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Description of the General Equilibrium Model of Ecosystem Services (GEMES)

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Abstract

This paper serves as documentation for the General Equilibrium Model of Ecosystem Services (GEMES). GEMES is a regional computable general equilibrium model that is composed of values derived from natural capital and ecosystem services. It models households, producing sectors, and governments, linked to one another through commodity and factor markets. GEMES was designed to model the typical resource-dependent economy, and so it has several innovations not found in other general equilibrium models; for example, ecosystem services and natural capital are explicitly modeled, allowing for endogenous nonmarket values. Households gain utility from nonconsumptive use of natural resources, and the value of those resources depends on both the state of the resource and the costs of turning that resource into an enjoyable experience. We allow for environmental regulations such as quotas on harvest and taxes on environmental goods.

Keywords: ecosystem services, general equilibrium, nonmarket values, ecological production functions, environmental regulation

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Introduction

Computable general equilibrium (CGE) models are computational representations of regional economies that focus on the links between production sectors, consumers, and factors of production. Key features of CGE models are market-clearing prices for goods and factors, the ability of firms to substitute between factors of production, and the ability of consumers to substitute between market goods. Endogenous prices and substitution possibilities distinguish CGE models from input-output models, which assume fixed prices, fixed ratios of factors of production, and fixed ratios between goods purchased by households. CGE models are appropriate when the effects of environmental policy or changes in the state of the resource are large enough to affect multiple sectors of the economy and when feedbacks among sectors, households, and other institutions are important. Users of CGE models should, however, be aware of the strong assumptions about optimizing behavior, perfect competition, and flexible relative prices that they rely on. Results are highly dependent, for example, on elasticity values used in the models (Harrison et al. 1993).

The use of CGE models in environmental policy is reviewed by Bergman (2005) and Loeschel (2002). Loeschel (2002) looks explicitly at the use of technological changes in CGE models. Lofgren et al. (2002) describe a typical and well-documented CGE model that is often used as a building block for other models. In the past, a major impediment to using CGE models in natural resource economics was their neglect of the nonmarket side of the economy. Environmental impacts in most CGE models typically occur through impacts outside the model or through separable effects on utility. The first approach assumes an unrealistic structural break between economic behavior and environmental quality. The second allows environmental quality to affect welfare but does not allow environmental quality to affect commodity demands, and thus prices, for other goods in the economy. Espinosa and Smith (1995) were among the first to address these shortcomings with a multi-region CGE trade model in which production creates air pollution. Air pollution, in turn, increases subsistence requirements by diverting resources toward health care. In the Espinosa and Smith model, reducing sulfur dioxide emissions reduces morbidity, which increases demands for other goods and may increase other types of pollutants through general equilibrium adjustments in the economy. Carbone and Smith (2010), also addressing air pollution with a CGE model, introduce nonmarket effects through effects of pollution on health and households' labor-leisure tradeoff. In the same paper, Carbone and Smith develop a method for welfare analysis when environmental quality and consumption goods are nonseparable elements of consumer preferences; Carbone and Smith then develop a CGE model using this method. Their work relies on advances in calibration techniques for general equilibrium models discussed in Rutherford (2002) and Sancho (2009). Warziniack et al. (2011) extend the Carbone and Smith framework to include nonmarket damages to the ecosystem and show that large biases exist when general equilibrium externalities are ignored. All approaches to date leave the value or price of the nonmarket component of the good fixed; so, while all other prices adjust to obtain a market equilibrium, previous studies neither allowed such adjustments for environmental goods nor recognized that willingness to pay (i.e., the market clearing price) is fundamentally an equilibrium concept.

The General Equilibrium Model of Ecosystem Services (GEMES) developed here is a regional computable general equilibrium model composed of values derived from natural capital and ecosystem services.[1] It models households, producing sectors, and governments linked to one another

[1] Natural capital is the stock of natural resources (water, fish, soil, etc.). Ecosystem services are the benefits humans derive from this stock (recreation, food, etc.).

through commodity and factor markets. GEMES was designed to model the typical resource-dependent economy, and so it includes several innovations not found in other CGE models; for example, demands for ecosystem services and natural capital are explicitly modeled.

This work builds off Warziniack (2011) by endogenizing nonmarket values (table 1) in a CGE. Values for natural capital and recreational experiences depend on other economic forces, such as prices of complementary goods and inputs. Firms use natural resources to produce goods and so derive added value that is accounted for in the model. Households gain utility from nonconsumptive use of natural resources, the value of which depends on both the state of the resource and the costs of turning that resource into an enjoyable experience. We allow for environmental regulations such as quotas on harvest and taxes on environmental goods.

The main intent of this paper is to document the full GEMES model so it can be referenced in papers focusing more on its applications. The paper is organized as follows: We first give a broad overview of the model, including a list of the types of goods in the economy. We then develop components of the model in detail, including firms' and households' decisions, as well as regulations on firms, trade, and government. A separate section presents market equilibrium conditions, and the final section describes data sources and parameterization of the basic model.

Table 1—List of model variables.

