If You Can't Take the Heat, Get Out of the Cerrado... Recovering the Equilibrium Amenity Cost of Non-Marginal Climate Change in Brazil

by

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Abstract

This paper presents a technique for valuing large changes in non-marketed local attributes (e.g., climate amenities) without data describing prices of locally traded commodities like housing. A model of endogenous local sorting is used to identify individuals' indirect utility functions, from which the value of the change in the local attribute is recovered, accounting for equilibrium impacts on markets for labor and locally traded commodities. Annual amenity costs of Brazilian climate change are estimated to be between \$0.9 and \$15.4 billion, depending upon the severity of the scenario considered and the role of migration costs.

Keywords: endogenous sorting equilibrium, wage-hedonics, agglomeration, congestion, climate amenity, global warming

JEL: R1, C35, O54

1. Introduction

The accumulation of anthropogenic greenhouse gases, most notably carbon dioxide, methane, clorofluorocarbons, and nitrous oxide, has been scientifically shown to trap radiant energy from the sun in the earth's atmosphere, raising the planet's average temperature. [IPCC (1995a)] International concern over the potential for this global climate change has been evident for more than a decade. Still, most countries have been slow to make credible, binding commitments to significantly reduce their greenhouse gas emissions. This is not surprising. The costs of abating these emissions are substantial, while predictions of the warming they could induce, as well as the subsequent costs to agriculture, ecosystems, coastal land, human health, and climate amenities, are wide ranging.[2] While the costs of climate change associated with agricultural production are, in principle, well-defined by market transactions, and while medical costs and coastal land values might be measured directly, the costs and benefits arising from ecosystem alteration, discomfort from climate-induced sickness, and changes in climate amenities are especially hard to measure and have added to the uncertainty surrounding the climate change debate.[3] This paper demonstrates a methodology for quantifying the last of these non-marketed effects of global warming that, unlike traditional hedonic techniques, is practical for valuing *non-marginal* changes in climate like those predicted by most general circulation models (GCM's), and for measuring the effects of climate change in developing countries with readily available data.[4]

Wage-Hedonic Valuation of Climate Amenities

Measuring the value of non-marketed commodities like climate amenities is an old problem in environmental economics. The most common approach, wage-hedonics, recognizes that climate amenities are characteristics of locations in which individuals can choose to live, work, and play. The technique uses information about an individual's choice of location and the tradeoffs between wages, housing costs, and (un)desirable local attributes implicit in that choice in order to impute a price for the latter. Specifically, the individual is assumed to choose the place to live that maximizes her utility given the bundles of attributes that define the set of locations in her choice set. *Ceteris paribus*, the individual who chooses to live in a location with an "undesirable" climate must do so because she is made as well-off as she would be in a location with a preferred climate by receiving a better bundle of other local attributes.

Early work in wage-hedonic valuation derived the marginal willingness to pay for non-marketed local attributes using only correlations between wages and the attributes. [Nordhaus and Tobin (1972), Meyer and Leone (1977), Getz and Huang (1978)] Conditioning upon non-wage, non-climate characteristics, the individual was assumed to require a wage-premium (i.e., a compensating wage-differential) in return for living in the less-agreeable climate. From these differentials, the value that the individual places on the non-marketed climate attribute could be recovered. Later analyses demonstrated that this simple approach ignores an important component of value. [Rosen (1979), Cropper (1981), Henderson (1982), Hoehn, Berger, and Bloomquist (1987), Bloomquist, Berger, and Hoehn (1988)] In particular, in order to obtain more of a desirable local attribute by moving to a preferred location, an individual must not only sacrifice wage compensation (i.e., by moving into a more popular and heavily-supplied labor market), but also must pay more for a residence in which to live at that popular destination, as well as for any other locally traded commodities (i.e., goods and services not easily arbitraged across geographic space and whose prices, consequently, are determined in local markets). Indeed, equilibrium in markets for both labor and these commodities must be modeled concurrently before the full hedonic gradient can be recovered.

Assuming that individuals can move freely between locations, wage-hedonic theory suggests that incomes and prices for locally traded commodities will adjust so that all individuals achieve a common level of utility, V^*, in equilibrium. Willingness-to-pay for a small change in a local attribute (e.g., C_j = climate in location j) around this equilibrium can then be measured with the amount of other consumption (proxied by the income of individual i in location j, $I_{i,j}$) that the individual is willing to sacrifice in exchange for a marginal increase in C_j, holding fixed utility and choice of location. Roback (1982) demonstrates how this marginal rate of substitution can be calculated with a now well-known expression that utilizes information on the individual's consumption of locally-traded commodites (proxied by housing, h_i), and on how the price of housing (P_j^h) and individuals' incomes vary with C_j:

$$(1) \qquad WTP_{i,j}^{C} = \frac{\dfrac{\partial V_{i,j}^{*}}{\partial C_j}}{\dfrac{\partial V_{i,j}^{*}}{\partial I_{i,j}}} = h_i \frac{\partial P_j^h}{\partial C_j} - \frac{\partial I_{i,j}}{\partial C_j}$$

$\partial P_j^h/\partial C_j$ and $\partial I_{i,j}/\partial C_j$ are typically recovered from least-squares regressions of prices and incomes on a vector of local attributes, including C_j.

Two problems arise in the use of this technique for valuing climate change. The first pertains primarily to developing-country applications, in which the tradeoffs between wages, local attributes, and local prices often take place in less urbanized areas where data on the latter are unavailable. When consumption surveys do exist, they are not typically conducted outside of the most populous regions or cities (e.g., the Brazilian *Pesquisa sobre Padrões de Vida* (PPV) and *Pesquisa de Orçamentos Familiares* (POF) surveys),[5] and when they do extend outside these regions, useful information is not always collected on the prices of housing, transportation, services, and other commodities whose prices are determined in local markets (e.g., the Indian National Sample Survey [Deaton and Tarozzi (2000)]). Application of the traditional wage-hedonic technique is therefore forced to either ignore significant parts of the country, or to omit the first term on the right-hand-side of equation (1), leading to biased estimates of value.

A second problem with using the wage-hedonic technique to value the amenity consequences of climate change (which is not unique to developing country applications) arises because most GCM's of greenhouse warming predict non-marginal increases in temperature (between 1 and 4.5° C) and dramatic changes in precipitation (as large as ±30%) over the next fifty years. The expression for willingness-to-pay in equation (1), however, is a valid measure of value only in a small neighborhood around the status quo climate, and assumes a marginal change in climate that is not sufficient to alter individuals' location choices. Considering the significant changes in climate that most GCM's predict and the long time horizon over which individuals will be able to adapt to those changes, this assumption is untenable.

Random Utility Valuation of Climate Amenities

The technique developed in this paper uses spatial variation in labor markets, settlement patterns, and geographic features of the Brazilian landscape to estimate an equilibrium model of household location choice that addresses both of these problems. To solve the second problem, we adapt a random utility model originally developed in the empirical industrial organization literature for use in recovering differentiated product demands. In particular, we employ discrete-choice techniques that model an individual's optimal choice of a location (i.e., a discrete bundle of local attributes) in which to live, given the full set of available alternatives. From the tradeoffs implicit in this decision, we estimate indirect utility functions for heterogeneous individuals, even at points far from the status quo equilibrium. With these estimated functions, we need not rely on the marginal relationships used by Roback and subsequent authors to recover values, but can instead simulate the change in wages required to compensate individuals for any sized climate change, accounting for equilibrium impacts on markets for labor and locally traded goods. This allows us to consider four Brazilian climate change scenarios of increasing severity taken from actual GCM analyses.

Note that the traditional wage-hedonic model could also be extended to the valuation of large changes in local attributes – although in a limited sense (i.e., still ignoring the equilibrium impacts of those changes on markets for labor and locally traded goods). Doing so without relying on arbitrary functional-form assumptions for identification, however, requires the use of data exhibiting *cross-market variation* – i.e., containing information about observationally equivalent individuals in different markets (e.g., different cities in the valuation of a local pollutant), who one assumes to be the same in every way except for being confronted with different choice sets. [Mendelsohn (1985)] With such data, the wage-hedonic model could recover points on multiple hedonic gradients for a particular type of individual, and use them to identify a demand curve for the non-marketed local attribute. Having such a demand curve is necessary for valuing a large change in that attribute with a compensating or equivalent income variation. Cross-market variation, however, is difficult to come by in most empirical contexts. This is especially true in the valuation of climate amenities, where wide geographic regions (i.e., countries or even continents) are typically treated as single markets.

The random utility framework for valuing large changes in a non-marketed local attribute is not a magic cure-all for this identification problem. Non-parametric identification requires the same sort of variation in the data as traditional wage-hedonics. The important difference between the wage-hedonic and random utility frameworks is that the latter can exploit *effective* cross-market variation, even in a single cross-section, by using (i) information about peoples' birth locations and (ii) the fact that migration is costly. Together, (i) and (ii) imply that individuals born in different places will perceive the set of locations from which they can choose in a random utility model differently, meaning that such individuals are effectively in different markets. [Bayer and Timmins (2003a)] The intuition behind this sort of effective cross-market variation cannot, however, be extended to valuing large changes in the wage-hedonic framework, as it does not assist in the direct recovery of multiple hedonic gradients.

Returning to the first problem, our model uses the information contained in equilibrium settlement patterns to identify, in a reduced-form sufficient for valuing local attributes, the utility effects of re-equilibrating prices for locally traded goods. In particular, the discrete-choice model we use to recover indirect utility provides us with an implicit demand curve for commodities like housing, transportation, and services. We combine this with a set of explicitly parameterized supply curves in order to obtain an estimable reduced-form indirect utility function that incorporates equilibrium in the market for these commodities. This will prove sufficient for valuing large changes in climate, as our interest will be in the combination of the direct effect of climate on utility and its indirect effects that come through the re-equilibration of markets for locally traded commodities and labor (the latter of which we have data to model explicitly).

In addition to addressing these two problems, our approach to valuing climate amenities also allows us to empirically recover the utility costs of migration and to control for the limitations they impose on mobility. These constraints can have important implications for valuation techniques based on equilibrium sorting, like the marginal wage-hedonic technique and the approach we develop in this paper. The marginal wage-hedonic technique assumes that individuals can initially migrate without cost in order to optimally trade-off climate amenities with wage compensation and local prices (i.e., ignoring their "initial conditions", or birth locations), but then assumes that individuals choose not to move at all in response to the climate change being valued. Especially in the developing country context and considering non-marginal climate change, these are poor assumptions.[6] The estimation technique we develop allows us to recover the utility costs of migration, and to allow those costs to differ with distance and individual attributes like education. We demonstrate that these costs have a significant effect on individuals' abilities to adapt to large climate changes, with important implications for the value of climate amenities. In particular, we show how the amenity costs of climate change would vary if individuals were either unable to alter their location choice at all in response to climate change, or if geographic space were made irrelevant and migration were costless.

The paper proceeds as follows. Section 2 describes a model of optimal individual location choice, which serves as the core of our estimable equilibrium model. Section 3 discusses the data we use in our application to Brazil, and Section 4 explains how those data and the model of individual behavior in Section 2 are employed by our estimation algorithm. Section 5 reports parameter estimates, calculates monetized changes in utility for a series of Brazilian greenhouse warming scenarios predicted by the IPCC, and compares those results to values derived from simple compensating wage differentials and under counterfactual mobility assumptions. Section 6 concludes.

2. A Model of Individual Location Choice

Like the marginal wage-hedonic approach, the estimation technique described in this paper is based on an equilibrium model of optimal individual location choice. Unlike that approach, however, it uses the equilibrium model to recover estimates of the parameters of the individual's indirect utility function (accounting for the role of locally determined prices in a reduced-form way), along with an equation describing how local labor market equilibria adjust to the re-sorting decisions individuals make in response to climate change. With these equations, the value of climate amenities can be easily recovered with a series of simulations in the form of compensating wage variations.

The model of optimal individual location choice begins with the specification of utility. The utility, $U_{i,j,k}$, that an individual *i* of type *k* (defined by a vector of observable attributes) receives from living and optimally spending income in location *j* is assumed to be determined by his consumption of a universally traded numeraire commodity (Q_i), housing ($h_{i,k}$), which proxies for a basket of commodities (the composition of which can vary with type *k*) whose price is determined in local markets, a function of the migration distance that *i* would have needed to travel in order to live in location *j* given his birth location ($M_{i,j,k}$),[7] an exogenously supplied and non-rivalrously consumed vector of climate (C_j) and non-climate (X_j) local attributes, the congestion or agglomeration effects of equilibrium population density ($\mathit{\Delta}_j$), an unobserved (by the econometrician) local attribute ($\varphi_{j,k}$), and an idiosyncratic stochastic component ($\upsilon_{i,j,k}$):

$$U_{i,j,k} = \alpha_{0,k}\, Q_i^{\alpha_{Q,k}}\, h_{i,k}^{\alpha_{h,k}}\, e^{f(M_{i,j,k};\, \bar{\alpha}_{M,k})}\, X_j^{\alpha_{X,k}}\, C_j^{\alpha_{C,j,k}}\, \mathit{\Delta}_j^{\alpha_{\mathit{\Delta},k}}\, e^{\varphi_{j,k}}\, e^{v_{i,j,k}} \tag{2}$$

$\varphi_{j,k}$ is allowed to vary with location and individual type, while $\upsilon_{i,j,k}$ differs with the location and the particular individual. Flexibility is introduced into the utility function in two ways. First, parameters are allowed to vary with individual type:

(3) $$\alpha_{\bullet,k} = \alpha_{\bullet,0} + \alpha_{\bullet,1}\, z_{i,k}$$

where $z_{i,k}$ is a vector of individual attributes that define *i* to be of type *k*. An individual's type is taken to be exogenous to the model.[8] The second source of flexibility in this utility specification comes in the relationship between climate and utility, which is allowed to be non-monotonic. Specifically,

(4) $$C_j^{\alpha_{C,j,k}} = C_j^{\alpha_{C1,k} + \alpha_{C2,k} C_j}$$

This functional form allows, for example, the marginal contribution of temperature to utility to be positive when temperature is low but to become negative when temperature is high (i.e., a "bliss point") if $\alpha_{C1,k} > 0$ and $\alpha_{C2,k} < 0$, and does so in a more flexible fashion than functional forms traditionally used to model these sorts of non-monotonicities (e.g., quadratic utility).

