SHARE	Initial share of the foreign-born population	%	2–4	379	6.3%	6.3%	0.8%	35.0%
	POPGRO_00to16	Population growth, 2000–16	Residents	2–4	379	105,000	3,000	–135,000	2,086,000
	POP_18to34_00to16_PER	Change in 18–34-year-olds	%/year	2–4	379	0.91%	0.97%	–1.16%	5.07%
	POP_35to54_00to16_PER	Change in 35–54-year-olds	%/year	2–4	379	–0.01%	1.03%	–1.86%	4.87%
	POP_55+_00to16_PER	Change in ≥55-year-olds	%/year	2–4	379	3.58%	1.62%	0.72%	16.76%
	HHSIZE_00to16_per	Change in household size	%/year	2–4	379	0.02%	0.23%	–0.63%	1.01%
Land use and transport	*VACANT_00to16_per*	Vacant housing units	%/year	2–4	379	0.19%	0.14%	–0.40%	0.82%
	SFDETACH_00to16_per	Single-family detached housing units	%/year	2–4	379	0.11%	0.16%	–0.23%	1.43%
	HIGHDEN_00to16_per	Housing units in structure with 20+ units	%/year	2–4	379	0.02%	0.09%	–0.34%	0.39%
	DRIVE_00to16_per	Workers who commute by driving	%/year	2–4	379	–0.10%	0.11%	–0.81%	0.15%
	HOMEWORK_00to16_per	Workers who work from home	%/year	2–4	379	0.08%	0.07%	–0.07%	0.51%
	LONGCOM_00to16_per	Workers with commutes over 60 min	%/year	2–4	379	0.02%	0.07%	–0.35%	0.31%
Regional economics	*GDP_01to16_PER*	Growth in GDP	%/year	5	379	0.05	0.02	0.01	0.18
	NATRES_01_PERCAP	Growth in natural resources GDP	2018 US$	5	379	0.73	1.52	–	13.41
	MANUF_01_PERCAP	Growth in manufacturing GDP	2018 US$	5	379	5.26	3.71	–	23.44
	TRANWARE_01_PERCAP	Growth in transport/warehouse GDP	2018 US$	5	379	0.69	0.56	–	3.73
Physical drivers and constraints	*AVGWINTEMP*	Average January temperature	°F	6	379	34.19	12.49	2.75	65.20
	PRECIP	Average annual precipitation	Inches	6	379	38.26	13.97	3.38	76.66
	U_SAT_01	Urban development saturation[b]	%	1	379	67.6%	10.6%	32.5%	95.6%
	P_SAT_01	Periphery development saturation[b]	%	1	379	15.2%	7.1%	6.2%	66.4%
	U_CONSTR	Urban with development constraints[c]	%	1, 7	379	11.7%	9.0%	0.1%	57.7%
	P_CONSTR	Periphery with development constraints[c]	%	1, 7	379	28.8%	20.9%	0.5%	88.5%
	E_CONSTR	Exurban with development constraints[c]	%	1, 7	379	35.4%	24.8%	0.4%	99.3%