Variable	Description
Prices	
PD	Domestic prices paid to firms
PE	Prices on exports
PM	Prices on imports
PX	Price for Armington demand good
PES	Price to firms for ecosystem services
WTP	Price to households for ecosystem services
PF	Factor prices
PR	Price of recreational trips
PC	Price of consumption goods
PT	Price of a recreational trip
p_e	Price of effort
Firms variables	
Y	Equilibrium output
DY	Human inputs
V	Intermediate inputs
VA	Value-added
K	Capital
L	Labor
ES	Environmental goods used by firms
CV	Unit cost of human-produced composite input
C	Total cost of production
TAX	Taxes
CVA	Unit cost of value-added composite

Household variables	
U	Household utility
R	Recreation
C	Composite of consumption goods
TRIP	Recreational trip
ESH	Environmental goods used by households
I	Income
EFFORT	Human effort to recreate
HX	Household demand
FACPMT	Payment to factors of production
FAC	Demand for factors
HINTINC	Household interest income
HEXINC	Household exogenous income
HTRNS	Government transfers to households
HHI	Gross household income
HHID	Household disposable income
Aggregate variables	
X	Total demand in the economy
XE	Export demand
XD	Total domestic demand
Q	Total supply in the economy
QD	Domestic supply
QIMP	Imported supply
QGOV	Government supply
QINV	Supply from investments
IT	Demand for investments

Model Overview

Figure 1 shows the basic features of GEMES. The system consists of flows of real goods and monetary payments. Households own factors of production that firms demand, paying wages that become household income. Households in turn buy goods and services from firms. Equilibrium conditions in factor and commodity markets determine wage rates and regional prices. Trade occurs with domestic and international trade partners; prices for imports and exports are fixed. The novel features of GEMES involve the use of ecosystem services, which are used by both households and firms creating utility and value. These features are described in more detail in the relevant sections.

Types of Goods

The economy consists of several types of goods, defined as follows:

- *Domestically produced goods:* Domestically produced goods are produced by local firms. They are indexed by $j \in J$. Firms receive domestic prices PD_j.
- *Import and export goods:* Domestically produced goods are exported out of the region, and goods from the same industries are imported. The set of traded goods is the same as the set of domestically produced goods, thus traded goods are also indexed with j. The price received for exports is PE_j; the price paid for imports is PM_j.
- *Armington goods:* Goods consumed by households and goods used as intermediate inputs by firms are Armington composites (Armington 1969), which are aggregates of domestically produced and imported goods. No Armington good exists that is not either produced locally or imported, thus Armington goods are also indexed with j. The price paid for Armington composite good j is PX_j.
- *Environmental goods:* Goods provided by nature are indexed $n \in N$. Firms can use environmental inputs in their production process, and households can get utility from directly consuming environmental goods. Environmental goods are generally offered for free but have a shadow price associated with them of PES_{nj} when paid by the firm and WTP_{nh} when paid by the household. Amounts of environmental goods consumed by firms and households are ES_{nj} and ESH_{nh}.

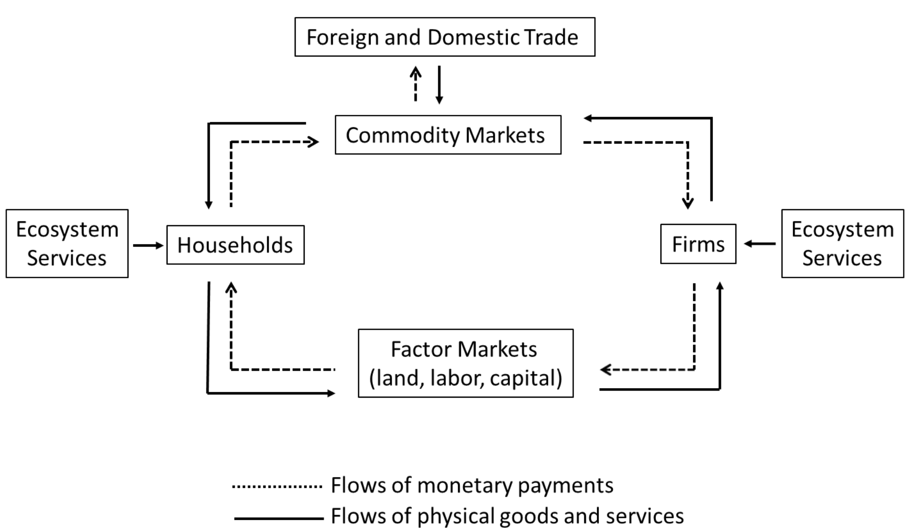

Figure 1—Overview of GEMES.

- *Primary factors:* Primary factors of production are inputs that are not produced and generally include capital and labor. The set of primary factors of production is indexed $f \epsilon F$, and each factor is paid price PF_f.

Producer Behavior

Each sector of the economy is modeled by a representative firm. Let Y_j be equilibrium output of firm $j \epsilon J$. Production of output Y_j occurs through a nested production function, shown in figure 2. Production in each nest is assumed to be homogenous of degree one, allowing the firm's problem to be solved one nest at a time.