The individual solves a two-part problem. First, he determines optimal quantities of Q_i and $h_{i,k}$ to consume, subject to the following budget constraint:

(5) $$Q_i + P^h_{j,k}\, h_{i,k} = W_{i,j,k}$$

Like the marginal wage-hedonic literature, this model abstracts from the individual's labor-leisure decision, considering only the wage that he could earn in location *j*, $W_{i,j,k}$. Utility maximization produces the following demand functions:

(6) $$Q_i = W_{i,j,k} \frac{\alpha_{Q,k}}{\alpha_{Q,k} + \alpha_{h,k}} \qquad h_{i,k} = \frac{W_{i,j,k}}{P^h_{j,k}} \frac{\alpha_{h,k}}{\alpha_{Q,k} + \alpha_{h,k}}$$

Substituting these expressions back into equation (2) and taking logs yields the indirect utility function:

$$\ln V_{i,j,k} = A_{0,k} + (\alpha_{Q,k} + \alpha_{h,k}) \ln W_{i,j,k} - \alpha_{h,k} \ln P^{h}_{j,k} + f(M_{i,j,k}; \bar{\alpha}_{M,k}) \tag{7}$$
$$\alpha_{C1,k} \ln C_j + \alpha_{C2,k} C_j \ln C_j + \alpha_{X,k} \ln X_j + \alpha_{\Delta,k} \ln \Delta_j + \varphi_{j,k} + v_{i,j,k}$$

where

$$A_{0,k} = \ln \alpha_{0,k} + \alpha_{Q,k} \ln \frac{\alpha_{Q,k}}{\alpha_{Q,k} + \alpha_{h,k}} + \alpha_{h,k} \ln \frac{\alpha_{h,k}}{\alpha_{Q,k} + \alpha_{h,k}} \tag{8}$$

It is not possible to observe the wage that each individual would earn in every location, but rather only that which he earns in the location where we actually find him residing. In the micro data we use for estimation, however, we do see many other observationally similar individuals living in other locations, and are able to observe their wages. From these data, we can impute the wage each individual would earn in every location with a series of location-specific regressions of wages on individual attributes. These regressions are described in more detail in Section 3. We can then split $W_{i,j,k}$ into a type-specific component fitted with the output of these regressions ($\hat{W}_{j,s}$, where k indexes a subset of the attributes in s) and an idiosyncratic error ($\varepsilon_{i,j,k}{}^{W}$):

$$W_{i,j,k} = \hat{W}_{j,s}\, e^{\varepsilon^{W}_{i,j,k}} \tag{9}$$

For notational simplicity, we re-label the aggregate idiosyncratic error in the indirect utility function:

$$\eta_{i,j,k} = v_{i,j,k} + (\alpha_{Q,k} + \alpha_{h,k})\varepsilon^{W}_{i,j,k} \tag{10}$$

Migration distance plays an important role in the individual's utility-maximizing choice of location. The marginal wage-hedonics literature traditionally assumes free mobility in modeling these decisions. This assumption is tenuous in the developing country context, especially for individuals with particular attributes (e.g., certain caste affiliations or little education). Inclusion of the term $f(M_{i,j,k}; \overline{\alpha}_{M,k})$ allows us to recover utility costs of migration that vary non-linearly with distance and with individual attributes. Specifically, we estimate a two-step function in migration distance for each type *k*:

$$f(M_{i,j,k};\overline{\alpha}_{M,k}) = \alpha_{M1,k}\, d_{i,j,k}^{M1} + \alpha_{M2,k}\, d_{i,j,k}^{M2} \tag{11}$$

where $d_{i,j,k}^{M1} = 1$ if the migration distance from individual *i*'s birth state to the state containing location *j* is greater than 764 km (i.e., the 33rd percentile of the distribution of potential migration distances in our Brazilian application) and $d_{i,j,k}^{M2} = 1$ if that distance exceeds 1380 km (i.e., the 66th percentile). As we will show below, estimated migration costs are non-linear in distance, vary significantly with education level, and have important implications for individuals' abilities to adapt to global warming.

Labor supply in every location (measured by population density) is determined in equilibrium by individuals' indirect utility maximizing choices of where to live. Wages are therefore endogenously determined by the process of individuals sorting over locations. This matters both for our estimation procedure and for simulating the response of the labor market to non-marginal changes in climate. We address these issues in more detail in Sections 4 and 5.

In addition to implicitly defining a supply curve for labor, individuals' maximization of indirect utility defines a demand curve for housing and other commodities whose prices are set in local markets. The following equation specifies a flexible and inclusive supply relationship for these commodities:

$$\ln P_{j,k}^{h} = \delta_{0,k} + \delta_{X,k} \ln X_j + \delta_{C1,k} \ln C_j + \delta_{C2,k}\, C_j \ln C_j + \delta_{\Delta,k} \ln \Delta_j + \varepsilon_{j,k}^{h} \tag{12}$$

which is allowed to vary with climate and non-climate attributes of location *j*, as well as with population density. Prices and the marginal effects of local attributes on those prices are allowed to differ with individual type *k* – this reflects the fact that quality levels (indeed, the very definition of what constitutes a unit of *h*) are likely to differ with consumers' attributes. $\varepsilon_{j,k}^{h}$ measures any determinants of the price of housing and other locally-traded commodities in location *j* that are not observed in available data.

We combine equation (12) with equation (7) to yield a reduced-form indirect utility function that can be taken to data:

$$\begin{aligned} ln\ V_{i,j,k} &= \pi_{0,k} + \pi_{W,k}\ ln\ \hat{W}_{j,s} + \pi_{M1,k}\ d_{i,j,k}^{M1} + \pi_{M2,k}\ d_{i,j,k}^{M2} + \\ &\quad \pi_{X,k}\ ln\ X_j + \pi_{C1,k}\ ln\ C_j + \pi_{C2,k}\ C_j\ ln\ C_j + \pi_{\Delta,k}\ ln\ \Delta_j - \alpha_{h,k}\ \varepsilon_j^{h} + \varphi_{j,k} + \eta_{i,j,k} \end{aligned} \tag{13}$$

where, for example, $\pi_{X,k} = \alpha_{X,k} - \alpha_{h,k}\,\delta_{X,k}$. Since the parameters of equation (7) are not of direct interest in the valuation of large changes in climate (i.e., our interest will be in the combined effects on housing and labor markets, along with the direct effects on utility), this reduced-form treatment of the indirect utility function is sufficient.[9]

A number of notational simplifications are made in order to transform equation (13) into an expression that is convenient for estimation. First, given a vector of parameters, an observable location-and-type-specific component of indirect utility ($\theta_{j,k}$) can be defined:

$$\theta_{j,k} = \pi_{0,k} + \pi_{X,k}\ ln\ X_j + \pi_{C1,k}\ ln\ C_j + \pi_{C2,k}\ C_j\ ln\ C_j + \pi_{\Delta,k}\ ln\ \Delta_j \tag{14}$$

Next, the two location-and-type-specific unobservable terms can be combined with the type-specific indirect utility constant to make a single unobservable attribute ($\xi_{j,k}$).

$$\xi_{j,k} = \varphi_{j,k} - \alpha_{h,k}\ \varepsilon_{j,k}^{h} \tag{15}$$

For the purposes of identification, we will assume that $\xi_{j,k}$ is distributed independently of each of the exogenously determined attributes of location *j*, (X_j, C_j), for each type of individual *k*. While the independence of $\xi_{j,k}$ and some elements of X_j might reasonably be questioned, it is important to note that this assumption is no different from that made about the error term and exogenous local attributes in traditional wage-hedonic analyses. Moreover, in Section 4 we will provide a strategy with which one can instrument for local attributes that are endogenously determined by the process of individuals sorting over locations. A similar strategy may not always be available in the traditional wage-hedonic framework.

With these simplifications, the indirect utility function for individual *i* in location *j* can be written concisely as:

$$(16) \qquad \ln V_{i,j,k} = \pi_{W,k} \hat{W}_{j,s} + \pi_{M1,k} d^{M1}_{i,j,k} + \pi_{M2,k} d^{M2}_{i,j,k} + \theta_{j,k} + \xi_{j,k} + \eta_{i,j,k}$$

As stated previously, in the second stage of his optimization problem the individual chooses the location in which to live that maximizes this indirect utility, taking as given the optimal allocation of income between Q_i and $h_{i,k}$ wherever that may be. The characteristics of every location are allowed to enter into this location decision (with more distant locations made less attractive by the disutility of migration), and each location constitutes a discrete bundle of local attributes. The conditional logit model is well-suited to describing such a choice problem (see Cropper et al (1993) for a Monte Carlo-based discussion of the merits of discrete choice valuation methods in the context of property value hedonics) and is used owing to its computational tractability. $\eta_{i,j,k}$ is therefore assumed to be distributed i.i.d. Type-I Extreme Value across locations and individuals for all those of a particular type *k*.

These modeling assumptions imply the following probability that a type-*k* individual chooses to live in location *j*:

$$(17) \qquad P(\ln V_{i,j,k} \geq \ln V_{i,l,k} \;\forall\; l \neq j) = \frac{EXP\;[\pi_{W,k}\,\hat{W}_{j,s} + \pi_{M1,k}\,d^{M1}_{i,j,k} + \pi_{M2,k}\,d^{M2}_{i,j,k} + \theta_{j,k} + \xi_{j,k}]}{\sum_{l=1}^{J} EXP\;[\pi_{W,k}\,\hat{W}_{l,s} + \pi_{M1,k}\,d^{M1}_{i,l,k} + \pi_{M2,k}\,d^{M2}_{i,l,k} + \theta_{l,k} + \xi_{l,k}]}$$

so that, given a large number of type-k individuals (M_k), their equilibrium population in location j is determined by:

$$(18) \qquad pop_{j,k} = M_k\,\frac{EXP\;[\pi_{W,k}\,\hat{W}_{j,s} + \pi_{M1,k}\,d^{M1}_{i,j,k} + \pi_{M2,k}\,d^{M2}_{i,j,k} + \theta_{j,k} + \xi_{j,k}]}{\sum_{l=1}^{J} EXP\;[\pi_{W,k}\,\hat{W}_{l,s} + \pi_{M1,k}\,d^{M1}_{i,l,k} + \pi_{M2,k}\,d^{M2}_{i,l,k} + \theta_{l,k} + \xi_{l,k}]}$$

From data in the 10% micro sample of the 1991 Brazilian Demographic Census, we can calculate these type-specific populations for each location j. Note that $pop_{j,k}$ appears on both sides of equation (18) – on the right-hand-side as a determinant of equilibrium population density, $\Delta_j = \sum_k pop_{j,k}/area_j$, in $\theta_{j,k}$. In fact, equilibrium $pop_{j,k}$ is a function of not only the equilibrium population density in location j, but of the equilibrium population *in every location* as well. Equation (18) therefore describes a simultaneous system of $K*J$ non-linear equations in as many unknowns.

3. Data

Most of the data used to identify the parameters of this model come from the 10% micro sample of the 1991 Brazilian Demographic Census. [IBGE (1996)] Data are reported at the level of the individual, but since we consider households as the relevant decision-making units, we focus our attention on household heads. The data describe, among other things, monthly income and weekly hours of the household head in his/her primary employment activity (from which we calculate hourly wage),[10] age, sex, years of education, and sector of employment.[11] Data also report the municipio (i.e., county) in which the household is located at the time of the census, along with the state in which the household head was born.[12] We measure migration distance between the state capitals of the birth state and state of residence with the Haversine formula.[13] In order to deal with numerical issues in the estimation procedure relating to the size of the choice set, we re-define households' locations by microregions (i.e., statistical designations of between six and a dozen contiguous municipios). Eliminating locations with missing attribute data, there were 495 microregions in our final data set.

We impute $\hat{W}_{j,s}$ for all types in microregion j by regressing the natural log of wages of all individuals in a random sub-sample living in that microregion (in particular, the minimum of 3000 and all available individuals) on a constant, age, the natural log of years of education, and dummy variables for their sex and sector of employment, and repeat this process for each of the 495 microregions in our data set. All parameter estimates are of the expected sign, and nearly all are statistically significant at traditional levels. Table 2 summarizes the results of these regressions. Controlling for sector of activity, sex, and age, the average elasticity of wages with respect to an additional year of education is 0.17. There are also clear wage premiums for men, those in more skilled sectors, and those with more experience (proxied by age).

We do not maintain the same degree of heterogeneity in our specification of the utility function, allowing π parameters to differ only with education level (i.e., [0, 4], [5, 8], [9, 12], and [13+] years),[14] but additional categories could easily be added as long as there were a sufficient number of individuals of each type in the micro data to calculate non-zero type-specific shares for each microregion.

Population density is measured by the total number of individuals of all types in each microregion per km^2.[15] Climate measures represent 30 year averages of rainfall and temperature. Measurements were taken at weather stations throughout Brazil, and values were interpolated with a series of weighted non-linear least squares regressions for the center of each municipio; this process is described in Sanghi et al (1997), from whom the data were generously provided. Land-area-weighted average microregion climate data were then constructed from these municipio data. Rainfall is measured in centimeters while temperature is measured in degrees celsius.

Data describing the distances from each microregion's center to the nearest major port, state capital, and São Paulo were constructed from latitude-longitude coordinate data and the Haversine formula. The locations of state capitals were determined long before the settlement decisions being modeled, and the locations of major ports were pre-determined in large part by access to deep-water harbors and navigable channels. Dummy variables indicating proximity to mineral deposits, navigable rivers, and interstate highways were constructed by determining whether each lay inside a 25 km radius circle drawn around the area-weighted center of each microregion on a detailed map. Indicators of the potential for soil erosion were provided by Embrapa, the Brazilian federal agency for agricultural research.

Regional designations are used for summarizing estimation results. Figure 1 illustrates the division of Brazil into five geographically and socio-economically homogenous regions (i.e., North, Northeast, Southeast, Center-West, South). Table 1 summarizes the data according to these regional definitions. The North region is characterized as sparsely populated, poor, and largely inaccessible. The Northeast region is the poorest region of Brazil. It has the lowest life-expectancy and wages, little access to mineral deposits or navigable rivers, and the highest proportion of individuals with fewer than nine years of education. The Center-West region combines a diverse set of characteristics, mixing poor rural areas, dense forests, and the federal capital city of Brasilia, where education levels and incomes are high. The Southeast and the South are the most economically developed regions of Brazil. Education levels, income, and life-expectancy are all high in these regions, and dense highway networks make it easy to get around. The economic opportunities afforded by living in these regions clearly explain much of their high population density.

