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Effects of agent heterogeneity in the presence of a land-market: A systematic test in an agent-based laboratory

Qingxu Huang [a,*], Dawn C. Parker [b,1], Shipeng Sun [c], Tatiana Filatova [d,2]

[a] Center for Human-Environment System Sustainability, State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, No. 19, Xinjiekouwai St., Beijing 100875, China
[b] Faculty of Environment, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L3G1, Canada
[c] Institute on the Environment, University of Minnesota, Twin Cities, 325 Learning & Environmental Sciences, 1954 Buford Avenue, St. Paul, MN 55108, United States
[d] Centre for Studies of Technology and Sustainable Development, Faculty of Management and Governance (MB), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

Representing agent heterogeneity is one of the main reasons that agent-based models become increasingly popular in simulating the emergence of land-use, land-cover change and socioeconomic phenomena. However, the relationship between heterogeneous economic agents and the resultant landscape patterns and socioeconomic dynamics has not been systematically explored. In this paper, we present a stylized agent-based land market model, Land Use in eXurban Environments (LUXE), to study the effects of multidimensional agents' heterogeneity on the spatial and socioeconomic patterns of urban land use change under various market representations. We examined two sources of agent heterogeneity: budget heterogeneity, which imposes constraints on the affordability of land, and preference heterogeneity, which determines location choice. The effects of the two dimensions of agents' heterogeneity are systematically explored across different market representations by three experiments. Agents' heterogeneity exhibits a complex interplay with various forms of market institutions as indicated by macro-measures (landscape metrics, segregation index, and socioeconomic metrics). In general, budget heterogeneity has pronounced effect on socioeconomic results, while preference heterogeneity is highly pertinent to spatial outcomes. The relationship between agent heterogeneity and macro-measures becomes more complex when more land market mechanisms are represented. In other words, appropriately simulating agent heterogeneity plays an important role in guaranteeing the fidelity of replicating empirical land use change process.

1. Introduction

Land-use and land-cover change (LUCC) in the context of an urban environment is the result of the dynamics of coupled human and natural systems. Agent-based models (ABMs) have advantages in simulating the complexity (e.g. nonlinearity, path-dependence, heterogeneity, and emergence) in these systems and integrating empirical findings from multiple disciplines (e.g. geography, sociology, economy, and psychology) (Batty, 2005; Liu et al., 2007). For these reasons, both theoretical and empirical ABMs have been developed to simulate urban LUCC (Clifford, 2008; Grimm, 1999; Liu et al., 2007; Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003; Robinson et al., 2007).

One of the essential advantages of ABM is its ability to connect heterogeneous individual decision-making processes with emergent spatial patterns. In fact, empirical studies show that the heterogeneity among agents, including preferences for amenity, risk perceptions, income differences, demographic and household characteristics and different strategies of land development and management, plays a pivotal role in determining spatial landscape patterns and socioeconomic outcomes (Brown & Robinson, 2006; Ghoulmie, Cont, & Nadal, 2005; Ligmann-Zielinska, 2009; Magliocca, Safirova, McConnell, & Walls, 2011). In addition to agent heterogeneity, representations of land-market processes, for example, preferences, budget constraints, and competitive bidding, are important factors in bridging the gap between rigorous spatial dynamics models and existing ABMs that omit these components (Irwin, 2010; Parker et al., 2012).

Although agent heterogeneity and market representation are main components in modeling urban LUCC, the effects of agent heterogeneity under various land market representation have not been systematically inspected (Irwin, 2010; Parker & Filatova, 2008; Parker et al., 2012). The deficiency lies in several aspects.

* Corresponding author. Tel.: +86 58804921.
E-mail addresses: q22huang@uwaterloo.ca (Q. Huang), dcparker@uwaterloo.ca (D.C. Parker), sunx0170@umn.edu (S. Sun), t.filatova@utwente.nl (T. Filatova).
[1] Tel.: +1 519 888 4567.
[2] Tel.: +31 53 489 3530.

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First, few models incorporate market process. Second, even though almost every ABM has agent heterogeneity to some extent, few studies have systematically tested the effects of continuous variation in the magnitude of agent heterogeneity on the output, especially in a model that has land market mechanisms (Parker et al., 2012). Moreover, several studies come to conflicting conclusions regarding the effects of agent heterogeneity on projected land-use patterns (more details in Section 2.3). Third, the interactions between multiple sources of agent heterogeneity may be overlooked since some models treat agents with a single heterogeneous characteristic.

Using a stylized Agent-based land market model (ABLMM), named LUXE (Land Use in eXurban Environments), which simulates residential choices under different levels of market representations, we systematically investigate the multidimensional effects of agent heterogeneity on spatial and socioeconomic patterns of LUCC. In our model, there are two sources of agent heterogeneity. One is income heterogeneity, which imposes constraints on the affordability of buying land; the other is preference heterogeneity, which influences locational choice. Landscape measures (e.g. edge density) as well as socioeconomic measures (e.g. evenness index) are used to analyze the spatial patterns of land use and land price. The innovation of this study is to comprehensively explore the effects of agent heterogeneity in an ABLMM. The findings could potentially provide insights on the design of ABMs as well as reconcile some conflicts in the outcomes of existing ABMs.