VARIABLES	METROPOLITAN		URBAN		PERIPHERY		EXURBAN	
	COEFFICIENT	SE	COEFFICIENT	SE	COEFFICIENT	SE	COEFFICIENT	SE
POP_00	0.31	0.24	0.26**	0.09	0.08	0.15	–0.04	0.02
MEDINC_00	0.25**	0.09	0.09**	0.03	0.12*	0.05	0.03	0.02
FORBORN_00_SHARE	–0.34***	0.09	–0.10**	0.03	–0.17***	0.05	–0.08**	0.03
POPGRO_00to16	1.76***	0.20	0.54***	0.09	0.92***	0.12	0.30***	0.06
POP_18to34_00to16_PER	0.07	0.07	0.05	0.03	0.03	0.04	0.00	0.02
POP_35to54_00to16_PER	0.16	0.09	0.06	0.03	0.09	0.05	0.01	0.02
POP_55_00to16_PER	–0.11	0.08	–0.08*	0.03	–0.02	0.04	0.00	0.02
HHSIZE_00to16_PER	–0.19**	0.07	–0.08**	0.02	–0.10**	0.04	–0.02	0.02
VACANT_00to16_PER	0.17**	0.06	0.05*	0.02	0.10**	0.03	0.03	0.01
SFDETACH_00to16_PER	0.09*	0.04	0.03	0.02	0.04	0.02	0.01	0.01
HIGHDEN_00to16_PER	–0.14*	0.06	–0.04	0.03	–0.09*	0.04	–0.02	0.01
DRIVE_00to16_PER	0.20**	0.08	0.03	0.03	0.11**	0.04	0.06***	0.02
HOMEWORK_00to16_PER	0.19**	0.07	0.05*	0.02	0.11**	0.04	0.03*	0.01
LONGCOM_00to16_PER	–0.12**	0.04	–0.02	0.02	–0.08**	0.02	–0.02*	0.01
GDP_01to16_PER	0.00	0.05	–0.03	0.02	0.00	0.02	0.03	0.02
NATRES_01_PERCAP	0.15**	0.06	0.03	0.02	0.05*	0.03	0.06**	0.02
MANUF_01_PERCAP	0.01	0.05	–0.01	0.02	0.02	0.03	0.00	0.01
TRANWARE_01_PERCAP	0.15***	0.05	0.04**	0.01	0.10***	0.03	0.01	0.01
AVGWINTEMP	–0.01	0.08	–0.02	0.03	–0.03	0.05	0.04*	0.02
PRECIP	0.05	0.08	0.04	0.03	0.03	0.05	–0.02	0.02
U_SAT_01	–0.03	0.06	–0.07**	0.03	0.04	0.03	0.01	0.01
P_SAT_01	0.01	0.05	0.00	0.02	0.02	0.02	–0.02	0.01
U_CONSTR	0.09	0.07	0.01	0.03	0.06	0.04	0.02	0.02
P_CONSTR	–0.22*	0.11	–0.05	0.05	–0.16*	0.06	–0.02	0.02
E_CONSTR	–0.01	0.07	0.00	0.03	0.01	0.04	–0.02	0.02
_cons	–1.00	0.54	0.10	0.22	–0.87**	0.29	–0.24	0.13
	$F(25, 377) = 29.30$		$F(25, 373) = 24.92$		$F(25, 376) = 27.71$		$F(25, 370) = 8.50$	
R^2	0.854		0.8283		0.8335		0.6943	

Table 3: Model 1 results.

Note: Results are ordinary least squares (OLS) (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$); all coefficients and standard errors (SE) are normalized (see also note 1).

The first model group has the OLS regressions of 2001–16 data. The initial population (*POP_00*) is only significant ($p < 0.01$) for urban. Higher incomes coincide with more expansion in urban ($p < 0.01$) and periphery ($p < 0.05$), with a stronger relationship (higher coefficient) in the latter (0.09–0.12). The proportion of immigrants (*FORBORN_00_SHARE*) was highly significant and inversely related to expansions at all scales (metropolitan and periphery $p < 0.001$; urban and exurban $p < 0.01$), again, the strongest effect falling in the periphery (–0.17 versus –0.10 urban and –0.08 exurban). Population growth is also highly significant across all geographies (all $p < 0.001$), with a positive relationship that is also strongest in the periphery (0.92 versus 0.54 urban and 0.30 exurban). It is important to note the magnitude of normalized coefficients for *POPGRO_00to16* far exceeds all other variables. The various age cohorts are of limited significance, with only urban growth in 55 and over (*POP_55_00to16_PER*) exceeding the 0.05 threshold, and with negative coefficient (–0.08). Growth in household size is significant ($p < 0.01$) for all but exurban, all with a negative relationship. All LUT variables are significant at metropolitan (either $p < 0.05$ or < 0.01),

