Land Economics, August 2017, 93(3): 413-436

How Does Urbanization Affect Water Withdrawals? Insights from an Econometric-Based Landscape Simulation

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Abstract

Effects on water resources are an understudied aspect of the environmental consequences of urbanization. We study how urban land development affects water withdrawals on a regional scale to account for market adjustments, human behavioral responses, and government institutions. Fine-scale econometric and simulation methods are used to represent the spatial heterogeneity associated with determinants of water withdrawals. Our analysis reveals a complicated relationship between future water withdrawals and changes in socio-economic drivers. Despite population growth of approximately 85% and a doubling of income, water withdrawals in two urban areas increase by at most 12% and in another area, decrease slightly.

I. INTRODUCTION

Although the environmental consequences of urbanization have been well studied (Wu 2008), its implications for water resources have received less attention. The effect of urban expansion on water withdrawals depends on a number of competing factors. On its own, growth in urban population has an indeterminate effect on total water consumption. While previous studies have shown that urban water demand typically increases with population and income (Olmstead et al. 2007; Mansur and Olmstead 2012; Barbier and Chaudhry 2014), increases in population density have been shown to have the opposite effect (Gaudin 2006). The effect of urbanization on total urban water withdrawals therefore depends on whether growth is occurring at the intensive margin (increase in the density of development) or extensive margin (increase in the area of the city). Moreover, if cities expand at the extensive margin, some land in undeveloped uses, such as farms and forest, may be converted to urban uses. The net effect of new development on water withdrawals will depend on the relative quantities of water consumed by farmers and urban households. Urban growth policies also influence the amount and density of future development, thereby influencing water withdrawals through these same channels.

In this paper, we investigate the effects of urbanization on future water withdrawals with a detailed case study of the Willamette Valley of Oregon. The objectives of this study are to 1) quantify how water withdrawals change in response to land development drivers, including population and income growth and permanent precipitation reductions, 2) investigate the relative importance of the economic and institutional pathways through which water withdrawals are affected, and 3) explore the implications of changes in land-use policies for future water withdrawals. To project future outcomes and identify the relative importance of the underlying mechanisms, we develop a parcel-scale structural simulation model of land markets, land development decisions, and institutional rules governing water and land use. The model is parameterized using new econometric estimates developed for this analysis and estimates published previously. Prior studies that combine econometric estimation and spatial simulation include analyses of fisheries (Smith and Wilen 2003), land conservation (Newburn et al. 2006; Lewis et al. 2011), endangered species protections (Langpap and Kerkvliet 2010), and carbon sequestration policies (Antle et al. 2003; Mason and Plantinga 2013). Our study advances this literature by including external drivers of the system and by explicitly modeling the institutional rules that affect natural resource use. Previous studies analyze hypothetical policies, but rarely represent existing institutions in detail.

The present study also sheds light on two key ways in which future climate change may affect the Willamette Valley. A recent paper by Albouy et al. (2016) predicts that western Oregon, which includes the Willamette Valley, will be one of a few places in the continental U.S. where quality of life will increase under future climate change. A natural implication of this is that the population of the region should grow over the coming century. By illustrating how future population growth, which is mediated by land-use policy, influences water withdrawals, the present study provides an initial exploration of one potential impact of climate change on the study area. In addition, most climate projections for the Pacific Northwest show that unabated growth in greenhouse gas emissions will result in decreased levels of summer precipitation (Mote et al. 2014). To give a sense of how such changes in precipitation might affect water withdrawals, our study considers two future scenarios in which the level of growing-season precipitation is permanently reduced relative to a historical benchmark. Since most land development occurs on agricultural land in our study region, lower precipitation affects land-use patterns by lowering the opportunity cost of development.

Although this paper considers how some possible outcomes of future climate change will influence water withdrawals, it does not aim to provide a complete characterization of how climate change will affect the Willamette Valley. While continued population growth and decreased summertime precipitation are likely to manifest in our study area, additional changes, such as increased temperatures and more volatile precipitation patterns, are also expected to occur. Furthermore, despite the detail with which current water and land institutions are modeled, the present framework does not address structural change in institutions that may take place over the next fifty years. For example, the prior appropriations doctrine, which has governed water withdrawals in most of the western U.S. for more than a century, may evolve in years to come in response to increased regional water scarcity. The present study explicitly accounts for institutional rules and reveals the channels through which broad-scale urbanization drivers affect water withdrawals, treating the existing institutional framework governing land and water use as exogenous.

In the first stage of the adopted econometric framework, we quantify the effects of three critical drivers of the net economic returns to land. First, the analysis requires a functional relationship that relates a policy-maker's decision about where to locate an urban growth boundary with the net returns to development. A challenge identified in prior research is the endogeneity of zoning policies in econometric analyses of land development and prices, as zoning and development decisions tend to operate on the same set of observable and unobservable land market characteristics (Quigley and Rosenthal 2005; Ihlanfeldt 2007; Butsic et al. 2011; Kok et al. 2014). Second, since population growth is a primary driver of the demand for developed land, it is necessary to quantify how a given change in population affects development returns. Third, we need to establish a Ricardian-type relationship between precipitation and the value of land in agriculture (as in, e.g., Schlenker et al. 2005), since any climate-induced changes in the value of agricultural land alter the opportunity cost of development. Once estimated, the hedonic relationships are used to predict land values in a set of second-stage land-development models. The estimation framework employed here extends the approach taken in Bockstael (1996) by using panel data and adding a sample selection mechanism to the first stage developed land hedonic model.

Spatial simulations are conducted over the period 2000 to 2070 to investigate the effects of land-use policy, future population growth, and persistent drought on land use and water withdrawals. Land-use change in the model is driven by econometrically-estimated transition rules that account for the constraints imposed by zoning and urban growth boundaries (UGBs). The simulations allow for adjustments through time in UGBs following rules specified under current Oregon law. Simulations are conducted for three urban areas (Eugene-Springfield, Salem-Keizer, Woodburn), selected to represent differences in amounts of irrigated and non-irrigated agricultural land in the surrounding area. In Oregon, as in much of the western U.S., irrigation rights for agriculture are linked to specific parcels of land, which can be identified with available spatial data. We also draw on estimates from the economics literature to estimate annual water demand by the residential sector in each city. In the simulations population growth is treated as exogenous, but the stringency of UGB expansion rules is varied in order to generate different development patterns and population densities. The analysis also features simulations of permanent precipitation declines, as happens in a persistent drought, which affect the plot-level opportunity cost of development. Comparisons across simulations gauge the relative effects of persistent drought and population growth on water withdrawals and identify the relative importance of economic and institutional channels.

The simulation results suggest that, despite population growth of approximately 85% and a doubling of real income, water withdrawals increase by at most 12%, and decrease slightly in one city. A counterintuitive finding is that land-use policies that allow more sprawling development patterns can reduce water withdrawals compared to policies that achieve more compact development patterns. The key mechanism in this case is the development of irrigated agricultural land, which results in a net reduction in water withdrawals. Overall, the amount and spatial pattern of irrigation rights and new development are critical determinants of how water withdrawals are affected by land-use policy and climate.

The next section presents the key components and theoretical foundation of our framework. Section III presents the econometric models of land values and land-use change and section IV discusses landscape simulations. A final section provides conclusions.

II. CONCEPTUAL FRAMEWORK AND THEORETICAL FOUNDATION

In this section, we describe the key economic relationships accounted for in the modeling framework. Although the conceptual model is primarily based on prior work (e.g., Capozza and Helsley 1989), the empirical application that follows marks a departure from typical urban development analyses (e.g., Lubowski et al.2006) in that it uses land values, as opposed to rents, as the primary determinant of development decisions. As discussed below, we use land value data because they are available for all parcels at multiple points in time. Here, we provide an overview of the theory underpinning our analysis in order to make clear how it is adapted to land value data.