In the upper nest, a firm-specific composite of human-produced inputs DY_j is combined with nature-provided ecosystem inputs ES_{nj} using constant returns to scale technology $Y_j(DY_j, ES_{nj})$. Firms vary in their ability to utilize ecosystem services and their optimal mix of human-produced inputs; they, therefore, face unique unit costs, or shadow prices, for using ecosystem services PES_{nj} and unique unit costs for the human-produced composite CVj. Two approaches exist for modeling ecosystem services. The first approach is to assume the level of ecosystem services is exogenous to the firm such that

$$C_j^Y\left(CV_j, PES_{nj}\right) = min_{DY_j, ES_{nj}}\left\{CV_j DY_j : Y_j\left(DY_j, ES_{nj}\right) = \overline{Y}_j; ES_{nj} \leq \overline{ES_{nj}}\right\} \qquad [1]$$

The second modeling approach is to assume the cost of utilizing ecosystem services is endogenous to the firm such that

$$C_j^Y\left(CV_j, PES_{nj}\right) = min_{DY_j, ES_{nj}}\left\{CV_j DY_j + PES_{nj} ES_{nj} : Y_j\left(DY_j, ES_{nj}\right) = \overline{Y}_j\right\} \qquad [2]$$

Regardless of approach, the first order conditions are the same,

$$CV_j - \mu_j \frac{\partial Y_j}{\partial DY_j} = 0 \qquad [3]$$

$$PES_{nj} - \mu_j \frac{\partial Y_j}{\partial ES_{nj}} = 0 \qquad [4]$$

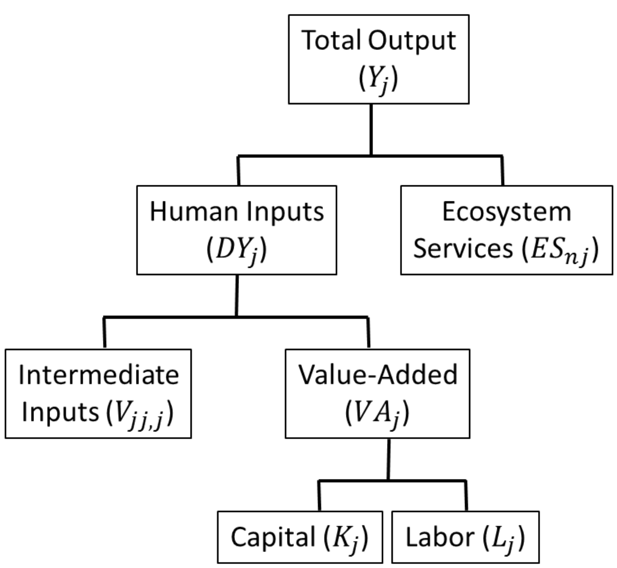

Figure 2—Nested production function.

The optimum occurs where

$$\frac{CV_j}{PES_{nj}} = \frac{\partial Y_j / \partial DY_j}{\partial Y_j / \partial ES_{nj}} \qquad [5]$$

We assume $Y_j(DY_j, ES_{nj})$ is Cobb-Douglas, such that $Y_j = \phi_j DY_j^{\alpha_j} ES_{nj}^{1-\alpha_j}$. Given domestic prices PD_j, input demands are

$$DY_j = \frac{\alpha_j PD_j Y_j}{CV_j} \qquad [6]$$

$$ES_{nj} = \frac{(1-\alpha_j) PD_j Y_j}{PES_{nj}} \qquad [7]$$

If the approach with exogenous ecosystem services is chosen, equation 7 can be inverted to get the marginal value of ecosystem services

$$PES_{nj} = \frac{(1-\alpha_j) PD_j Y_j}{ES_{nj}} \qquad [8]$$

The nest is closed by assuming profits are 0 at this level. With Cobb-Douglas production, this implies

$$PD_j = \frac{1}{\phi_j} \left(\frac{CV_j}{\alpha_j} \right)^{\alpha_j} \left(\frac{PES_{nj}}{1-\alpha_j} \right)^{1-\alpha_j} \qquad [9]$$

The human-produced composite is produced following a standard structure for modeling firms in CGE models. Taxes of type t are paid as a fixed share of output at rate $atax_{tj}$, such that

$$TAX_{tj} = atax_{tj} DY_j \qquad [10]$$

After-tax output is produced with intermediate inputs and a value-added composite of primary factors. Let $V_{jj,j}$ be the level of intermediate inputs from firm jj to firm j and VA_j be the level of value-added composite used by firm j. This nest is assumed to be Leontief, such that

$$V_{jj,j} = aint_{jj,j} DY_j \qquad [11]$$

$$VA_j = ava_j DY_j \qquad [12]$$

The Leontief assumption implies

$$CV_j = \sum_t atax_t CV_j + \sum_{jj} aint_{jj,j} PX_{jj} + ava_j CVA_j \qquad [13]$$

The value-added composite includes capital and labor, combined using a CES production function $VA_j = \psi_j \left(\delta_j K_j^{-\rho_j} + (1-\delta_j) L_j^{-\rho_j} \right)^{-1/\rho_j}$, where $\sigma_j = \left(\frac{1}{1+\rho_j} \right)$ is the elasticity of substitution between labor and capital and ψ_j is an efficiency parameter. The firm's optimal mix of capital and labor is found by minimizing the unit cost of producing the value-added component,

$$CVA_j(PF_K, PF_L) = min_{K_j, L_j} \left\{ PF_K * K_j + PF_L * L_j : VA_j(K_j, L_j) = VA_j \right\}. \qquad [14]$$

