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Alternative Renewable Resource Strategies: A Simulation of Optimal Use[1]

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The depletion of forested wetlands is a pressing environmental concern, but has wetland depletion and conversion to agricultural cropland been excessive? A dynamic analysis of resource exploitation in the presence of environmental consequences is required. The structure and parameters of a model of socially optimal wetland use are found to bear a well-defined relationship to those which emerge from a private-market model of wetland exploitation, providing a basis for internalizing environmental externalities and for identifying optimal resource-exploitation strategies. Empirical analysis focuses on the area of severest wetland losses in the United States, the Lower Mississippi Alluvial Plain.

1. INTRODUCTION

The continuing depletion of forested wetlands constitutes one of the world's most pressing land use problems. Massive losses of tropical rain forests in a number of developing countries have received increasing attention, but forested wetland losses in the United States have also been severe. Since the time of European settlement, nearly 60% of America's original endowment of 215 million acres of inland wetlands—forested bottomlands, marshes, bogs, swamps, and tundra—has been converted to other uses. This depletion has been particularly rapid during the past 30 years.

There is much concern because wetlands, in their natural state, provide valuable ecological services, including improved water quality, erosion control, floodwater storage, provision of hardwood timber, fish and wildlife habitat, and recreational opportunities. Alternatively, through development, wetlands provide valuable sites for agriculture, mining, oil and gas extraction, and urbanization.

Has wetland depletion in the United States been excessive? Specifically, how has the rate of depletion during the past 40 years compared with what would have been optimal from a socioeconomic perspective? Answering this question requires a dynamic analysis of natural resource exploitation in the presence of negative environmental consequences.

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1.1. A Generic Overview of the Analysis

Since the seminal work of Hotelling [13], a substantial literature has developed for examining the socially optimal use of natural resources through the construction of dynamic optimization models.[2] A parallel line of research has featured dynamic optimization models of individual firms carrying out resource extraction under competitive or other market conditions.[3] The solutions (necessary conditions for optimality) of both social-optimum and market models may provide useful indications of the direction of impact of a change in a given variable on the resource's extraction or price path. But, because of the relative simplicity of these models or the lack of requisite data, they have rarely been used to examine the magnitude of impacts under alternative policy scenarios.

A separate economic literature has developed on externalities, including methods for evaluating some in economic terms.[4] Despite the fact that many empirical studies have estimated the value of environmental externalities, such studies have yet to be fully exploited by employing their empirical estimates of such values in simulations of socially optimal behavior.[5]

An important obstacle to the development of comprehensive models of natural resource supply in the presence of environmental consequences has been the aggregation problem. Theoretically consistent models of rational individual behavior have been used to develop econometrically estimatable models of natural resource supply only by resorting to representative-firm assumptions.[6] Given the heterogeneity which exists across individual endowments of many natural resources, such representative-firm models are particularly problematic. Bohi and Toman [2] described the failure in the literature "to bridge the gap between a theory of individual decisions and data that reflect numerous interdependent influences."

In this paper, the representative-firm approach is avoided by integrating a model of unobserved heterogeneity of land quality with a model of rational, individual firm-level behavior; a framework is thus developed for the identification of socially optimal natural resource exploitation in the presence of environmental impacts. A conceptual bridge is formed between theoretical models of optimal behavior and statistical models of actual market performance, and an econometric link is established between dynamic optimization models of natural resource use and economic assessments of environmental externalities.

1.2. Forested Wetlands and Agricultural Production

The largest remaining wetland habitat in the lower 48 states is the 5.2-million-acre bottomland hardwood forest of the Lower Mississippi Alluvial Plain. In addition to being the most important wetland resource in the United States, this

[2]Peterson and Fisher [18] survey nonrenewable resource models. The most comprehensive treatment of renewable resource models is by Clark [3].

[3]Bohi and Toman [2] provide an overview of this literature as it applies to nonrenewable resources.

[4]Baumol and Oates [1] and Freeman [8] provide summaries of the theory of environmental externalities and alternative methods of evaluation, respectively.

[5]Theoretical models which provide for environmental impacts within the context of optimal control models of natural resource use include those of Keeler, Spence, and Zeckhauser [17]; Forster [7]; Cropper [5]; Smith [21]; and Kamien and Schwartz [16].

[6]Examples include [4] and [15].

area is also one of the most seriously threatened. Less than 5.2 million acres—about 20% of the original area—remains, the bulk having been converted to agricultural cropland.

Stavins and Jaffe [23] examined the principal causes of forested wetland depletion in the Alluvial Plain during the period 1935–1984, focusing on the unintentional role played by federal government flood-control and drainage projects. They found that wetland depletion had largely been the result of economic incentives, and that federal projects had significantly tipped those incentives toward conversion of wetlands to agricultural uses. It remains to ask whether the federal government ought to be thanked or condemned for providing this service. This question can be addressed by comparing the actual rate of forested wetland depletion with what would be optimal from a socioeconomic perspective.