The components of the model include exogenous drivers, the institutions that govern the use of water and land, land markets, land-use change, and water withdrawals (Figure 1). Given our focus on a single region, population, income, and agricultural commodity markets are treated as exogenous. Assumptions on population and income yield a version of the closed city model examined in the urban economics literature (e.g., Capozza and Helsley 1989). For an application to cities in Oregon, it is also appropriate to treat the institutions governing water as exogenous, as water provision and use is regulated by state and federal laws that have been in place since the early twentieth century (Oregon Water Resources Department (OWRD) 2013). In contrast, land-use planning, while overseen by a state agency, is implemented by cities and counties through a process that can adjust to changing urbanization pressures. As such, a bi-directional relationship is allowed between land-use planning and land-use change, as shown in Figure 1. Exogenous drivers and institutions have direct effects on land markets through the rents associated with developed and agricultural lands. Changes in relative rents resulting from real income and population growth, for example, give rise to incentives for land-use change which, in turn, affect water withdrawals.

The land market is represented with hedonic price equations (Rosen 1974, Freeman 2003) for developed and undeveloped (agricultural or forest) land. The equilibrium rents from development for parcel i in time t are specified as:

$$R_i^d(t) = R^d(\mathbf{X}(\mathrm{t}), \mathbf{Z}_\mathrm{i}), \tag{1}$$

where $\mathbf{X}(\mathrm{t})$ is a vector of city-level time-varying attributes, such as population density and income, and $\mathbf{Z}_\mathrm{i}$ is a vector of time-invariant location-specific attributes such as distance to the city center.[1] The rents from undeveloped land are specified as:

$$R_i^u(t) = R^u(\mathbf{X}(\mathrm{t}), \mathbf{Z}_\mathrm{i}). \tag{2}$$

For agricultural and forest lands, the important elements of $\mathbf{X}(\mathrm{t})$ and $\mathbf{Z}_\mathrm{i}$ include climate, water rights, and soil characteristics. In a competitive land market, the price of land equals the present discounted value of the stream of rents. Assuming development is irreversible, the price of developed land is given by:

$$P_i^d(t) = \int_t^{\infty} R^d(\mathbf{X}(\mathrm{s}), \mathbf{Z}_\mathrm{i})e^{-r(s-t)}ds, \tag{3}$$

where r denotes a constant discount rate. In contrast, the price of undeveloped land is a function of rents from agriculture or forestry and development:

$$P_i^u(t) = \int_t^{t_i^*} R^u\,(\mathbf{X}(\mathrm{s}), \mathbf{Z}_\mathrm{i})e^{-r(s-t)}ds + \int_{t_i^*}^{\infty} R^d(\mathbf{X}(\mathrm{s}), \mathbf{Z}_\mathrm{i})e^{-r(s-t)}ds - Ce^{-r(t_i^*-t)}, \tag{4}$$

where t_i^* is the time at which parcel i is developed and C is the conversion cost.

Our model of land-use change focuses on the decision by an individual landowner to convert undeveloped land to a developed use. Assuming the owner of parcel i is a price-taker, the optimal development time is found by maximizing the land value in equation [4] with respect to t_i^*. The associated first-order condition is:

$$R^d(\mathbf{X}(\mathrm{t}_\mathrm{i}^*), \mathbf{Z}_\mathrm{i}) = R^u(\mathbf{X}(\mathrm{t}_\mathrm{i}^*), \mathbf{Z}_\mathrm{i}) + rC. \tag{5}$$

The second-order condition[2] requires that the rate of change in development rents exceeds the rate of change in agricultural rents at t_i^*:

$$\frac{d}{dt}R^d(\mathbf{X}(\mathrm{t}_\mathrm{i}^*), \mathbf{Z}_\mathrm{i}) > \frac{d}{dt}R^u(\mathbf{X}(\mathrm{t}_\mathrm{i}^*), \mathbf{Z}_\mathrm{i}). \tag{6}$$

Estimation of the empirical land-use change model relies on an analogous optimal development rule stated in terms of land prices. Conditions [5] and [6] imply that for $t < t_i^*$, $P_i^u > P_i^d - Ce^{-r(t_i^*-t)}$ and that for $t = t_i^*$, $P_i^u = P_i^d - C$. Therefore, a parcel should be kept in agricultural use as long as the price of undeveloped land is greater than the developed price net of conversion costs.

Water withdrawals are fundamentally tied to uses of the land (Figure 1). Urban households and other occupants of developed land purchase water from municipal utilities or pump it from underground aquifers. For urban users, the aggregate demand for water in time *t* is specified as:

$$Q^d(t) = Q^d\big(P^w(t), \mathbf{W}(\mathrm{t})\big), \qquad [7]$$

where $P^w(t)$ is the price paid by urban users to water utilities or the per-unit cost of pumping groundwater and $\mathbf{W}(\mathrm{t})$ is a vector of demand shifters that includes income and pricing structure (e.g., Olmstead 2010). Aggregate demand is affected as well by the number of residents in the city and population density (Gaudin 2006). For agriculture, whether and how much water can be used for irrigation is determined by water rights. Water rights are appurtenant to the land and, thus, affect agricultural rents (equation [2]). We write the total quantity of water used in agriculture in time t as:

$$Q^u(t) = Q^u\big(\mathbf{W}(\mathrm{t}), \mathbf{E}(\mathrm{t})\big), \qquad [8]$$

where $\boldsymbol{E}(t)$ characterizes the allocation of agricultural water rights at time t. The elements of $\mathbf{W}(\mathrm{t})$ important for agricultural water withdrawals include seniority of water rights and characteristics of the land, such as drainage. Equations [7] and [8] represent water withdrawals by urban and agricultural users. We do not account for return flows to the hydrological system.

Lastly, we model the institutions that govern land use and water withdrawals, treating the existing institutional frameworks in our study area as given. Oregon’s statewide land-use planning system is distinctive for its comprehensiveness and stringency (Paulsen 2013). The cornerstone of the system is the requirement that each city designate a UGB to limit low-density urban development. Development is allowed within the boundary, subject to zoning requirements, and restricted to a large degree outside the boundary. As such, the UGB effectively determines the size and the population density of the city. At the scale of individual parcels, the UGB determines whether a parcel can be developed and, therefore, the potential rents it can generate. While the UGB is fixed at any point in time, we model the process for expanding UGBs that accommodates growing demand for urban land. In this way, changes in land use have an influence on land-use planning (Figure 1). Cities in Oregon are required to maintain a 20-year supply of developable land within their UGBs. When this condition is no longer met, additional land is brought inside the UGB in a way that respects statewide planning goals related to agriculture, environment, transportation, and other objectives. Typically, the new lands brought into the UGB are contiguous to the existing boundary. In addition, lands that are zoned for rural development uses (e.g., parcels in rural residential and rural commercial zones) are usually the first to be added. Once these lands are exhausted, the UGB can expand into areas zoned for exclusive farm use or forest conservation. In our simulations, we approximate the threshold rule for UGB expansions and establish a hierarchy for adding new lands to the UGB.

The allocation of Oregon's water resources is governed by the prior appropriation doctrine, a seniority-based system that assigns water rights in the order that claims are made. Oregon's version of prior appropriation features conjunctive management of the state's surface water and groundwater resources and contains a "use it or lose it" provision, meaning that water rights that are not exercised at least once every five years are forfeited.[3] Irrigation water rights are also forfeited if land is converted to non-agricultural uses, such as development. Thus, the allocation of rights $\mathbf{E}(\mathrm{t})$ can change over time as the result of land-use change. Of primary relevance to our analysis is the spatial heterogeneity in agricultural water endowments created by the prior appropriation doctrine. The right-hand side of Figure 2 illustrates the pattern of irrigation water rights in the environs of the cities we examine.[4] Much of the undeveloped land surrounding Woodburn is in irrigated agriculture, whereas Eugene has little irrigated agricultural land in its environs and Salem provides an intermediate case. These three cities represent alternative spatial patterns of irrigation water endowments on a landscape, providing a comparison of the different ways in which population, income, and climate can affect water withdrawals in agriculture.

III. ECONOMETRIC MODELS OF LAND VALUES AND LAND-USE CHANGE

The econometric models of land values are estimated with parcel-level panel data. Predicted land values based on the hedonic models are then used in a model of land-use change estimated using panel data on past development decisions. The time period covered by both pieces of the econometric analysis is 1973-2000. Below, we present the hedonic property value (HPV) models for undeveloped (agriculture and forest) and developed land, and the model of land development. Following that, we describe the data we use and the estimation results.