The demand functions for capital and labor are therefore

$$K_j = VA_j \left(\frac{\delta \, CVA_j}{PF_K} \right)^{\sigma_j} \psi_j^{\sigma_j - 1} \qquad [15]$$

$$L_j = VA_j \left(\frac{(1-\delta) \, CVA_j}{PF_L} \right)^{\sigma_j} \psi_j^{\sigma_j - 1} \qquad [16]$$

Using the price index for CES functions, we close this nest by

$$CVA_j = \frac{1}{\psi_j} \left(\delta_j^{\frac{1}{1+\rho_j}} PF_K^{\frac{\rho_j}{1+\rho_j}} + (1-\delta_j)^{\frac{1}{1+\rho_j}} PF_L^{\frac{\rho_j}{1+\rho_j}} \right)^{1+\frac{1}{\rho_j}} \qquad [17]$$

Equations 6–7, 9–13, and 15–17 represent the system that describes the firms' production decisions.

Household Behavior

The household consumption bundle contains marketed and nonmarketed goods. Our treatment of nonmarket goods in general equilibrium is novel. Reflecting the history of GEMES's development, we refer to the bundle of nonmarket goods in the household utility function as recreation, which is composed of individual trips that have real costs and allow one to enjoy the natural environment. Trips are taken to engage in various recreational activities.

An individual maximizes utility by taking recreational trips to enjoy several types of activities and by consuming a composite of other goods. We model the problem as if household decisions are made in three steps: (1) the individual decides how to divide income between recreation R and a composite of all other consumptive goods C; (2) for the portion of income allocated to recreation, the individual decides which activity $s = \{1,2,\ldots,S\}$ to do on $TRIP_s$; and (3) the individual minimizes the cost of providing the recreational experience on trips, where the recreational experience is produced by a combination of individual effort $EFFORT_{sh}$ and the level of ecosystem services ESH_{sh}, which may be different from the ecosystem services utilized by firms. Figure 3 depicts the nesting structure.

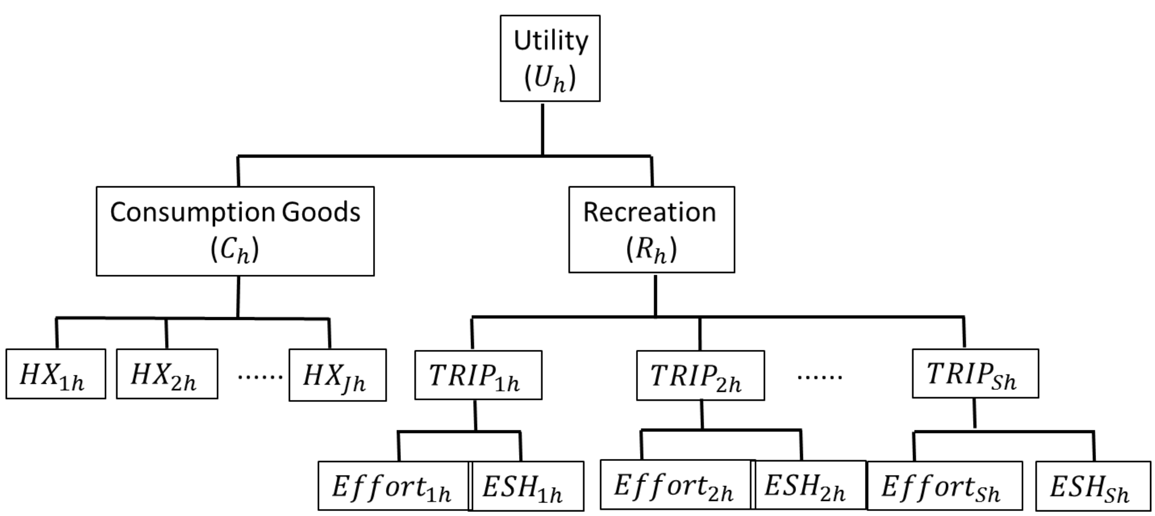

Figure 3—Nesting structure for household behavior. Substitution possibilities at each level in the nest are described by constant elasticity of substitution (CES) functions.

Step 1: Income Allocation Between Recreation and Other Consumption Goods

Suppressing household subscripts, let *PR* be the price of recreational trips, *PC* be the price of other goods, and *I* be an exogenous level of income. The budget constrained utility maximization problem is

$$Max\ U(R,C)\ s.t. I - PR\ R - PC\ C = 0 \tag{18}$$

Assume the utility function $U(R,C)$ is well behaved with U_R, $U_C > 0$, U_{RR}, $U_{CC} < 0$, and $U_{RC} \geq 0$ (subscripts indicating partial derivatives). Defining λ as the marginal utility of income, the necessary conditions for a maximum are

$$U_R = \lambda P``````````R \tag{19}$$

$$U_C = \lambda PC \tag{20}$$

$$I = PR\ R + PC\ C \tag{21}$$

Together the first order conditions require a mix of consumption goods and trips such that the rate at which the individual is willing to exchange one for the other (marginal rate of substitution) just equals the market rate of exchange in terms of the price ratio and the budget constraint is not violated. The simultaneous solution of equations 19–21 implicitly defines demand functions for $R = R(PR, PC, I)$ and $C = C(PR, PC, I)$.