VARIABLES	**METROPOLITAN**		**URBAN**		**PERIPHERY**		**EXURBAN**	
	COEFFICIENT	**SE**	**COEFFICIENT**	**SE**	**COEFFICIENT**	**SE**	**COEFFICIENT**	**SE**
_IYear_2011	–0.78*	0.31	–0.53***	0.13	–0.24	0.14	–0.01	0.08
POP	0.27	0.54	0.37	0.29	–0.02	0.30	–0.08	0.08
MEDINC	0.44*	0.18	0.24**	0.08	0.22*	0.10	–0.02	0.03
FORBORN_SHARE	–1.00***	0.19	–0.33***	0.09	–0.51***	0.09	–0.16***	0.04
POPGRO	6.23***	0.67	2.24***	0.33	3.17***	0.31	0.81***	0.17
POP_18to34_PER	–0.24	0.16	–0.10	0.08	–0.10	0.07	–0.04	0.04
POP_35to54_PER	0.30	0.18	0.12	0.08	0.18	0.10	0.00	0.05
POP_55_PER	–0.17	0.17	–0.27***	0.08	0.01	0.09	0.10*	0.05
HHSIZE_PER	–0.30*	0.14	–0.15**	0.06	–0.19**	0.06	0.04	0.04
VACANT_PER	0.47**	0.15	0.18**	0.06	0.27***	0.07	0.03	0.04
SFDETACH_PER	0.16	0.10	0.06	0.04	0.08	0.05	0.01	0.03
HIGHDEN_PER	–0.34*	0.14	–0.10	0.06	–0.20**	0.07	–0.04	0.04
DRIVE_PER	0.45***	0.12	0.10	0.05	0.26***	0.07	0.09***	0.03
HOMEWORK_PER	0.33***	0.10	0.10*	0.04	0.18***	0.05	0.05*	0.02
LONGCOM_PER	–0.35**	0.13	–0.17**	0.06	–0.16*	0.07	–0.01	0.02
GDP_PER	–0.04	0.11	–0.05	0.04	–0.02	0.06	0.03	0.03
NATRES_PERCAP	0.37***	0.10	0.05	0.04	0.09*	0.04	0.24***	0.04
MANUF_PERCAP	–0.02	0.08	–0.04	0.04	0.03	0.04	–0.01	0.02
TRANWARE_PERCAP	0.21	0.12	0.01	0.05	0.16*	0.07	0.03	0.03
U_SAT	–0.13	0.16	–0.21*	0.08	0.07	0.08	0.01	0.03
P_SAT	–0.10	0.12	–0.03	0.06	–0.06	0.07	–0.02	0.03
_cons	0.91	1.16	1.51**	0.56	–0.73	0.57	0.09	0.25
	$F(21, 749) = 39.72$		$F(21, 720) = 29.22$		$F(21, 738) = 39.78$		$F(21, 689) = 12.73$	
R^2	0.7945		0.7407		0.7823		0.5710	

Table 4: Model 2 results.

Note: Results are ordinary least squares (OLS) (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$); all coefficients and standard errors (SE) are normalized (see also note 1).

with increases in high density (*HIGHDEN_00to16_per*) and longer commutes (*LONGCOM_00to16_per*) being the only two with a negative coefficient. Only growth in vacancy (*VACANT_00to16_per*) and homework (*HOMEWORK_00to16_per*) were significant for urban (both $p < 0.05$), and both positive, relatively small coefficients. All LUT variables but growth in single-family homes (*SFDETACH_00to16_per*) are significant for periphery (either $p < 0.05$ or < 0.01), with the same directionality as the metropolitan model. Increases in commuting by driving (*DRIVE_00to16_per*) are highly significant ($p < 0.001$) in the exurbs and positive, but growth in long commutes ($p < 0.05$) inversely relates to exurban expansion. Natural resource gross domestic product (GDP) per capita is significant and positive for metropolitan ($p < 0.01$), periphery ($p < 0.05$), and exurban ($p < 0.01$), with greater coefficient magnitude in the exurbs than periphery (0.06 versus 0.05). Transport and warehouse GDP per capita is especially significant in the periphery ($p < 0.001$; 0.10) with a higher coefficient than in urban ($p < 0.01$; 0.04). Average winter temperature is only significant in the exurbs ($p < 0.05$) and positively correlated with a relatively small coefficient (0.04). Finally, greater urban saturation is negatively associated in the urban model ($p < 0.01$; –0.07), while peripheral development constraints are negatively, and somewhat strongly, related to periphery expansion ($p < 0.05$; –0.16).

