Best Practices for Using Hedonic Property Value Models to Measure Willingness to Pay for Environmental Quality

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Introduction

The hedonic property-value model is among the most direct illustrations of how private markets can reveal consumers' willingness to pay (WTP) for measures of environmental quality. There have been thousands of applications of the model since it was first developed in the 1970s and its use has accelerated with increases in data accessibility and advances in econometrics and computing power. The hedonic model's enduring popularity is easy to understand. It begins with an intuitive premise that is both economically plausible and empirically tractable. The model envisions buyers choosing properties based on housing attributes (e.g., indoor space, bedrooms, bathrooms) and on location-specific amenities (e.g., air quality, park proximity, education, flood risk). In the absence of market frictions, spatial variation in amenities can be expected to be capitalized into housing prices. When buyers face the resulting menu of price–attribute–amenity pairings in the housing market,

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We are grateful for helpful comments and suggestions from Noelwah Netusil and participants in the 6th World Congress of Environmental Economics (Gothenburg, Sweden, June 2018).

Review of Environmental Economics and Policy, volume 14, issue 2, Summer 2020, pp. 260–281
doi: 10.1093/reep/reaa001
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their purchase decisions can reveal their WTP for marginal changes in each of the amenities.[1]

In recent years, the standard approach to empirical hedonic research has evolved to incorporate insights from the "credibility revolution" in applied microeconometrics. This revolution has raised expectations about data quality and econometric transparency. Recent research has also improved our understanding of how parameters identified through quasi-experimental research designs relate to welfare measures (i.e., measures of WTP). Based on an examination and synthesis of the evidence in the literature, this article summarizes "best practices" for hedonic property-value modeling when the goal is to measure households' WTP for a change in an environmental amenity.[2] Most of the studies that helped to establish best practices in hedonic modeling used rich data on metropolitan housing markets in advanced economies. Data describing housing transactions, characteristics, and amenities are becoming increasingly available around the world, creating new opportunities to use hedonic models for policy analysis.[3] Although hedonic property-value models are used for many purposes, our focus here is on measures of welfare that can be used to inform public policy.

We argue that the starting point for these best practices is a research design that identifies a source of exogenous variation in an amenity that is observable by prospective buyers (e.g., air quality). Data on the sale prices and physical attributes of individual houses, together with location-specific measures for amenities, are then used to estimate a flexible housing-price function. Under ideal conditions, the derivative of this price function can then be interpreted as indicating the amenity's implicit price, which can then be used to calculate household marginal WTP (MWTP) for the amenity. In principle, the process of estimating MWTP is straightforward. In practice; however, several key modeling decisions must be made, including choosing measures of sale prices and amenities and choosing the econometric specification. We conclude that although the steps required to develop a "best practices" study may seem daunting, the effort is both worthwhile and important for developing measures of MWTP that can help to inform policy. Indeed, the modern hedonic property-value model has been refined through more than forty years of intense scrutiny to become one of the premier approaches to valuing changes in environmental amenities in academic research, litigation, and public policy (Palmquist and Smith 2002; United States Environmental Protection Agency 2010).

The remainder of the article is organized as follows. The next section summarizes the foundations of the hedonic property-value model. We then discuss best practices for using hedonic property-value models to measure the WTP for environmental quality. In particular, we discuss best practices for defining the market, collecting data, choosing an econometric

[1] Nearly 100 years ago, in some of the first work on hedonic modeling, Waugh (1929, p. 100) proposed a remarkably similar "statistical analysis." He suggested that ". . .instead of compiling the reported likes and dislikes of individuals, this type of statistical analysis attempts to estimate these preferences for the whole group of dealers or consumers in the market area by measuring the market price differentials due to a number of quality factors."

[2] This article is part of a symposium on best practices for revealed-preference approaches to nonmarket valuation. The other articles are Bateman and Kling (2020), which introduces the symposium; Evans and Taylor (2020), which examines revealed-preference methods for estimating the value of reduced mortality risk; and Lupi, Phaneuf, and von Haefen (2020), which discusses best practices for recreation-demand analysis.

[3] See the online supplementary material for a summary of data availability and sources of information on house sales, sample applications of the hedonic property-value model for twenty-four countries, and additional discussion of modeling issues that may arise in rural areas and less-than-ideal data settings.

specification for the hedonic-price function, mitigating omitted-variable bias, and using MWTP measures to inform policy. It is important to note that MWTP measures can also be combined with additional information about households to estimate amenity-demand curves and assess the WTP for nonmarginal changes in environmental amenities; however, we leave the task of defining best practices in hedonic demand estimation to future research. We conclude with a summary and a discussion of priorities for future research in this area.

Foundations of the Hedonic Property Value Model

The hedonic framework has a long history in economics (e.g., Waugh 1929; Court 1939; Griliches 1961; Lancaster 1971). Rosen's (1974) seminal paper established the hedonic framework as an equilibrium model for understanding what differentiated-product prices could reveal about consumer demand for product attributes.[4] In the housing context, the hedonic model incorporates information about the supply of housing, including developers' decisions about new home construction and factors that influence resales of existing homes, as well as household preferences and income. After buyers and sellers negotiate transactions, market equilibrium occurs when no households can increase utility by moving. This equilibrium concept implies a relationship between house prices and house characteristics that reveals each buyer's MWTP for each characteristic, assuming that buyers are fully informed, freely mobile, and able to purchase continuous levels of each characteristic.[5] In the remainder of this section, we present key features of the hedonic property-value model.[6]

The Housing Price–Amenity Function Reveals Each Buyer's MWTP for the Amenity

Figure 1a graphs housing prices as a function of the measure of one of the local amenities (e.g., air quality), holding physical characteristics and other amenities constant. Figure 1b illustrates the process through which this price function reveals buyers' MWTP for the amenity.[7] There are two buyers' bid curves, each of which indicates the maximum amount the respective buyer is willing to pay (as a function of the amenity level and holding other influences on their choices constant). Purchases occur where the bid curves are tangent to the price function. That is, buyer 2 purchases a house with amenity level A_2 at a price of P_2 and buyer 1 purchases a less expensive house (P_1) in a lower-amenity area (A_1). These two coordinate sets—(P_1, A_1) and (P_2, A_2)—are the points at which each buyer's MWTP for a small change in

[4]It offers a direct analog to the Cowles Commission's approach to connecting structural and reduced-form models (Morgan 1990).