Regional temperature differences can be explained, in large part, by latitude. The spatial variance in summer temperature is small (making it difficult to identify its amenity value), but is larger in the winter. In order to achieve statistically meaningful predictions, we combine seasonal temperatures into an average annual measure. Regional and seasonal differences in rainfall are more pronounced, but are generally characterized by wet summers and dry winters. The South region is an exception, in that it receives precipitation evenly throughout the year, while the Northeast region is sometimes characterized by droughts that reduce its average summer rainfall accumulation. In order to facilitate the incorporation of climate change predictions from Brazilian GCM's, we use average rainfall in two seasons: March - May (fall) and September - November (spring).

The utility costs of migration play an important role in determining just how free individuals really are to move in response to a non-marginal change in climate. We recover these costs from observed long-run migration decisions of household heads. Tables 3 (a) - (d) summarize these decisions at the regional level separately for each of the four education groups. Each table reports the percentage of the particular population group born in a region (left-hand column) that is in residence in each region (top row) in 1991. It is clear from the large diagonal elements in each of these matrices that there are significant costs to migrating out of one's birth region. Moreover, distance plays an important role in migration behavior – of those living in the North region, the fewest migrants had come from the South and Southeast regions, while considering those living in the South region, the fewest migrants had come from the North and Northeast regions. Other regional trends in migration can be observed. For example, there is very little movement into the North region, especially amongst those with little education. Of those born in the North, the only significant outward migration is to the Northeast (and to the Southeast for those with more than eight years of education). In percentage terms, the largest migratory outflows for all education groups tend to be from the Center-West region, especially into the Northeast and Southeast, with very little offsetting inward migration. In absolute terms, the most significant migration flows are into the Southeast, as evidenced by the large off-diagonal elements in the third column of each table. Moreover, very few individuals of any education group born in the South or Southeast migrate to other regions. These last two features of Tables 3 suggest that individuals find desirable the attributes of the South and Southeast – these include a developed infrastructure, good earning potential, agglomeration effects of densely settled population, cooler temperatures, and regular (but not excessive) rainfall. It is now up to the estimation model to separate individuals' values for these alternative attributes in order to recover the cost of climate change.

4. Estimation

The estimation algorithm proceeds in two stages, paralleling those used by Berry, Levinsohn, and Pakes (2001). We begin by estimating the parameters $\pi_{W,k}$, $\pi_{M1,k}$, and $\pi_{M2,k}$ and a vector of fixed effects, $\Theta_{j,k} = \theta_{j,k} + \xi_{j,k}$, by running separate conditional logit regressions using micro-data grouped by education type. In particular, the probability that a type k individual will choose to live in location j is given by:

$$(19) \qquad P(\ln V_{i,j,k} \geq \ln V_{i,l,k} \; \forall \; l \neq j) = \frac{EXP\;[\pi_{W,k}\;\hat{W}_{j,s} + \pi_{M1,k}\;d^{M1}_{i,j,k} + \pi_{M2,k}\;d^{M2}_{i,j,k} + \Theta_{j,k}]}{\sum_{l=1}^{J} EXP\;[\pi_{W,k}\;\hat{W}_{l,s} + \pi_{M1,k}\;d^{M1}_{i,l,k} + \pi_{M2,k}\;d^{M2}_{i,l,k} + \Theta_{l,k}]}$$

We estimate values for $\pi_{W,k}$, $\pi_{M1,k}$, and $\pi_{M2,k}$ and $\Theta_{j,k}$ by maximizing the probability of observing individuals living in their actual microregions of residence. Migration distance dummies ($d_{i,j,k}{}^{M1}$, $d_{i,j,k}{}^{M2}$) and the predicted component of wages ($\hat{W}_{j,s}$) are likely to be correlated with $\xi_{j,k}$,[16] but by estimating their effects on utility using individual-level data (i.e., embedding $\xi_{j,k}$ in the estimated type-and-location fixed effect $\Theta_{j,k}$ in the first-stage and basing the estimation instead on the individual's idiosyncratic error, $\eta_{i,j,k}$), we avoid this problem. Δ_j, the population density in microregion j, is likely to be correlated with the location's unobservable attribute as well. This will complicate the second-stage of the estimation algorithm, but does not present a problem at this stage as both variables are also subsumed into the type-and-location fixed effect $\Theta_{j,k}$.

Because it can be numerically cumbersome to estimate the full vector of fixed effects with non-linear optimization over the space of all parameters, we follow the procedure described in Berry (1994), backing-out values of $\Theta_{j,k}$ so that the model exactly predicts type-specific population shares given a vector of parameters [$\pi_{W,k}$, $\pi_{M1,k}$, $\pi_{M2,k}$]. In practice, we begin by guessing values for $\pi_{W,k}$, $\pi_{M1,k}$, and $\pi_{M2,k}$, and then determine the vector of $\Theta_{j,k}$'s that makes the resulting predicted type-specific shares exactly equal the observed type-specific population shares by solving the following system of simultaneous equations:

$$s_{j,k} = \frac{1}{M_k} \sum_{i \in k} P(V_{i,j,k} \geq V_{i,l,k} \;\forall\; l \neq k) \qquad \forall\; j,k \tag{20}$$

Berry (1994) demonstrates that equation (20) will be a contraction mapping, ensuring a unique solution and providing a simple iterative algorithm to solve for the vector of $\Theta_{j,k}$'s, given some normalization (e.g., $\Theta_{1,k} = -1 \;\forall\; k$). The algorithm proceeds by calculating the likelihood function associated with the parameters and fitted fixed effects, and updates the parameter vector so as to increase that likelihood. The process repeats until the likelihood function is maximized.

The second-stage of the estimation algorithm decomposes the final estimates of the type-and-location-specific fixed effects into their component parts. In particular, the fixed effects can be written as a set of four regression equations – one for each education group:

$$\begin{aligned}
\Theta_{j,1} &= \pi_{0,1} + \pi_{X,1} \ln X_j + \pi_{C1,1} \ln C_j + \pi_{C2,1} C_j \ln C_j + \pi_{\Delta,1} \ln \Delta_j + \xi_{j,1} \\
\Theta_{j,2} &= \pi_{0,2} + \pi_{X,2} \ln X_j + \pi_{C1,2} \ln C_j + \pi_{C2,2} C_j \ln C_j + \pi_{\Delta,2} \ln \Delta_j + \xi_{j,2} \\
\Theta_{j,3} &= \pi_{0,3} + \pi_{X,3} \ln X_j + \pi_{C1,3} \ln C_j + \pi_{C2,3} C_j \ln C_j + \pi_{\Delta,3} \ln \Delta_j + \xi_{j,3} \\
\Theta_{j,4} &= \pi_{0,4} + \pi_{X,4} \ln X_j + \pi_{C1,4} \ln C_j + \pi_{C2,4} C_j \ln C_j + \pi_{\Delta,4} \ln \Delta_j + \xi_{j,4}
\end{aligned} \tag{21}$$

The primary complication in recovering estimates of $[\pi_{0,k}, \pi_{X,k}, \pi_{C1,k}, \pi_{C2,k}, \pi_{\Delta,k}]$ lies in the endogeneity of Δ_j, the population density in microregion j. As was evident from equation (18), $\Delta_j = \sum_k pop_{j,k}/area_j$ is itself a function of $\xi_{j,k}$, and locations with desirable unobservable attributes for a particular education group will, *ceteris paribus*, tend to have larger numbers of residents with that level of education, leading to a greater overall population. This creates a difficult simultaneity problem that is well-known in the literature on spillovers, agglomeration and congestion effects, and network externalities – i.e., in models in which the utility an individual receives from making a particular choice depends upon the number and/or type of other individuals making the same choice in equilibrium. In our model, failure to control for this source of endogeneity will bias upward estimates of $\pi_{\Delta,k}$ (i.e., over-predicting the benefits of agglomeration) with the potential to bias estimates of the other parameters as well.

Bayer and Timmins (2003a) derive a set of instruments that can be used for this and other similar models of endogenous sorting. Instruments for Δ_j are based on measures of location *j*'s isolation in exogenous attribute space.[17] The additional information introduced by these measures can explain, in part, why a particular alternative has a large or small share while still being uncorrelated with the alternative's unobservable attribute ($\xi_{j,k}$), making it a good instrument for Δ_j in equation (21). Specifically, the instruments rely upon the fact that the set of individuals who choose to live in a particular location is determined both by the underlying characteristics of that location as well as by the availability of potential substitute locations. That is, when close substitutes are available, a location will be chosen less often, all else equal. The availability of close substitutes thus satisfies the first criterion for a good instrument – namely, it is correlated with Δ_j. Moreover, since we have assumed that $\xi_{j,k}$ is distributed independently from the exogenous observable attributes of location *j* for each type *k*, it is reasonable to assume that (functions of) the observable, exogenous attributes of the potential substitutes for location *j* would be independent of $\xi_{j,k}$ as well, satisfying the second criterion for a good instrument. The only tasks in practically constructing instruments for Δ_j, then, are to determine what constitutes the set of "close substitutes" for each location *j* and to establish a metric with which to gauge location *j*'s isolation from that set in exogenous attribute space.

A logical first choice for a measure of an alternative's isolation in exogenous attribute space would simply be the summation of the distances (e.g., $\|\bullet\|$-metric) between each of its attributes and those of the relevant closest alternatives in the choice set. This measure of isolation, however, fails to account for the relative intensity of individuals' preferences for various exogenous attributes. In order to derive an instrument that controls for individual preferences, Bayer and Timmins (2003a) propose a multi-step estimator, whereby the system of regression equations in (21) is first estimated by ordinary least squares, yielding biased estimates of the indirect utility function parameters for each type of individual. With these estimates, we calculate the utility the individual could get from each alternative, based only on exogenous determinants (i.e., $\widetilde{V}_{i,j,k} = \pi_{X,k} \ln X_j + \pi_{C1,k} \ln C_j + \pi_{C2,k} C_j \ln C_j$). We can then determine the proximity of "nearby" substitutes by examining the distribution of $(\widetilde{V}_{i,l,k} - \widetilde{V}_{i,j,k})$ $\forall\, l \neq j$; i.e., defining "isolation" by the immediacy of alternatives in exogenously determined utility space.[18] Bayer and Timmins (2003a) show how the information in these differentials can be combined in an even more efficient manner by using as instruments fitted type-specific shares based only on exogenous attributes:

$$(22) \qquad \widetilde{s}_{j,k} = \frac{1}{M_k} \sum_{i \in k} \left(e^{\widetilde{V}_{i,j,k}} \Big/ \sum_{l=1}^{J} e^{\widetilde{V}_{i,l,k}} \right)$$

In so doing, these instruments closely approximate the optimal instruments for endogenously determined type-specific shares (i.e., expected shares, integrated over $\xi_{j,k}$ with values of $s_{j,k}$ implicitly defined by equation (18)), but avoid the problem that arises when that vector of predicted shares is not unique.[19] Predicted shares based only on exogenous attributes will provide a good approximation to optimal predicted shares as long as the utility effects of population density are not too large relative to the utility effects of the exogenously determined attributes, and will always be uniquely determined. Bayer and Timmins (2003a) describe the performance of these instruments with Monte Carlo simulations in a variety of empirical settings.

With these instruments for Δ_j in hand, it is a simple matter to estimate the parameters of equation (21) by linear three-stage least squares regression.

5. Estimation Results and the Costs of Climate Change

Table 4 reports the results of the first- and second-stages of this estimation procedure.[20] Marginal utilities of wage compensation are positive for all four education groups. The magnitudes of those parameters are not directly comparable across education groups, however, unless we assume that the microregion-and-type-specific component of indirect utility in the first microregion ($\Theta_{1,k}$) is actually the same for all k.[21] If this were the case, then the marginal utility of wage compensation would fall with education. Migration cost functions are statistically significant and vary qualitatively with education. In particular, the marginal cost of another km migrated rises with distance for those in the [0,4] education group, while it falls for the other groups. Moreover, migration costs generally fall for both distance bands with increasing education (keeping in mind the limitations on comparing parameters across education groups).

Turning to the second-stage parameter estimates, we find significant utility costs of increasing the distance to the nearest state capital for all education groups, while increasing distance to São Paulo is only a significant disamenity for the [13 +] education group. Proximity to navigable rivers and interstate highways, on the other hand, has significant amenity value. Moreover, this value increases with education, both in terms of marginal utility and in terms of the marginal rate of substitution with wage compensation.[22] A similar argument can be made with respect to the indirect utility effect of population density, which measures the combined impact of the direct effects of agglomeration or congestion on utility and the indirect effect of population density working through the price of locally traded commodities (which we would expect to function like a congestion effect). The final row of each table reports the parameter estimates associated with population density if our instrumenting strategy were not employed and the system of equations in (21) were estimated instead as seemingly unrelated regressions. Note the significant upward bias, which results in an overstatement in the size of the agglomeration effect. This bias, moreover, spills-over into the other parameter estimates, even changing the signs of the predicted effects of the climate variables on utility (complete SUR results available upon request).

The Costs of Climate Change: Simulation Procedure

The estimates reported in Table 4 are next used in simulations designed to recover the welfare effects of non-marginal climate change. We consider a set of actual climate change predictions taken from a series of GCM's of Brazil performed as part of the Special Report on Emissions Scenarios (SRES) for the IPCC, described by Hulme and Sheard (1999). The three scenarios range from mild to severe warming, depending upon assumptions made about the increase in atmospheric CO_2 concentrations over the next 50 years and the sensitivity of climate systems to those changes, but also differ in their predictions about rainfall. Figures 2 (a) - (c) through 4 (a) - (c) describe the changes predicted by each of these scenarios in average annual temperature and seasonal precipitation on a 4° longitude, 2.5° latitude grid covering all of Brazil. From a simple visual inspection of these figures, it is apparent that (with the possible exception of Scenario #1), predicted climate changes are large and inconsistent with a model based upon relationships that hold only in a small neighborhood around the status quo.

