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Population stress: A spatiotemporal analysis of population change and land development at the county level in the contiguous United States, 2001–2011

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ABSTRACT

The past century has witnessed rapidly increasing population-land conflicts due to exponential population growth and its many consequences. Although the measures of population-land conflicts are many, there lacks a model that appropriately considers both the social and physical contexts of population-land conflicts. In this study we introduce the concept of *population stress*, which identifies areas with populations growing faster than the lands available for sustainable development. Specifically, population stress areas are identified by comparing population growth and land development as measured by land developability in the contiguous United States from 2001 to 2011. Our approach is based on a combination of spatial multicriteria analysis, zonal statistics, and spatiotemporal modelling. We found that the population growth of a county is associated with the decrease of land developability, along with the spatial influences of surrounding counties. The Midwest and the traditional "Deep South" counties would have less population stress with future land development, whereas the Southeast Coast, Washington State, Northern Texas, and the Southwest would face more stress due to population growth that is faster than the loss of suitable lands for development. The factors contributing to population stress may differ from place to place. Our "population stress" concept is useful and innovative for understanding population stress due to land development and can be applied to other regions as well as global research. It can act as a basis towards developing coherent sustainable land use policies. Coordination among local governments and across different levels of governments in the twenty-first century is a must for effective land use planning.

1. Introduction

The global population exponentially increased throughout the twentieth century. The estimated global population in 2016 was approximately 7.4 billion and is expected to increase to 9.6 billion in 2100 (Gerland et al., 2014). Population growth has been documented as a social and environmental issue. Under the condition of limited resources, regional population growth can induce severe community vulnerabilities (Neumann et al., 2015) such as water scarcity (Falkenmark, 2013), livestock and food insecurities (Godber and Wall, 2014), and burdens on health care (Dall et al., 2013). Population growth and redistribution, however, is constrained by land development and conversion, and in a trade-off relationship they collectively affect community vulnerability (Chi, 2010a). The nexus of population, land, and community vulnerability is covered in a large body of literature of population-land conflicts. Such conflicts include hot spots in wildfire-urban interfaces, coastal and flooding areas, exurban areas, ecosystem areas around national parks, declining urban areas, abandoned rural lands, and others.

1.1. Quantifying population-land conflicts

How are population-land conflicts quantified and measured in existing research? Although population-land conflicts involve both social and physical contexts, unfortunately existing research measures either social or physical contexts rather than both. The social context of population-land conflicts is determined by multiple social or socioeconomic subcomponents, such as legal regulation (Grout et al., 2011; Lestrelin et al., 2012), social/environmental policy (Lambin et al., 2014), economic values of lands (Lambin and Meyfroidt, 2010), and social networks (Barton, 2009; Marull et al., 2010). These subcomponents under the social context are, however, more ontological and theoretical and cannot be directly measured by the sizes of lands. In order to determine the change of land through a social context, traditional studies such as political ecology research have generally applied "metabolism" to define the critical point of land change through policy

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(Gandy, 2004; Marull et al., 2010) or the concept of "hybridity" to identify the socioenvironmental modification from multiple backward and forward changes through political decisions and social movements (Brownill and Carpenter, 2009; Forsyth, 1996; Holman and Rydin, 2013; Qureshi and Haase, 2014). Moving toward mathematical modelling, (Kennedy et al., 2011) reviewed over 50 articles related to urban metabolism and environmental assessments and found that using urban metabolism as a model framework can integrate social sciences and biophysical sciences. It can also help analyze policy and technology outcomes to achieve sustainability goals. However, most studies integrating mathematical modelling also indicated the focus of "urban metabolism" has shifted from a critical point of land change through policy to a critical point of land change through time. Because of this shift of focus, most quantitative-based urban metabolism models can provide results for policy decision making but cannot include elements of land policies or governmental regulations during the modelling process. However, recent reviews of political ecology (Angelo and Wachsmuth, 2015; Gandy, 2015; Sharma-Wallace, 2016) indicate that most studies of metabolism and hybridity were qualitative based without using any mathematical or statistical modelling techniques.