1.3. *Preview of the Paper*

In Section 2 of the paper, a theoretical model of privately optimal resource use is developed in the context of alternative strategies for forested wetlands and agricultural production (Fig. 1). A dynamic optimization model of individual, rational economic behavior yields a set of necessary conditions under which individual landowners may be expected to seek to convert their forested wetlands to agricultural production or to abandon their agricultural croplands and allow them to return to forest. Variation across land parcels constitutes the basis for

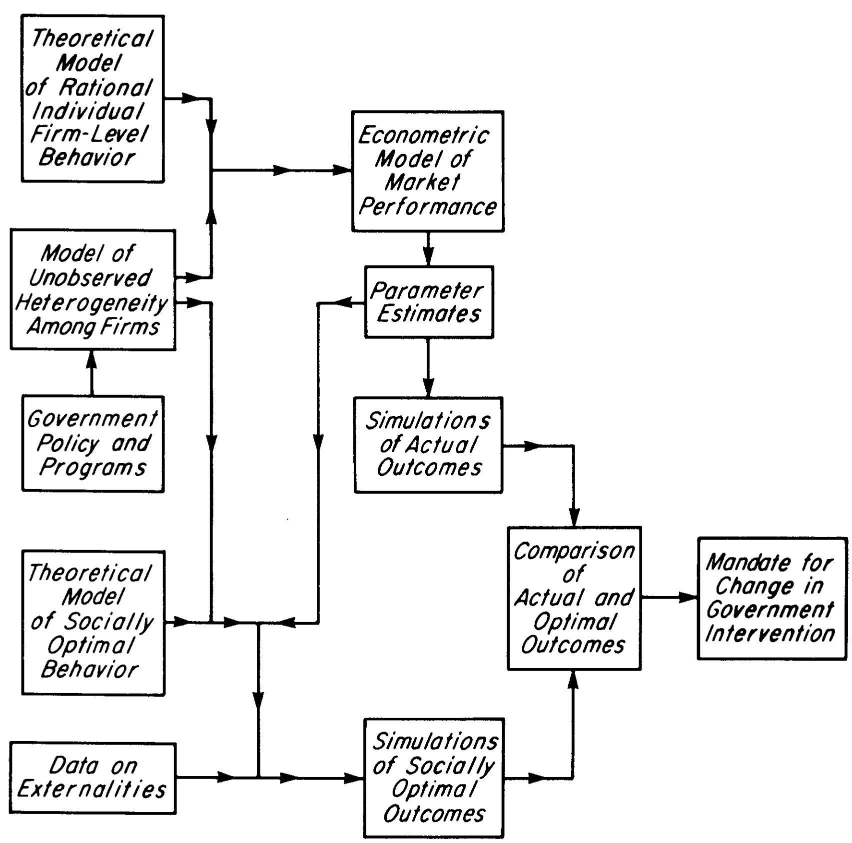

FIG. 1. Conceptual flow chart of the methodology.

aggregation of the individual necessary conditions into an econometrically estimatable model of land use.

In Section 3, a model of socially optimal wetland use is developed, the structure and parameters of that model bearing a well-defined relationship to those which emerge from the model of private-market wetland usage. This relationship provides a means for internalizing environmental externalities and thus for identifying the socially optimal time path of resource use.

In Section 4, the empirical link is established between the private-market and social-optimum models by employing the results of an econometric analysis of land use in 36 counties of the Lower Mississippi Alluvial Plain during the period 1935–1984; estimated parameters are used in counterfactual dynamic simulations to estimate the rate of wetland depletion which would have occurred had environmental externalities been considered by landowners. Part 5 develops conclusions and policy implications.

2. PRIVATELY OPTIMAL RESOURCE USE: MARKET ALLOCATIONS OF FORESTED WETLANDS AND AGRICULTURAL PRODUCTION

Landowners are assumed to observe current and past values of economic, hydrologic, and climatic factors relevant to decisions regarding the use of their lands for forestry or for agricultural production.[7] On this basis, they form expectations of future values of respective variables. In particular, landowners observe agricultural prices and production costs, typical agricultural yields for their area, typical timber returns, and the suitability of individual land parcels for agriculture.[8]

2.1. Dynamic Optimization Model of Forestry and Agricultural Production

It is assumed that landowners attempt to maximize the expected long-term economic return to the set of productive activities which can be carried out on their land. Land-use decisions are thus functions of the relative expected economic returns from alternative uses.[9] A landowner continually faces a decision of whether to keep land in its current (forested or agricultural) state, to convert forested land to agricultural production, or to abandon agricultural land and allow it to return to forest. Thus, a risk-neutral landowner faced with this decision will seek to maximize the present discounted value of the stream of expected future returns[10]:

$$\max_{\{g_{ijt}v_{ijt}\}} \int_0^\infty \left[[A_{it}q_{ijt} - MZ_{it}][g_{ijt} - v_{ijt}] - C_{it}g_{ijt} + f_{it}S_{ijt} + W_{it}g_{ijt} - D_{it}v_{ijt} \right] e^{-r_t t}\, dt \tag{1}$$

[7]For this geographic area, it is empirically reasonable to focus on these two alternative land uses and to exclude consideration of potential municipal uses of drained wetlands.

[8]A prime factor determining the suitability of land for agricultural production in the area of this study is its wetness, i.e., the degree of natural and/or artificial protection from flooding and poor drainage.

[9]The potential sale of land parcels is economically irrelevant, since a new owner would face the same conversion/abandonment decision.

[10]The specification of the objective function and the relationship of the model to other natural resource problems may be more obvious when one notes that the term which represents the (discounted present value of) expected future net revenue from agricultural production, $A_{it}q_{ijt} - MZ_{it}$, is the price of farmland in a competitive market.

subject to

$$\dot{S}_{ijt} = v_{ijt} - g_{ijt} \tag{2}$$

$$0 \leq g_{ijt} \leq \bar{g}_{ijt} \tag{3}$$

$$0 \leq v_{ijt} \leq \bar{v}_{ijt} \tag{4}$$

where i indexes counties, j indexes individual land parcels, and t indexes time; uppercase letters represent stocks or present values; and lowercase letters represent flows. The variables are