Our baseline procedure for simulating the welfare effects of non-marginal climate change accounts for individuals' re-optimization in their choice of location as well as for the effects of those decisions on equilibria in markets for labor and other commodities whose prices are determined locally. We begin by taking a random sample of 3500 household heads and treat each as representative of a continuum of individuals with preferences that differ according to the idiosyncratic component of indirect utility. We can then calculate the type-specific share of the total population that will choose to live in each microregion after the realization of each climate scenario (i.e., in the year 2050) with a simple iterative procedure.[23] Beginning by using the observed 1991 values for the population density as it appears on the right-hand-side of indirect utility, we use our estimated parameters to predict type-specific shares, which are aggregated and used to calculate new population densities. These are inserted back into the right-hand-side of indirect utility, and the process is repeated until the type-specific shares converge. Under the status quo climate scenario, unobserved local attributes ($\xi_{i,j}$) were determined so that predicted shares would equal actual shares. Under that scenario, this process converges immediately. Under the alternative climate scenarios, however, the iterative procedure needs to be repeated approximately one dozen times before yielding a vector of equilibrium type-specific populations at machine precision.[24]

In the second stage of the simulation procedure, we use these predicted equilibrium population distributions under alternative climate scenarios to calculate the change in utility experienced by each of the 3500 individuals in our random sub-sample. For each individual, we begin by taking $q = 1,2, ..., 500$ random draws for the vector of Type-I Extreme Value idiosyncratic unobservables ($\eta_{i,j,k}{}^{q}$), and calculate the overall utility associated with each microregion for each draw. We use the appropriate predicted population distribution from the first stage of the simulation procedure at this point to calculate agglomeration or congestion effects, along with the effects on equilibrium wages in each location. In order to control for the latter, we require an expression describing how offered wages would respond to changes in population induced by individuals re-sorting in response to large climate changes. Going back to the set of wage equations estimated in order to impute wages for locations in which individuals were not residing:

$$\ln W_{i,j,k} = \psi_j + z_{i,k}{}' \gamma_j + \varepsilon^W_{i,j,k} \tag{23}$$

we have all the tools necessary to derive such an expression. In particular, all local attributes particular to each microregion (i.e., indexed only by j) were subsumed in microregion specific constants (ψ_j) in those regressions. We now use an instrumental variables regression procedure to decompose those constants into the constituent effects of observable local attributes, including equilibrium population density.

$$\psi_j = \rho_0 + Y_j{}' \rho_Y + \rho_\Delta \Delta_j + \varepsilon^{\psi}_j \tag{24}$$

Interpreting this regression as a labor demand equation (i.e., to accompany the labor supply equation implicit in our sorting model), we have a convenient instrument for population density – predicted population density based only on exogenous attributes, as described in equation (22). These predictions of labor supply should be uncorrelated with unobservable determinants of wages if we assume those determinants to be orthogonal to observable local attributes. Moreover, because migration costs were found to inhibit mobility, we can also use as an instrument population density measured in the 1970 Demographic Census (i.e., under the supposition that a greater population in 1970 is a reasonably exogenous predictor of a greater labor supply in 1991). IV estimation results for this regression procedure are reported in Table 5. Population density is statistically significant with the expected negative sign.[25] The instruments, moreover, pass a χ^2-test of the overidentifying restrictions with a test statistic of 0.155 ($P(\chi^2_{(2)} < 5.99) = 0.95$).

Having determined the equilibrium utility that the individual could enjoy in each microregion under each climate scenario, we next determine the individual's best choice of location for each vector of idiosyncratic error draws under the status quo and post-climate-change scenarios:

$$(25) \qquad j^*_{0,q} = \max_{\{j\}} \left[\pi_{0,k} + \pi_{W,k} \ln \hat{W}^0_{j,s} + \pi_{M1,k} d^{M1}_{i,j,k} + \pi_{M2,k} d^{M2}_{i,j,k} + \Theta^0_{j,k} + \eta^q_{i,j,k} \right]$$

$$(26) \qquad j^*_{1,q} = \max_{\{j\}} \left[\pi_{0,k} + \pi_{W,k} \ln \hat{W}^1_{j,s} + \pi_{M1,k} d^{M1}_{i,j,k} + \pi_{M2,k} d^{M2}_{i,j,k} + \Theta^1_{j,k} + \eta^q_{i,j,k} \right]$$

where $(\hat{W}_{j,s}{}^0, \Theta_{j,k}{}^0)$ and $(\hat{W}_{j,s}{}^1, \Theta_{j,k}{}^1)$ represent equilibrium wages and microregion-and-type-specific indirect utility components (which incorporate equilibrium population densities) under the status quo and post-climate-change scenarios, respectively. These optimal decisions yield utilities $V^*_{i,j^*_{0,q},k}$ and $V^*_{i,j^*_{1,q},k}$ corresponding to the q^{th} simulation draw.

Finally, we calculate the change in maximized utility associated with each climate change scenario. Recall that the indirect utility functions were arbitrarily normalized (i.e., by assuming $\Theta_{1,k} = -1 \; \forall \; k$) and cannot, therefore, be compared directly across types. Moreover, the magnitude of a change in an indirect utility is, essentially, an arbitrarily defined concept as well. For these reasons, welfare measures like equivalent and compensating income variations are typically preferred. Such measures are not well-defined in equilibrium problems of this sort, however, as wages (i.e., the left-hand-side of an expenditure function that we would use to construct these welfare measures) are themselves determined endogenously by the re-equilibration process. Each individual's marginal utility of wages is therefore determined endogenously by the process of re-sorting into a new equilibrium after climate change, and it is not clear which marginal utility should be used as a basis for welfare calculations. There is no generally recognized solution to this problem. We therefore use two approximations, monetizing (and making comparable across types) the change in maximized utility with both the marginal utility of wages in the status quo and after climate change.[26]

(27)
$$\Delta V^{0}_{i,q} = \frac{V^{*}_{i,j^{*}_{1,q},k} - V^{*}_{i,j^{*}_{0,q},k}}{\partial V^{*}_{i,j^{*}_{0,q},k} \Big/ \partial \hat{W}_{j^{*}_{0},s}} \qquad \Delta V^{1}_{i,q} = \frac{V^{*}_{i,j^{*}_{1,q},k} - V^{*}_{i,j^{*}_{0,q},k}}{\partial V^{*}_{i,j^{*}_{1,q},k} \Big/ \partial \hat{W}_{j^{*}_{1},s}}$$

A negative value of $\Delta V_{i,q}^{0,1}$ indicates that the individual is made worse-off by the climate change. The process is repeated 500 times for each of the 3500 individuals, and their monetized utility change is averaged over these draws, "integrating-out" the idiosyncratic unobservable component of indirect utility ($\eta_{i,j,k}$).

(28)
$$\Delta V^{0,1}_{i} = \frac{1}{500} \sum_{s=1}^{500} \Delta V^{0,1}_{i,s}$$

In addition to the baseline, we carry-out two alternative simulations in order to determine the importance of mobility in the valuation exercise. In the first alternative (i.e., "No Migration"), we restrict individuals' abilities to migrate in response to climate change. In particular, we conduct the baseline simulation exercise, but impose prohibitive migration costs on leaving one's initial microregion. This is equivalent to the assumption underlying the traditional marginal wage-hedonic analysis (if it were applied to a large climate change) in that it does not allow re-optimization over location choice. In the second alternative simulation (i.e., "Free Mobility"), we remove the constraints of geography entirely and set all migration costs to zero – i.e., allowing individuals to choose freely from microregions in every part of Brazil in response to climate change.

Before turning to the results of these simulations, we comment on the equilibrium forces at work when the counterfactual mobility assumptions are introduced. An obvious effect of restricting individuals' ability to migrate is that the costs of climate change will increase simply because potentially utility-increasing alternatives will have been removed from the choice set. Similarly, eliminating all barriers to migration should reduce the costs of climate change by opening-up new alternatives. Without equilibrium labor market or agglomeration/congestion effects, this would be the whole story. Introducing these equilibrium effects, however, we cannot say *a priori* whether individuals will be made better- or worse-off by reduced or increased mobility. For example, an individual choosing to remain in a microregion with increased amenity value caused by greenhouse warming could actually be made worse-off if many more people choose to move there because migration costs were eliminated, driving down wages and driving up the prices of locally-traded goods. Similarly, restricting the ability to migrate entirely might actually increase this individual's utility by keeping out labor market competition and keeping those prices down.

The Costs of Climate Change: Simulation Results

Tables 6 (a) - (c) summarize the results of these simulation procedures for the three alternative climate scenarios, respectively. Monetized changes in utility (reported in 1991 US dollars per hour) are typically negative (indicating a utility cost of climate change) and reasonable in magnitude. The only exceptions are in the South and Southeast (i.e., the cooler regions of the country), where we see positive changes for those with more than four years of education. There are a number of other features of the simulation results that are common across specifications and climate change scenarios. Looking first at the baseline simulations, utility falls under every climate change scenario within an education group as one moves from cooler to warmer regions of Brazil (i.e., South, Southeast, Center-West, Northeast, North). In the Northeast and North regions, where estimates suggest that the status quo climate is already beyond the "bliss point" in utility, monetized changes in utility decrease (i.e., become more negative) with increased education. In the South and Southeast regions (where the status quo climate is still below that bliss-point), the pattern reverses, with rising monetized changes in utility accompanying increased levels of education. Looking across scenarios, changes in utility become more negative for individuals of a particular education group in the North, Northeast, and Center-West regions with progressively more severe climate change. Results in the South and Southeast are not as easily generalized across scenarios, but much of this can be attributed to the wide variations across scenarios in predicted rainfall changes in these regions. Welfare effects differ very little with the choice of marginal utility of wages for normalization, particularly when one restricts attention to those with twelve or fewer years of education; as is evident from Table 1, this group represents the vast majority of Brazilians. Note that, because we report monetized changes in utility averaged across many heterogeneous individuals, it is possible for the numbers in Tables 6 (a) - (c) to differ in sign with the choice of normalization. This occurs infrequently and almost exclusively with the [13 +] education group.

These education-group-and-region specific results are easily summarized by calculating annual monetized changes in utility (considering only household heads and assuming that each works 2000 hours a year) for each climate change scenario, aggregating across the whole of Brazil. These values appear in the next-to-last row of each table. Annual costs are reasonable in magnitude, yet still economically significant, ranging from $873 million (0.22% of 1991 Brazilian GDP) under Scenario #1 using the status quo marginal utility of wages to $15.392 billion (3.79% of GDP) under Scenario #3 using the post climate change marginal utility of wages. These results are comparable in percentage and absolute terms with, for example, the agricultural costs of climate change predicted for the US. [Mendelsohn, Nordhaus, and Shaw (1994)]

Comparing results from the baseline simulations with those from the "No Migration" counterfactuals, welfare effects are more negative in the Center-West, Northeast, and North (i.e., the regions where climate change is clearly detrimental), and even in the Southeast region. This is particularly the case for the [9, 12] and [13 +] education groups; the effect of restricted mobility on the lower education groups is minimal, as these groups had not been able to migrate easily in the baseline simulation anyway. Signaling the importance of considering equilibrium effects, however, the opposite result obtains in the South region. Restricting migration keeps out would-be migrants to the South who would otherwise drive-up housing prices and drive-down wages. The added costs of restricted mobility to those in the rest of the country dominate, however, significantly raising the aggregate cost of climate change in every scenario. Individuals' ability to migrate (even imperfectly) in response to non-marginal climate change clearly plays an important role in determining (in particular, reducing) the overall cost of that change.

Turning finally to the "Free Mobility" counterfactual simulations, there are significant increases in welfare compared to the baseline simulations in the Northeast, Center-West, and North regions (i.e., the regions individuals would most likely flee in response to climate change) for all education groups. In the Southeast and South regions, however, the equilibrium effects of individuals being free to re-sort in response to climate change yield reductions in welfare, relative to the baseline changes, for all education groups and scenarios. The reason for this result, as described earlier, is simply that few individuals would choose to leave these regions in response to climate change anyway, yet with perfect mobility, many more individuals would migrate into them from the North, Northeast, and Center-West, depressing wages and raising prices for housing and other locally-traded commodities. Because of the greater initial population density in the southern half of Brazil, the sum of these two competing effects is actually to raise the aggregate costs of climate change under free mobility relative to the baseline, although not always by as much as does completely restricting migration.

For the sake of comparison, we conclude by comparing the results of these simulations with values derived from simple compensating wage differentials – i.e., from a marginal wage-hedonic analysis that ignores the first term on the right-hand-side of equation (1) because of the aforementioned data constraints. While this comparison is inherently unfair in that we know the compensating wage differential by itself to be a biased measure of the cost of climate change, it does give a sense of whether or not the methodology described in this paper is valuable – i.e., whether or not that bias is empirically relevant. Table 7 reports the results of a simple reduced-form wage equation from which we are able to measure the change in equilibrium wages associated with a change in climate. Table 8 uses these results to calculate the change in wages associated with the three alternative climate change scenarios. The most striking result is that, with the *exception* of the South region under Scenario #1, all of the estimated compensating wage differentials are negative, implying *benefits* from climate change. Moreover, the size of these benefits tends to be larger in warmer parts of the country (i.e., North, Northeast, and Center-West) and to increase with the severity of climate change, rising from \$0.99 billion under Scenario #1 to \$2.59 billion under Scenario #3. The difference in sign between these results and those derived from our equilibrium model has obvious implications for the position from which a developing country like Brazil could negotiate with the developed world in post-Kyoto discussions over global greenhouse gas abatement efforts.

6. Conclusions

This paper illustrates a technique for valuing the equilibrium amenity effects of non-marginal climate change that is applicable even under the sorts of data constraints commonly encountered in developing country contexts. Traditional wage-hedonic theory, based on marginal relationships that hold only for small changes around the status quo, is inappropriate for valuing the amenity consequences of global climate change – general circulation models predict temperature increases of up to 4.5 °C and changes in rainfall of up to ±30%. Moreover, that technique is impractical without data on the prices of housing and other locally traded commodities; such data are often unavailable in large developing countries such as Brazil and India. Our model exploits spatial variation in settlement patterns to overcome this data constraint, and adapts empirical techniques from the differentiated product demand estimation literature in order to recover indirect utility functions that can be used to value large changes in climate, accounting for the equilibrium impacts on settlement patterns.