The second model, a pooled OLS regression, applies a dummy variable (*_IYear_2011*) to represent the year within two panels of data. It is highly significant for urban ($p < 0.001$) and significant in

VARIABLES	METROPOLITAN		URBAN		PERIPHERY		EXURBAN	
	COEFFICIENT	SE	COEFFICIENT	SE	COEFFICIENT	SE	COEFFICIENT	SE
POP	–0.81	8.26	–0.94	3.58	1.12	4.16	–1.00	1.54
MEDINC	0.42***	0.12	0.12*	0.06	0.24***	0.06	0.06**	0.02
FORBORN_SHARE	0.23	0.26	–0.05	0.10	0.22	0.13	0.08	0.09
POPGRO	2.08	1.46	0.88	0.63	1.20	0.70	0.00	0.26
POP_18to34_PER	–0.32***	0.08	–0.15***	0.04	–0.13**	0.04	–0.04**	0.01
POP_35to54_PER	–0.21*	0.10	–0.06	0.04	–0.10	0.05	–0.05*	0.02
POP_55_PER	–0.23**	0.09	–0.12**	0.05	–0.10*	0.04	–0.01	0.02
HHSIZE_PER	0.04	0.04	0.02	0.02	0.00	0.02	0.01	0.01
VACANT_PER	–0.01	0.04	–0.01	0.02	0.00	0.02	0.00	0.01
SFDETACH_PER	–0.03	0.03	–0.01	0.01	–0.02	0.01	–0.01	0.01
HIGHDEN_PER	0.01	0.03	0.01	0.02	–0.01	0.02	0.00	0.01
DRIVE_PER	0.05	0.03	0.01	0.01	0.04*	0.02	0.00	0.01
HOMEWORK_PER	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.01
LONGCOM_PER	–0.03	0.04	–0.02	0.02	–0.01	0.02	0.00	0.01
GDP_PER	0.08*	0.04	0.03*	0.02	0.03	0.02	0.02	0.01
NATRES_PERCAP	0.03	0.05	0.01	0.02	0.00	0.02	0.01	0.02
MANUF_PERCAP	0.03	0.06	0.02	0.02	–0.01	0.03	0.02	0.01
TRANWARE_PERCAP	–0.05	0.07	–0.04	0.03	–0.02	0.03	0.00	0.01
U_SAT	–0.96**	0.31	–0.66***	0.16	–0.17	0.13	–0.13*	0.06
P_SAT	–0.76*	0.37	0.01	0.16	–0.64***	0.19	–0.12	0.07
_cons	6.22	4.81	4.35	2.22	0.71	2.29	1.21	0.85
	$F(20,378) = 38.43$		$F(20,377) = 39.03$		$F(20,377) = 31.92$		$F(20,378) = 5.77$	
Rho	0.85374996		0.92344281		0.95368965		0.98109961	
R^2	0.802, 0.208, 0.336		0.791, 0.012, 0.026		0.802, 0.494, 0.460		0.367, 0.141, 0.093	
	(Within, between, overall)		(Within, between, overall)		(Within, between, overall)		(Within, between, overall)	

Table 5: Model 3 results.

Note: Results are ordinary least squares (OLS) (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$); all coefficients and standard errors (SE) are normalized (see also note 1).

metropolitan ($p < 0.05$). It is nearly significant for periphery ($p = 0.089$) but not at all in exurban ($p = 0.892$). Initial population is no longer significant, while income, immigrant share, and population growth show nearly the same patterns as in model 1. Growth in age 55 and over increases significantly (to $p < 0.001$) and continues to have a negative effect in urban (–0.27); however, it is now significant ($p < 0.05$) in exurban but with a positive coefficient (0.10). Growth in household size and vacancy continue significantly in urban and periphery (at either $p < 0.01$ or < 0.001), with negative and positive coefficients, respectively. Increases in high-density housing units now have greater significance in the periphery ($p < 0.01$) and remain inversely related. Increases in driving are positive and highly significant ($p < 0.001$) in the periphery and exurbs, but stronger in the former (0.26 versus 0.09). Growth in working from home and long commuting are like model 1, except long commuting is no longer significant for exurban. Regional economic variables are also similar to model 1, except warehousing is no longer significant at urban and is less so at periphery ($p < 0.05$). Urban saturation remains significant, but less so ($p < 0.05$) and is still negative.