A = discounted present value of the infinite stream[11] of typical expected agricultural revenues per acre in the county;
q = parcel-specific index of feasibility of agricultural production, including effects of soil quality and soil moisture;
g = acres of land converted from forested to agricultural use;
v = acres of cropland abandoned (gradually returned to a forested condition);
MZ = expected cost of agricultural production per acre, expressed as the discounted present value of an infinite future stream;
C = average cost of conversion per acre (indexed by weather conditions)[12];
f = expected annual net income from forestry per acre;
S = stock (acres) of forests;
r = real interest rate;
W = windfall of net revenue per acre from a one-time clear cut of forest (prior to conversion);
D = expected present discounted value of loss of income due to gradual regrowth of forest (harvesting does not occur until the year $t + R$, where R is the exogenously determined rotation length)[13];
$\bar{g}$ = maximum feasible rate of conversion, defined such that

$$\int_t^{t+\Delta} \left[\bar{g}_{ij\tau} \right] d\tau = S_{ijt} \tag{5}$$

for arbitrarily small interval, Δ, over which $\bar{g}_{ij\tau}$ is constant;

[11]A continuous-time rather than discrete-time model is employed, despite the fact that a discrete-time formulation would be more realistic. The continuous-time approach is favored because of its notational simplicity and because it allows for easy interpretation of the model's solution in the context of the natural resource economics literature.

[12]Precipitation and consequent soil moisture are later allowed to influence conversion costs; the conversion cost term in Eq. (1) is then replaced by $C_{it} \cdot \exp\{\alpha_2 \mathrm{PHDI}_{it}\} \cdot g_{it}$, where α_2 is an estimated parameter and PHDI_{it} is the Palmer Hydrological Drought Index.

[13]The expected present discounted value of loss of income due to gradual regrowth of forest, D_{it}, is defined as

$$D_{it} = \int_t^{t+R} \{ f_{i\tau} e^{-r(\tau - t)} \} \, d\tau = F_{it} \cdot \{1 - e^{-rR}\}$$

where F_{it} is the present discounted value of an infinite future stream of annual net forest income, i.e., $F_{it} \cdot r = f_{it}$. Thus, if $R = 0$, $D_{it} = 0$ (i.e., if regrowth is instantaneous, there is no loss of revenue due to harvest delay); and if $R = \infty$, $D_{it} = F_{it}$ (if the regrowth period is infinitely long, there is a complete loss of all forest revenue).

$\bar{v}$ = maximum feasible rate of abandonment, defined such that

$$\int_{t}^{t+\Delta}\left[\bar{v}_{ij\tau}\right] d\tau = T_{ijt} - S_{ijt} = \mathrm{AG}_{ijt} \tag{6}$$

for arbitrarily small interval, Δ, over which $\bar{v}_{ij\tau}$ is constant.
AG = stock (acres) of agricultural land; and
T = total acreage of parcel in the flood plain available for conversion.

2.2. *Solving the Optimization Problem: Necessary Conditions for Land Conversion and Abandonment*

Because of the linear nature of the objective function [Eq. (1)], the optimal control turns out to have the usual "bang-bang" form. The solution proceeds as follows. First, the Hamiltonian equation,[14] with λ_{ijt} as costate variable, is

$$\begin{aligned}\mathscr{H}_{ijt} = \Big[\big[A_{it}q_{ijt} - \mathrm{MZ}_{it}\big]\big[g_{ijt} - v_{ijt}\big] - C_{it}g_{ijt} + f_{it}S_{ijt} \\ + W_{it}g_{ijt} - D_{it}v_{ijt}\Big] \cdot e^{-r_t t} + \lambda_{ijt} \cdot \big[v_{ijt} - g_{ijt}\big] \cdot e^{-r_t t}.\end{aligned} \tag{7}$$

According to the maximum principle [19], the following complementary slackness conditions must hold:

$$g^*_{ijt} = \bar{g}_{ijt} \quad \text{if } \frac{\partial \mathscr{H}(\cdot)}{\partial g_{ijt}} > 0; \qquad g^*_{ijt} = 0 \text{ otherwise} \tag{8}$$

$$v^*_{ijt} = \bar{v}_{ijt} \quad \text{if } \frac{\partial \mathscr{H}(\cdot)}{\partial v_{ijt}} > 0; \qquad v^*_{ijt} = 0 \text{ otherwise.} \tag{9}$$

An additional necessary condition for the maximization of Eq. (1) is

$$\frac{\partial \mathscr{H}(\cdot)}{\partial S_{ijt}} = -\frac{d}{dt}\left[\lambda_{ijt} \cdot e^{-rt}\right] \tag{10}$$

$$\lambda_{ijt} = \frac{f_{it}}{r} + \frac{\dot{\lambda}_{ijt}}{r}. \tag{11}$$

Evaluation of the partial derivatives in the first set of necessary conditions yields

$$g^*_{ijt} = \bar{g}_{ijt} \quad \text{if} \quad \left[A_{it}q_{ijt} - \mathrm{MZ}_{it} - C_{it} + W_{it} - \lambda_{ijt}\right] > 0 \tag{12}$$

$$v^*_{ijt} = \bar{v}_{ijt} \quad \text{if} \quad \left[-A_{it}q_{ijt} + \mathrm{MZ}_{it} - D_{it} + \lambda_{ijt}\right] > 0. \tag{13}$$

[14]The specification implies that all prices and costs are exogenously determined in broader national or international markets. In the present application, such an assumption is reasonable. The specification also implies that there are no costs of adjustment associated with the abandonment of agricultural land and its subsequent return to a forested state. If tree farming were prevalent in the area, the specification would need to be modified accordingly.