Step 2: Allocate Trip Income Across Trips Targeting Activities

After spending $PC\ C$ on consumption goods, the consumer has $I - PC\ C$ to spend on recreation. Trip expenditures are divided among trips, $TRIP_s$, targeting specific activities, which is equivalent on average to trips targeting multiple activities given the substitution possibilities of the nesting structure. Let the price of trips targeting activity *s* be PT_s and the well behaved subutility function be $R(TRIP_1, TRIP_2, \ldots, TRIP_n)$. The second stage optimization problem becomes

$$Max\ R(TRIP_1, TRIP_2, \ldots, TRIP_n)\ s.t. (I - PC\ C) - \sum_{s=1}^{n} PT_s TRIP_s = 0 \tag{22}$$

If the marginal utility of trip income is λ^R, then the necessary conditions for an interior solution are

$$\partial R / \partial TRIP_s = \lambda^R PT_s\ for\ all\ s \in [1, .., n] \tag{23}$$

$$(I - PC\ C) = \sum_{s=1}^{n} PT_s TRIP_s \tag{24}$$

The system defined by equations 23–24 requires the individual to take trips targeting each activity until the marginal rates of substitution for all pairs of activities are equal to the price ratio of trips and trip income is exhausted. The simultaneous solution of equations 23–24 implicitly defines demand functions for targeted trips $TRIP_s = TRIP_s\ (PT_1, \ldots PT_n, PC, I)$. Given the demand functions, the indirect subutility function can be found (Varian 1992) with its associated unit expenditure function, which gives the price index for recreation and the link back to step (1), $PR = PR(PT_1, .. PT_n, PC, I)$.

Step 3: Minimize the Cost of Providing the Recreational Experience From a Trip by Combining Effort and Ecosystem Services

Trips targeting activities are a good, denoted here as a recreational experience, which could be measured in terms of actual outcome or just enjoyment of the activity. The recreational experience on a targeted trip is a good produced by individuals combining human effort $EFFORT_s$ and ecosystem services ESH_s. While individuals choose the effort they exert, they take the level of ecosystem services as given (a measure of environmental quality, provided by nature). Though ecosystem services are beyond the control of any one individual, they are an input to their production of the recreational experience, and so have cost or value in a nonmarket, virtual sense. Thus, while ecosystem services are taken as given, their nonmarket values are not. Nonmarket values are endogenous to the individual and follow from the inversion of the demand function for ecosystem services.

We assume the individual behaves as if he or she minimizes the costs of providing the recreational experience from a trip, where costs flow from the market costs of effort, p_e (generally taken as a fraction of the market wage), and the virtual costs, or willingness to pay, for ecosystem services WTP_s,

$$Min\ p_e EFFORT_s + WTP_s ESH_s\ s.t.\ TRIP_s = TRIP_s(EFFORT_s, ESH_s) \qquad [25]$$

Letting the Lagrange multipliers associated with the trip production function be λ^s, the necessary conditions for an interior solution are (for all $s \epsilon [1, .., n]$)

$$p_e = \lambda^s(\partial TRIP_s/\partial EFFORT_s) \qquad [26]$$

$$WTP_s = \lambda^s(\partial TRIP_s/\partial ESH_s) \qquad [27]$$

$$TRIP_s = TRIP_s(EFFORT_s, ESH_s) \qquad [28]$$

The first necessary condition [26] requires effort to be expended until the marginal cost of effort just equals the marginal value product of that effort. The second necessary condition [27] requires the nonmarket value of the ecosystem service to equal the marginal value product of the ecosystem service in producing the recreational experience. The third necessary condition [28] requires production of the experience to be efficient. Together, the conditions provide the familiar cost minimization requirement in a two input setting, so that the input mix is adjusted to the level at which the marginal technical rate of substitution between ecosystem services and effort in the production of the recreational experience just equals the price ratio of effort and ecosystem services for any given level of recreation produced. The simultaneous solution of equations 26–28 provides input demand functions for effort $EFFORT_s = EFFORT_s(p_e, ESH_s, TRIP_s)$ and inverse demand functions for the nonmarket values of ecosystem services $WTP_s = WTP_s(p_e, ESH_s, TRIP_s)$ (as in Carbone and Smith 2013). From these functions a cost function for the targeted recreational activity can be constructed

$$C_s(p_e, ESH_s, TRIP_s) = p_e EFFORT_s(p_e, ESH_s, TRIP_s) + WTP_s(p_e, ESH_s, TRIP_s) ESH_s \qquad [29]$$

We assume $TRIP_s(EFFORT_s, ESH_s)$ is homogenous of degree one, so the associated cost function is homogenous of degree one in $TRIP_s$. Defining $c_s(p_e, ESH_s, TRIP_s)$ as the unit cost of the targeted activity (and equivalent to the price of the targeted trip PT_s) allows the statement and link between step (2) and (3) to be

$$C_s(p_e, ESH_s, TRIP_s) = c_s(p_e, ESH_s) TRIP_s = PT_s TRIP_s \qquad [30]$$

The conditions above define the optimal trips targeting each activity given the unit cost of targeting each activity.