Model 3 uses the same panel data as model 2, but instead applies panel regression that tests fixed effects over time without the use of a dummy variable. Household income is now significant across the board ($p < 0.05$ in urban, < 0.001 in periphery, < 0.01 in exurban), with the highest coefficient in the periphery (0.24 versus 0.12 urban and 0.06 exurban). Notably, population growth is no longer significant at any scale. Growth in young adults (*POP_18to34_PER*) becomes significant for first time ($p < 0.001$ metropolitan and urban, $p < 0.01$ periphery and exurban), all with negative coefficients (–0.15 urban versus –0.13 periphery and –0.04 exurban). Similarly, growth in age 55 and over has both higher significance and a stronger coefficient at urban ($p < 0.01$; –0.12) than periphery ($p < 0.05$; –0.10). All LUT variables are no longer significant, with the exception of increased driving in the periphery ($p < 0.05$, 0.04). Overall GDP growth (*GDP_PER*) is the only significant economic variable ($p < 0.05$ for metropolitan and urban). Increasing urban saturation has high significance and an extremely strong negative coefficient in urban ($p < 0.001$; –0.66), with a considerably smaller exurban coefficient ($p < 0.05$; –0.13). Periphery saturation is significant for the first time, and highly so ($p < 0.001$, –0.64), indicating a strong negative temporal effect.

4. DISCUSSION

4.1 TRADITIONAL AND EMERGING VARIABLES

The results of this analysis highlight the continued relevance of traditional drivers, such as population growth and income, while shedding light on emerging ones. Crucially, the gradient-based, longitudinal approach demonstrates the complexity of expansion by illuminating variability across time and space, in terms of both estimator significance and coefficients.

Both OLS models show the substantial effect of population growth across scales, but exurban coefficients were smaller, pointing to a weaker link to overall metropolitan growth. Further, population growth is not significant in any of the fixed-effect models (model group 3), suggesting the temporal trend—a major decline—comes from factors other than slower population growth. As expansion rates exhibit substantial regional variation, even when controlling for population growth (Richter 2020), other variables must also explain regional differences in relative rates of expansion.

Two traditional variables that remain salient are median income and the share of foreign-born residents. Income is significant in both urban and periphery models, hinting that regions with higher incomes simultaneously affect greater infill development and suburbanization. How these two interact remains an unanswered research question. Income is also important temporally, but in a different manner. Given that incomes drop over the study period—US$60,000 in 2000 to about US$54,000 in 2011 (both in 2018 US$)—the positive coefficient suggests that declining incomes, perhaps due to the Great Recession, played an important role in reducing expansion. The share of foreign-born residents, like population growth, is significant only in OLS models. Thus, it does not speak to the reduction trend, though a strong negative coefficient across the expansion gradient in OLS models points to a crucial expansion-limiting process that requires further study. One possible explanation is that immigrants, who possess different cultural expectations regarding density, are likely to be more comfortable in denser developments.

Among emerging variables are the growth in young adult and older households, both of which theoretically exhibit more compact locational preferences (Nelson 2013; Myers 2016). OLS models show that growth in older households (age 55+) has a negative effect on expansion, but only in urban areas. Conversely, growth in young households (age 18–34) is highly significant in the fixed-effect model. Coefficients are negative across the gradient, but more so in urban areas. Thus, older households are more strongly linked with cross-sectional variation, while the growth of young households helps to explain declines in expansion over the study period. Surprisingly, growth in household size, an indicator of families with children, has a negative relationship in OLS models. Family households are more likely to prefer suburban homes with a yard, and thus should drive greater expansion; however, increasing household size translates into fewer households for a given population, likely offsetting the effect of population growth. This may change as the Millennial cohort enters family formation in the years following the study period.

LUT variables show mixed relationships that seem to offset one another, mostly within OLS models. Increasing vacancy has a strong relationship to expansion, especially in peripheral areas. This points to a tension between new construction and existing structures. Growth in single-family homes is not significant at any sub-geography. However, greater prevalence of high-density residences (those with 20+ units) has a strong negative influence on peripheral expansion. Increases in commuting by car links to greater expansion in both the periphery and exurbs, but this is offset when commutes are excessive (over 60 min). Working from home, which is significant and positive across the geographies, requires further investigation. Overall, LUT appears to have a greater effect on the periphery and exurbs than in urban areas and has a limited temporal effect within the study period.