Substituting from Eq. (11) into Eq. (12),

$$g^*_{ijt} = \bar{g}_{ijt} \quad \text{if} \quad \left[A_{it}q_{ijt} - \mathrm{MZ}_{it} - C_{it} + W_{it} - \frac{f_{it}}{r}\right] > \frac{\dot{\lambda}_{ijt}}{r}. \tag{14}$$

Assuming that landowners have static expectations regarding all variables, the necessary condition for *target* allocations of land between forest and agricultural uses reduces to

$$\begin{aligned} g^*_{ijt} &= \bar{g}_{ijt} \quad \text{if} \quad A\left[_{it}q_{ijt} - \mathrm{MZ}_{it} - C_{it} - \mathrm{FN}_{it}\right] > 0 \\ g^*_{ijt} &= 0 \quad \text{otherwise} \end{aligned} \tag{15}$$

where FN_{it} is net forestry revenue, $F_{it} - W_{it}$, and $F_{it} = f_{it}/r$.

Likewise, for abandonment of farmland, Eq. (11) is substituted into Eq. (13), yielding for *targeted* abandonment the necessary condition:

$$\begin{aligned} v^*_{ijt} &= \bar{v}_{ijt} \quad \text{if} \quad \left[\tilde{F}_{it} - A_{it} \cdot q_{ijt} + \mathrm{MZ}_{it}\right] > 0 \\ v^*_{ijt} &= 0 \quad \text{otherwise} \end{aligned} \tag{16}$$

where delayed net forest revenue is defined as $\tilde{F}_{it} = F_{it} - D_{it}$.

To characterize the solution, let

$$X_{ijt} = A_{it} \cdot q_{ijt} - \mathrm{MZ}_{it} - C_{it} - \mathrm{F}N_{it} \tag{17}$$

$$Y_{ijt} = \tilde{F}_{it} - A_{it} \cdot q_{ijt} + \mathrm{MZ}_{it}. \tag{18}$$

The solution to the maximization problem then implies that conversion or abandonment will occur under the following conditions:

Conversion occurs if $X_{ijt} > 0$ and parcel is forested. (19)

Abandonment occurs if $Y_{ijt} > 0$ and parcel is cropland. (20)

2.3. Unobserved Heterogeneity and Aggregation of Necessary Conditions

Equations (19) and (20) imply that all land in a county of a given quality will be in the same use in the steady state,[15] but, in reality, counties are observed to be a mix of forest and farmland. Although this may partly reflect deviations from the steady state, it is due largely to heterogeneity of land.

This heterogeneity can be characterized in terms of a probability density function, $\mathscr{f}_i\{q_{ijt}\}$, where q primarily reflects variations in frequency of flooding, drainage, and soil conditions, and thus depends on the natural lay of the land, the type of soil, and the existence of manmade flood-control and drainage projects.

[15]Letting the time interval Δ in Eqs. (5) and (6) be equal to unity (a single time period), the continuous-time model yields the following result for a discrete-time situation: when conversion occurs, $g^*_{ijt} = S_{ijt}$; and when abandonment occurs, $v^*_{ijt} = \mathrm{AG}_{ijt}$. In other words, for each homogeneous parcel j, it is always optimal either to convert the entire parcel from forested condition to agricultural use (only, of course, if it is in a forested state), to abandon the entire parcel (only if it is agricultural cropland), or to do nothing.

This distribution is posited as a parametric lognormal relationship, because the general shape of that distribution is reasonable for a distribution of land quality

$$\begin{aligned} \log(q_{ijt}) &\sim N(\mu, \sigma^2) && \text{with probability } d_{it} \\ q_{ijt} &= 0 && \text{with probability } (1 - \mathrm{d}_{it}) \end{aligned} \tag{21}$$

where μ and σ^2 are the mean and variance of the normal distribution, and d_{it} is the probability that agricultural production is feasible, such that

$$d_{it} = \left[\frac{1}{1 + \left[1/e^{\pi(\mathbf{z})}\right]}\right] \tag{22}$$

$$\pi(\mathbf{z}) = \mathrm{DRY}_i + \beta_1 \cdot \mathrm{PROJ}_{it} \tag{23}$$

where DRY_i is a measure of the percentage of county i which is naturally protected from periodic flooding, PROJ_{it} is an index of the share of county i at time t which has been artificially protected from flooding [by Corps of Engineers and Soil Conservation Service (SCS) projects], and β_1 is a parameter which indicates the impact of artificial flood protection relative to the impact of natural flood protection.[16]

In this relatively simple, first approximation, federal flood-control and drainage projects have the effect of rendering agricultural production feasible; and on the feasible land, the index of feasibility, q_{ijt}, is distributed lognormally and unchanging over time, i.e., linked exclusively to soil texture and soil nutrients. This approach assumes that selection by the Corps and SCS of specific land parcels for protection is independent of potential yields; the distribution of potential yields is identical to the distribution of actual yields.

A more general approach is to allow for the possibility that decisions to protect land from flooding are not made independently of the land's relative potential for agricultural production. Thus, the yield distribution is affected by flood protection. In terms of the basic model, the underlying heterogeneity is itself affected by the presence of flood-control projects. In this more general approach, the parameters of the lognormal distribution, μ and σ, are themselves functions of PROJ_{it}:

$$\begin{aligned} \log(q_{ijt}) &\sim N\left[\mu(1 + \beta_2 \mathrm{PROJ}_{it}), \left[\sigma_i(1 + \beta_3 \mathrm{PROJ}_{it})\right]^2\right] \quad \text{with prob. } d_{it} \\ q_{ijt} &= 0 \quad \text{with prob. } (1 - d_{it}). \end{aligned} \tag{24}$$

Whereas in the simpler model the impact of federal projects on land-use decisions is captured by the parameter β_1 (and its multiplicative effect with other parameters in the nonlinear model), in the more general model, there are three project-impact parameters, β_1, β_2, and β_3.