The allocation of expenditures between consumptive goods follows standard CGE procedures. Households choose consumption levels HX_{jh} to minimize the cost of achieving subutility level $\overline{C}$. The mathematical expression of this optimization is

$$\text{Min } PX_j HX_{jh} \text{ s.t. } \overline{C} = C(HX_{1h}, HX_{2h}, .., HX_{jh}) \quad [31]$$

The first order conditions require

$$\frac{\partial C / \partial HX_{jh}}{\partial C / \partial HX_{ih}} = \frac{PX_j}{PX_i} \quad [32]$$

Equilibrium Conditions

The price of effort is the same for all activities, thus

$$p_e = PT_s \frac{TRIP_{s,EFFORT}}{TRIP_{s,ESH}} = PT_t \frac{TRIP_{t,EFFORT}}{TRIP_{t,ESH}} \; \forall \, s,t \in [1,2,\ldots,n], s \neq t \quad [33]$$

Note $\frac{TRIP_{s,EFFORT}}{TRIP_{s,ESH}}$ is the marginal technical rate of substitution in the production of the experience for activity s for a given level of ecosystem services. A key insight of this analysis is that trip rates and nonmarket value are equilibrium concepts, jointly determined by the relative levels of ecosystem services.

In summary, the equilibrium conditions from steps (1–3) are

Step 1:

$$\frac{U_R}{U_C} = \frac{PR}{PC} \quad [34]$$

Step 1 says people balance recreation and other goods, depending on how much they value recreation and how expensive it is to engage in the activity. The economic valuation literature tries to determine how much people value recreation, U_R, which is given in step 2.

Step 2:

$$\frac{\partial R / \partial TRIP_s}{\partial R / \partial TRIP_t} = \frac{PT_s}{PT_t} \; \forall \, s,t \in [1,2,\ldots,n] \quad [35]$$

In step 2 we see that the number of trips an individual takes targeting an activity depends on both the enjoyment from that activity and the relative price of getting there. We would expect nearby activities (the local park) to get more pressure from people even if they are not as productive or enjoyable as other activities (the Grand Canyon). This equilibrium condition is at the heart of the travel cost literature, which estimates $\partial R / \partial TRIP_s$ given PT_s.

Step 3:

$$\frac{TRIP_{t,EFFORT} / TRIP_{t,ESH}}{TRIP_{s,EFFORT} / TRIP_{s,ESH}} = \frac{PT_s}{PT_t} \; \forall \, s,t \in [1,2,\ldots,n] \quad [36]$$

Enjoyment of a given trip depends on an experience, defined by the interplay of human-exerting effort to recreate and nature-provided resources to enjoy. In equilibrium, the marginal value of increasing levels of ecosystem services depends on how effort-intensive or nature-intensive the enjoyment of that activity is, relative to all other activities. If enjoyment of activity s is relatively more effort-intensive, such that $|TRIP_{s,EFFORT}/TRIP_{s,ESH}| > |TRIP_{t,EFFORT}/TRIP_{t,ESH}|$, then effort is relatively more productive than ecosystem services in production of recreation and the marginal value of the stock s is relatively low. Conversely, if enjoyment of activity s is ecosystem service-intensive, such that $|TRIP_{s,EFFORT}/TRIP_{s,ESH}| < |TRIP_{t,EFFORT}/TRIP_{t,ESH}|$ then ecosystem services are relatively more productive than effort in production of recreation and the marginal value of stock s is relatively high.

Benchmark trips and levels of effort are available in the data. Value of time spent recreating and benchmark willingness to pay for environmental quality can be transferred from the valuation literature. We can, therefore, calculate a benchmark marginal value of ecosystem services. The entire system can be calibrated and used to measure values of environmental policies or damages from environmental degradation.

GEMES uses calibrated share forms of constant elasticity of substitution (CES) utility and production functions following Rutherford (2002):

$$U = \left[\theta_u \left(\frac{R}{R_0}\right)^{\rho_u} + (1-\theta_u)\left(\frac{C}{C_0}\right)^{\rho_u}\right]^{1/\rho_u} \quad [37]$$

$$R = \left[\sum\nolimits_s \theta_s \left(\frac{TRIP_s}{TRIP_{s,0}}\right)^{\rho_R}\right]^{1/\rho_R} \quad [38]$$

$$TRIP_s = \left[\theta_s \left(\frac{ESH_{sh}}{ESH_{sh,0}}\right)^{\rho_s} + (1-\theta_s)\left(\frac{EFFORT_s}{EFFORT_{s,0}}\right)^{\rho_s}\right]^{1/\rho_s} \quad [39]$$

The "θ"s represent cost shares in the benchmark data; for example, $\theta_t = \frac{p_{t,0}x_{t,0}}{\sum_s p_{s,0}x_{s,0}}$. The "$\rho$"s are parameters based on elasticities of substitution, and "0" subscripts denote benchmark values.