Hedonic property value models

The appropriate functional form of the HPV model has been considered in prior work (e.g., Milton 1984; Cropper et al. 1988; Kuminoff et al. 2010). In the recent literature, Cropper et al. (1988) is often cited in support of relatively simple, parsimonious functional forms that tend to minimize bias in the presence of omitted variables. However, Kuminoff et al. (2010) suggest that more complicated functional forms (e.g., quadratic Box-Cox) outperform simpler ones in models with spatial fixed effects. Because we use the HPV models for prediction, it is necessary to measure effects of time-invariant factors, thus ruling out parcel-level fixed effects models. As a result, a simple log-linear functional form is used in all three HPV models. Specifically, the dependent variable is the log of the real per-acre value of land, net of the value of any structures or other improvements.[5]

Undeveloped land HPV models

Separate HPV models of agricultural and forest land values are estimated using a correlated random effects (CRE) (Mundlak 1978) estimator. The set of parcels that enter either the agriculture or forest sample are located outside of UGBs and zoned for exclusive farm use (EFU) or forest conservation (FC), respectively. We restrict our samples in this way in an effort to obtain land values due solely to undeveloped uses, as opposed to a combination of undeveloped returns and capitalized future development rents.[6] Estimates of the returns to undeveloped uses, net of any influence related to future development potential, are needed for the estimation of the land-use change models discussed below. The undeveloped land HPV models are specified as:

$$P_{it}^{u} = \theta_0 + \boldsymbol{\theta}_1 \mathbf{X}_{\mathbf{i}} + \boldsymbol{\theta}_2 \mathbf{Y}_{\mathrm{it}} + \gamma_i + \varepsilon_{it}, \qquad [9]$$

where γ_i represents a time-invariant parcel-specific unobserved effect, ε_{it} represents an idiosyncratic disturbance term with mean zero, $\mathbf{X}_i$ is a vector of exogenous time-invariant variables, $\mathbf{Y}_{\mathbf{it}}$ represents a vector of time-varying variables with corresponding parcel means $\overline{\mathbf{Y}}_{i.}$, and $\theta_0, \boldsymbol{\theta}_1,$ and $\boldsymbol{\theta}_2$ are parameters to be estimated. Equation [9] is estimated with the CRE estimator, which partially controls for the influence of time-invariant unobservable factors by including the parcel means of the time-varying variables as regressors, sometimes referred to as a "Mundlak device" (Mundlak 1978). In particular, we specify the Mundlak device as $E[\gamma_i|\mathbf{Y}_{it}] = \boldsymbol{\theta}_3\overline{\mathbf{Y}}_{i.}$, where $\overline{\mathbf{Y}}_{i.} = T_i^{-1}\sum_{t=1}^{T_i}\mathbf{Y}_{it}$ and $\boldsymbol{\theta}_3$ is an additional set of parameters to be estimated.[7] The advantage of the CRE estimator for our application is that it allows estimation of coefficients on observable time-invariant parcel characteristics, while allowing for correlation between the time-invariant parcel unobservable γ_i and the time-varying independent variables $\mathbf{Y}_{it}$. The CRE model can be viewed as a middle ground between fixed and random effects estimators (Wooldridge 2010).

Separate sets of parcel characteristics are included as regressors in the agriculture and forest specifications. For agriculture, these include climate conditions (precipitation, minimum temperature), soil quality, lot size, slope, and the holding and priority date of irrigation rights. With quadratic and interaction terms, we allow the effect of precipitation to be non-linear and depend on whether the parcel has a water right. The set of forest characteristics consists of slope, elevation, soil quality, ownership, river presence, and distance to the nearest wood processing mill. In both models, distance to the nearest UGB and characteristics of the closest cities are included as independent variables to account for any remaining influence of future development potential. Appendix Table A1 contains a complete description of the variables included in the agriculture and forest HPV models.[8]

Developed land HPV model

A key econometric challenge in estimating the developed land HPV model is accounting for the possibility that UGB designations are endogenously related to land market outcomes. Specifically, there likely are unobserved characteristics of land parcels (e.g., the profitability of future subdivision) that influence market value as well as the decision by planning authorities to include them inside the UGB (Grout et al. 2011, Dempsey and Plantinga 2013). Given the lack of parcel-level temporal variation in UGB designations[9] and the need to estimate coefficients on time-invariant variables, we use the Hausman and Taylor (1981) estimator (hereafter, HT).[10] We treat as endogenous the time-invariant effect of a developed parcel being included within a UGB. Although we do not observe changes in UGB status over time for developed parcels, there is cross-sectional variation in UGB designation because some development is permitted outside of UGBs and some parcels were already developed prior to the designation of UGBs.[11]

The developed land HPV model is specified as:

$$P_{it}^{d} = \beta_0 + \boldsymbol{\beta}_1 \mathbf{X}_i + \beta_2 UGB_i + \boldsymbol{\beta}_3 \mathbf{Z}_{it} + \gamma_i + \varepsilon_{it}, \tag{10}$$

where γ_i represents a time-invariant parcel-specific unobserved random effect, ε_{it} represents an idiosyncratic disturbance term with mean zero, $\mathbf{X}_i$ is a vector of time-invariant control variables, UGB_i is an endogenous (due to its correlation with γ_i) UGB indicator that takes the value one for parcels inside the UGB and is zero otherwise, $\mathbf{Z}_{it}$ is a vector of time-varying factors, and $\beta_0, \boldsymbol{\beta}_1, \beta_2,$ and $\boldsymbol{\beta}_3$ are parameters to be estimated. Included in $\mathbf{X}_i$ are variables representing the effects of distance to the nearest urban center, slope, county, and parcel size. $\mathbf{Z}_{it}$ includes variables for population density and household income of the closest city of at least 20,000 people and the squares of these variables, assessed value of any physical improvement[12], a full set of time dummies, and interactions between UGB_i and each time dummy.

As instruments for the UGB variable, the HT estimator uses the parcel-level means of the time-varying regressors, i.e., $\bar{\mathbf{Z}}_{i.} = T_i^{-1} \sum_{t=1}^{T_i} \mathbf{Z}_{it}$ for all i. In the closed-city urban equilibrium model (e.g., Capozza and Helsley 1989), the size of the city and, hence, population density are determined simultaneously with developed land rents. Population density is treated as exogenous in our application because the size of the city is determined by the planning authority. We expect the UGB indicator to be negatively correlated with population density, as higher population density indicates more compact development and a greater likelihood that developed parcels will be outside the UGB. For the nearest city's household income, we would expect a positive correlation with the UGB indicator, assuming land for development is a normal good. However, it could also be the case that the residents of high-income cities have a stronger preference for smart-growth urban containment policies, which would suggest a negative relationship between income and the UGB variable. Additional time-varying variables that serve as instruments are the inverse Mill's ratio (see below) and parcel-level improvement values. The full set of independent variables included in the developed land HPV model is listed in Appendix Table A1.

To facilitate estimation of the land-use change model, below, we use the developed land HPV function to predict the values of undeveloped parcels in developed use. This requires a model that is representative of the population of land parcels. However, the estimated HPV relationship for developed land is necessarily derived from land value data on parcels that are already developed. If there are unobserved factors that influence both the decision to develop land and the subsequent value of that land, our estimates may be affected by sample selection bias. Accordingly, we employ the sample selection correction developed by Wooldridge (1996) for panel data. We use the full sample of developed and undeveloped parcels to estimate cross-sectional probit models for each of the years represented in the samples of property values,

$$Prob(s_{it} = 1 | \mathbf{h}_{it}) = \Phi(\boldsymbol{\tau}'\mathbf{h}_{it}), \qquad [11]$$

where s_{it} equals one if parcel i is in the developed sample in time t and zero if parcel i is included in either the agriculture or forest sample at time t or has dropped out of the developed sample, $\mathbf{h}_{it}$ is a vector of observable factors that explains inclusion in the developed sample, $\boldsymbol{\tau}$ is a vector of parameters to be estimated, and Φ is the standard normal CDF. Because $\mathbf{h}_{it}$ varies over time, the estimated equations can be used to form a time-varying inverse Mill's ratio (IMR) that is included in the developed HPV model.[13] We include in $\mathbf{h}_{it}$ the full set of covariates (aside from the UGB dummy[14]) used in the developed land hedonic specification, as well as an additional variable—an indicator variable for whether the parcel has an irrigation water right—to facilitate identification of the coefficient on the IMR variable. The option to irrigate farmland should increase the likelihood that land is retained in agricultural use due to higher yields, the capacity to produce higher-priced irrigated crops, and increased adaptation to changing weather conditions. However, once a parcel is developed, the irrigation right is extinguished under Oregon water law. Thus, the irrigation water right explains the probability that a parcel will be in the developed sample, but can be excluded from the HPV model for developed land.