[5]These assumptions have subtle implications. For example, "free mobility" does not imply that it must be costless to move. Buyers' choices will still reveal their MWTP at the time of their purchase decisions if they were able to choose continuous levels of each characteristic, while facing a fixed cost of moving. However, the assumptions may be violated if some prospective buyers are excluded from renting or buying properties because of discrimination.

[6]For a technical discussion, see Palmquist (2005), Kuminoff, Smith and Timmins (2013), Freeman, Herriges and Kling (2014), Phaneuf and Requate (2017), or Taylor (2017).

[7]In the Rosen (1974) model, each point on the price function is the tangency between a particular seller's offer curve and a particular buyer's bid curve. These are the points at which market trades occur. To focus on demand, we do not show sellers' offer curves in figure 1b.

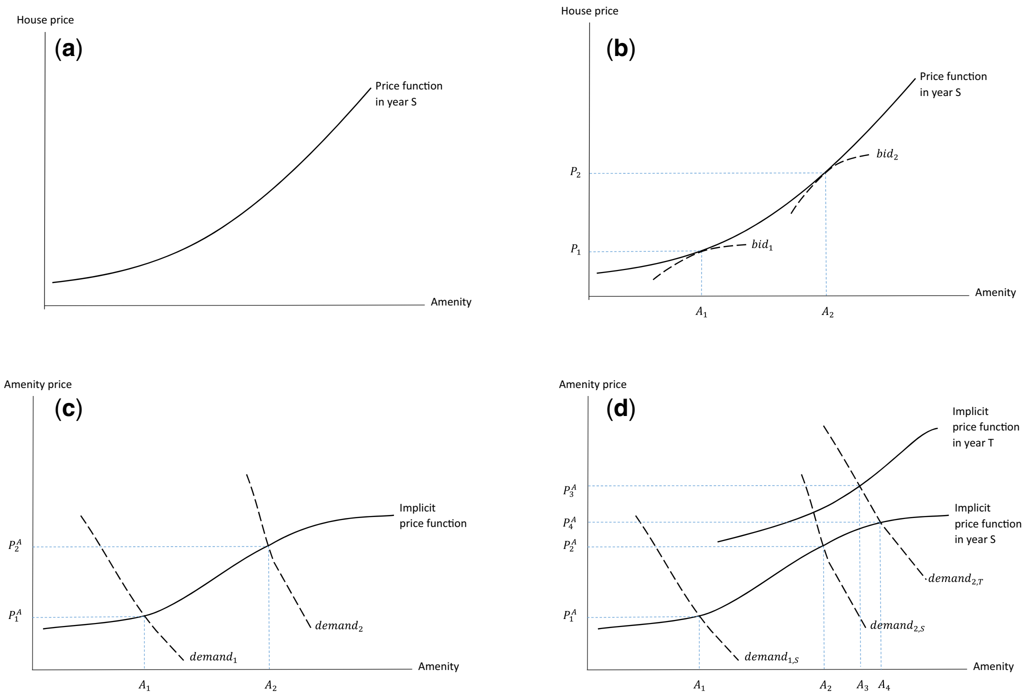

Figure 1 Using the hedonic-price function to infer buyers' MWTP for an amenity.
Notes: (a): The hedonic housing price–amenity function. (b): The buyers' purchase decisions. (c): The implicit-price function reveals buyers' MWTP. (d): The implicit-price function and MWTP change over time.

the amenity (the bid curve's slope) equals the implicit price that each buyer must pay to obtain that small change (the price function's slope).

Figure 1c illustrates this same result in a different way. The algebraic forms used for the hedonic-price function (illustrated in figure 1a) and the buyer bid curves (in figure 1b) imply algebraic forms for the implicit-price function for the amenity and the buyer demand curves in figure 1c (i.e., the derivatives of the hedonic-price function and bid curves). Figure 1c shows that the implicit-price function for the amenity intersects the buyers' demand curves at their chosen amenity levels. Thus, one can estimate each buyer's MWTP for the amenity in three steps: (a) estimate the hedonic-price function using observed sales data, (b) estimate the implicit-price function by partially differentiating the price function with respect to the amenity of interest, and then (c) interpret the resulting implicit-price values paid by each buyer as estimates of the buyer's MWTP.

More Information Is Needed to Estimate Each Buyer's Demand for the Amenity

Figure 1c also illustrates that knowing buyers' MWTP is not sufficient to estimate their demand curves. Just as prices in other consumer markets are equal to MWTP at a point on the demand curve, the implicit-price function for the amenity reveals only a marginal value, not the entire demand curve. In other words, home purchases reveal information about demand for the amenity only at the points where the demand curves for the amenity intersect the implicit-price function. It is important to note that any number of flatter or steeper demand specifications could be drawn through the point (P_1^A, A_1). Thus, additional information about buyers would be needed to infer their demand for the amenity from the implicit-price function or, equivalently, to predict their WTP for nonmarginal changes in amenity levels. Researchers have developed several strategies for providing this additional information, which we will return to later.

The Housing Price–Amenity Function and MWTP May Change Over Time

Thus far, we have described how the hedonic-price function reveals each buyer's MWTP for the amenity at a point in time. Over time, buyers' MWTP may change and this may be reflected as a change in the implicit-price function for the amenity. Factors that may cause buyers' MWTP to change include policies that increase worker productivity, induce migration, provide new information about the amenity, or change amenity levels (e.g., stricter regulations on air pollution). Figure 1d shows the market-clearing implicit-price functions for an amenity that changes between an initial year S and a subsequent year T. The year-S implicit-price function identifies MWTP for the initial set of buyers in year S, while the year-T implicit-price function identifies MWTP for a different set of buyers in year T.[8] As we will discuss later, keeping track of temporal changes in implicit amenity prices is important for estimating MWTP for amenities.