We assume C is CES with elasticity of substitution σ_h. Defining $\rho_h = 1/(1-\sigma_h)$, in equilibrium

$$PC_h = \frac{1}{\psi_h}\left(\sum\nolimits_j \theta_j^{\frac{1}{1+\rho_h}} PX_j^{\frac{\rho_h}{1+\rho_h}}\right)^{1+\frac{1}{\rho_h}} \quad [40]$$

Household Income

Household income (HHI_h) is derived through a two-stage process. Households are endowed with varying amounts of labor and capital. These factors are exchanged in factor markets, and through the production process generate value-added. Total value-added expenditures flow first to the factor "institutions" and are then redistributed to households. Total payments to factors are:

$$FACPMT_f = \left(\sum_j FAC_{f,j}\, PF_f\right)\left(1 - \sum_t afout_{t,f}\right) \quad [41]$$

where $FAC_{f,j}$ is the amount of factor f demand by sector j and $afout_{t,f}$ is the portion of factor payments that leaves the region.

Household incomes are based on the share of the factor that household owns $(\theta f_{h,f})$. They also receive interest income ($HINTINCo_h$), foreign income $HEXINCo_{h,t}$, and Federal, State, and local government transfers ($HTRNS_{h,g}$). In the current version of the model, all other sources of household income are held constant, but this is an assumption easily relaxed.

$$HHI_h = \sum_f (\theta f_{h,f} FACPMT_f) + \sum_g (HTRNS_{h,g}) + HINTINCo_h + \sum_t (HEXINCo_{h,t}) \qquad [42]$$

Households pay taxes to the Federal and State governments at fixed tax rates $htr_{g,h}$. Households also partake in saving in domestic and foreign markets. The domestic savings rate is represented by mps_h and the foreign savings rate is represented by $mpsf_{t,h}$. It is assumed that the tax rates and savings rates are constant and are derived from the benchmark data. Disposable income is defined by:

$$HHID_h = HHI_h \left[1 - \left(\sum_g htr_{g,h} \right) - mps_h - \left(\sum_t mpsf_{t,h} \right) \right] \qquad [43]$$

Trade

Product Differentiation in Supply

Product differentiation is introduced to the supply side for all sectors through the use of constant elasticity of transformation (CET) functions following De Melo and Tarr (1992). Industry output for all sectors is allocated to regional consumption, XD_j, or exported in aggregate to foreign and domestic markets, XE_j, through a constrained maximization of industry revenues given regional domestic prices PD_j and export prices PE_j, subject to a CET function with substitution possibilities governed by elasticities of transformation. The CET function (equation 44) and resultant first order condition (equation 45) determines the mix of goods allocated for regional consumption and exports:

$$X_j = AT_j \left[\sum_t (cetf_{jt} XE_{jt}{}^{\rho t_j}) + cetd_j XD_j^{\rho t_j} \right]^{\frac{-}{\rho t_j}} \qquad [44]$$

$$XD_j = \frac{cetd_j}{\sum_t cetf_{jt}} \left(\frac{PE_j}{PD_j} \right) \qquad [45]$$

The optimization allows for substitution between production for regional and export markets, driven by the relative prices of regional goods and exports, and the magnitude of substitution possibilities given by the elasticity of transformation $\sigma t_j = 1/(\rho t_j\text{-}1)$. The distribution parameters are $ceft_{jt}$ and $cetd_j$, and AT_j is the efficiency parameter.

Product Differentiation in Demand

Product differentiation in aggregate demand for all sectors Q_j is achieved through the use of the "Armington assumption" (Armington 1969). Regional consumers demand a composite of regionally produced goods QD_j and imports QM_j, from both domestic and foreign sources, where the differentiation is assumed to occur in perfectly competitive markets. The blend of regional and imported goods is found through households minimizing the costs of meeting their composite commodity demands given regional prices PD_j and import prices PM_j, prices, and substitution possibilities from CES functions with elasticity of substitution σc_j. The CES functions and resulting first order conditions determine the mix of imports and regional production:

$$Q_j = AC_j \left[armd_j QD_j^{\rho c_j} + \sum_t armf_{tj} QIMP_{tj}^{\rho c_j} \right]^{\frac{1}{\rho c_j}} \quad [46]$$

$$QIMP_{tj} = \frac{armd_j}{\sum_t armf_{tj}} \left(\frac{PD_j}{PM_j} \right)^{\sigma c_j} \quad [47]$$

where $armd_j$ and $armf_{tj}$ are the distribution parameters and AC_j is the efficiency parameter.

Government

Federal, State, and local governments operate under balanced budgets, produce and consume goods, and tax trade-related activity. Government revenues are from taxes, sales of governmentally produced commodities, and government borrowing and transfers. These revenues are redistributed in lump sum to both consumers and producers to maintain a balanced budget.