In contrast to a simple model of compensating wage differentials, the results of our model predict significant annual amenity costs from climate change in Brazil, ranging from just under ¼ to over 3 ¾ percent of GDP, depending upon the particular climate change scenario being considered. Counterfactual simulations using alternative assumptions about mobility, moreover, suggest that constraints on migration play an important role in determining the size and distribution of these costs. Less-educated residents of Brazil's poorer northern states, in particular, suffer more as a result of being unable to move easily in response to climate change. On the other hand, those in the southern states (educated and uneducated alike) benefit in equilibrium from those constraints, which inhibit southward migration flows that would otherwise depress wages and raise the prices of locally traded commodities. These results suggest that wage-hedonics, which ignores migration costs and, in particular, how those costs vary with distance and individual attributes, will yield biased estimates of value.

While accounting for the equilibrium impacts of climate change on labor supply and the demand for locally traded commodities, our model is still partial equilibrium in its treatment of firms and labor demand. The distribution and sectoral composition of firms (in particular, agriculture) may change dramatically in response to large changes in temperature and rainfall, but this distribution is held fixed in the current analysis. Further research using comparable micro data on firm location and production decisions will be required in order to properly model firms' decisions and to develop a truly general equilibrium framework for valuing the costs of climate change.

Table 1
Descriptive Statistics, 1991 Demographic Census and Other Data Sources
Full Data Panel

Variable	Regional Average				
	North	North-East	Center-West	South-East	South
Number of Microregions	51	186	8	156	94
Population Density (Persons per km^2)	0.42	1.16	0.06	2.47	0.78
Population Density 1970 (Persons per km^2)	0.22	0.55	0.03	1.90	0.42
% Household Heads, [0,4] Years Education	61.0	62.0	49.9	51.4	48.6
% Household Heads, [5,8] Years Education	18.9	15.7	21.0	22.3	23.7
% Household Heads, [9,12] Years Education	14.6	15.7	16.2	16.0	17.0
% Household Heads, [13+] Years Education	5.6	6.6	12.9	10.4	10.6
Hourly Wage, [0,4] Years Education	1.00	0.67	1.11	1.15	0.99
Hourly Wage, [5,8] Years Education	1.55	1.22	1.66	1.68	1.40
Hourly Wage, [9,12] Years Education	2.84	2.26	3.28	2.86	2.63
Hourly Wage, [13+] Years Education	6.11	5.36	8.05	6.60	4.81
Average Temperature (°C)	26.24	25.52	23.87	21.40	18.97
Fall Rainfall (cm)	22.40	13.30	11.88	9.51	13.36
Spring Rainfall (cm)	13.98	4.73	15.76	15.49	14.71
Distance from State Capital (km)	323	197	171	197	236
Distance from Port (km)	567	214	1224	245	252
Distance from São Paulo (km)	2441	1944	1226	428	677
Erosion Potential = 1	0.33	0.40	0.50	0.22	0.01
Erosion Potential = 2	0.42	0.59	0.74	0.16	0.00
Erosion Potential = 3	0.25	0.24	0.19	0.20	0.26
Erosion Potential = 4	0.14	0.16	0.04	0.20	0.00
Erosion Potential = 5	0.40	0.18	0.02	0.13	0.17
% Minerals	0.12	0.02	0.63	0.08	0.15
% Rivers	0.73	0.08	0.00	0.21	0.20
% Highways	0.06	0.22	0.63	0.37	0.46

Table 2
Microregion Wage-Equation Estimation Results
Summary of Coefficients from 495 Regressions

Variable	Average Estimate	Std Dev Estimates	Average t-statistic	Variable	Average Estimate	Std Dev Estimates	Average t-statistic
Constant	4.592	0.285	46.92	*MANUFACTURE*	0.308	0.158	6.07
AGE	0.007	0.004	5.11	*SERVICE*	0.452	0.160	9.26
MALE	0.376	0.121	5.63	*PROFESSIONAL*	0.595	0.193	9.05
				ln *EDUCATION*	0.173	0.079	14.53

Tables 3 (a) - (d)
Migration Patterns Between the Regions
% Born in Birth Region Living in Residence Region

0 - 4 Years of Education

		Residence				
		N	NE	SE	S	CW
Birth	N	82.37	9.30	3.79	1.71	2.82
	NE	4.25	72.39	20.58	0.60	2.18
	SE	0.77	9.71	85.37	3.07	1.08
	S	0.50	0.54	8.93	88.39	1.65
	CW	4.32	20.54	16.22	15.14	43.78

5 - 8 Years of Education

		Residence				
		N	NE	SE	S	CW
Birth	N	77.47	8.55	6.58	3.95	3.45
	NE	4.34	64.87	27.29	1.06	2.44
	SE	1.11	7.04	86.27	4.18	1.41
	S	1.00	0.82	8.27	88.67	1.24
	CW	6.91	15.21	18.89	12.44	46.54

9 - 12 Years of Education

		Residence				
		N	NE	SE	S	CW
Birth	N	67.37	12.08	13.35	4.24	2.97
	NE	4.15	78.56	14.07	1.37	1.85
	SE	1.95	8.01	83.14	4.84	2.06
	S	1.17	1.22	7.99	87.73	1.90
	CW	9.94	23.20	27.62	9.39	29.83

13 + Years of Education

		Residence				
		N	NE	SE	S	CW
Birth	N	51.48	18.34	21.30	5.33	3.55
	NE	3.66	74.46	16.06	2.05	3.77
	SE	1.78	5.85	81.74	7.06	3.57
	S	1.70	2.02	8.90	85.03	2.35
	CW	10.60	17.22	47.68	12.58	11.92

Table 4
Parameter Estimates

Variable	Education = [0, 4]		Education = [5, 8]		Education = [9, 12]		Education = [13 +]	
	Estimate	t-stat	Estimate	t-stat	Estimate	t-stat	Estimate	t-stat
First-Stage:								
ln W	1.540	28.95	1.043	12.94	0.726	8.43	0.508	4.57
d^{M1}	-1.942	-62.45	-1.828	-54.96	-1.778	-48.60	-1.565	-31.48
d^{M2}	-3.658	-54.71	-1.338	-22.28	-1.151	-18.44	-0.871	-10.59
Second-Stage:								
Constant	-14.946	-1.19	-26.934	-1.83	-31.442	-2.02	-49.792	-2.580
ln R_{Fall}	1.023	2.10	1.785	2.95	1.699	2.56	1.743	2.29
ln R_{Spring}	0.476	2.74	0.782	3.78	0.861	3.89	0.241	0.88
ln Temp	5.623	1.08	9.871	1.62	11.556	1.79	20.077	2.51
R_{Fall} • ln R_{Fall}	-0.014	-1.64	-0.020	-2.01	-0.021	-1.88	-0.019	-1.48
R_{Spring} • ln R_{Spring}	-0.026	-3.36	-0.023	-2.63	-0.025	-2.73	-3.69 x 10^{-3}	-0.33
Temp • ln Temp	-0.070	-1.20	-0.115	-1.67	-0.128	-1.76	-0.234	-2.59
ln Dist to Capital	-0.083	-1.36	-0.188	-2.68	-0.202	-3.03	-0.197	-3.16
ln Dist Sao Paulo	7.04 x 10^{-3}	0.07	-0.146	-1.31	-0.103	-0.87	-0.262	-1.94
River	0.110	2.05	0.390	3.14	0.408	3.04	0.547	3.32
Highway	0.320	3.35	0.434	3.69	0.425	3.46	0.617	4.14
ln Pop Density	-0.046	-0.82	8.05 x 10^{-3}	0.12	0.060	0.84	0.102	1.26
ln Pop Density (SUR estimation)	0.469	17.28	0.595	18.74	0.674	19.63	0.793	17.74
R^2	0.014		0.217		0.247		0.320	

Table 5
Wage Equation Microregion-Specific Constant Decomposition
Instrumental Variables Estimation,[27] Dependent Variable = ψ_j
N = 495, Heteroskedastic-Consistent Standard Errors, $R^2 = 0.227$
χ^2 Test of Overidentifying Restrictions = 0.155, $P(\chi^2_{(2)} \leq 5.99) = 0.95$

Variable	Estimate	t-stat	Variable	Estimate	t-stat
Constant	4.346	39.01	Erosion Potential = 4	-0.023	-0.522
ln Pop Density	-0.027	-1.90	Erosion Potential = 5	0.269	6.29
Erosion Potential = 1	0.087	2.54	SP State Dummy	0.280	7.12
Erosion Potential = 2	0.110	3.54	Mineral Deposits	0.091	2.25
Erosion Potential = 3	0.186	4.80	ln Distance to Port	5.96×10^{-3}	0.29

Table 6 (a)
Average Change in Utility, Climate Change Scenario #1
Monetized by Marginal Utility of Wages at (1) Status Quo, (2) Post Climate Change
1991 US Dollars

Region	Education	Average Wage	Baseline		No Migration		Free Mobility	
			(1)	(2)	(1)	(2)	(1)	(2)
South	13 +	4.81	0.45	0.22	1.13	0.84	0.03	-0.31
	9 - 12	2.63	0.16	0.12	0.32	0.27	-0.01	-0.06
	5 - 8	1.40	0.05	0.04	0.12	0.10	-0.03	-0.05
	0 - 4	0.99	-0.04	-0.05	-0.04	-0.04	-0.05	-0.06
Southeast	13 +	6.60	0.23	-0.00	-0.12	-0.24	0.05	-0.26
	9 - 12	2.86	0.09	0.04	0.02	-0.00	-0.01	-0.06
	5 - 8	1.68	0.02	-0.00	-0.01	-0.03	-0.03	-0.06
	0 - 4	1.15	-0.04	-0.05	-0.04	-0.05	-0.05	-0.06
Center-West	13 +	8.05	-0.06	-0.38	-1.66	-2.55	0.06	-0.25
	9 - 12	3.28	-0.06	-0.12	-0.46	-0.56	-0.02	-0.08
	5 - 8	1.66	-0.05	-0.08	-0.15	-0.18	-0.03	-0.05
	0 - 4	1.11	-0.05	-0.06	-0.08	-0.09	-0.05	-0.05
Northeast	13 +	5.36	-0.51	-0.88	-0.81	-1.15	0.05	-0.29
	9 - 12	2.26	-0.18	-0.23	-0.22	-0.27	-0.01	-0.07
	5 - 8	1.22	-0.11	-0.14	-0.14	-0.17	-0.03	-0.06
	0 - 4	0.67	-0.04	-0.05	-0.04	-0.05	-0.04	-0.05
North	13 +	6.11	-0.50	-1.03	-1.51	-2.80	0.08	-0.23
	9 - 12	2.84	-0.25	-0.34	-0.39	-0.51	-0.01	-0.06
	5 - 8	1.55	-0.16	-0.21	-0.27	-0.36	-0.02	-0.05
	0 - 4	1.00	-0.06	-0.08	-0.08	-0.10	-0.04	-0.05
Aggregate Annual Cost (2,000 hours worked per year, billions 1991 $US)			-0.873	-3.821	-2.106	-5.059	-1.920	-5.498
Percent of 1991 Brazilian GDP			-0.22	-0.94	-0.52	-1.25	-0.47	-1.36

Table 6 (b)
Average Change in Utility, Climate Change Scenario #2
Monetized by Marginal Utility of Wages at (1) Status Quo, (2) Post Climate Change
1991 US Dollars

Region	Education	Average Wage	Baseline		No Migration		Free Mobility	
			(1)	(2)	(1)	(2)	(1)	(2)
South	13 +	4.81	0.49	0.19	1.26	0.91	0.02	-0.47
	9 - 12	2.63	0.17	0.12	0.35	0.29	-0.03	-0.12
	5 - 8	1.40	0.05	0.03	0.13	0.11	-0.04	-0.08
	0 - 4	0.99	-0.05	-0.06	-0.05	-0.05	-0.06	-0.07
Southeast	13 +	6.60	0.26	-0.06	-0.17	-0.35	0.04	-0.40
	9 - 12	2.86	0.08	0.02	0.01	-0.02	-0.03	-0.11
	5 - 8	1.68	0.01	-0.03	-0.02	-0.04	-0.04	-0.08
	0 - 4	1.15	-0.05	-0.06	-0.05	-0.05	-0.06	-0.07
Center-West	13 +	8.05	-0.14	-0.60	-2.02	-3.49	0.03	-0.42
	9 - 12	3.28	-0.11	-0.20	-0.59	-0.77	-0.03	-0.12
	5 - 8	1.66	-0.08	-0.13	-0.20	-0.25	-0.04	-0.08
	0 - 4	1.11	-0.06	-0.07	-0.10	-0.12	-0.06	-0.07
Northeast	13 +	5.36	-0.62	-1.18	-0.99	-1.55	0.02	-0.46
	9 - 12	2.26	-0.25	-0.34	-0.32	-0.41	-0.03	-0.13
	5 - 8	1.22	-0.15	-0.20	-0.20	-0.25	-0.04	-0.08
	0 - 4	0.67	-0.05	-0.06	-0.05	-0.06	-0.05	-0.06
North	13 +	6.11	-0.55	-1.30	-1.76	-3.73	0.09	-0.34
	9 - 12	2.84	-0.31	-0.45	-0.48	-0.67	-0.03	-0.12
	5 - 8	1.55	-0.19	-0.27	-0.32	-0.45	-0.04	-0.08
	0 - 4	1.00	-0.08	-0.10	-0.10	-0.12	-0.05	-0.06
Aggregate Annual Cost (2,000 hours worked per year, billions 1991 $US)			-1.619	-5.904	-3.353	-7.767	-2.853	-8.062
Percent of 1991 Brazilian GDP			-0.40	-1.46	-0.83	-1.92	-0.70	-1.99

Table 6 (c)
Average Change in Utility, Climate Change Scenario #3
Monetized by Marginal Utility of Wages at (1) Status Quo, (2) Post Climate Change
1991 US Dollars