With this background on the foundations of the hedonic property-value model, we turn next to best practices for using the hedonic model to estimate the MWTP for environmental amenities. The first step is to define the market.

Best Practices for Defining the Market

The conceptual logic of the hedonic model implies that the market should be defined so that it satisfies the "law of one price function." This principle means that identical houses will sell for the same price throughout that market. The precise spatial and temporal boundaries that satisfy this condition may vary across space and over time as information, institutions, and moving costs change. One common practice is to define the market as a single metropolitan area over a few years (e.g., Pope 2008b; Abbott and Klaiber 2013). An alternative is to pool data over larger areas and longer periods and to model the hedonic-price function as evolving over space and time (e.g., Kuminoff and Pope 2014; Walls et al. 2017).

In principle, moving costs could lead to violations of the law of one price function. However, for households that move *within* metropolitan areas, moving costs are unlikely to vary substantially. This is because the physical and financial costs of moving (e.g., realtor fees, truck rentals) do not tend to change across within-metropolitan-area destination locations and the psychological costs of moving are more limited because within-metropolitan-area moves typically allow households to maintain ties to family, friends, and neighborhoods. Thus, the law of one price function can be maintained between locations within a metropolitan area through arbitrage (i.e., buyers will not purchase a given house if they can purchase an equivalent one in the same metropolitan area for substantially less). In contrast, the law of one

[8]We assume that buyer 1 has left the market, and thus we do not include a year-T demand function in the graph. Buyers who can be observed multiple times, such as buyer 2, may have experienced changes in their personal circumstances that change their demand (e.g., wealth shocks).

price function is less likely to be satisfied if the market is defined to include several metropolitan areas and/or several years.

Challenges with Larger Geographic Areas and Longer Study Periods

One challenge with defining the market to include several metropolitan areas is that a move *between* metropolitan areas may impose large moving costs. In addition, workers who move between metropolitan areas may be forced to change jobs. Variations in local tax policies and the cost of living (aside from housing) across metropolitan areas also increase moving costs. Because the hedonic property-value model ignores labor-market considerations and heterogeneous moving costs, a focus on multiple metropolitan areas limits the model's ability to translate hedonic prices into MWTP measures. Thus, one option for avoiding this problem is to use data on commuting patterns to determine the circumstances in which moving to a different metropolitan area would likely imply moving to a new job.

Pooling data over a long period such as a decade or more introduces similar types of problems. For example, housing-price functions may change during boom–bust cycles because macroeconomic factors change the amounts homebuyers are willing to pay for amenities. Homebuyers' MWTP for amenities may also evolve with changes in policy. For instance, a policy that improves air quality may reduce homebuyers' MWTP for further air quality improvements (i.e., by moving them down their demand function for air quality). These types of changes are inconsistent with the principles underlying the law of one price function, thus limiting the model's ability to translate hedonic prices into MWTP measures.

Using Econometric Flexibility to Maintain the Law of One Price Function

In principle, some sources of spatial–temporal variation in the shape of hedonic-price functions can be addressed through flexibility in the econometric specification (e.g., McMillen and Thorsnes 2003). For example, when pooling data over multiple metropolitan areas and years, researchers can add interactions between time dummies, geographic dummies, and price function parameters to allow price functions to differ across space and time. Overall, narrowing the assumed market will tend to improve the internal validity of the hedonic property-value model by increasing the likelihood that the law of one price function holds.[9]

Best Practices for Data Collection

Once the market has been defined, the next step is to collect data. The gold standard for data collection in hedonic property value studies is to obtain a random sample (or the universe) of housing-transaction prices and characteristics for the relevant study area.[10] In recent years,

[9]Narrowing the assumed market may reduce external validity (i.e., the ability to apply the results to other markets) and the ability to examine geographically coarse amenities, such as climate features. If the goal is to understand how amenities affect the choice of a metropolitan area, then residential sorting models provide an approach for incorporating job opportunities and moving costs (Kuminoff, Smith, and Timmins 2013).

[10]We acknowledge the potential for selection bias when focusing only on houses that sell. Gatzlaff and Haurin (1998) propose a correction procedure that uses information on the non-price characteristics of houses that do not sell.

data on housing-transaction prices, characteristics, and amenities have become increasingly available for large portions of Australia, Japan, South Korea, and the United States. In addition, a few countries, such as Denmark and Sweden, have granted researchers access to administrative records containing rich socioeconomic panel data on buyers and sellers. In other countries, such as Canada and Portugal, it is still difficult to obtain microdata on transactions. The online supplementary material provides a country-by-country summary of what we could determine about data availability, data sources, and sample applications for Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Netherlands, Norway, Poland, Portugal, South Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States. While this set of countries is far from comprehensive, it provides a starting point for researchers looking for housing data or sample applications. The online supplementary material also includes a discussion of additional challenges that may arise in less than ideal data settings, including regulation of prices, sparse transactions, and lack of transaction prices.

Hedonic property-value studies that meet the gold standard for data collection often focus exclusively on single-family houses. In most parts of the United States, for example, housing transactions are a matter of public record and are usually filed with county tax-assessment boards.[11] This access allows researchers to work with data that approximate the universe of single-family housing sales in specific time periods. In the remainder of this section, we discuss best practices for preparing the data and assigning amenity levels to houses, and the challenges with using data other than single-family house transactions.