Equation (19) indicates that there is an incentive to convert forested wetlands to agricultural cropland if $X_{ijt} > 0$. Hence, there is a threshold value of q_{ijt}, denoted

[16]The logistic specification is used to constrain d_{it} to values between zero and unity, because the empirical measures of federal (U.S. Army Corps of Engineers and Soil Conservation Service) project impact areas and natural flood protection are only indexes of protection.

TABLE I
Model of Forested Wetland Conversion and Agricultural Cropland Abandonment

$$\mathrm{FORCH}_{it} = \mathrm{FORCH}^{\mathrm{c}}_{it} \cdot D^{\mathrm{c}}_{it} + \mathrm{FORCH}^{\mathrm{a}}_{it} \cdot D^{\mathrm{a}}_{it} + \lambda_i + \phi_{it}$$

$$\mathrm{FORCH}^{\mathrm{c}}_{it} \cdot (-1) = \gamma_c \Big[d_{it} \cdot \big[1 - \mathbf{F}\big[[\log[q^x_{it}] - \mu(1 + \beta_2 \mathrm{PROJ}_{it})\big]\big/\sigma(1 + \beta_3 \mathrm{PROJ}_{it})\big]\big] + \left[\frac{S}{T}\right]_{i,t-1} - 1\Big]$$

$$\mathrm{FORCH}^{\mathrm{a}}_{it} = \gamma_a \Big[d_{it} \cdot \big[\mathbf{F}\big[[\log[q^y_{it}] - \mu(1 + \beta_2 \mathrm{PROJ}_{it})\big]\big/\sigma(1 + \beta_3 \mathrm{PROJ}_{it})\big]\big] + [1 - d_{it}] - \left[\frac{S}{T}\right]_{i,t-1}\Big]$$

$$d_{it} = \left[\frac{1}{1 + [1/e^{\pi(z)}]}\right] \quad (22) \qquad \text{where } \pi(z) = \mathrm{DRY}_i + \beta_1 \mathrm{PROJ}_{it} \quad (23)$$

$$q^x_{it} = \left[\frac{\mathrm{FN}_{it} + \mathrm{MZ}_{it}}{A_{it} - \alpha_1 C_{it} \cdot \exp\{\alpha_2 \mathrm{PHDI}_{it}\}}\right] \quad (25) \qquad q^y_{it} = \left[\frac{\tilde{F}_{it} + \mathrm{MZ}_{it}}{A_{it}}\right] \quad (26)$$

q^x_{it}, above which the incentive for conversion manifests itself[17]:

$$q^x_{it} = \left[\frac{\mathrm{FN}_{it} + \mathrm{MZ}_{it}}{A_{it} - \alpha_1 C_{it} \cdot \exp\{\alpha_2 \mathrm{PHDI}_{it}\}}\right]. \tag{25}$$

Likewise, Eq. (20) indicates that there is an economic incentive to abandon farmland and allow it to return to forest if $Y_{ijt} > 0$. Therefore, there exists a threshold value of q_{ijt}, denoted q^y_{it}, below which the incentive for abandonment manifests itself:

$$q^y_{it} = \left[\frac{\tilde{F}_{it} + \mathrm{MZ}_{it}}{A_{it}}\right]. \tag{26}$$

As is described in detail by Stavins and Jaffe [23], the individual necessary conditions for forested wetland conversion and farmland abandonment may be aggregated into a single-equation model, in which the parameters of the basic benefit–cost relationship [Eqs. (19) and (20)] and of the underlying, unobserved heterogeneity [Eqs. (22), (23), and (24)] can be estimated simultaneously. A fixed-effects model is specified, the parameters of which can be estimated with county dummy variables employed to eliminate any bias due to the fixed effect. The final private-market specification is presented in Table I. All variables in the table are as defined above; FORCH_{it} is the change in forest land as a share of total county area; D^{c}_{it} and D^{a}_{it} are dummy variables for conversion and abandonment, respectively; λ_i is a county-level fixed-effect parameter, ϕ_{it} is an independently (but not necessarily homoscedastic[18]) error term; γ_{c} and γ_{a} are partial

[17] In Eq. (25), conversion cost is allowed to be heterogeneous across land parcels and flood-control projects are assumed to affect conversion costs. So, the conversion cost term is replaced by $\alpha_1 \cdot q_{ijt} C_{it} g_{it}$, where α_1 is a parameter which captures the relative effect of heterogeneity on conversion costs. Due to limitations of the data, α_1 and α_2 (effect of weather on conversion cost) cannot be estimated in the same equation. The specification reported here constrains α_1 to equal 1.0, consistent with estimates. The equation also allows for the parametric effect of weather on conversion costs.

[18] Heteroscedasticity-consistent standard errors were calculated according to [27], and are reported in the table of econometric results.

adjustment coefficients for conversion and abandonment; and **F** signifies the cumulative, standard normal distribution function.

3. SOCIALLY OPTIMAL RESOURCE USE

The first basic theorem of welfare economics indicates that "socially optimal" land use would result from a well-functioning, free-market economy in the absence of externalities.[19] The previously specified (private, market-based) dynamic optimization model may now be expanded into a model of socially optimal use of wetlands in one of two ways. Both approaches involve internalizing environmental externalities.[20] First, one may view the relevant externalities as environmental benefits of forested wetlands. The social optimization problem may then be posited by substituting the term $(f_{it} + e_{it}) \cdot S_{ijt}$ for the $f_{it}S_{ijt}$ term in Eq. (1), where e_{it} is average annual environmental benefit per acre from forested wetlands.[21] From this perspective, socially optimal use of the land is achieved if landowners, when deciding how to utilize their wetlands, take into account all benefits of forested wetlands, not only their financial benefits from timber production.