Land-use models

We estimate linear probability and binary logit models of the decision to convert agricultural and forested land to developed uses. Land development constitutes the focus of the analysis because it represents the primary source of observed land-use change in the Willamette Valley, accounting for approximately 87% of all plot-level conversions (USGS 2013). For each agricultural and forested plot, the estimated hedonic relationships are used to calculate the value of keeping the land in its current use and the hypothetical value of the plot were it to be developed. According to the theory developed in Section II, the net benefit of converting parcel i to developed use at time $t = t_i^*$ is given by:

$$y_{it}^* = P_{it}^d - P_{it}^u - C. \qquad [12]$$

For estimation of the land-use models, one approach is to specify the latent variable y_{it}^* as:

$$y_{it}^* = \beta_0 + \beta_1 \hat{P}_{it}^d + \beta_2 \hat{P}_{it}^u + \mu_i + \varepsilon_{it}, \qquad [13]$$

where $\hat{P}_{it}^d$ and $\hat{P}_{it}^u$ are price estimates from the hedonic models in [9] and [10], μ_i is a plot-level time-invariant unobserved determinant of the net benefits of development, and ε_{it} is a random disturbance term.[15]

We exploit the panel structure of the data on land use and property values to identify the parameters in [13]. In all models, the probability that a parcel is developed between period t and $t + n$ is assumed to depend on period t prices. As a first step, we estimate linear probability models (LPMs) of the decision to convert agricultural or forested land to developed use. The advantage of the LPM is that plot-level fixed effects can be included to control for time-invariant unobservable factors μ_i. While the LPM provides a useful benchmark, it is not suitable for use in simulations as it can generate predicted transition probabilities outside of the unit interval. Results from an augmented version of the pooled logit model are used for the simulations. In addition to the land value estimates, we include as covariates the plot means of the predicted land values, $\bar{P}^d_{i.}, \bar{P}^u_{i.}$. This specification is a non-linear variation on equation [9] in that the Mundlak device is specified as $E[\mu_i|\hat{P}^u_{it}, \hat{P}^d_{it}] = \varphi_1\bar{P}^d_{i.} + \varphi_2\bar{P}^u_{i.}$, but the residual variance of the plot-specific random effect μ_i is assumed to be zero.[16] The Mundlak device partially mitigates the potential bias resulting from correlation between unobservable time-invariant plot characteristics and the predicted land value covariates.

An alternative approach to estimating the land-use model would be to specify parcel land-use decisions as a direct function of the parcel characteristics included in equations [9] and [10], foregoing the step of estimating HPV models. This reduced-form approach has been used in previous empirical land-use applications (e.g., Carrion-Flores and Irwin 2004, Towe et al. 2008) and has the advantage of not requiring data on property values. However, for the present analysis there are important advantages of the two-stage approach. Because the first-stage HPV model is linear, standard instrumental variables methods can be used to address endogeneity of the UGB variable. Alternatives to these methods (e.g., Petrin and Train 2010) are needed if the UGB variable enters directly into the pooled logit model. Additionally, as Bigelow (2015) shows, the two-stage approach offers some efficiency gains given the relative infrequency with which land development decisions take place. Lastly, the two-stage approach allows us to disentangle the effects of variables that influence the value of both developed and undeveloped land (e.g., slope), whereas the reduced-form model only provides a net effect (Bigelow 2015).

Data sources

Rather than use transactions data to estimate the HPV models, we construct a panel of real market values (RMVs) from county assessor databases. In Oregon, RMVs are different from the assessed values used to determine property taxes. According to the Oregon Department of Revenue (2014), the RMV represents "… the price your property would sell for in a transaction between a willing buyer and a willing seller…" To generate the RMV for a given parcel, an initial estimate is first made by a county appraiser using recent sales data for comparable properties (Oregon Department of Revenue 2014). Over time, the RMV is adjusted in response to general market trends and more recent transactions for similar parcels (Oregon Department of Revenue 2014). While previous authors have found that appraised values are limited in their ability to capture the marginal value of certain plot characteristics (e.g., Ma and Swinton 2012), Grout et al. (2011) find a close correspondence between RMVs and transaction prices in the Portland, Oregon market. For this study, the use of RMV data has clear advantages over transactions data. In contrast to RMV data, transaction data are not readily available for the years that span the timeframe of our analysis. The RMV data provide repeated land value observations for a randomly-selected sample of parcels in the study region, and the panel structure of the data facilitates identification of the model parameters in the ways described above. However, given that the RMV data do not represent observed land parcel transactions, there is potential for measurement error in the property value model dependent variables. If measurement error is present and systematically related to one or more of the explanatory variables, the predictions generated with the property value models will be biased.[17]

RMV data were collected from four counties (Benton, Lane, Marion, and Washington) to represent the major urban areas within the Willamette Valley (Corvallis, Eugene-Springfield, Salem, and Portland) and achieve north-to-south coverage of the study area. For each county, an initial sample of tax lots is drawn from a comprehensive database of real property accounts for the year 2000. Each sample is stratified according to three land-use categories (developed, agricultural, and forest). Larger samples were assembled in counties with more tax lots, because land values in these areas, particularly for developed lands, tend to vary more as the result of fine-scale factors. To construct the panel of observations, we collect RMVs for our initial (year 2000) use-specific tax lot samples and then worked backward through time to obtain observations for 1992, 1986, 1980, and 1973.[18] As an example, after assembling the developed land parcel sample for Benton County using a digitized 2000 property roll, we then collect the real market value data for that same set of parcels in 1992 from non-digitized (microfilm and/or paper records) county files, doing the same for 1986, 1980, and 1973. This same data collection process is repeated for each of the use-county combinations resulting in twelve separate parcel-level RMV panel data sets.

After cleaning the data, the final samples consist of 2,659 developed parcels, 588 agricultural parcels, and 464 forested parcels.[19] The samples of property values exhibit reverse attrition, meaning that the number of parcels in each sample declines as we move back in time. For developed land, this happens because subdivision creates new tax lots that are not recorded in earlier periods. As such, some parcels contained in the initial sample disappear or experience a large jump in acreage as we move back in time, indicating that they were part of a larger parent parcel that was subdivided.[20] These earlier observations are omitted from the HPV estimation, leaving an unbalanced panel containing a larger number of observations in more recent years.[21] Descriptive statistics for all variables used in the HPV models are reported in Appendix Table A2.

Land-use data is from the Land Cover Trends (LCT) project, a U.S. Geological Survey (USGS) product that provides spatially-explicit land cover data at 60m resolution for the Willamette Valley ecoregion (USGS 2013). Each 60m plot is classified using modified Anderson Level I land cover categories, which proxy for land use (Loveland et al. 2002). For this analysis, we used plots classified as developed, agriculture, and forest.[22] The LCT provides repeated observations of plots in 1973, 1980, 1986, 1992, and 2000, coinciding with the land value data. The LCT data do not provide wall-to-wall coverage of the Willamette Valley, but instead consist of a random sample of 10x10 km “blocks”, each containing approximately 28,000 plots. The left-hand side of Figure 2 illustrates the 32 LCT blocks available for the Willamette Valley ecoregion.

Given our use of fine-scale spatially-explicit data on land use, spatial dependence among the error terms is a concern, particularly for the logit model (Brady and Irwin 2011). Similar to Carrion-Flores and Irwin (2004), spatial sampling is used to mitigate the potential for biased parameter estimates. Specifically, the land development models are estimated with a block-stratified random sample of 96,000 pixels drawn from the Willamette Valley LCT population. The sample used for estimation is restricted to LCT plots that start in agriculture or forest in 1973 and then either remain in the initial use or get developed in later years. Once a plot is developed, it is removed from the sample, resulting in an unbalanced panel of land-use observations. A summary of the land-use data is provided in Appendix Table A3. Importantly, the LCT samples are representative of the total amount of land converted from agriculture and forest to development between 1973 and 2000.