Preparing the Data

It is reasonable to expect that publicly available data on housing sales, which are often collected for other reasons, will include some data entry errors as well as some sales that did not occur through a competitive bidding process. Identifying and excluding these cases reduces the potential for measurement error. For example, it is common practice to exclude transactions in which the buyer and seller share the same last name and thus have a higher probability of being related. Similarly, it is common practice to drop foreclosure sales and purchases by real-estate investment firms, because there is a higher probability that the property has characteristics or quality issues not documented in transactions data. Finally, it is common to remove outliers that clearly indicate data entry errors (e.g., a house with 1,800 bedrooms or 3 square feet). Many researchers address such outliers by dropping a small fraction of sales that have the highest and lowest values for each characteristic. Because there is no commonly accepted threshold for outliers, it is important to document these types of decisions and assess their impact on the study's findings.

Assigning Amenity Levels to Houses

The hedonic model's logic requires the researcher to characterize how buyers perceive the amenity levels at each residential location. This requires developing an objective measure of spatial variation in the amenity that can be matched to individual houses. This task can be

[11] "Cleaned" data that had been previously filed with county boards can be purchased from CoreLogic, ATTOM Data Solutions, and other vendors.

complicated by the often "patchy" nature of amenity data. For example, air quality monitoring stations generate data on pollution levels, but houses may be located in "gaps" between monitoring stations. This means that researchers must use spatial interpolation, air-dispersion models, or predictions from satellites to assign pollution levels to houses. Similarly, proximity to recreation sites such as beaches, lakes, and parks may be measured by geographical distance, driving distance, total travel time, or the share of land devoted to that recreation use within some geographic area around a house. Thus, researchers must decide which measure best reflects the landscape characteristics that matter to homebuyers.

Another issue is whether homebuyers' beliefs about the amenity coincide with objective measures and, if not, to consider alternative ways of modeling buyer beliefs. The broader, nonmarket-valuation literature suggests that subjective beliefs about environmental quality (and nonenvironmental goods) are not always consistent with objective measures (Boyd et al. 2015). Thus, it is important to document the information channels that may influence buyers' beliefs and assess the sensitivity of estimates of MWTP to the measures of the amenity under consideration. For example, Davis (2004) shows that the measurement of cancer risk associated with a cluster of leukemia cases is robust to several different assumptions about how homebuyers formed their beliefs about the evolving level of risk. In contrast, Pope (2008a) finds that a new law requiring real-estate agents to disclose information about airport noise caused housing prices to adjust around an international airport, suggesting that the disclosure rule changed prospective buyers' beliefs about the spatial extent of noise. Assuming that the information disclosure improved buyers' knowledge about noise levels near the airport, sales after the post-disclosure period would be expected to provide more accurate estimates of MWTP to lower airport noise.

Because housing is a durable asset, households' purchase decisions may also reflect their expectations about the evolution of local-amenity levels in the future. When buying a house in the current period, for example, a forward-looking household would assess both the current and anticipated future flows of amenities when considering the current purchase price. Ignoring such forward-looking behavior can result in underestimating or overestimating MWTP. Bishop and Murphy (2019) show how to convert hedonic-price function estimates into households' MWTP when buyers are forward-looking over changing amenity levels.

Challenges with Using Data Other Than Single-Family House Transactions

Data on the sales prices and characteristics of single-family house transactions are not always available. As an alternative, researchers sometimes use data on predicted prices, rental prices, and sales of bare land, as well as spatially aggregated summary measures such as means or medians. These alternative types of housing data sets present additional challenges for interpreting price function parameters as measures of MWTP.

Predicted prices

Census data sets often include a self-reported property "value," which is generated from survey questions that ask occupants how much they think their properties would sell for. Predicted prices may also come from property assessors and other companies (e.g., Zillow).

Actual transaction prices are always preferable to predicted prices. The problem with predicted prices is that they include measurement error that is correlated with buyer demographics, housing characteristics, and neighborhood amenities (Banzhaf and Farooque 2013).[12] This correlation may lead to bias in the price function's parameter estimates.

Rental prices

In principle, housing rents may be used instead of or in conjunction with sales prices.[13] However, rental rates may be more complicated to work with than data on single-family transactions due to ambiguity about key rental-contract features, such as which party pays for utilities and maintenance. The short-term nature of rental contracts may also weaken the incentive for renters to become fully informed about local amenities prior to entering the market. On the other hand, rentals may better reflect current amenity flows. In addition, the use of rental-rate data may be particularly useful for deriving unbiased measures of average MWTP for amenities in neighborhoods where rates of owner occupation are low.

Sales of vacant land

Estimating a hedonic model of vacant land sales is consistent with the idea that the price function maps how prices vary with land characteristics. However, important institutional factors, such as zoning, prior easements, and access to public water supplies, affect how land may be used. If these factors cannot be observed, they may bias estimates of price function parameters.

Spatially aggregated data

Individual records of transaction prices are preferable to spatially aggregated measures, such as mean or median prices within Census tracts, zip codes, or counties, because theory does not provide guidance about how to move from aggregate prices to aggregate measures of MWTP. Specifically, regressing mean prices on mean amenity levels may yield an unbiased estimate of the hedonic-price function, but it will not yield an unbiased estimate of the implicit-price function (i.e., the derivative), which is necessary to derive MWTP for the amenity.[14] Moreover, median prices do not necessarily equal the price level at the medians of the attribute levels, which means that hedonic-price regressions that use medians may be biased from the outset. Thus, using summary statistics such as means and medians as if they were transaction-level prices can bias estimates of MWTP.

Apart from problems of interpretation, median prices have been found to introduce measurement error that can bias price function parameters. For example, in a study of Superfund cleanups of hazardous-waste sites in the United States, Gamper-Rabindran and Timmins (2013) find that focusing on the median house within a neighborhood produces lower

[12]The problem may be especially pronounced when prices are predicted using an algorithm (e.g., Zillow's zestimate). In this case, a hedonic regression may simply produce a reconstruction of the algorithm.

[13]This can be done by converting sales prices into annualized user costs of housing using standard formulas in the literature (Poterba 1984; Himmelberg, Mayer, and Sinai 2005).