The other, parallel approach is to view externalities as environmental costs associated with the conversion of forested wetlands to agricultural cropland. In this case, the social optimization problem is posited by substituting the term $(\mathrm{MZ}_{it} + E_{it})$ for the MZ_{it} term in Eq. (1), where E_{it} is average environmental cost per acre due to conversion of forested wetlands to cropland, expressed as the discounted present value of an infinite future stream.[22] From this second perspective, socially optimal use of the land is achieved if landowners, when deciding how to utilize their wetlands, take into account the environmental costs of agricultural production, in addition to the financial costs of agricultural production.

These two perspectives on the nature of an externality are, of course, fundamentally equivalent. The two approaches lead to the same set of necessary conditions. There is no loss of generality involved in focusing on the first perspective. Substitution of the term $(f_{it} + e_{it}) \cdot S_{ijt}$ for $f_{it}S_{ijt}$ in the objective functional leads to a parallel modification of the Hamiltonian [Eq. (7)] and to the following generalization of Eqs. (25) and (26) for the threshold values of q_{ijt} for socially

[19] Strictly speaking, the simulated environmental-cost-internalized time paths of changes in forested acreage are not necessarily optimal paths; rather, they represent paths which would be taken if Pigouvian taxes were utilized in order to encourage movement toward optimal steady-state levels of forests and cropland. This is because a partial adjustment model is utilized and the partial adjustment parameters are not necessarily the same in the market model and the true social optimum model.

[20] In addition to the effects of environmental externalities, another potential source of divergence between actual and socially optimal conversion of forested wetlands is associated with the public goods nature of flood-control projects: in the absence of other externalities, the market may be expected to underprovide such projects. This effect is opposite in direction to that of environmental externalities, which are the focus of the analysis here.

[21] A more general specification of environmental values would allow for downward-sloping demand for environmental amenities. This would substitute the function $e_{it} = e[S_{it}/T_{it}]$ for the set of e_{it} values.

[22] Consistent with other notation, $e_{it} = r \cdot E_{it}$.

TABLE II
Parameter Estimates

Parameter	Interpretation	Estimate
γ_a	Abandonment partial adjustment	0.36717[a] (0.184)[b]
γ_c	Conversion partial adjustment	0.64826 (0.154)
μ	Mean of unobserved quality distribution	1.11650 (0.364)
σ	Standard deviation of unobserved quality distribution	0.43848 (0.067)
β_1	Project impact on agricultural feasibility	8.93700 (2.465)
β_2	Project impact on heterogeneity mean	0.77193 (0.774)
β_3	Project impact on heterogeneity standard deviation	0.42799 (0.183)
α_2	Weather impact on conversion cost	1.59720 (0.304)
	Goodness-of-fit[c]	0.6747
	Log likelihood value	791.698
	Degrees of freedom	316

[a] The model also contains 36 county dummies.
[b] Robust standard error estimates appear below parameter estimates.
[c] This dynamic goodness-of-fit statistic is equal to 1 − Theil's U statistic, based on comparing predicted and actual net rates of conversion and abandonment, at the county level, across time.

optimal conversion and abandonment, respectively:

$$q_{it}^{x} = \left[\frac{\mathrm{FN}_{it} + \mathrm{MZ}_{it} + E_{it}}{A_{it} - \alpha_1 C_{it} \cdot \exp\{\alpha_2 \mathrm{PHDI}_{it}\}}\right] \tag{27}$$

$$q_{it}^{y} = \left[\frac{\tilde{F}_{it} + \mathrm{MZ}_{it} + E_{it}}{A_{it}}\right]. \tag{28}$$

The final model of socially optimal forested wetland conversion and agricultural cropland abandonment is specified by substituting Eqs. (27) and (28) for Eqs. (25) and (26), respectively, in Table I.

4. SIMULATING OPTIMAL RESOURCE USE IN THE PRESENCE OF ENVIRONMENTAL CONSEQUENCES

Using panel data for 36 counties in Arkansas, Louisiana, and Mississippi, during the period 1935–1984,[23] the parameters of the model embodied in Table I were

[23] For descriptions of the data employed, see [22].

estimated with nonlinear least-squares procedures. Results are found in Table II. The overall results lend support to the basic validity of the model. Estimated parameters are all of the expected sign, and nearly all estimates are significant at the 90, 95, or 99% level.[24] The dynamic goodness-of-fit, based upon Theil's [25] measure, is 0.675.

Once the parameters of the market model—α_1, α_2, β_1, β_2, β_3, γ_a, γ_c, μ, σ—have been estimated, the optimal time path of conversion and abandonment is identified through counterfactual, dynamic simulations with the social-optimum model.[25] This method accounts for environmental externalities, but other externalities may also be present. In particular, a major source of divergence from the social optimum may be associated with the presence of subsidies in the form of large-scale federal flood-control and drainage projects. Since, in the absence of federal projects, the private market may have led to the construction of some projects, bounds on the socially optimal rate of conversion may be established by comparing counterfactual simulations with and without the federal projects.[26]

4.1. Environmental Benefits of Forested Wetlands

A variety of public benefits are lost when forested wetlands are drained, cleared, and converted to agricultural cropland, including water quality effects, floodwater storage, erosion control, groundwater recharge, fish and wildlife habitat, and recreational opportunities [11]. The water quality effects of wetlands are of particular importance; wetlands help maintain and improve the quality of waters which flow over and through them by trapping suspended sediments, removing nutrients, and processing chemical[27] and organic wastes. Because of their location between land and water, wetlands are particularly effective filters, intercepting runoff from land and helping to filter sediments, nutrients, and wastes from passing waters [24].