Of regional economic considerations, natural resource and transport and warehousing GDP per capita are significant in OLS models. Exurban expansion is likely stimulated by a stronger natural resource economy while warehousing tends toward peripheral locations. Both spatial patterns make sense. Exurban residents often seek an alternative to urbanity, with amenity-rich landscapes being highly attractive. Warehousing seeks optimization between minimizing distance to consumers and cheaper land prices. In terms of temporal effects, overall GDP growth (which increases, unlike income) appears linked to increased urban expansion later in the study period, suggesting a relationship between economic growth and infill development.

Finally, physical variables appear to both drive and constraint expansion. Higher winter temperatures point to exurban expansion, complementing the trend with natural resource GPD per capita, though the potential impacts of both are relatively small compared with other factors. Greater urban saturation seems to limit further urban expansion while constraints in the periphery constrict peripheral expansion, with both relationships being of greater magnitude than the aforementioned exurban relationships. In the fixed-effect model, urban and periphery saturation are both highly significant and have extremely impactful negative relationships to expansion within the same geography. This could hint that development can be self-limiting, though urban saturation is also inversely related to exurban expansion, likely due to a process other than constrictions in the available land. These patterns may be a function of endogeneity or other methodological concerns, especially in the periphery, where mean saturation in 2011 is quite low (only 18% versus 71% for its urban counterpart).

4.2 POLICY IMPLICATIONS

Overall, factors that tend toward increasing expansion often were strongest in the periphery. Those that limit expansion manifest either as negative effects, sometimes across multiple scales, or as drivers of central growth that is inherently more space efficient. This suggests a combination of both carrot and stick is necessary when designing policy to reduce expansion. Despite the exploratory nature of this work, some of the above findings lend themselves toward specific policies. First and foremost, policymakers must consider expansion to be more than a predictable expression of population and economic growth. As this analysis demonstrates, socio-demographic, LUT, economic, and physical factors all play an important role. In addition to this general guidance, two interrelated policy recommendations stand out.

First, the locational preferences of different age cohorts are powerful enough to dampen expansion. Local land-use and housing policy should be attentive to such demographic trends and be prepared to fully capitalize on demand for central living by encouraging higher density residential construction in central areas. Given the millennial cohort peaked in 2015 and is entering family formation in mass (Myers 2016), this necessarily extends to the construction of family-suitable urban housing typologies in the 2020s.

Second, the highly significant relationship between growth in commuting via driving and periphery/exurban expansion aligns with the displacement of transit riders. Increases in driving typically come at the expense of transit ridership (since working from home, the other alternative, is almost universally increasing). That this pattern accompanies peripheral and exurban expansion speaks to the need for poor residents to locate where land is cheapest. Thus, it is imperative that anti-displacement policies accompany incentives for denser residential construction, for both reasons of social justice and to prevent such expansion.

These policies are applicable not only in the US but also in many developing contexts; however, the timing and magnitude of demographic change will be unique to the policy context. And the meaning of specific relationships may differ. In some countries, growth in immigrants or residents from wealthy nations may stimulate expansion, not stifle it. Some of the factors linked with declining urban expansion, such as declining incomes and increased saturation, may be undesirable or difficult to implement. But the broader impetus—to consider not just more diverse factors but also how impacts vary across space and time—remains relevant to policymakers in the US and beyond.

4.3 LIMITATIONS AND PATH FORWARD

This analysis prototypes a spatial approach that subdivides the urban region into a gradient from urban to peripheral to exurban expansion. As with any prototype, reflection is necessary to move forward. A dearth of socio-economic data prevents the division of the 15-year study period into three equal intervals, limiting longitudinal insight. The reliance on the 2000 Census UA geography causes the urban subregion to be over-bounded—the 2010 version leverages NLCD data to tighten urban footprint boundaries. And creating the periphery geography with buffers instead of functional units, like census tracts, limits most explanatory variables to the coarser metropolitan geography. This reduces quantitative analytical power, particularly in understanding interactions between subregions. Finally, exurban measurement of expansion is likely undercounted in the NLCD due to difficulty in locating isolated structure (Irwin *et al.* 2007).