Estimation Results

The developed land hedonic estimates are highly significant and conform to expectations (Table 1).[23] Briefly, results for the developed HPV model (panel 1) indicate that household income and population density increase developed land values at decreasing rates and that land values rise with improvements, and decrease with slope and distance to the nearest city center. The coefficient on the time-varying IMR variable is positive and significant, indicating that land that is already developed commands a higher price than undeveloped land.[24]

The developed HPV results also confirm that parcels contained within a UGB are worth more than those outside of a UGB.[25] However, the effect of being inside the UGB, while always positive, has diminished over time. The coefficients on the UGB-year interaction terms are negative and decreasing, [26] suggesting that the value of developed land outside of UGBs has risen more rapidly than land inside of UGBs. Once the UGBs were adopted, the supply of developed land in rural areas, including land for residential housing, became essentially fixed. If demand for developed land outside of UGBs has increased (due, for example, to reduced transport costs and changing preferences for rural amenities), then these lands have become increasingly scarce over time, which explains why their values have risen more rapidly. By the year 2000, the UGB premium is roughly 60%, which, on average, equates to a per-acre gain in land values of $46,000. This effect is at the lower end of the range of estimates produced by Grout et al. (2011), which should be expected, given that the Grout et al. study focuses on the high-priced Portland Metro area.

The HPV results for agricultural and forest land also accord with prior expectations (Table 1, panels 2 and 3). The estimated coefficients for site characteristics (e.g., slope, land quality) are consistent with previous studies (Palmquist and Danielson 1989, Snyder et al. 2007). In the agricultural model, the value of irrigated agricultural land is increasing in the seniority of the water right, with each additional year of seniority increasing land values by 0.3% (p = 0.03).[27] Growing-season precipitation has a positive and diminishing effect on agricultural land values. However, the marginal effect of precipitation is only significant for agricultural parcels without water rights. Specifically, the marginal effect of precipitation is 0.6% (p = 0.84) for irrigated parcels, and 6.6% (p = 0.04) for non-irrigated parcels, indicating that decreases in rainfall have essentially no effect on agricultural land values for parcels with irrigation water rights.[28] In both the forest and agricultural hedonic results, the population density and household income variables have positive effects that are significantly different from zero, and the negative coefficient on UGB distance suggests capitalized future development rents are greater closer to existing cities. Recall that the sample only included parcels in areas zoned for agricultural and forest uses. Thus, these results suggest that despite the current zoning, future development opportunities are anticipated and capitalized in current prices of these lands.

Table 2 contains estimated marginal effects from the land development models. The second panel of Table 2 contains results from the LPM models with plot fixed effects. Consistent with expectations, the probability that agricultural and forest land is converted to developed use is increasing in the developed land value and decreasing in the respective value of undeveloped land. All marginal effect estimates are significantly different from zero at the 5% level, with the exception of the forest value marginal effect which is significant at the 10% level. Results for the augmented pooled logit model are qualitatively similar (Table 2, panel 1).[29] An increase in the value of land in a given use increases the probability that land will be converted to or retained in that use. Specifically, a $1000 increase in developed land values increases the probability that land will be converted from agriculture by 0.0005, while the effect for forest land is 0.0001. To give a sense of the magnitude of these effects, a $1000 increase represents a 2.5-6% increase in the average yearly developed land value prediction for agricultural plots, and a 3-7% increase for forest plots. The own-value (in $1000) effect for retaining land in an undeveloped use is -0.04 for agriculture and -0.09 for forest. The differences in the magnitudes of the developed-value and own-value marginal effects suggest there are large option values associated with delaying irreversible development decisions (Plantinga et al. 2002).

IV. LANDSCAPE SIMULATIONS

Simulation Methods

We conduct a series of landscape simulations for three urban areas (Salem, Eugene, and Woodburn) in the Willamette Valley over the period 2000 to 2070. For each city, a 30x30 km grid from the 2001 National Land Cover Database (NLCD) is used to measure baseline land use.[30] Additional spatial data on the determinants of land values (the variables in Appendix Table A1) are collected or measured. Using the estimated equations [9], [10], and [13], we simulate urban development to 2070 in 10-year increments. In the simulation model, population (Oregon Office of Economic Analysis 2011) and real income (Woods and Poole 2011) projections drive growth in developed land values over time. The population projections are to 2040, while the income projections end in 2050. Given that the forecasted trends are approximately linear, a linear extrapolation is used to extend the population and real income projections to 2070.[31] Regarding the real income projections, Woods and Poole use total personal income (TPI) which is typically more inclusive than the money income metrics from other data sources such as the US Census Bureau. We apply the growth rate from Woods and Poole's county-level real TPI projections to the Census-based household money income measures (in 2000 U.S. dollars) used in the property value models. For each simulated landscape, we measure total water withdrawals in each city and surrounding area (equations [7] and [8]) with empirical models described in Appendix B. The determinants of urban water demand are the price set by the municipal water board, the pricing structure, city population and population density, household income, and climate. Water withdrawals for agriculture are calculated using georeferenced data on irrigation water rights from the Oregon Water Resources Department (OWRD; see Appendix B for additional detail). We assume that all current irrigation rights are fully exercised in each simulation year. In addition, water rights seniority, which is included as an explanatory variable in the agricultural land value equation, is updated over the course of the simulation time horizon to reflect increases in the value of irrigable land.

Table 3 lists characteristics for the year 2000 for each of the cities included in the landscape simulations. The cities of Salem, Eugene, and Woodburn were chosen to illustrate how the relationship between urbanization and water withdrawals depends on the spatial distribution of water endowments across the landscape. Woodburn has the lowest population (19,557 persons) and average household income ($33,722/household) of the three cities, but contains by far the largest amount of irrigated agricultural land in its surrounding area (approximately 71% of all land). Eugene, at the other extreme, has the largest population (192,215 persons) and relatively little irrigated agriculture in its surrounding area (22% of all land). Compared to Eugene, Salem has a slightly smaller population (169,768 persons), higher income ($40,051/household), and more of its surrounding land in irrigated agriculture (40% of all land). The initial sizes of the Salem and Eugene UGBs are comparable in area, at 43,346 and 48,779 acres, respectively, while the Woodburn UGB is much smaller at just 4,035 acres. Although Woodburn is the smallest of the three urban areas in terms of both area and population, it is also the densest at just over 6 persons per acre. The Salem and Eugene UGBs are nearly identical in terms of initial density at 5.20 and 5.19 persons per acre, respectively. For each of the three cities, the Woods and Poole income growth projections suggest that real income will more than double between 2000 and 2070.

Consistent with Oregon’s land use planning system, all new development in the simulations occurs inside of UGBs on land that is “developable”, defined as privately-owned land in crops, pasture, forest, or range. For each transition period, each eligible plot’s predicted development probability is reformulated so that it corresponds to a 10-year time-step, and then compared to a random draw from a U(0,1) distribution, as in Lewis and Plantinga (2007).[32] If the development probability is greater than the random draw, the plot’s land use is changed to urban and remains in that use until the end of the simulation. Otherwise, the plot remains undeveloped and is eligible for development in the next transition period. This procedure is repeated for every plot and transition period, producing simulated landscapes on a decadal time-step. To capture the range of potential landscape patterns, we generate 100 sets of landscapes using different random draws from the U(0,1) distribution.

As the simulation proceeds and undeveloped plots are converted to developed use, UGBs expand to encompass additional developable plots. The percentage of privately-owned land within the UGB in a developed use is used as the trigger for UGB expansions. To investigate how the density of new land development influences future water use, we construct three different UGB scenarios based on expansion thresholds of 60%, 70%, and 80% of land in a developed use. These scenarios are referred to as the “high sprawl”, “moderate sprawl”, and “compact development” scenarios, respectively. For comparison, in the initial year of the simulation (2000), the developed shares were 79.1%, 78.5%, and 80.2% for the Salem, Eugene, and Woodburn UGBs, respectively. When the developed share threshold is exceeded, new parcels of land are brought inside the UGB until the developed share is once again below the threshold value. The criteria for selecting parcels to bring into the UGB are contiguity to the existing UGB, zoning, and distance to major roads and the UGB center. These criteria approximate the rules that are applied by local zoning authorities.