[14]The derivative of the price function evaluated at the mean amenity level does not equal the mean of the derivatives.

estimates of MWTP than when individual house records are used. This is because hazardous-waste sites tend to be located near the lowest-price houses within a neighborhood, and thus the benefits of cleanups are mainly capitalized into housing prices at the lowest quantiles of the housing-price distribution. Problems with median prices are not limited to studies of hazardous-waste sites. For example, using data for Los Angeles, Banzhaf and Farooque (2013) compare several commonly used measures for house prices and find that among all of these measures, medians have the weakest correlation with local public goods, income, and other indices. While the reasons for this finding are not fully understood, the finding does suggest that results of hedonic models that are based on median prices should be interpreted with caution.

Best Practices for Selecting an Econometric Specification

Next, we briefly consider best practices for choosing an econometric specification for the hedonic-price function. First, the price function should be assumed to be nonlinear. This is consistent with Ekeland, Heckman, and Nesheim (2004), who prove that transactions between heterogeneous buyers and sellers yield an equilibrium price function that is "generically" nonlinear.[15] In addition, Cropper, Deck, and McConnell (1988) show that relatively flexible nonlinear specifications for the price function provide more accurate estimates of average MWTP for housing characteristics than simpler linear and log-linear specifications when omitted-variable bias is not a concern. Moreover, Kuminoff, Parmeter, and Pope (2010) find that flexible nonlinear models continue to outperform linear models even when spatial dummy variables are used to reduce omitted-variable bias.[16] Another reason for using nonlinear functional forms is that they allow the market equilibrium to reflect complementarities between amenities. For example, the implicit price of proximity to a public park may vary with the levels of crime, noise, and air quality (Albouy, Christensen, and Sarmiento-Barbieri 2018).

Second, as a rule, applications should both rely on robust standard errors of the hedonic-price function parameters and cluster at a spatial–temporal scale of variation in the amenity of interest. This practice is motivated by the common belief that it is prudent to assume that the errors may exhibit heteroskedasticity and autocorrelation (spatial and temporal). Some applications have also experimented with spatial-weighting models. While such models may enhance small-sample efficiency, their standard errors may be biased.[17] Thus, most applications avoid making such assumptions.

[15] In other words, extraordinarily strong assumptions about the shapes of utility functions and housing-production functions would be required to generate linear hedonic price functions as equilibrium outcomes.

[16] Semiparametric and nonparametric methods can provide additional flexibility when estimating hedonic price functions and their gradients, although there is currently no evidence on the implications of the bias-variance trade-off implicit in such approaches (e.g., Bajari and Benkard 2005; Parmeter, Henderson, and Kumbhakar 2007; McMillen and Redfearn 2010; Bishop and Timmins 2018).

[17] Such bias can arise because spatial-weighting models require the researcher to specify the true parametric form of the error-correlation structure (e.g., a distance-decay weighting matrix). Incorrect specification of this structure can lead to biased standard errors.

Best Practices for Mitigating Omitted-Variable Bias

Theory and empirical evidence suggest that environmental amenities will be spatially correlated due to natural features of geography (e.g., mountains, oceans), environmental feedback effects (e.g., urban heat islands), and voting on local public goods (Kuminoff, Smith and Timmins 2013). This potential for spatial correlation has fueled widespread concern about omitted-variable bias. This concern has two components. First, it seems unlikely that researchers would be able to include every amenity that matters to buyers. Second, unobserved amenities are likely to be correlated with the amenity of interest, thus causing bias. For example, if wealthy and well-educated homebuyers move to areas with better air quality and then vote to increase public school funding, estimates of MWTP for air quality will be biased upward if school quality is omitted from the model. The potential for this type of behavior by homeowners means that, for the resulting estimates to be credible, the research design must isolate exogenous variation in the amenity of interest. In the remainder of this section, we discuss several research designs that have been implemented to address this requirement, including difference-in-differences (DIDs), matching estimators, spatial dummy variables, and boundary-discontinuity designs. Although it is important to assure econometric credibility by mitigating omitted-variable problems, efforts to assure econometric credibility can sometimes hinder the ability to interpret the estimates as measures of MWTP. We discuss this trade-off for each of these research designs.

DID Research Designs

Numerous studies have interpreted environmental-policy changes and natural experiments as quasi-random "treatments" to amenities to identify how these shocks lead to changes in housing prices. This process is generally known as "capitalization," although its meaning has evolved over time. Econometric models of the capitalization process generally fit within a DID framework, which is distinguished by the way in which it analyzes how changes in amenities cause housing prices to change.[18] Most DID studies assume a stationary price function.

Advantages of the DID framework

The main advantage of the DID framework is that it mitigates omitted-variable bias. The seminal study by Chay and Greenstone (2005) illustrates the DID framework by showing how nonattainment of the U.S. Environmental Protection Agency's standards for maximum-allowable particulate-matter concentrations at the county level can be used as an instrumental variable to mitigate omitted-variable bias that could arise when analyzing how spatially varying reductions in particulate matter between 1970 and 1980 affected the (county level)

[18]This group of models includes fixed-effect and first-difference estimators that use data on repeated sales of the same houses. It also includes estimators that pool repeated cross-sections of transactions from the same geographic market. Sometimes these models utilize instrumental variables and/or regression-discontinuity designs.

median, self-reported property value.[19] In addition to addressing concerns about omitted amenities, the study's use of instrumental variables addresses potential bias from measurement errors in air pollution levels. Chay and Greenstone's quasi-experimental approach has since been applied to microlevel housing-transaction data to estimate the capitalization effects of changes in a wide range of amenities, including cancer risk (Davis 2004), fracking externalities (Muehlenbachs, Spiller, and Timmins 2015), air pollution reductions (Bento, Freedman, and Lang 2015), sand dune construction (Dundas 2017), and open space (Lang 2018).