Region	Education	Average Wage	Baseline		No Migration		Free Mobility	
			(1)	(2)	(1)	(2)	(1)	(2)
South	13 +	4.81	0.51	-0.06	1.56	1.03	-0.07	-1.11
	9 - 12	2.63	0.15	0.05	0.41	0.31	-0.10	-0.32
	5 - 8	1.40	0.02	-0.02	0.13	0.10	-0.09	-0.20
	0 - 4	0.99	-0.09	-0.11	-0.08	-0.10	-0.11	-0.14
Southeast	13 +	6.60	0.22	-0.45	-0.48	-0.94	-0.03	-0.98
	9 - 12	2.86	0.03	-0.09	-0.08	-0.16	-0.11	-0.32
	5 - 8	1.68	-0.03	-0.10	-0.09	-0.14	-0.10	-0.20
	0 - 4	1.15	-0.09	-0.11	-0.09	-0.11	-0.10	-0.13
Center-West	13 +	8.05	-0.30	-1.29	-2.84	-6.93	-0.10	-1.04
	9 - 12	3.28	-0.19	-0.42	-0.93	-1.44	-0.11	-0.34
	5 - 8	1.66	-0.15	-0.27	-0.33	-0.51	-0.09	-0.19
	0 - 4	1.11	-0.10	-0.13	-0.15	-0.21	-0.10	-0.12
Northeast	13 +	5.36	-0.90	-2.28	-1.41	-2.92	-0.03	-1.04
	9 - 12	2.26	-0.42	-0.72	-0.54	-0.91	-0.12	-0.34
	5 - 8	1.22	-0.24	-0.40	-0.32	-0.53	-0.10	-0.21
	0 - 4	0.67	-0.08	-0.11	-0.08	-0.12	-0.08	-0.11
North	13 +	6.11	-0.83	-2.77	-2.31	-7.58	0.00	-0.93
	9 - 12	2.84	-0.49	-0.91	-0.71	-1.19	-0.10	-0.31
	5 - 8	1.55	-0.30	-0.52	-0.44	-0.78	-0.10	-0.20
	0 - 4	1.00	-0.12	-0.17	-0.14	-0.20	-0.09	-0.12
Aggregate Annual Cost (2,000 hours worked per year, billions 1991 $US)			-5.317	-15.392	-8.199	-19.419	-6.516	-18.426
Percent of 1991 Brazilian GDP			-1.31	-3.79	-2.02	-4.79	-1.61	-4.54

Table 7

Compensating Wage Differentials Regression

Reduced-Form Wage Equation, Dependent Variable = ln($W_{i,j,k}$)

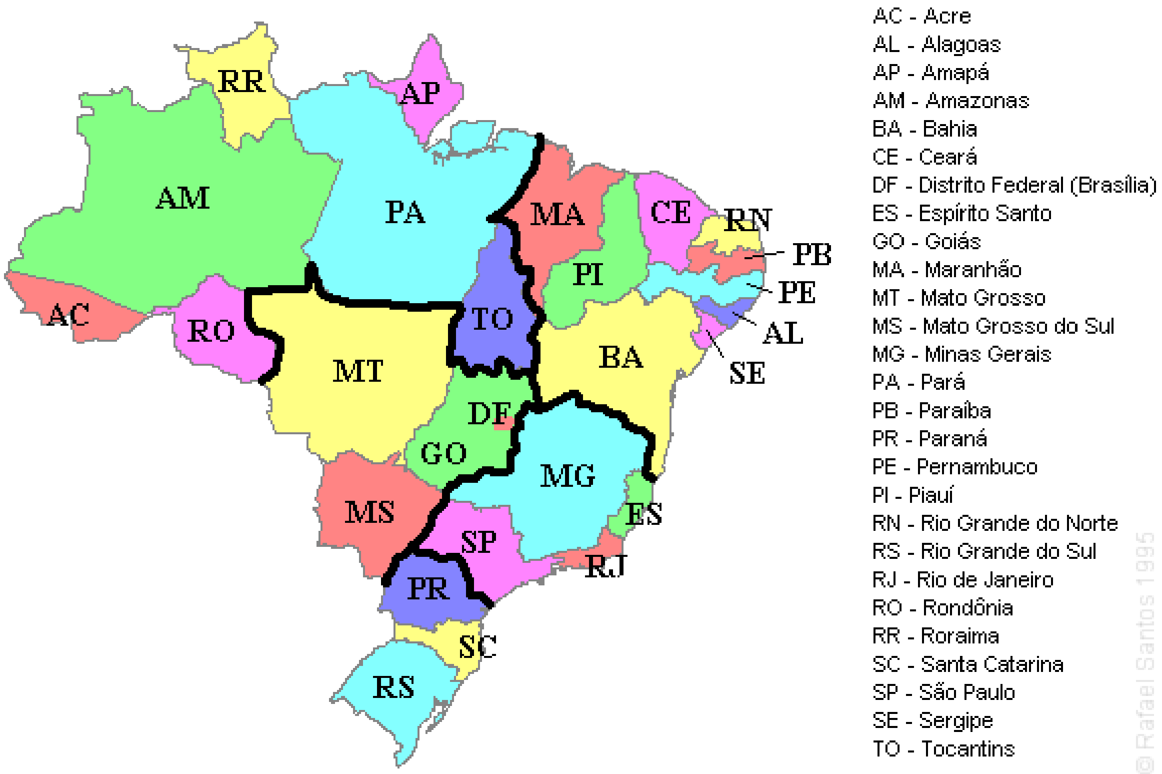
$R^2 = 0.329$, Excluded Category = {Southeast, Agricultural Sector}

Variable	Estimate	t-statistic	Variable	Estimate	t-statistic
Constant	0.573	0.33	Erosion Potential = 4	-0.177	-7.61
ln R_{Fall}	0.353	4.05	Erosion Potential = 5	-0.013	-0.78
ln R_{Spring}	0.184	6.06	Mineral Deposits	0.014	0.73
ln Temp	1.246	1.70	North	0.293	7.83
R_{Fall} • ln R_{Fall}	-5.32×10^{-3}	-3.54	Northeast	-0.046	-1.33
R_{Spring} • ln R_{Spring}	-7.55×10^{-3}	-5.50	Center-West	0.273	6.59
Temp • ln Temp	-0.015	-1.78	South	-0.024	-0.79
ln Dist to Capital	-0.017	-3.22	Male	0.367	21.41
ln Dist Sao Paulo	-0.139	-14.34	ln Age	0.460	26.29
River	0.012	0.73	Manufacturing Sector	0.402	26.90
Highway	0.023	1.87	Service Sector	0.408	26.50
Erosion Potential = 1	0.018	1.06	Professional Sector	0.796	39.64
Erosion Potential = 2	0.027	1.28	ln Education	0.250	73.13
Erosion Potential = 3	0.053	2.89			

Table 8
Median Compensating Wage Differentials (Marginal Wage-Hedonics)
1991 US Dollars

Region	Education	Average Wage	Climate Change Scenario		
			1	2	3
South	0 - 4	0.99	-0.01	-0.01	-0.02
	5 - 8	1.40	0.00	-0.00	-0.02
	9 - 12	2.63	0.00	-0.00	-0.02
	13 +	4.81	0.00	-0.00	-0.03
Southeast	0 - 4	1.15	-0.01	-0.01	-0.02
	5 - 8	1.68	-0.01	-0.01	-0.03
	9 - 12	2.86	-0.02	-0.02	-0.04
	13 +	6.60	-0.02	-0.02	-0.05
Northeast	0 - 4	0.67	-0.01	-0.02	-0.03
	5 - 8	1.22	-0.02	-0.03	-0.06
	9 - 12	2.26	-0.03	-0.04	-0.08
	13 +	5.36	-0.03	-0.05	-0.09
Center-West	0 - 4	1.11	-0.02	-0.04	-0.05
	5 - 8	1.66	-0.04	-0.05	-0.08
	9 - 12	3.28	-0.05	-0.06	-0.11
	13 +	8.05	-0.06	-0.08	-0.14
North	0 - 4	1.00	-0.01	-0.02	-0.03
	5 - 8	1.55	-0.04	-0.05	-0.07
	9 - 12	2.84	-0.05	-0.06	-0.08
	13 +	6.11	-0.05	-0.07	-0.09
Aggregate Annual Cost (2,000 hours worked per year, billions 1991 US dollars)			-0.99	-1.31	-2.59

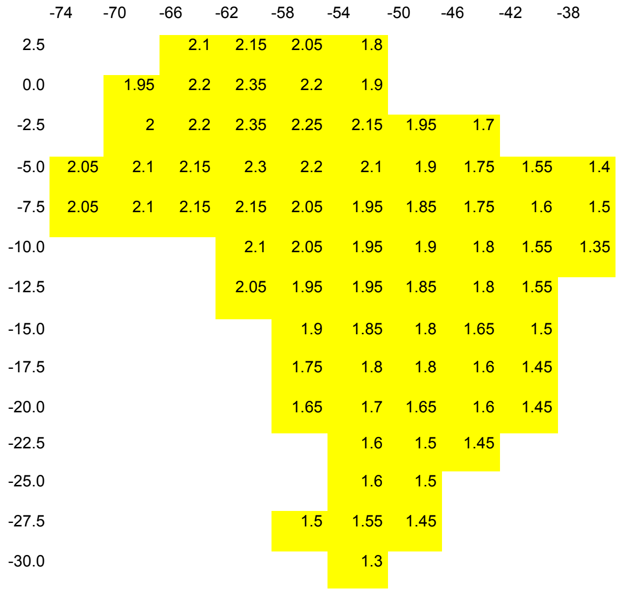
Figure 1 – Map of Brazil[28]



AC - Acre
AL - Alagoas
AP - Amapá
AM - Amazonas
BA - Bahia
CE - Ceará
DF - Distrito Federal (Brasília)
ES - Espírito Santo
GO - Goiás
MA - Maranhão
MT - Mato Grosso
MS - Mato Grosso do Sul
MG - Minas Gerais
PA - Pará
PB - Paraíba
PR - Paraná
PE - Pernambuco
PI - Piauí
RN - Rio Grande do Norte
RS - Rio Grande do Sul
RJ - Rio de Janeiro
RO - Rondônia
RR - Roraima
SC - Santa Catarina
SP - São Paulo
SE - Sergipe
TO - Tocantins

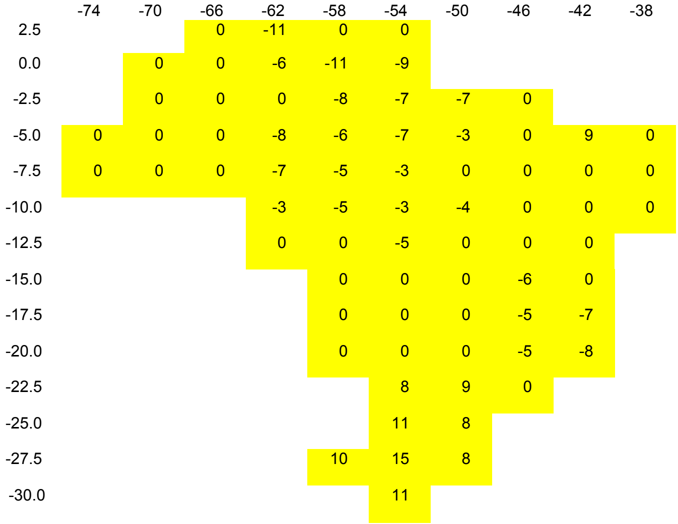
Figures 2 (a) - (c)
Climate Change Scenario #1

Average Annual Temperature Increase, ° Celsius



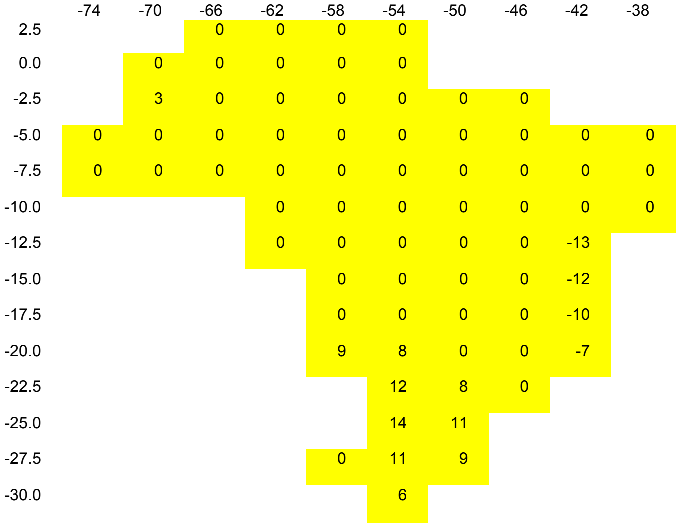
	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			2.1	2.15	2.05	1.8				
0.0		1.95	2.2	2.35	2.2	1.9				
-2.5		2	2.2	2.35	2.25	2.15	1.95	1.7		
-5.0	2.05	2.1	2.15	2.3	2.2	2.1	1.9	1.75	1.55	1.4
-7.5	2.05	2.1	2.15	2.15	2.05	1.95	1.85	1.75	1.6	1.5
-10.0				2.1	2.05	1.95	1.9	1.8	1.55	1.35
-12.5				2.05	1.95	1.95	1.85	1.8	1.55	
-15.0					1.9	1.85	1.8	1.65	1.5	
-17.5					1.75	1.8	1.8	1.6	1.45	
-20.0					1.65	1.7	1.65	1.6	1.45	
-22.5						1.6	1.5	1.45		
-25.0						1.6	1.5			
-27.5					1.5	1.55	1.45			
-30.0						1.3				

% Change in Rainfall, March - May



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			0	-11	0	0				
0.0		0	0	-6	-11	-9				
-2.5		0	0	0	-8	-7	-7	0		
-5.0	0	0	0	-8	-6	-7	-3	0	9	0
-7.5	0	0	0	-7	-5	-3	0	0	0	0
-10.0				-3	-5	-3	-4	0	0	0
-12.5				0	0	-5	0	0	0	
-15.0					0	0	0	-6	0	
-17.5					0	0	0	-5	-7	
-20.0					0	0	0	-5	-8	
-22.5						8	9	0		
-25.0						11	8			
-27.5					10	15	8			
-30.0						11				

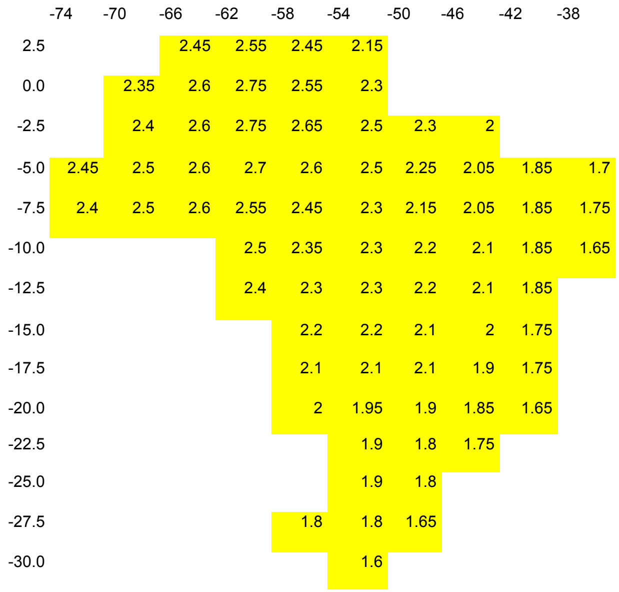
% Change in Rainfall, September - November