4.2. Economic Valuation of Environmental Benefits

Hedonic models, contingent valuation procedures, and the travel-cost method have been used to value environmental benefits of forested and other wetlands.[28] Although valuation techniques are well developed, most studies are limited by available data or by conceptual problems of respective methodologies [20]. Specific estimates may be no more than rough approximations of true externality values.

[24]Also, both parameter and standard error estimates are robust with respect to modifications of the specification.

[25]The simulations involve a two-step approach for establishment of the conversion and abandonment dummy variables.

[26]To simulate "no federal projects," the appropriate variable, PROJ_{it}, is set equal to zero for all i and t, while all other variables are at their actual, historical levels. An additional source of divergence from the social optimum exists when farm-level agricultural crop prices are insulated from the market by federal commodity programs. If effective farm-level prices are used in the econometric estimation, this externality may be internalized in the counterfactual, social-optimum simulation by using agricultural product prices which reflect the social values of commodities.

[27]The impact on water quality of conversion of forested wetlands to agricultural use is twofold (in regard to chemical pollution): forested wetlands trap chemical pollutants, and crop production leads to runoff into waterways of pesticide and fertilizer residues.

[28]A classic wetland valuation study is that of Hammack and Brown [12]; a more recent example is [6]. Surveys of previous studies are found in [9, 20].

Empirical estimates of annual environmental benefits of wetlands range from \$25 per acre (fish and wildlife habitat in northern Louisiana) to more than \$8000 per acre (water quality enhancement in central Georgia). This wide range of estimates is due to more than the uncertainty associated with assessment methods. To a large degree, it reflects actual heterogeneity of wetland environmental values, a function of both physical diversity of wetlands and geographic and demographic variations in the demand for wetland services.[29] Given this heterogeneity of wetland values and the uncertainty of individual estimates, the analysis in this paper does not focus on a specific set of estimated values, but presents a spectrum of results for a range of externality levels.

4.3. Simulating the Socially Optimal Rate of Conversion and Abandonment

The estimated parameters from the econometric model are utilized for the respective parameters in the social-optimum simulation model, and initial conditions are taken as given. By combining historical values of variables with alternative estimates of environmental externality values, E_{it},[30] in a series of dynamic simulations, estimates are made of changes which would have occurred in forested wetland acreages *if* landowners had taken environmental consequences into account as they made their land-use decisions. Bounds are established by calculating "social-optimum" simulations with and without federal projects.[31]

The results of the two sets of simulations are summarized in Table III. For externality values ranging from \$25 to \$1000 (per acre per year), the socially optimal, total 50-year net change in forested wetland acreage in the study area is reported, first, for the case of federal projects having been constructed and maintained at their actual, historical level, and second, for the case of no federal projects having been constructed during the post-1934 period.[32]

As can be seen in Fig. 2, zero-level net depletion would have been optimal if environmental benefits were about \$150/acre (per year). If no projects had been built, however, zero net depletion would have been optimal at an environmental externality level of only \$80/acre (per year). This is not to suggest that under these two scenarios, no conversion (or abandonment) would have occurred, only that the net change at the end of the 50 years would have been nil.

Given the bounds which are established on socially optimal wetland use by the two sets of simulations, the horizontal distance between the two curves has an

[29]Additional examples include \$27/acre per year for Massachusetts inland recreational fishing benefits [26]; \$490/acre per year for Michigan coastal wetland waterfowl and recreational fishing benefits [14]; and \$6800/acre annually for waste assimilation in Virginia wetlands [10].

[30]Although the simulations employ a constant (real) level of E for all counties and time periods, the model allows for use of different externality values across counties and across time.

[31]These bounds could be narrowed if the implicit, marginal subsidy inherent in federal flood-control and drainage projects were estimated. This estimate (in dollars per acre per year) should be subtracted from the "with-federal-projects line" in Fig. 2, shifting it to the left. An empirical difficulty is that it is the marginal subsidy implicit in federal projects, not the average subsidy, which is required for such calculations.

[32]Simulations are scaled so that the factual simulation (environmental externality value = 0; "with federal projects") yields the actual net change which occurred during each time period. Thus, the first row of figures in Table III are indicative of the actual total depletion which occurred (3.637 million acres) and the depletion which would have occurred had there been no projects (2.487 million acres). The difference between these, 1.150 million acres, is the depletion due to federal projects during the study period.

TABLE III
Simulated Socially Optimal Changes in Forested Wetlands for Alternative Values of Environmental Benefits, 36 Counties, Lower Mississippi Alluvial Plain, 1935–1984

Value of environmental benefits per acre	Simulated socially optimal changes	
	With federal projects[a]	No federal projects[b]
(dollars)	(1000 acres)	
0	−3637	−2487
25	−3012	−1560
50	−2313	−839
75	−1660	−150
100	−1029	+486
125	−474	+1056
150	+35	+1548
175	+527	+2031
200	+938	+2491
225	+1385	+2939
250	+1776	+3276
275	+2109	+3596
300	+2391	+3909
325	+2695	+4185
350	+3002	+4449
375	+3282	+4646
400	+3529	+4820
425	+3726	+5004
450	+3990	+5209
475	+4122	+5387
500	+4326	+5474
600	+4792	+5895
700	+5204	+6192
800	+5572	+6340
900	+5848	+6455
1000	+6052	+6567

[a]Simulated socially optimal changes in forested wetland acreage, given the existence of federal flood-control and drainage projects.