Challenges of using the DID framework

The main challenge for interpreting results from the DID approach is that price functions may change over time (see figure 1d). Indeed, theory suggests that environmental policies and other events that create quasi-experimental changes in amenity levels may also cause price functions to adjust. This possibility means that the prices of houses in both the "control" group and the "treated" group are affected by the policy.[20] However, the key issue is not whether price functions change, but whether the changes are small enough to ignore. Such changes are important because large changes in price functions that are not specifically modeled may undermine the estimation of MWTP.

To illustrate this challenge, Kuminoff and Pope (2014) show that when a price function shifts over time, a standard DID model that ignores this shift will result in biased estimates of the slope of the price function and thus biased estimates of MWTP. This bias arises because the standard DID model combines information from two hedonic-price functions (i.e., that describe markets before and after the amenity "treatment") into a single estimate of MWTP. In an application of the DID framework to public school quality, Kuminoff and Pope (2014) show that housing-price functions in five U.S. metropolitan areas changed during the 2003–2007 boom period, which coincided with the implementation of the "No Child Left Behind Act."[21] They show that incorrectly assuming a time-constant price function would have produced a 75 percent downward bias in estimates of MWTP for school quality. This outcome contrasts with a 94 percent upward bias in cross-sectional models that ignore the omitted-variable problem. In addition, Klaiber and Smith (2013) find that cross-sectional models that ignore the omitted-variable problem may or may not outperform DID research designs if the latter are compromised by price function changes.

Strategies for interpreting DID estimates

One strategy for addressing the challenge of interpreting DID estimates of MWTP is to collect data on random variation in the size of the change in the amenity of interest, which, as noted by Kuminoff and Pope (2014), can be used to identify MWTP in the posttreatment period. A second strategy is to model the change in the price function; this is done by generalizing the

[19]Although this study is notable for its innovative approach of using instrumental variables to mitigate omitted-variable bias, concerns have been raised regarding its use of median prices and predicted prices, and the assumption that the law of one price function holds across the United States from 1970 to 1980.

[20]This result is distinct from any changes that may occur due to macroeconomic forces and other background events during the study period.

[21]This policy targeted school quality and sought to improve information conveyed to parents.

DID model by interacting price function parameters with time-period dummies, which allows the shape of the price function to change over time. Kuminoff, Parmeter and Pope (2010) show that this strategy, which has been implemented in recent empirical studies (e.g., von Graevenitz 2018), improves the accuracy of estimates of MWTP in both the pretreatment and posttreatment periods. Banzhaf (2018) further shows that this approach can identify a lower bound on a general-equilibrium welfare measure under much weaker econometric assumptions (e.g., allowing for moving costs). A third strategy is to model how omitted variables change over time and to assume that buyers have rational expectations for that process (Bajari et al. 2012).

Matching Estimators

Another option for mitigating omitted-variable bias is to use matching estimators, which match houses that received an amenity treatment with a set of untreated control houses (e.g., Abbott and Klaiber 2013; Walls et al. 2017). The goal is to find control houses that are as similar as possible to each treated house in terms of observed and unobserved physical and locational characteristics. This process uses observed property characteristics (e.g., observed amenities) to control for unobserved amenities. The challenge here is to determine the precise criteria for selecting matches between treated and untreated houses. In addition, although the econometric properties of matching estimators have been thoroughly analyzed in the program-evaluation literature, their accuracy in estimating MWTP for amenities in housing markets has yet to be evaluated.

Use of Spatial Dummy Variables

Transactions data on house purchases often offer large sample sizes, which make it possible to include a set of spatial dummy variables for local neighborhoods, such as school districts, zip codes, or Census tracts, to absorb the price effect of omitted amenities. Kuminoff, Parmeter, and Pope (2010) show that including such spatial dummy variables can mitigate omitted-variable bias and improve the accuracy of estimates of MWTP. The choice of geographic scale for these dummy variables presents a bias-variance trade-off: defining neighborhoods to be smaller reduces bias by better controlling for omitted amenities but increases variance by relying on less within-neighborhood variation in the amenity of interest. GIS maps showing how the amenity varies within and across candidate neighborhoods can help to provide information about this bias-variance trade-off (e.g., von Graevenitz 2018), which can be used to define neighborhoods appropriately.[22]

Boundary-Discontinuity Research Designs

Boundary-discontinuity designs can be used to improve the spatial dummy-variable approach by relying on variation in amenity levels within a neighborhood. The idea is to identify an amenity's marginal implicit price based on sharp changes in amenity levels that occur along administrative or geographic boundaries. By limiting the estimation sample to houses

[22]Abbott and Klaiber (2011) show how to use the Hausman and Taylor (1981) estimator to judge the importance of this tradeoff.

that are located within close proximity to boundaries (e.g., within a quarter mile) and using dummy variables for neighborhoods that surround each boundary (which absorbs all of the omitted amenities that are common to both sides of the boundary), this strategy assumes that a significant difference in the amenity of interest is most likely to lead to a price differential. Applications of this approach have included school-attendance zone boundaries (Black 1999), flood-zone boundaries (Pope 2008b), and public water-service-area boundaries (Muehlenbachs, Spiller, and Timmins 2015).

While the boundary-discontinuity design is consistent with the hedonic model's conceptual foundation, it faces at least two challenges. First, bias can arise if different types of households choose to live on opposite sides of a boundary. For instance, if wealthier households tend to locate on the "high quality" side of a school-zone boundary, and that side of the boundary also tends to spend more property-tax revenue on neighborhood parks, the estimate of MWTP for school quality will be biased if parks are not included in the model. Bayer, Ferreira, and McMillan (2007) address this challenge by controlling for differences in the socioeconomic status of households on opposite sides of boundaries. The second challenge is that the resulting measures of MWTP for school quality may have limited ability to inform policies aimed at the broader housing market. Indeed, although it is common to assume that boundary neighborhoods are representative of the broader population, we are not aware of any empirical studies that evaluate this assumption.