Another limitation concerns the selection of independent variables. Though 25 independent variables are used across a wide array of data categories, important factors remain missing. For example, land-use regulations should be highly influential to expansion processes; however, data from early surveys are limited in size and scope. The recent efforts to create a national zoning atlas[2] may remedy some of these hurdles. Labor dynamics or education institutions (which is a major driver of residential choice in the US) are two other areas that might influence expansion processes.

Despite these limitations, the use of an expansion gradient clearly has merit. Moving this concept from prototype into more refined analyses is achievable, especially with regard to improving operationalization to target more explicitly interplay across the gradient and between spatial scales. Two substantive paths forward include (1) refining operationalization of the gradient scale and (2) deepening the hierarchical basis for analysis.

As alluded to above, census tracts could form the basis for implementing the expansion gradient. Individual units that cross all three subregions, as identified in this study, ought to be removed from the data sample to improve instrumental validity. Such an approach could continue to rely on a discrete gradient typology, as used here, or might consider techniques that capitalize on spatial granularity—instead of three subregions, a tract-based approach could have hundreds that reflect a more continuous gradient.

A second recommendation for future work is that scholars deepen the hierarchal aspects of the gradient concept. This work applies two scales—the urban region and a discrete subregional gradient—yet both coarser and finer geographies are clearly relevant. Angel *et al.* (2011) demonstrate the efficacy of nation-scale analysis, and though the present paper includes a single country, a similar approach might leverage the state scale. More importantly, expansion fundamentally occurs below the gradient scale at what might be called the ‘development scale.’ Construction, financing, and design all contribute to expansion, *e.g.* through the generation of different ‘parcel densities’ (Angel *et al.* 2021a). Sophisticated spatial analytical tools, such as those used in landscape ecology (*e.g.* Clark *et al.* 2009), could general useful metrics at the development scale, though many insights likely require more qualitative forms of enquiry to describe place-based drivers and processes. The ‘development scale’ also represents a key opportunity to integrate with land-use regulations, which typically vary across the municipal scale.

Refining spatial and hierarchical granularity are not mutually exclusive, and ultimately, integrating both approaches will be highly beneficial to understanding the processes of expansion. However, it is important to recognize that greater quantitative power alone is insufficient. Conceptual clarity remains necessary when operationalizing urban land-change research in a data-rich environment (Richter 2021).

5. CONCLUSIONS

Expansion is a dynamic and evolving process, one which this research provides new insight into by leveraging a variety of social and ecological data. This analysis is receptive to temporal dynamics, evaluating statistical relationships across time. Crucially, this work leverages urban ecology theory to implement a gradient-based approach that decomposes expansion from an urban regional phenomenon into spatially explicit constituents.

An approach sensitive to the spatial heterogeneity of expansion processes is increasingly relevant as scholars now recognize the tendency for densification within the urban footprint and expansion beyond to occur simultaneously (Angel *et al.* 2021b). Isolation of peripheral development is necessary to target new growth that tends to be of lower urban quality (Angel 2018). And the rapid growth in US exurban regions (Berube *et al.* 2006) grants urgency to studies targeting it. Yet, development in any of these subregions does not operate independently. Urban systems are highly connected and extensive. Social–demographic trends, land-use and transportation planning, regional economic patterns, and physical context all interact in ways scholars are only beginning to understand. This implementation of a gradient-based approach embraces this complexity, taking a necessary step forward in the study of urban expansion.

NOTES

1 Normalization of model coefficients and standard errors involves two steps. First, each value is divided by the standard deviation for that independent variable (except for constants and the year dummy variable in pooled OLS models). This makes all units more interoperable given their vastly different magnitudes and variability. Next, all values are min-scaled, *i.e.* divided by the minimum value across all models within a given table/model type. This brings all values into a range from –1.00 to 8.26, easing interpretation. This asymmetrical approach (versus normalizing between –1.00 and 1.00) reflects the desire to retain visibility of the relative magnitudes between positive and negative effects.

2 See https://www.zoningatlas.org/.

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COMPETING INTERESTS

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