In contrast, the physical context of population-land conflicts is determined by quantifying the geophysical environment, for example, estimating sizes and amounts of each land type. Previous studies researching physical contexts include using geographic information system (GIS) and remote sensing techniques and land use and land cover (LULC) to predict land use changes (Alexakis et al., 2014; El-Kawy et al., 2011; Hu and Wang, 2013; Ye et al., 2013) or using global environmental modelling techniques such as the Community Earth System Model (CESM), Global Land-use Model (GLM), or Global Change Assessment Model (GCAM) to quantify the land cover and to estimate future simulations (Chen and Dirmeyer, 2016; Di Vittorio et al., 2014). These techniques provide the results of net change of land cover or frequencies of land changes in a study period, without considering the influences of land policies or governmental regulations for development. One common example is that LULC analyses can involve stochastic statistical modelling or complex economic modelling for spatiotemporal assessment, such as the Markov model (Halmy et al., 2015; Singh et al., 2015; Xu and Huang, 2014), but land policies were not the factors of such models.

In summary, previous population-land studies linked to the social context of land use and development focused on hypothetically defining the land without quantitative assessments, while most studies linked to the physical context reported only land change by statistical modelling without fully considering the socioeconomic values or the sociopolitical issues of lands. This reveals, therefore, a gap in the knowledge of how to combine both the social context and the physical context to develop a quantitative model for appropriately estimating population-land relationship and identifying hot spots of population-land conflicts.

1.2. Population stress

To consider both the social and physical contexts for defining and quantifying population-land relationships, we introduce in this study a concept called *population stress*. We define population stress as an area that experiences faster population growth than land development. Such areas often experience high-density development. They need more resources than an average developing area to support the increased population. This creates higher demands on food, water, energy, and infrastructure. Such areas, in turn, experience higher "stress" than an average developing area.

But why is population growth an appropriate indicator of the social context of population-land conflicts? After all, the social context has many elements, including social, economic, demographic, and policy elements; and community vulnerability is affected not only by population growth but also its consequences. That said, we argue that population growth is a reasonable indicator (and probably the best indicator) to represent the overall social context because regional population change is a spatiotemporal dynamic flow between demographic characteristics, socioeconomic conditions, infrastructure, the natural environment, and land use and development (Chi and Ventura, 2011), and population change is found to be associated with over 80 factors in these domains (Chi, 2009). It should be noted that population growth is not the only indicator, and not always the best indicator, to represent the social context of population-land conflicts. Depending upon the specific population-land conflict, a different indicator could be better suited to social context. For example, if inequality is the focus of a population-land conflict study, socioeconomic statuses (e.g., race/ethnicity, income, and education) might be better indicators of the social context. Our focus in this study is to identify hot spots of areas that experience population stress, that is, population growth faster than land development. For this purpose, population growth is a reasonable indicator of the social context of population-land conflicts.

1.3. Land developability

Our population stress measure is essentially a comparison between population growth and land development. While population growth is easy to calculate, land development can be measured in a variety of ways, as discussed previously. In order to measure land development in relation to population change with consideration of both social and physical contexts, a conceptual idea called "land developability" would be an appropriate measure (Chi, 2010a). The concept of land developability is to quantify the availability for land development in a particular region based on spatial information of both social and geophysical factors, including 1) federal restriction, 2) environmental risk, and 3) urban structure. By making use of the component of spatial heterogeneity, this index could 1) be used to develop a spatiotemporal model for analyzing socioenvironmental impacts on population change and 2) correlate with socioeconomic factors such as transportation (Chi, 2010b; Chi, 2012), deforestation (Clement et al., 2015), and natural amenities (Chi and Marcouiller, 2013a) for further demographic assessment. In contrast to common land vulnerability indices that only indicate the negative impacts of land development for environmental risk assessment, the land developability index can demonstrate both the positive and negative sides of land development, resulting in a balanced judgement of land conversion for the use of determining regional population dynamics. Analyzing population dynamics alongside land developability will not only be an application of regional planning but is also essential for predicting spatial demographic trends, economic geographic patterns, and sociodemographic changes through spatiotemporal modelling.

Reviewing the previous studies that have applied the land developability index in modelling, we found that most studies focused on a relatively small geographic extent, such as counties within a state (Chi, 2010b; Chi, 2012; Chi and Marcouiller, 2013a). There is a lack of research interpreting the relationship between land developability and population change in a greater region (e.g., the contiguous United States). This missing interpretation is the key to reducing the socioenvironmental vulnerability of a country and to enhancing population forecasting in a national context. Within the context of rapid urban sprawl and rural development in the twenty-first century, the land developability index can be useful for analyzing regional/national population change in order to 1) locate areas with less stress for migration and 2) locate regions that may need to change their corresponding land types for sustainable development (e.g., change urban lands to green cities).

We hereby develop the first national study to investigate the relationship between land developability and population change with a spatiotemporal approach. We selected the contiguous United States as our study site because it has faced substantial changes in terms of population and land use in the past decades. In an aspect of regional scale, the changes of landscape can be a driving force of national mitigation