In addition to the UGB scenarios, we examine two persistent drought scenarios. These scenarios entail permanent reductions in growing season precipitation of 2 and 6 inches. In 2000, the mean growing season precipitation was 13.04, 13.23, and 13.24 inches in Salem, Eugene, and Woodburn, respectively. Based on the econometric results, a reduction in growing season precipitation at the average level observed in the data will decrease the value of non-irrigated agricultural land and increase the likelihood that these lands will be developed. Although reduced precipitation has a small net effect on the value of irrigated lands (see above discussion on the agricultural land value model), the more rapid development of non-irrigated lands leads to more frequent UGB expansions, indirectly increasing the conversion of irrigated agricultural lands to developed use. While the precipitation reductions are somewhat arbitrary and ignore potentially significant intertemporal fluctuations in growing season rainfall, they represent one aspect of the changes predicted during the summer months in the study area (Mote et al. 2014). For each persistent drought scenario, we calculate urban water withdrawals under the alternative assumptions that households a) entirely offset the reduction in precipitation with additional outdoor watering or b) keep outdoor watering constant at the level with no precipitation shock. In this way, we bound the possible ways in which urban water users may respond to the reduction in precipitation. We assume that the precipitation changes do not influence indoor urban water use. The two precipitation scenarios are conducted with the 70% UGB expansion rule.

Simulation results

UGB expansion scenarios

For each urban area and UGB expansion scenario, we report total water withdrawals over the period 2020-2070 (Figure 3). Additional details on the simulation results are found in Appendix C. In Salem, despite a more than doubling of household real income and population, total water withdrawals increase by 2070 only by 4-7% under the three scenarios (panel a). While population and real income growth increase water demand, higher population densities and the conversion of irrigated agricultural land to developed use have large countervailing effects. The largest share of new land development takes place on non-irrigated agricultural land (63-69%), but a considerable amount of irrigated agricultural land is also converted (31-36%). Very little forest is developed (< 1%). Total water withdrawals for urban users increase by about 19,000 acre-feet per year by 2070, but withdrawals for agriculture decline by between 30-60% of this amount. Surprisingly, the upward trend in total water withdrawals is dampened by land-use regulations that permit lower-density development. Relative to the compact development scenario, the growth in total water withdrawals by 2070 is 16% lower under the moderate sprawl scenario and 43% lower under the high sprawl scenario. The looser development rules result in the conversion of more irrigated agricultural plots, which dominates the positive effect on urban water demand of relatively lower population densities.

Because of the large amount of irrigated agricultural land in its vicinity, total water withdrawals in Woodburn decline slightly under all three UGB expansion rules (panel b). Despite a doubling of household real income and population by 2070, total water withdrawals drop as most new land development occurs on irrigated agricultural lands. In contrast to Salem, the bulk of new land development in Woodburn takes place on formerly irrigated land (57-59%), followed by non-irrigated land (41-42%) and forest (< 1%). In the moderate and high sprawl scenarios, less stringent UGB expansion rules accelerate the decline in water withdrawals. As in

Salem, the lower population density under these scenarios increases urban water withdrawal, but not enough to overcome the declines in agricultural water withdrawals resulting from land development.

In Eugene, total water withdrawal increases by 16-17% by 2070 under the three scenarios (panel c). Although population and real income growth in Eugene are similar to the other cities, total water withdrawals in Eugene increase by more because there is little surrounding land in irrigated agriculture. Much of the new development in Eugene takes place on formerly non-irrigated agricultural land (69-78%), while Eugene also experiences the largest number of forest conversions (5%). The principal moderating effect on total water withdrawal is the gain in population density, which increases from 3,521 to 5,012 persons per square mile by 2070 under the compact development scenario. Total water withdrawal changes little across the three UGB scenarios because, in all cases, the water savings from greater conversion of irrigated agricultural land are offset by the increase in urban water withdrawals induced by lower population densities.

Persistent drought scenarios

Figure 4 displays total water withdrawals for the three cities under the alternative assumptions regarding urban outdoor watering. Each panel in the figure shows total water withdrawals over time for the 2- and 6-inch precipitation reductions and the baseline trend with no reduction in precipitation. A comparison of the results for Salem reveals that the relative effect of reduced precipitation turns on the assumption of how residential households alter their outdoor watering. When urban households offset the precipitation reductions (panel a), total water withdrawal is initially higher, but over time, as relatively more land is developed under the scenarios with reduced precipitation, the decline in irrigation more than offsets the gain in urban withdrawals. When urban water withdrawals for outdoor purposes remain constant (panel b), reduced precipitation leads to lower water withdrawals throughout the entire simulation period. The lower total water withdrawals that accompany reduced precipitation are due to the fact that a decrease in precipitation lowers the value of non-irrigated agricultural land, which increases development and triggers more frequent and larger UGB expansions. The UGB expansions increase the conversion of irrigated agricultural land to development, thereby reducing total water withdrawals. The area of irrigated agricultural land developed by 2070 rises by 17% under the 6-inch precipitation reduction scenario compared to the baseline (Table 3). This effect is more than offset when urban households respond to precipitation reductions by increasing outdoor watering. A similar pattern is seen in Eugene (panels e and f), except that water withdrawals remain higher throughout the simulation when urban substitution takes place (panel e).

Although the differences across the scenarios are not large, the results demonstrate how persistent drought conditions influence water withdrawals by decreasing the opportunity cost of land development. These indirect effects are especially pronounced in the case of Woodburn (panels c and d). In this case, reductions in precipitation cause a further decline in water withdrawals regardless of how urban water users adjust outdoor watering. Under the 6-inch reduction scenario, the area of agricultural land converted to development increases by 66% relative to the baseline (Table 3). Because so much of the land surrounding Woodburn is in irrigated agriculture, some of these lands are inevitably brought into the UGB and subsequently developed. The net effect of development, as seen in the UGB scenarios, is to decrease total water withdrawals.

V. CONCLUSIONS

In this study, we have explored the potential ways in which water withdrawals are influenced by urbanization patterns, and specific drivers of urbanization. The empirical analysis is conducted for an individual region, Oregon's Willamette Valley, so as to better account for important market adjustments, human behavioral responses, and government institutions. While we are unable to predict how the current policy framework in Oregon will change in the future, this detailed approach allows us to explicitly model existing institutions governing land and water allocation and reveals a complicated relationship between future water withdrawals and changes in environmental and socio-economic drivers. In particular, the analysis identifies mechanisms through which growth in population and real income and declines in precipitation can cause total water withdrawals to decrease. Rising population and real income increases the demand for urban water withdrawals, but can also lead to the conversion of agricultural land to developed uses. To the extent that irrigated agricultural lands are developed, the net effect on water withdrawals can be negative. This effect is reinforced by higher population densities, as households occupying less land tend to demand less water. Declines in precipitation can decrease the value of non-irrigated agricultural land, leading to more land development and lower overall water withdrawals. In the three cities examined in the simulations, average population growth is roughly 85% and real income more than doubles in each case. Nevertheless, water withdrawals increase by at most 17% and in one city decrease slightly. In addition, persistent drought conditions are found to have relatively small negative effects on total water withdrawals.

The mechanisms that determine water withdrawals depend critically on the government institutions that regulate natural resources. In the study region, land development tends to reduce water withdrawals because Oregon irrigation water rights are tied to particular parcels of land and cannot be transferred to other parcels when the land leaves agriculture. Moreover, UGBs determine which parcels are eligible for development and define the extent of the urban area, thereby influencing population density. The simulation results suggest that less stringent UGB expansion rules result in lower water withdrawals, as the water savings from conversion of irrigated agricultural land outweigh the increased water withdrawals that result from lower population densities. UGBs also play an important role in determining the effects of persistent drought on total water withdrawals. A reduction in precipitation lowers the value of non-irrigated agricultural land, leading to more development and larger UGB expansions. As a result, more irrigated land is developed, lowering water withdrawals. Whether precipitation decreases lead to higher or lower water withdrawals depends in part on how residential households modify outdoor watering in response to this change.