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			0	0	0	0				
0.0		0	0	0	0	0				
-2.5		3	0	0	0	0	0	0		
-5.0	0	0	0	0	0	0	0	0	0	0
-7.5	0	0	0	0	0	0	0	0	0	0
-10.0				0	0	0	0	0	0	0
-12.5				0	0	0	0	0	-13	
-15.0					0	0	0	0	-12	
-17.5					0	0	0	0	-10	
-20.0					9	8	0	0	-7	
-22.5						12	8	0		
-25.0						14	11			
-27.5					0	11	9			
-30.0						6				

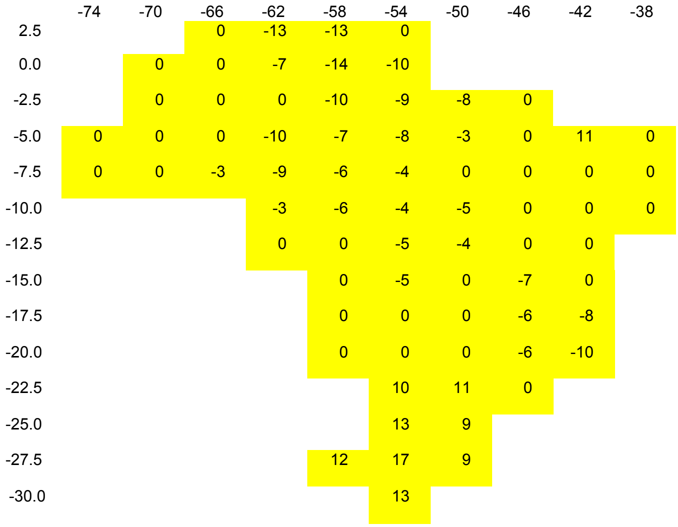
Figures 3 (a) - (c)
Climate Change Scenario #2

Average Annual Temperature Increase, ° Celsius



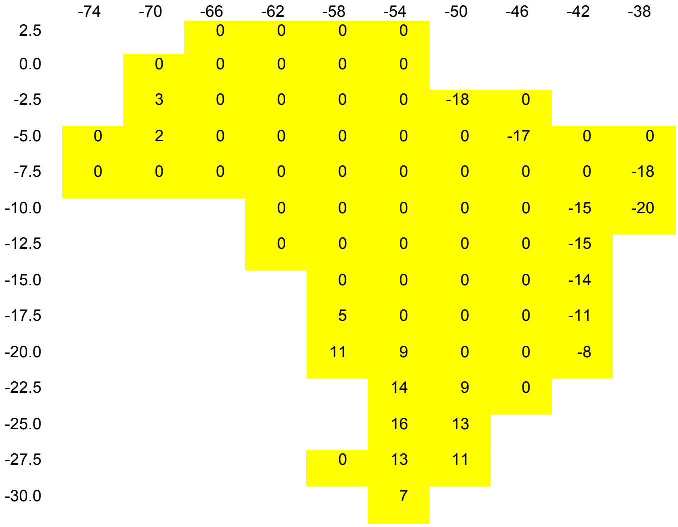
	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			2.45	2.55	2.45	2.15				
0.0		2.35	2.6	2.75	2.55	2.3				
-2.5		2.4	2.6	2.75	2.65	2.5	2.3	2		
-5.0	2.45	2.5	2.6	2.7	2.6	2.5	2.25	2.05	1.85	1.7
-7.5	2.4	2.5	2.6	2.55	2.45	2.3	2.15	2.05	1.85	1.75
-10.0				2.5	2.35	2.3	2.2	2.1	1.85	1.65
-12.5				2.4	2.3	2.3	2.2	2.1	1.85	
-15.0					2.2	2.2	2.1	2	1.75	
-17.5					2.1	2.1	2.1	1.9	1.75	
-20.0					2	1.95	1.9	1.85	1.65	
-22.5						1.9	1.8	1.75		
-25.0						1.9	1.8			
-27.5					1.8	1.8	1.65			
-30.0						1.6				

% Change in Rainfall, March - May



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			0	-13	-13	0				
0.0		0	0	-7	-14	-10				
-2.5		0	0	0	-10	-9	-8	0		
-5.0	0	0	0	-10	-7	-8	-3	0	11	0
-7.5	0	0	-3	-9	-6	-4	0	0	0	0
-10.0				-3	-6	-4	-5	0	0	0
-12.5				0	0	-5	-4	0	0	
-15.0					0	-5	0	-7	0	
-17.5					0	0	0	-6	-8	
-20.0					0	0	0	-6	-10	
-22.5						10	11	0		
-25.0						13	9			
-27.5					12	17	9			
-30.0						13				

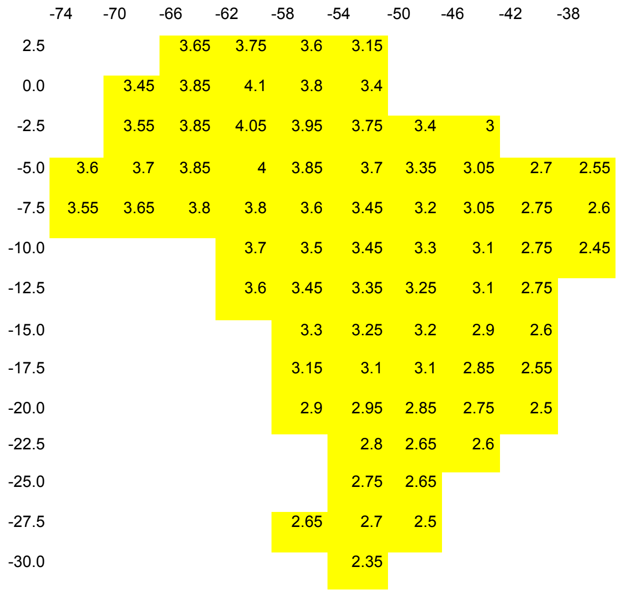
% Change in Rainfall, September - November



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			0	0	0	0				
0.0		0	0	0	0	0				
-2.5		3	0	0	0	0	-18	0		
-5.0	0	2	0	0	0	0	0	-17	0	0
-7.5	0	0	0	0	0	0	0	0	0	-18
-10.0				0	0	0	0	0	-15	-20
-12.5				0	0	0	0	0	-15	
-15.0					0	0	0	0	-14	
-17.5					5	0	0	0	-11	
-20.0					11	9	0	0	-8	
-22.5						14	9	0		
-25.0						16	13			
-27.5					0	13	11			
-30.0						7				

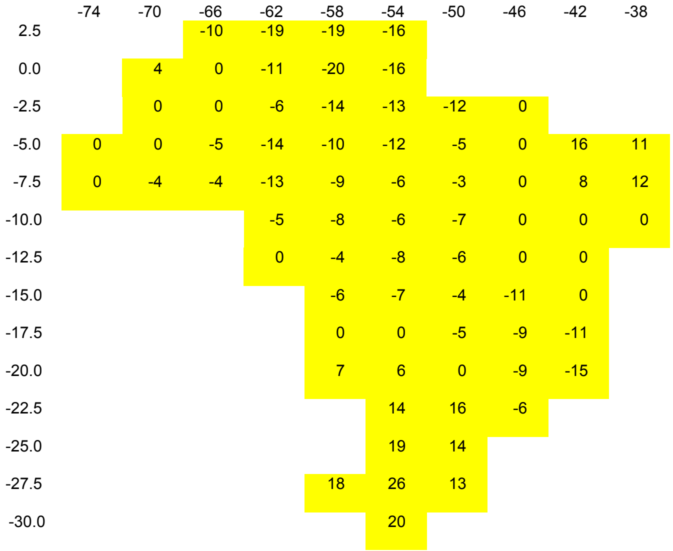
Figures 4 (a) - (c)
Climate Change Scenario #3

Average Annual Temperature Increase, ° Celsius



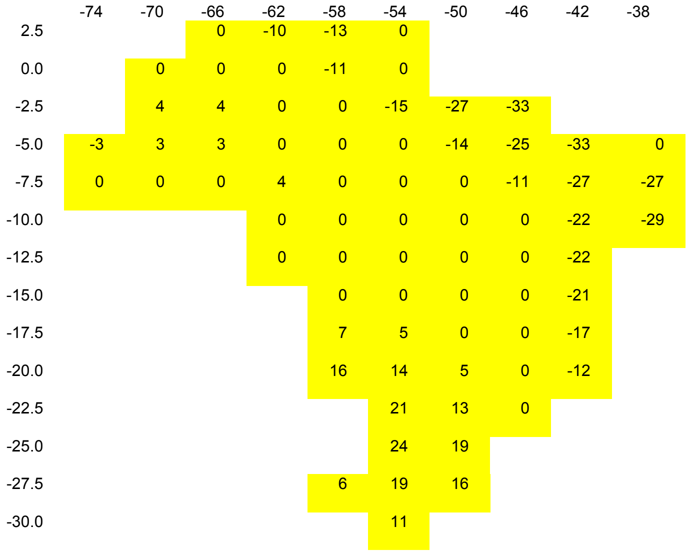
	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			3.65	3.75	3.6	3.15				
0.0		3.45	3.85	4.1	3.8	3.4				
-2.5		3.55	3.85	4.05	3.95	3.75	3.4	3		
-5.0	3.6	3.7	3.85	4	3.85	3.7	3.35	3.05	2.7	2.55
-7.5	3.55	3.65	3.8	3.8	3.6	3.45	3.2	3.05	2.75	2.6
-10.0				3.7	3.5	3.45	3.3	3.1	2.75	2.45
-12.5				3.6	3.45	3.35	3.25	3.1	2.75	
-15.0					3.3	3.25	3.2	2.9	2.6	
-17.5					3.15	3.1	3.1	2.85	2.55	
-20.0					2.9	2.95	2.85	2.75	2.5	
-22.5						2.8	2.65	2.6		
-25.0						2.75	2.65			
-27.5					2.65	2.7	2.5			
-30.0						2.35				

% Change in Rainfall, March - May



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			-10	-19	-19	-16				
0.0		4	0	-11	-20	-16				
-2.5		0	0	-6	-14	-13	-12	0		
-5.0	0	0	-5	-14	-10	-12	-5	0	16	11
-7.5	0	-4	-4	-13	-9	-6	-3	0	8	12
-10.0				-5	-8	-6	-7	0	0	0
-12.5				0	-4	-8	-6	0	0	
-15.0					-6	-7	-4	-11	0	
-17.5					0	0	-5	-9	-11	
-20.0					7	6	0	-9	-15	
-22.5						14	16	-6		
-25.0						19	14			
-27.5					18	26	13			
-30.0						20				

% Change in Rainfall, September - November



	-74	-70	-66	-62	-58	-54	-50	-46	-42	-38
2.5			0	-10	-13	0				
0.0		0	0	0	-11	0				
-2.5		4	4	0	0	-15	-27	-33		
-5.0	-3	3	3	0	0	0	-14	-25	-33	0
-7.5	0	0	0	4	0	0	0	-11	-27	-27
-10.0				0	0	0	0	0	-22	-29
-12.5				0	0	0	0	0	-22	
-15.0					0	0	0	0	-21	
-17.5					7	5	0	0	-17	
-20.0					16	14	5	0	-12	
-22.5						21	13	0		
-25.0						24	19			
-27.5					6	19	16			
-30.0						11				

REFERENCES

Adams, Richard M. 1989. "Global Climate Change and Agriculture: An Economic Perspective." *American Journal of Agricultural Economics*. 71(5): 1272-1279.

Bayer, Patrick and Christopher Timmins. 2003a. "Estimating Equilibrium Models of Sorting Across Locations." Yale University Department of Economics Working Paper.

________. 2003b. "A Note on the Equilibrium Properties of Models of Locational Sorting." Yale University Department of Economics Working Paper.

________. 2003c. "An Equilibrium Approach to Estimating the Amenity Consequences of Global Warming for the United States." Yale University Department of Economics Working Paper.

Berry, Steven. 1994. "Estimating Discrete Choice Models of Product Differentiation." *RAND Journal of Economics*. 25:242-262.

Berry, Steven, James Levinsohn, and Ariel Pakes. 1995. "Automobile Prices in Market Equilibrium." *Econometrica*. 63: 841-890.

________. 2001. "Differentiated Products Demand Systems from a Combination of Micro and Macro Data: The New Car Market." Cowles Foundation Working Paper #1337. Yale University Department of Economics.

Bloomquist, Glenn C., Mark C. Berger, and John P. Hoehn. 1988. "New Estimates of Quality of Life in Urban Areas." *American Economic Review*. 78(1):89-107.

Bresnahan, Timothy. 1981. "Departures from Marginal-Cost Pricing in the American Automobile Industry," *Journal of Econometrics*. 17:201-227.

________. 1987. "Competition and Collusion in the American Automobile Oligopoly: The 1955 Price War." *Journal of Industrial Economics*. 35:457-482.

Cragg, Michael and Matthew Kahn. 1997. "New Estimates of Climate Demand: Evidence from Location Choice." *Journal of Urban Economics*. 42:261-284.

Cropper, Maureen. 1981. "The Value of Urban Amenities." *Journal of Regional Science*. 21(3):359-373.

Cropper, Maureen L., Leland Deck, Nalin Kishor, and Kenneth E. McConnell. 1993. "Valuing Product Attributes Using Single Market Data: A Comparison of Hedonic and Discrete Choice Approaches." *The Review of Economics and Statistics*. 75(2):225-232.

Deaton, Angus and Alessandro Tarozzi. 2000. "Prices and Poverty in India." Mimeo, Research Program in Development Studies, Princeton University.

Evenson, Robert E. and Denisard Alves. 1998. "Technology, Climate Change, Productivity, and Land Use in Brazilian Agriculture." Mimeo, Yale University Department of Economics.

Getz, Malcolm and Huang, Y.C. 1978. "Consumer Revealed Preference for Environmental Goods." *Review of Economics and Statistics*. 60: 449-459.