Best Practices for using MWTP Estimates to Inform Policy

A research design that uses exogenous variation in the amenity of interest to estimate a credible measure of MWTP can help to inform policy. However, before using MWTP estimates for policy analysis, it is important to first assess their robustness to modeling choices. For some policy analyses, it may also be useful to assess how MWTP estimates vary across demographic groups and to combine MWTP estimates with additional information to assess the WTP for nonmarginal changes in amenities. This section discusses best practices for assessing robustness, heterogeneity, and the WTP for nonmarginal changes in amenities.

Assessing Robustness

Every hedonic property-value study relies on modeling choices that affect welfare implications. We have focused here on the choice of the amenity variable, the source of variation in the amenity, the decisions made about sample composition (including removing observations that are likely coding errors or outliers), and the parametric assumptions that stem from the specification chosen for the price function. It is important to report the robustness of welfare conclusions to these and other modeling choices to alleviate concerns that the results may be driven by arbitrary assumptions or outlier observations. Dundas (2017, figure 5) provides an informative graphical example of robustness within a targeted sensitivity analysis.

Assessing Heterogeneity in MWTP Estimates

If it is possible to match housing-transaction records to administrative data on households, then the heterogeneity in MWTP estimates can be linked to buyers' demographic characteristics (e.g., race, income, education, children), to analyze how MWTP varies within and between policy-relevant demographic groups. In the United States, this has been done by combining publicly available Home Mortgage Disclosure Act data that describe basic demographic characteristics of buyers who finance their purchases through federally insured mortgages with data that describe housing transactions (e.g., Bishop and Timmins 2018). In some European countries, researchers have linked property transactions with even more detailed government records on household demographics to explore how MWTP varies across different demographic groups (von Graevenitz 2018).

Assessing WTP for Nonmarginal Changes in the Amenity

As discussed earlier, a buyer's single observed house purchase reveals only one point on the buyer's amenity-demand curve. This means that the full amenity-demand function, which is needed to measure WTP for a policy that is expected to produce a nonmarginal change in the amenity, cannot be derived for each household.[23] The literature has presented a variety of econometric strategies to provide additional information for estimating amenity-demand functions. These strategies include imposing restrictions on: the parametric form of utility (e.g., Bajari and Benkard 2005); the scope of preference heterogeneity (e.g., Ekeland, Heckman, and Nesheim 2004; Bishop and Timmins 2019); the stability of preference heterogeneity across cities (Bartik 1987; Zabel and Kiel 2000); the stability of household preferences over time (Bishop and Timmins 2018; Banzhaf 2020); and migration patterns (Bartik 1987; Zhang, Boyle, and Kuminoff 2015). Several of these studies provide proof-of-concept applications. However, there is no consensus in the empirical literature about which is the best practices approach for amenity-demand function estimation.

Instead of estimating amenity-demand functions, some studies use MWTP estimates to construct "back-of-the-envelope" approximations of the WTP for policies that are expected to produce nonmarginal changes in amenities. The most common approach is to multiply MWTP by the change in the amenity. For this calculation to yield a valid measure of WTP, demand for the amenity must be perfectly elastic. The likelihood that this assumption is valid and thus that the calculation provides a reasonable approximation of WTP decreases with the size of the change in the amenity. When the change in the amenity is believed to be too large to assume perfectly elastic demand curves, an alternative approach is to establish bounds on WTP following the logic of Varian (1982). To illustrate this approach, we return to figure 1d. In period T, household 2 is observed to pay an implicit price of P_3^A to consume A_3 units of the amenity. In period S, this household pays an implicit price of P_4^A to consume A_4 units. If, for example, we had only observed the period-T choice, the rectangle defined by $P_3^A \times (A_4 - A_3)$ would provide an upper bound for the WTP to increase the amenity from A_3 to A_4. In this case, the lower bound would be zero. If instead we had only observed the period-S choice, the rectangle defined by $P_4^A \times (A_4 - A_3)$ would provide a lower bound for the WTP to avoid decreasing the amenity level from A_4 to A_3. In this case, the upper bound would be infinity.

[23] Rosen (1974) proposed estimating the demand function by regressing MWTP estimates on the corresponding quantities consumed and consumer characteristics such as demographics. Unfortunately, this estimation strategy has an endogeneity problem (see Bartik [1987] and Epple [1987]) because unobserved tastes simultaneously determine both a buyer's MWTP for the amenity (at the point of consumption) and the quantity chosen.

When the household is observed at two or more points on the hedonic-price function (e.g., because the household is observed purchasing different houses in different years), the upper and lower bounds on the WTP can be made tighter (Varian 1982). Moreover, with additional functional-form restrictions, the demand curve can be calculated without econometric estimation. Indeed, Bajari and Benkard (2005) and Bishop and Timmins (2018) show that if we assume that the demand curve is linear, then two points are sufficient to identify the demand curve and no statistical estimation is needed. One can simply connect the two dots between (P_3^A, A_3) and (P_4^A, A_4). By extension, three points are sufficient to identify a quadratic demand curve, and so forth. Furthermore, Banzhaf (2020) shows that with two points, the connect-the-dots approach provides a second-order approximation to consumer welfare. In addition, even if one cannot follow households over time, a panel of houses allows us to identify this approximation with additional structure or, alternatively, to bound it. Bishop and Timmins (2018) present this connect-the-dots approach for air quality in the Bay Area of California and find considerable heterogeneity in WTP for amenities that may be useful for informing policy.

Conclusions and a Research Agenda

The choice of where to live may be the decision that has the greatest impact on a household's consumption of environmental amenities. It is natural to expect that analysis of housing markets can provide information about the WTP for changes in amenities. The hedonic property-value model provides an economically plausible and empirically tractable way to obtain this information. This article has summarized how recent advances in applied theory and econometrics have improved the model's credibility and policy relevance. Although we have discussed many challenges of following best practices for developing and implementing hedonic property value models, we urge researchers and policymakers not to allow these challenges to deter them from using the model. The literature has simply generated more insights about the "dos" and "don'ts" of hedonic modeling than what has been observed for other economic frameworks that are used to analyze policy. Indeed, the importance of the hedonic model is highlighted by the fact that it continues to be used extensively in the real world to inform both public and private decisions.[24] The bottom line is that hedonic property-value models that follow the "best practices" we have discussed in this article can provide credible estimates of what households are willing to pay for environmental amenities. We conclude with a discussion of some priorities for future research in this area.