While the results of this analysis suggest that low-density residential development tends to reduce water withdrawals, such development patterns can have a number of negative environmental consequences (Wu 2008, Irwin et. al 2009). Another potential way to achieve a decrease in total water withdrawals would be to increase urban water prices to reduce residential water withdrawals at the intensive margin. For Salem, the urban water demand model (Appendix B) suggests that the 2070 difference in water withdrawals between the high sprawl and compact development scenarios could be achieved if the baseline price of $1.93/ccf were raised to $2.68/ccf, a 39% increase. The use of pricing, as opposed to land use policy, to reduce water withdrawals could be particularly applicable in areas where the residential sector accounts for a relatively large share of total water withdrawals.

Although this study provides new insights into the potential consequences of urbanization on water withdrawals, a number of limitations bear mentioning. First, although the adopted modeling framework captures many of the adjustments in local land markets, agricultural commodity prices, along with water allocation institutions, are treated as exogenous. As such, when agricultural land is developed, our approach does not account for price changes that could induce intensive or extensive margin adjustments elsewhere. To the extent that these adjustments increase water withdrawals (e.g., for irrigation of new agricultural lands), the results presented here will overestimate water savings associated with land-use changes. We also do not account for potential water transfers between irrigators. These are permitted to a limited degree in Oregon, although they are far less common in our study area compared with other western states (Brewer et al. 2008). In future research, this modeling approach could be applied within a more comprehensive framework, such as a national-scale model of land-use change with endogenous commodity prices (Lubowski et al. 2006).

Second, we assume that all agricultural landowners fully exercise their water rights in every year. This may not happen if there is heavy rainfall in late spring, in which case we will overestimate agricultural water withdrawals. Further, we do not attempt to model groundwater dynamics within our framework. If groundwater-dependent farmers are unable to satisfy their water needs due to increased pumping costs that come about from aquifer depletion, then the estimates of future withdrawals will be attenuated. However, it is possible that current groundwater users would switch to surface water for their irrigation needs. It is also possible that that junior water rights holders will be shut off in the future due to insufficient supply for senior water users. Curtailment of water rights would increase the likelihood that the land would be developed; the consequences for water withdrawals are the same.

Third, we do not account for return flows to the hydrological system, which leads us to focus on water withdrawals, rather than net water use. This is a minor issue for irrigated agriculture, as low-efficiency irrigation technologies are rarely used in our study region (USDA

2015), but is significant in the case of urban water use. Much of the water consumed by urban residents is treated and deposited back to its original source, in which case, to the extent that water is not lost in transmission, changes in net urban water use that result from land development will be smaller than changes in water withdrawals. As such, from an environmental standpoint, net water use, or consumption, may be the more relevant metric to consider in designing water policy. While a sophisticated representation of the hydrological and urban water delivery system is beyond the scope of this analysis, the present framework could serve as a building block for a more comprehensive future study that integrates fine-scale hydrological and land-use models.[33]

Acknowledgements

The authors acknowledge helpful comments from seminar participants at Oregon State University, USDA Economic Research Service, and Western Michigan University. Useful feedback was also received from conference attendees at the Land Use and Ecosystem Services Provision Workshop held at the University of California, Santa Barbara in May 2014, the 2014 Heartland Environmental and Resource Economics Workshop at the University of Illinois, Urbana-Champaign, and the Association of Resource and Environmental Economists 2015 Summer Conference. The research was supported by a grant from the National Science Foundation Water Sustainability and Climate Program. The views expressed are those of the authors and should not be attributed to the U.S. Department of Agriculture or Economic Research Service.

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Manuscript tables

Table 1

Hedonic estimation results

	(1) Developed		(2) Agriculture		(3) Forest	
Variables	**Coefficient**	**Std. Error**	**Coefficient**	**Std. Error**	**Coefficient**	**Std. Error**
Slope	-0.019	0.005***	-0.010	0.012	-0.034	0.007***
Parcel size	-0.488	0.019***	-0.004	0.001***	-0.0002	0.000
HH income	0.054	0.008***	0.053	0.009***	0.108	0.014***
HH income^2	-0.0003	0.000***				
Pop. density	0.239	0.041***	0.252	0.055***	0.486	0.103***
Pop. density^2	-0.018	0.006***				
Inverse Mill's ratio	0.295	0.033***				
Improvement value	0.001	0.000***				
UGB (endog)	0.918	0.065***				
UGB*Year2000	-0.444	0.042***				
UGB*Year1992	-0.26	0.042***				
UGB*Year1986	-0.198	0.043***				
UGB*Year1980	0.017	0.043				
Dist. UGB			-0.023	0.013*	-0.112	0.051**
Dist. UGB^2					0.007	0.003**
Distance to city center	-0.041	0.008***				
Distance to city center^2	0.0004	0.000*				
Min. temperature			0.003	0.11		
Precipitation			0.360	0.194*		
Precipitation^2			-0.011	0.006*		
Irrigation right			1.749	1.488		
Irrigation right priority			0.003	0.002**		
Irrigation x precip			-0.216	0.202		
Irrigation x precip^2			0.006	0.007		
LCC12			0.525	0.192***		
LCC34			0.328	0.186*		
LCC1234					0.099	0.086
Elevation					-0.001	0.000***
PNI					0.415	0.066***
River presence					-0.078	0.087
Distance to mill					-0.112	0.051**
Distance to mill^2					0.007	0.003**
Number of parcels	2,659		586		464	
Number of observations	8,387		2,499		1,974	

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The coefficients in column (1) were generated with a Hausman-Taylor estimator where the UGB dummy variable is treated as endogenous. The results in columns (3) and (5) were generated with correlated random effects estimators. In all models, the dependent variable is the logged, per-acre value of land (in $2000 USD). All models also contain a constant term, county dummy variables, and year dummy variables. The agriculture and forest specifications also contain the selected parcel means of the time-varying covariates.

Table 2

Land-use model estimation results

	(1) Pooled logit		(2) Fixed effects LPM	
	Agriculture to development			
Variables	**Marginal effect**	**Std. Error**	**Marginal effect**	**Std. Error**
Developed use value	0.00048	0.00012***	0.00089	0.00010***
Agricultural use value	-0.03991	0.00013*	-0.02521	0.00781***
Mean dev. use value	-0.00025	0.01130***		
Mean ag. use value	0.15104	0.03647***		
Number of plots	41,840			
Number of observations	165,460			
	Forest to development			
Variables	**Marginal effect**	**Std. Error**	**Marginal effect**	**Std. Error**
Developed use value	0.00009	0.00004**	0.00035	0.00013**
Forest use value	-0.09399	0.05659*	-0.17935	0.09364*
Mean dev. use value	0.00000	0.00002		
Mean for. use value	0.15926	0.09675*		
Number of plots	31,476			
Number of observations	125,513			

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The above results pertain to binary-choice models representing plot-level development decisions. Dependent variables are coded as a '1' if the plot is developed at some point within the transition period. Standard errors clustered at the level of LCT blocks.

Table 3

Simulation area characteristics and selected simulation results

Table 3: Simulation area characteristics and selected results

Characteristics	Eugene	Salem	Woodburn
Income per household (2000)	35,054	40,051	33,722
Forecasted income growth (chg. 2000-2070)	45,388	54,341	43,708
Population (UGB; 2000)	192,215	169,768	19,557
Forecasted population growth (chg. 2000-2070)	110,734	194,431	21,131
Population density (people/acre; 2000)	5.19	5.20	6.02
Initial size of UGB (acres)	48,779	43,346	4,035
% of land in agricultural use	47.50	65.24	75.42
% of land in forest use	24.93	8.18	2.59
% of agricultural land irrigated	21.96	40.37	70.63
Selected results			
Compact Development - total agricultural conversions	1,836	7,357	1,183
Compact Development - total irrigated conversions	329	2,268	695
Moderate Sprawl - total agricultural conversions	2,112	9,520	1,569
Moderate Sprawl - total irrigated conversions	442	3,156	911
High Sprawl - total agricultural conversions	2,585	12,709	1,975
High Sprawl - total irrigated conversions	704	4,634	1,137
2-inch Precip. Reduction - total agricultural conversions	2,277	10,121	1,751
2-inch Precip. Reduction- total irrigated conversions	532	3,568	1,059
6-inch Precip. Reduction - total agricultural conversions	2,758	11,902	2,297
6-inch Precip. Reduction - total irrigated conversions	829	4,815	1,516

Notes: The selected results listed above represent the mean area (in acres) of agricultural land and irrigated agricultural land that is developed over the period 2000-2070 for each simulated scenario.