To meet this goal we address four research questions: (1) How does agents' heterogeneity in incomes or in locational preferences affect emergent land-use patterns? (2) How does the magnitude of heterogeneity in agents' population affect spatial and economic phenomena? (3) Do the collective effects from multiple sources of agent heterogeneity vary under different market representations? and (4) Are different representations of market elements able to reconcile some conflicting results about the effects of agent heterogeneity drawn by other models? The paper is organized in the following way. Section 2 provides an overview on modeling agent heterogeneity and land markets with ABMs. Section 3 presents the stylized ABLMM and the settings for the experiments design to explore the effects of agent heterogeneity under four market representations. In Section 4, results of different experiments are compared. Finally, Section 5 provides the general conclusion and discussion.

2. ABM and heterogeneity: a brief overview

Spatially explicit ABM is widely used for simulating complex urban land-use change phenomena, including residential choice (Brown et al., 2008; Kii & Doi, 2005; Ligmann-Zielinska, 2009; Torrens, 2007), social-economic segregation (Benenson, 1998; Benenson, Omer, & Hatna, 2002; Crooks, 2006; Feitosa, Le, & Vlek, 2011; Fossett & Waren, 2005; Jayaprakash, Warren, Irwin, & Chen, 2009; O'Sullivan et al., 2003), gentrification (Diappi & Bolchi, 2008; Jackson, Forest, & Sengupta, 2008; O'Sullivan, 2002), verification of location theory (Sasaki & Box, 2003), zoning and urban planning (Ligtenberg, Wachowicz, Bregt, Beulens, & Kettenis, 2004; Zellner et al., 2010), the housing market (Ettema, 2011; Filatova, Parker, & van der Veen, 2009; Filatova, van der Veen, & Parker, 2009; Magliocca et al., 2011; Parker & Filatova, 2008) and microsimulation of urban system (Ettema, Jong, Timmermans, & Bakema, 2007; Kii & Doi, 2005; Miller, Douglas Hunt, Abraham, & Salvini, 2008; Miller, Farooq, Chingcuanco, & Wang, 2011; Waddell, 2002; Waddell, Wang, & Liu, 2008; Wagner & Wegener, 2007). Agent heterogeneity plays an important role in these models.

2.1. Heterogeneous economic agents

In a spatial land market model, agent heterogeneity refers to the differences among either characteristics of individual decision makers (e.g. preferences, incomes) or their behavioral functions (e.g. expectations formation, decisions-making strategies). The differences could be either internal (e.g. demographic and household characteristics, personal experiences, expectations, and risk attitudes) or external (e.g. social networks, accessibility to information, and policies) (Irwin, 2010; Valbuena, Verburg, & Bregt, 2008). Generally speaking, two approaches are used to introduce agent heterogeneity at model initialization. The first method is to continuously vary the agent characteristics (e.g. income, preference, etc.). For example, Benenson (1999) found continuously varying economic characteristics (e.g. income and income growth rate) will result in a relatively stable residential distribution. Filatova, Parker, and van der Veen (2011) found qualitatively different results in spatial and economic metrics in hazard-prone areas between households with heterogeneous risk perceptions based on an empirical survey distribution and homogeneous agents with risk perception equal to the average of the population.

The second method to impose heterogeneity is to divide the agents into different categories. The typology of agents could be determined by either one attribute (e.g. ethnicity) or multiple criteria (e.g. income level and neighborhood circumstance) (An, 2012). Different groups of agents could share the same decision-making function but have different parameters for the function, or they could even have different decision-making strategies (e.g. Schreinemachers & Berger, 2006). For example, Li and Liu (2007) divided households into five groups and empirically calibrated their weights on the same utility function. Satisfactory results of residential development were produced by a few groups of agents. Ghoulmie and colleagues (2005) found, in a single-asset financial market, heterogeneity of agent strategies is one of the important ingredients in reproducing some regular patterns. Magliocca et al. (2011) also used different decision making processes for developers in the formation of rent expectations and suggested the path dependence of spatial patterns has direct linkage with individual heterogeneity.

2.2. Agent heterogeneity in an agent-based land market models

Classical analytical land-market models such as the Von Thünen model (Von Thünen, 1966) and the monocentric city models (Alonso, 1964; Mills, 1972; Muth, 1969) established theoretical benchmarks for economic models of urban land-use change, e.g., the downward-sloping rent gradient, which is also seen robustly in the real world. Such analytical models, however, are of limited utility for examining spatial and agent-level heterogeneity in combination. In response, the usefulness of spatially explicit ABMs that contain land market representations has been emphasized by reviews (Haase & Schwarz, 2009; Irwin, 2010; Irwin & Geoghegan, 2001; Ligmann-Zielinska & Jankowski, 2007; Parker & Filatova, 2008); however, ABMs that have a representation of an explicit land market remain relatively rare. A subset of these models has enabled researchers to extend these classical models to directly simulate individual's behavior in a land market, replicating the classical results as a model verification exercise (Chen, Irwin, & Jayaprakash, 2011; Filatova et al., 2009).

The importance of ABLMM in understanding the effects of agent heterogeneity on the processes and patterns of LUCC can be summarized in several aspects. First, ABLMM provides a more flexible platform that needs fewer assumptions and restrictions compared to traditional economic models. As discussed in greater detail in Section 2.3, models can embrace agent heterogeneity rather than use a representative agent, and focus more on the