Tax revenues are from indirect business taxes, primary factor taxes, and income taxes. Indirect business taxes include sales taxes, excise taxes, and other regionally specific taxes paid through day-to-day operations of industry (not including net income taxes). Factors are taxed according to the value of their employment, as shown in the section on household income. Households are taxed on their gross incomes. Government revenues are further supplemented through sales of government commodities, government interest received, and amounts that the government borrows.

Expenditures by the government are on government demand for commodities, transfers to households, and transfers to producers. A balanced budget is maintained through a balance of total revenues and expenditures.

Market Equilibria

Total available labor and capital are fixed, such that $\Sigma K_j = \overline{K}$ and $\Sigma L_j = \overline{L}$. These factor-market clearing conditions determine factor-market prices. The aggregate price level of goods is determined by the market clearing conditions

$$Q_j = X_j \quad [48]$$

$$QD_j = \sum_j Y_j + \sum_g QGOV_{g,j} + QINV_j \quad [49]$$

$$XD_j = \sum_h HX_{jh} + \sum_{jj} V_{j,jj} + \sum_g XGOV_{j,g} + IT_j \quad [50]$$

Parameterization of the Basic Model

Following standard practice, the base CGE is parameterized by a calibration technique as in Ballard et al. (1985) and De Melo and Tarr (1992) using a social accounting matrix (SAM). The calibration routine assumes the benchmark SAM is an equilibrium and relies upon the structure of the model to determine its unknown parameters. The calibration procedure sets benchmark input and output prices equal to unity by constant returns to scale and the units of the initial data being in value terms. Elasticities are taken from the literature.

Environmental quality data used in this model are taken from the valuation literature, both for calibration and for behavioral parameters. It should be noted that such benefit-transfers are complicated, especially when the values are transferred from the partial equilibrium literature (Brouwer 2000). The need for benefit-transfers in GEMES, therefore, brings up two important topics for future research. First, sensitivity analysis will be an important component on GEMES's use, with the need and ability to explore which environmental parameters have large behavioral implications and economic consequences. Second, there is a need for the valuation literature to consider general equilibrium externalities and how they affect willingness to pay for natural resources. Sensitivity analysis with GEMES may be able to highlight which values are the most critical and serve as a guide for future research.

Calibration and computational modeling is shown for several examples on the project website http://www.fs.fed.us/rmrs/projects/general-equilibrium-model-ecosystem-services-gemes.

References

Armington, Paul S. 1969. A theory of demand for products distinguished by place of production (Une théorie de la demande de produits différenciés d'après leur origine)(Una teoría de la demanda de productos distinguiéndolos según el lugar de producción). Staff Papers—International Monetary Fund. 16(1): 159–178.

Ballard, Charles L.; Fullerton, Don; Shoven, John B.; [et al.]. 1985. A general equilibrium model for tax policy evaluation. Chicago: University of Chicago Press. 264 p.

Bergman, Lars. 2005. CGE modeling of environmental policy and resource management. Handbook of Environmental Economics. 3: 1273–1306.

Brouwer, Roy. 2000. Environmental value transfer: State of the art and future prospects. Ecological Economics. 32(1): 137–152.

Carbone, Jared C.; Smith, V. Kerry. 2010. Valuing ecosystem services in general equilibrium. NBER Working Paper No. 15844. Cambridge, MA: National Bureau of Economic Research. 53 p.

Carbone, Jared C.; Smith, V. Kerry. 2013. Valuing nature in a general equilibrium. Journal of Environmental Economics and Management. 66(1): 72–89.

De Melo, Jaime; Tarr, David G. 1992. A general equilibrium analysis of U.S. foreign trade policy. Cambridge, MA: MIT Press. 309 p.

Espinosa, J. Andrés; Smith, V. Kerry. 1995. Measuring the environmental consequences of trade policy: A nonmarket CGE analysis. American Journal of Agricultural Economics. 77(3): 772–777.

Harrison, Glenn W.; Jones, Richard; Kimbell, Larry J.; [et al.]. 1993. How robust is applied general equilibrium analysis? Journal of Policy Modeling. 15(1): 99–115.

Loeschel, Andreas. 2002. Technological change in economic models of environmental policy: A survey. ZEW Discussion Papers No. 01-62. Manheimm, Germany: ZEW—Zentrum für Europäische Wirtschaftsforschung / Center for European Economic Research. 42 p.

Lofgren, Hans; Harris, Rebecca Lee; Robinson, Sherman. 2002. A standard computable general equilibrium (CGE) model in GAMS. Microcomputers in Policy Research 5. Washington, DC: International Food Policy Research Institute. 79 p.

Rutherford, Thomas. 2002. Lecture notes on constant elasticity functions. Boulder, CO: University of Colorado. 32 p.

Sancho, Ferran. 2009. Calibration of CES functions for real-world multisectoral modeling. Economic Systems Research. 21(1): 45–58.

Varian, Hal R. 1992. Microeconomic analysis. New York: W.W. Norton & Company. 576 p.

Warziniack, Travis; Finnoff, David; Bossenbroek, Jonathan; [et al.]. 2011. Stepping stones for biological invasion: A bioeconomic model of transferable risk. Environmental and Resource Economics. 50(4): 605–627.

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