Figure list

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[1] Similar relationships are produced from equilibrium models of urban areas (e.g., eq. [13] in Capozza and Helsley 1989).

[2] We are assuming that R^u and R^d are well-behaved functions of t. For example, a common formulation in urban equilibrium models (e.g., Capozza and Helsley 1989) is to specify R^u as constant and R^d as a monotonically increasing function of t.

[3] The forfeiture component of Oregon water law does not apply to municipalities, which are allowed to claim excess water supplies in preparation for future population growth. Specifically, per the Oregon Water Resources Department: "The OWRD allows incremental perfection of water rights for municipalities. In this case, part of a permit is certified; the balance is left as a permit. In order to delay certification of the uncertified portion of the permit, the municipality must continue to extend the permit. This option is available only to municipalities." (Cooper 2002)

[4] The right-hand side of Figure 2 illustrates the pattern of developed land and irrigation water rights for the three Willamette Valley cities featured in our simulations using a 30 x 30 km grid drawn around the center of each city's UGB. Data on land cover for each city comes from the resampled 100m version of the 2001 National Land Cover Database used in Lawler et al. (2014).This is the same layer used to initialize the landscape simulations discussed in Section IV. GIS information on the location of irrigation water rights comes from the Oregon Water Resources Department (OWRD): http://www.oregon.gov/owrd/pages/MAPS/index.aspx.

[5] Prior to estimation, all land values are adjusted for inflation to the year 2000 using the Consumer Price Index.

[6] According to the Oregon Department of Land Conservation and Development (http://www.oregon.gov/LCD), EFU zoning "limits development that could conflict with farming practices". FC zoning is the forest equivalent of EFU. The land parcels that comprise these zones have remained largely unchanged over time.

[7] The i subscript is included on T_i to allow for the possibility of an unbalanced panel.

[8] All supplemental appendix materials may be found online.

[9] For the cities we examine, only one UGB expansion occurred during the 1973-2000 study period.

[10] For a recent overview and application of HT estimation in the context of hedonic property valuation, see Abbott and Klaiber (2011).

[11] Outside UGBs, new development is confined to established rural development zones, which permit rural residential and rural industrial/commercial uses. The rural development zones have remained largely unchanged since the initial establishment of Oregon's land-use plan.

[12] We include the assessed value of physical structures to account for the possibility that the respective values of land and buildings (e.g., single-family residential homes) are not separable.

[13] The composition of the developed sample also changes over time because of subdivision, a process we describe in more detail below. The sample selection correction also addresses this source of potential attrition bias.

[14] Because all parcels in our undeveloped sample are outside of UGBs, the UGB variable would perfectly predict s_{it} for these parcels.

[15] Large values of $\hat{P}_{it}^u$ could be associated with high returns to undeveloped or developed uses, since the latter are capitalized into undeveloped land values. In preliminary regressions, we obtain the counterintuitive result that $\hat{P}_{it}^u$ has a *positive* effect on the probability that undeveloped land is developed, which likely reflects the fact that prices will be large for undeveloped lands just prior to development. To obtain a pure measure of the returns to undeveloped land, we set to zero the terms in $\hat{P}_{it}^u$ related to future development rents (population density, household income, and distance to closest UGB). Thus, we assume that a parcel is developed if the discounted stream of returns to developed use exceeds the discounted stream of returns to undeveloped use net of conversion costs. This is similar to the assumption made in most empirical land-use studies (e.g., Stavins and Jaffe 1990, Lubowski et al. 2006). Results from the preliminary regressions that include the full measures of undeveloped land values are available upon request.

[16] Given our aim of using the binary land development models for simulation, a mixed logit model (e.g., Newburn and Berck 2006, Wrenn and Irwin 2012) is not a viable option, as simulating the log-likelihood function is prohibitively time-consuming for our large data set (Lewis and Alig 2014).

[17] We note that many other economic analyses of land values use data that are not from actual transactions. For example, Ricardian analyses of climate and agricultural land values use self-reported land value estimates from the

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U.S. Census of Agriculture (Schlenker et al. 2005) or individual surveys of self-reported land values (Fezzi and Bateman 2015).

[18] The years used for RMV panel data sets match those for the Land Cover Trends (LCT) data used to estimate the land-use models.

[19] Parcels were removed from the initial sample if they 1) did not have a match in the county's GIS parcel layer, 2) had greater than a 10% discrepancy between their GIS acreage and that given by the assessor's office, 3) were not privately owned in all five sample years, 4) were less than 0.05 acres if in a developed use, or 5) were less than 10 acres if in an undeveloped use. These latter two restrictions were imposed to remove "slivers" of developed lands and agricultural and forest lands that are likely to be used primarily for rural residential purposes.

[20] There is also some reverse attrition with the forest and agricultural samples, although it is much less common and mainly due to redrawn property boundaries and parcel agglomeration. We do not explicitly model attrition in the undeveloped parcel samples.

[21] For the developed parcels where we observe an acreage discrepancy indicative of subdivision, we include them as undeveloped when estimating (10) for the years prior to the observed acreage change. Note, however, that there is no crossover of the parcels between the three different hedonic models. That is, developed parcels prior to sub-division are not included in any of the hedonic models, but do enter the developed hedonic model after the subdivision has taken place.

[22] Some LCT plots are coded sequentially as forest, mechanically disturbed, grassland, and then forest. These plots have undergone timber harvest and regrowth (Sleeter et al. 2012), and we treat them as forest in all time periods.

[23] Although the results are not presented here, we estimated the hedonic models with a variety of alternative specifications and estimators. The estimates are largely robust across different specifications and estimation procedures. Interested readers are directed to Bigelow (2015) for additional detail on the hedonic robustness checks.

[24] Results from the sample selection models are given in Appendix Table A4. Most importantly, the irrigation right dummy variable is highly significant in all five selection models. As expected, an irrigation right reduces the likelihood that a parcel will be included in the developed land sample.

[25] First-stage results from the HT instrumental variables estimation procedure are given in Appendix Table A5. We use the Cragg-Donald Wald F statistic (Cragg and Donald 1993) to test for weak instruments. The null hypothesis that the excluded instruments (the parcel means of the time-varying covariates) are weak is rejected at conventional levels of significance.

[26] The exception is the interaction term for 1980. The UGB legislation was originally passed in 1973, but was not implemented in most cities until the late 1970s. The results show that the UGB effect did not change until after the legislation had been in place for several years.

[27] Note that there is potentially a bidirectional relationship between agricultural land values and irrigation right seniority. Specifically, since seniority is based on the order in which claims were made on a given water source, earlier claims are more likely to have been made for land that has a higher agricultural use value. In the hedonic specification, we account for agricultural use value through the parcel size, slope, and land quality variables, but any remaining unobserved factors that influence agricultural productivity could potentially bias the coefficient estimates. However, we have also conducted the simulations using an agricultural hedonic specification in which seniority is not explicitly accounted for, and found that the results are largely unchanged from those presented here. This provides some assurance that the inclusion of the seniority variable has little effect on the main results of the analysis.

[28] We also tested for differences in the effect of precipitation between groundwater and surface water irrigators, but did not find any significant effect.

[29] The land development models have also been estimated with a variety of different estimators and specifications of the hedonic models, all of which produce results similar to those reported here in terms of sign and significance (Bigelow 2015).

[30] For the simulation, the resolution of the land-use data is 100m, which was derived by upscaling the original 30m 2001 NLCD raster data layer.

[31] Bigelow (2015) contains results from additional scenarios with alternate population growth trajectories. Results from a set of scenarios with lower income growth paths are also available upon request.

[32] In the LCT data, the mean transition period is 6.75 years. If the predicted probability of development over this time period is $\hat{p}$, then the corresponding 10-year probability is given by $\tilde{p} = 1 - (1 - \hat{p})^{\left(\frac{10}{6.75}\right)}$.

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[33] An example of a comprehensive study of this sort is the Willamette Water 2100 project: http://water.oregonstate.edu/ww2100/.