Expand the Use of Administrative Records

Increased access to government administrative records is important for improving our understanding of buyers' revealed preferences for local amenities. First, enhanced information about buyers, including their demographic characteristics, employment status, income levels,

[24]Triplett (1990) reported the first use of hedonic methods in a government price index in 1968 for new one-family houses sold. More recently, Triplett (2007) summarized the use of hedonic methods in developing price indexes and other measures for the national accounts. In the private sector, there are many areas where hedonic pricing is used in a proprietary fashion, most prominently in real estate by companies such as Zillow.

and wealth, can enable researchers to analyze how hedonic estimates of MWTP for amenities vary with these factors (e.g., von Graevenitz 2018). Second, the information contained in administrative records may be helpful for estimating the demand curves for an amenity. For example, administrative records could assist in isolating the households who "fit" various assumptions used to estimate demand curves.[25] Similarly, the administrative data sets used by Voorheis (2017) and Bishop, Ketcham, and Kuminoff (2018) to track the evolution of individuals' health and wealth could be matched to housing transactions to yield new insights about how changes in health and wealth affect the demand for specific amenities.

Focus on External Validation of the Estimated MWTP Function

Another research opportunity that would advance the empirical literature would be to determine which of the existing approaches to demand estimation (e.g., restricting the parametric form of utility versus restricting the stability of household preferences over time) is most suitable for policy analysis by testing the external validity of the assumptions used to move from point estimates of MWTP to a demand function. For example, Galiani, Murphy, and Pantano (2015) test the modeling assumptions in a discrete-choice model by developing testable, out-of-sample predictions about how changes in housing prices affect households' choices to change their neighborhoods. In principle, this approach could be adapted to identify testable predictions for how changes in local amenities would induce households to move.

Adapt the Marginal Value of Public Funds Concept to Hedonic Models

Recently, public economists have argued that the concept of a marginal value of public funds (MVPF) presented in Hendren (2015) offers an opportunity for economists ". . . to harness the fruits of the 'credibility revolution' for the public finance goal of welfare analysis" (Finkelstein 2018, p. 1). In the environmental context, the MVPF is defined as the WTP for a marginal change in an amenity relative to the net incremental cost of providing that change through a policy. The MVPF metric differs from a simple benefit–cost ratio because it incorporates the impact on the government budget of behavioral responses to the policy. For example, a policy that reduces air pollution may also reduce federal healthcare expenditures or raise property-tax revenues (by increasing property values). Adapting the MVPF concept to the hedonic property-value model has the potential to make MWTP estimates more useful for evaluating competing environmental policies. The challenge for future research would be to estimate how behavioral responses affect taxpayers (i.e., the policy elasticities) and then combine this information with hedonic estimates of MWTP and data on policy implementation costs. If this was done for multiple policies, the resulting MVPF measures could be used to rank polices according to their return on investment and determine the most efficient way to allocate a marginal increase in environment-related government expenditures. The

[25]For instance, consider household 2 in figure 1d, which is observed in both period S and period T under different implicit price schedules; in principle, one should be able to literally "connect the dots" and identify this household's demand curve, as long as the household's income and preferences remain constant (Bishop and Timmins 2018).

hedonic-equilibrium framework in Banzhaf (2019, 2020) could be used as a starting point for further research on the relationship between MWTP and MVPF.

Investigate Heterogeneity in Beliefs

Finally, there is evidence that consumers' beliefs about product attributes are often heterogenous, with some consumers being misinformed at the time of purchase even when it comes to high-stakes financial decisions such as choosing a college major (Wiswall and Zafar 2015), choosing a health insurance plan (Handel and Kolstad 2015), or developing a strategy to save money for retirement (Bernheim, Fradkin, and Popov 2015). The same is true for expensive durable goods such as cars (Busse et al. 2015), refrigerators (Houde 2017), and water heaters (Allcott and Sweeney 2017). When consumers are not fully informed about product characteristics, their choices may not accurately reveal their preferences. Some of these studies (e.g., Wiswall and Zafar 2015; Handel and Kolstad 2015) address this problem by incorporating survey data on consumers' beliefs. Adapting these approaches to measure homebuyers' beliefs about amenity levels could be used to improve the accuracy of hedonic property-value model estimates of welfare measures when buyers are not fully informed.

Evidence on the degree to which buyers are informed about the characteristics of their houses and neighborhoods is mixed. Myers (2019) finds that homebuyers are well-informed about how future energy costs vary with a house's heating technology (gas versus oil). In contrast, Pope (2008a, 2008b) finds that some homebuyers did not pay attention to publicly available information about flood risk and airport noise prior to mandatory disclosure laws that required them to sign forms stating their awareness of the amenities. Bakkensen and Barrage (2017) provide more direct evidence by surveying homebuyers about beliefs concerning flood risk. Their findings suggest that residents of more flood-prone areas are more likely to underestimate flood risk. Because the current evidence suggests that the accuracy of buyers' beliefs varies from context to context, future research on housing purchases should focus on adapting the methods that have been developed to incorporate heterogenous beliefs. Ma (2018) shows how the learning process can be modeled and finds that accounting for learning has a large impact on estimates of the WTP for brownfield remediation. Adapting Ma's approach to hedonic property-value models could both improve our understanding of households' beliefs and help to refine welfare measures. A useful first step would be to combine house transactions data with surveys that reveal buyers' beliefs about the spatial dispersion of amenities at a point in time. The next step would be to study how households' beliefs evolve over time as they process new information.

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