Henderson, Vernon. 1982. "Evaluating Consumer Welfare Amenities and Interregional Welfare Differences." *Journal of Urban Economics*. 11(1):32-59.

Hoehn, John P., Mark C. Berger, and Glenn C. Bloomquist. 1987. "A Hedonic Model of Interregional Wages, Rents, and Amenity Values." *Journal of Regional Science*. 27(4):605-620.

Hulme, M. and Sheard, N. 1999. *Climate Change Scenarios for Brazil*. Climatic Research Unit, Norwich, UK. 6pp.

Instituto Brasileiro de Geografia e Estatística 1996. *Censo Demográfico de 1991: Documentação dos Microdados da Amostra.*

Intergovernmental Panel on Climate Change. 1995a. "IPCC Second Assessment: Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change." Internet. Available 11/1/98. http://www.ipcc.ch/.

________. 1995b. "Summary for Policymakers: The Economic and Social Dimensions of Climate Change -- IPCC Working Group III." Internet. Available 11/1/98. http://www.ipcc.ch/.

Mendelsohn, Robert. 1985. "Identifying Structural Equations with Single Market Data." *The Review of Economics and Statistics*. 67(3):525-529.

Mendelsohn, Robert. 1998. "An Hedonic Study of the Nonmarket Impacts of Global Warming." Mimeo, Yale School of Forestry and Environmental Studies.

Mendelsohn, Robert, William Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *The American Economic Review*. 84 (4): 753-771.

Meyer, John R. And Robert A. Leone. 1977. "The Urban Disamenity Revisited." In Lowdon Wingo and Alan Evans (eds), *Public Economics and the Quality of Life*. Baltimore, MD: The Johns Hopkins University Press for Resources for the Future and the Centre for Environmental Studies.

Mohring, Herbert. 1971. "Alternative Welfare Gain and Loss Measures." *Western Economic Journal*. 9(4):349-368.

Nordhaus, William. 1996. "Climate Amenities and Global Warming." Mimeo, Yale University Department of Economics.

Nordhaus, William and James Tobin. 1972. "Is Growth Obsolete?" In *Economic Research: Retrospect and Prospect*. Vol.5. *Economic Growth*. New York: Columbia University Press.

OECD (1997) Internet. Available 1/1/2002. http://www.oecd.org/subject/climatechange/kyoto.htm

Roback, Jennifer. 1982. "Wages, Rents, and the Quality of Life." *Journal of Political Economy*. 90(6): 1257-1278.

Rosen, Sherwin. 1979. "Wage-Based Indices of Urban Quality of Life." in *Current Issues in Urban Economics*, Mieszkowski and Straszheim, eds.

Sanghi, Apurva, Denisard Alves, Robert Evenson, and Robert Mendelsohn. 1997. "Global Warming Impacts on Brazilian Agriculture: Estimates of the Ricardian Model." *Economia Aplicado*. 1(1).

Santos, Rafael. 1995. *States of Brazil*. Ande Tur Brazilian Travel Club. Internet. Available 1/1/2003. http://www.andetur.com/us/statesof.htm

Sinnott, R.W. 1984. "Virtues of the Haversine." *Sky and Telescope*. 68:159.

ENDNOTES

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2. See, for example, Cropper (1981), Bloomquist, Berger, and Hoehn (1988), Adams (1989), Mendelsohn, Nordhaus, and Shaw (1994), IPCC (1995a), Nordhaus (1996), Cragg and Kahn (1997), Evenson and Alves (1998), and Mendelsohn (1998).

3. The Intergovernmental Panel on Climate Change (IPCC), in the Summary of the Economic and Social Dimensions of Climate Change contained in its Second Assessment Report, notes that "non-market damage estimates are a source of major uncertainty in assessing the implications of global climate change for human welfare." The report adds that, "these uncertainties, and the resolution of uncertainty over time, may be decisive for the choice of strategies to combat climate change." [IPCC (1995b)]

4. This extension will prove relevant in the debate surrounding the proper role of LDC's in global greenhouse gas abatement efforts. By the year 2020, LDC's are expected to account for approximately 50% of all greenhouse gas emissions, in contrast to 30% today. [OECD (1997)] The IPCC reports, however, that "the literature on the [social costs of anthropogenically induced climate change] is controversial and mainly based on research done on developed countries, often extrapolated to developing countries." It goes on to state that "analysis of economic and social issues related to climate change, especially in developing countries where little work of this nature has been carried out, is a high priority for research." [IPCC (1995b)] Accurate measurement of the costs and benefits of climate change in LDC's, based on actual data from these countries, is particularly important as bargaining over emission reduction targets continues in the post-Kyoto era.

5. While an index for the rental price of housing can be constructed from the 1996 PPV for the Northeast and Southeast regions of Brazil or for Brazil's 13 largest cities over a number of years from the POF, data are not

available with which to construct a similar index for the remainder of the country – in particular, the most economically dis-integrated regions (i.e., the North and Center-West) along with rural parts of the Northeast, Southeast, and South. It is in these places where we would expect many commodities to have prices that vary with location, and compensating income differentials alone to be more severely biased measures of value. By instead using geographically comprehensive Brazilian census data, the method described in this paper avoids this problem. Moreover, by incorporating broader spatial variation in climate, it recovers statistically stronger predictions of the effects of global warming that are not based only on the preferences of those who live in densely settled areas. Finally, it avoids the potential problem of unobserved substitute locations.

6. Our empirical results confirm that this is indeed the case for Brazil – a developing country where individuals are generally considered to be quite mobile. We would expect constraints on mobility to have even greater implications for valuation in applications to countries like India and China.

7. We think about the cost of migration distance in this context as encompassing both the direct expenditure of resources to migrate and the disutility of living far from one's birthplace, family, childhood friends, etc...

8. While it would be desirable to account for the endogenous determination of individual attributes like education in conjunction with the individual's location decision, this complication is beyond the scope of the current model and is left for future research.

9. Note that, in order to calculate a marginal willingness-to-pay similar to Roback (1982), we would need to separate the effect of climate on housing prices from its direct effect on utility. The former is held constant in the expression for the marginal rate of substitution in equation (1), while the latter is allowed to vary. The inability to separate these effects is the fundamental reason why the traditional wage-hedonic valuation technique cannot be used in many developing country contexts, even for small changes in the local attribute.

10. We report all monetary values in 1991 US dollars, converting form cruzeiros at the average 1991 rate of 406.61:1. 1991 was a year of rapid inflation in Brazil, with exchange rates varying between 215.01:1 and 760.70:1.

11. The census reports the individual as being in one of eleven activity sectors, which we aggregate to four: agriculture, manufacturing, services, and professional.

12. As this variable was crucial to our modeling of migration costs, we were forced to discard observations from the original census data for whom a missing value was recorded. This could potentially introduce non-random

selection bias into our regressions, but comparisons of averages of other observable attributes across included and excluded individuals suggests that this is not the case.

13. The distance between two locations, *a* and *b*, is given by: $2R\ arcsin\ [\ min\ \{\ ((sin(½\ (lat_a - lat_b)))^2 + cos(lat_a)\ cos(lat_b)\ (sin\ (½\ (lon_a - lon_b)))^2)^{½},\ 1\}\ ]$, where *R* represents the radius of the earth. [Sinnott (1984)]

14. A category of reported education is roughly translated as "literate but no education"; we treat this group as having four years of education. Results are not sensitive to small changes in this assumption.

15. The estimation algorithm described below allows for the estimation of this sort of *anonymous agglomeration or congestion effect* (i.e., where the individual cares only about the total number of other individuals making the same choice), but could be easily adapted to include *social interactions*, in which the individual cares about the number and type of other individuals making the same decision (e.g., the number of other individuals in the same education group). We include social interactions in ongoing research on settlement patterns in Brazil and the US, but ignore this complication in the present paper because of the additional requirements it imposes on the exogenous variation in local attributes in implementing our instrument strategy. See Bayer and Timmins (2003a) for an elaboration on the data required to identify each form of interaction.

16. Consider a microregion *j* in 1991 with a large, positive unobservable attribute ($\xi_{j,k}$). If this implied that the value of the unobservable attribute of microregion *j* (and those of other nearby microregions) one generation prior (i.e., in 1960) were also high, it would be likely that the 1960 population of *j* and the surrounding microregions would have been large and that there would have been many births in that area. This would have created a large pool of people with small migration distances to location *j* in 1991, inducing a correlation between those distances and $\xi_{j,k}$. In the case of wages, the same unobservable attributes that make a location attractive in terms of amenities might also be attractive to certain types of firms. These firms would move disproportionately to microregions with high values of $\xi_{j,k}$, raising labor demand and $\hat{W}_{j,s}$ in those microregions.

17. The idea to use a product's isolation in characteristic space as an instrument was first developed by Bresnahan (1981, 1987) to instrument for price in estimating demand for differentiated products. Similar instruments have been used by Berry, Levinsohn, and Pakes (1995) and have been used in many other industrial organization applications to instrument for price.

18. For example, a large, positive difference in the observable and exogenous utility indices of an alternative *a*

and a particular choice *b* for individual *i*, type *k* (i.e., $\widetilde{V}_{i,a,k} - \widetilde{V}_{i,b,k}$) indicates that *a* is a good substitute for *b* for that individual. In fact, in observable and exogenous dimensions of utility, *a* is preferable to *b*. It is only the elements not included in the index (i.e., population density, wages, and unobservable $\varphi_{j,k}$) which might lead this individual to choose *b* over *a*. It will generally be the availability of an alternative like *a* that will limit the number of individuals choosing *b*. We can therefore use the presence of the good alternative *a*, identified by its very large, positive observable and exogenous utility differential with choice *b*, to instrument for Δ_b.

19. Bayer and Timmins (2003b) describe the conditions under which this equilibrium is likely to be unique in the presence of agglomeration effects, including a large choice-set and significant variation (relative to the size of an agglomeration effect in utility) in the exogenous attributes of those choices. Uniqueness always arises under congestion effects.

20. An alternative specification of indirect utility, not based on a well-defined direct utility function but not subject to many of the restrictions imposed by the Cobb-Douglas functional form:

$$V_{i,j,k} = \pi_{0,k} + \pi_{W,k} \sqrt{\hat{W}_{j,s}} + \pi_{M1,k}\, d^{M1}_{i,j,k} + \pi_{M2,k}\, d^{M2}_{i,j,k} + \pi_{X,k} X_j + \pi_{C1,k} C_j + \pi_{C2,k} C_j^2 + \pi_{\Delta,k} \Delta_j + \xi_{j,k} + \eta_{i,j,k}$$

yielded similar marginal effects for non-climate variables and monetized changes in utility from climate change. These results are not reported here but are available upon request. A third specification of indirect utility, which is common in models of demand for expensive, differentiated products like automobiles, takes the following form:

$$V_{i,j,k} = \pi_{0,k} + \pi_{W,k}\, ln\, (\hat{W}_{j,s} - P^{h}_{j,k}) + \pi_{M1,k}\, d^{M1}_{i,j,k} + \pi_{M2,k}\, d^{M2}_{i,j,k} + \theta_{j,k} + \xi_{j,k} + \eta_{i,j,k}$$

While it would be desirable to estimate such a specification in the current valuation exercise, its parameters are poorly identified given the constraints on available data. In particular, without data describing the prices of locally-traded commodities, we are forced to parameterize the supply of those commodities, as in equation (12). Because the determinants of $P_{j,k}^{h}$ only differ across locations and types, however, these parameters are separately identified from the fixed effect $\theta_{j,k}$ only by the logarithmic functional form applied to the term ($\hat{W}_{j,s}$ - $P_{j,k}^{h}$). In current research on estimating the amenity cost of non-marginal climate change in the US, where data on $P_{j,k}^h$ are available, Bayer and Timmins (2003c) do estimate a specification of this form.

21. As stated previously, we normalize $\Theta_{1,k} = -1$ for all four education groups in solving the contraction mapping described in equation (20). Even if these utilities are, in fact, different across education groups (as they likely are), this does not pose a problem for our equivalent variations calculations, as all comparisons are made across the utilities that *particular individuals* would receive by settling in alternative locations. For a particular individual with type *k*, all utility function parameters are estimated consistent with the normalization of $\Theta_{1,k}$ for his type.

22. Note that the marginal rate of substitution between proximity to rivers or highways and wages (i.e., the ratios of the marginal utilities of these utility arguments) is invariant to the normalization described in the previous footnote, and rises monotonically with education.

23. We implicitly assume at this point in the procedure that every household in 1991 replicates itself and then simulate the new households' choices of where to live in the year 2050; i.e., current location choices in the data become birth locations for our simulations. A more realistic simulation would account for how fertility rates differ with household head's type and location.

24. There is nothing in this process to guarantee a unique equilibrium, although one becomes more likely in our sorting model the greater the exogenous variation amongst local attributes relative to the size of any agglomeration effects. [Bayer and Timmins (2003b)] The possibility of multiple equilibria is an undesirable complication, but reflects an important aspect of reality. In the case of multiple equilibria, we take the outcome that arises if we begin with the observed pre-climate change population distribution (typically involving modest changes from that distribution).

25. In addition to population density, other determinants of labor demand (Y_j) were included in this regression. These included dummy variables indicating soil erosion potential on a 1-5 scale, dummy variables for the state of São Paulo and proximity to mineral deposits, and the log of distance to the nearest port. Climate variables might have also been included in this regression, but we found that they entered with weak statistical significance, yet still had the potential to greatly impact the sign and magnitude of our simulated welfare effects (depending upon the exact specification used). This highlights a weakness in the current model that merits further research – in particular, the behavior of firms (i.e., the *demand side* of the labor market) in response to climate change.

26. This approach imposes the most commonly used rule for aggregating across individuals (i.e., weighting by the recipricol of the marginal utility of income), while also addressing directly the ambiguity described by Mohring (1971) – i.e., that this marginal utility of income will differ depending upon which set of prices (pre- or post-climate change) are used. We show below that the values we derive do not change much depending upon which set of prices are used.

27. Fitted population density based on population shares predicted with only exogenous local attributes (see discussion in Section 4), along with actual population density in 1970, is used to instrument of population density. Because instruments are exogenous shifters of labor supply (i.e., through the endogenous sorting process), this equation can be interpreted as the aggregate demand curve for labor.

28. Map copyrighted by Santos (1995) for Ande Tur Brazilian Travel Club. Internet, Available 1/1/2003. http://www.andetur.com/us/statesof.htm. Regional boundaries have been added.