[b]Simulated socially optimal changes in forested wetland acreage in the absence of any federal flood-control and drainage projects.

interesting interpretation. Recall that the "with-projects" curve crosses the zero level of net change in forested wetlands at an environmental benefit value of about \$150/acre, while the "without-projects" curve intersects at about \$80/acre, a difference of \$70/acre. This suggests that, *on average*, landowners revealed themselves to be indifferent between flood-control projects and an annual payment of \$70/acre (when the allocation of land between forest and farmland was that of 1935). In other words, landowners' average annual marginal valuation of projects was \$70 per acre of protection. The analogous numbers for later periods, when there was less forest stock remaining, are given by the horizontal distance between the two curves at various points of total net loss of wetlands. Thus, the results confirm that the marginal valuation of project protection declined as more land was converted from forested condition to cropland and only land of inferior quality remained.

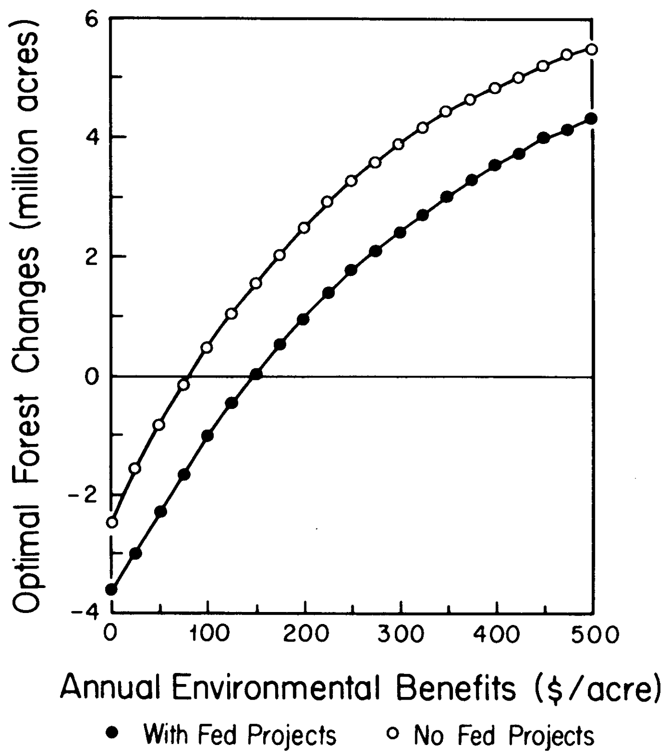

FIG. 2. Optimal forested area changes, Mississippi Alluvial Plain, 1935–1984.

5. CONCLUSIONS AND POLICY IMPLICATIONS

The simulations reported in this paper suggest that if all wetlands in the study area had annual ecological (external) values in the range of $80 to $150 per acre, zero-level net depletion of forested wetlands in the study area during the period 1935–1984 would have been socially optimal. But actual wetland values, of course, vary tremendously from one area to another: from less than $25/acre annually to as much as $10,000/acre per year.[33] What conclusions, then, can be drawn from the quantitative findings?

5.1. Placing the Analysis in Perspective

The simulation results can be placed in perspective by comparing them with the private valuation of land in the study area. First, recall that a range of $80 to $150 annual ecological value per acre would have justified no net loss of forested wetlands in the study area during the period 1935–1984. Such a range of annual benefits is equivalent to an average present value on the order of $2000 per acre.[34] This is more than twice the current market value of wetlands in the study area

[33]Better estimates of wetland values would permit extensions of the present analysis by (a) estimating wetland values (E_{it}) which vary across time and space; (b) taking into account the heterogeneity of wetland values within counties; and (c) utilizing a nonlinear environmental benefit function.

[34]Assuming a real annual discount rate of 5%.

(whether forested or cropped), typical land prices being in the range $500 to $900 per acre. Thus, abstracting for the moment from the wetland-valuation heterogeneity issue described above, the study indicates that only if the environmental values of the land were more than twice their market (agricultural) value would zero-level net depletion have been optimal.

The $2000 figure does not indicate the environmental value per acre required to stop conversion, but is the value which would have led, if internalized, to no net loss.[35] Assuming symmetric distributions of wetland values, for ease of calculation, the average environmental value which would have stopped a typical acre from being converted was about $1100 (the externality value which would have argued for half as much conversion as there actually was). This translates into an annual ecological benefit level of $55, which is well within the range of typical annual net (private) returns to conversion.[36] This is as expected, since social optimization would call for wetland conversion to be avoided when the value of externalities is in excess of the private returns to conversion.

5.2. *Policy and Methodological Implications*

A general implication of the analysis is that the federal government should begin to consider ways of narrowing the gap between the actual allocation of land between forested wetlands and agricultural cropland and what appears to be the socially desirable configuration, whether the chosen methods of narrowing this gap involve modifications of existing programs and policies or enactment of entirely new ones. The policy tools available to the government include changes in the way federal flood-control and drainage projects are planned, authorized, and financed; federal acquisition, easement, and oversight programs; provision for preferential property tax assessments; tax credits; conversion penalties (taxes); and cross-compliance legislation linked to receipt of federal commodity program payments.[37] In general, a central goal of new policies ought to be eliminating unwarranted public subsidies and internalizing environmental externalities.

The methodology developed here may be applied to a variety of problems in the natural resources field and other fields of economics, as well. One timely use of this approach would be to analyze the factors causing massive losses of tropical rain forests in areas such as the Amazon basin. Other potential uses of the approach include examination of the impacts of access-road construction on federal timber management practices, and analysis of the effects of federal and state highway construction on urban development. Moving beyond land-use issues, the approach could be applied elsewhere in the natural resources field to estimate socially optimal resource exploitation involving impacts on the environment.

[35]The environmental value of some wetlands is certainly greater than $2000 per acre ($115/acre per year). This is validated by the evidence, cited above, of annual wetland benefits in excess of this amount, and by the revealed preferences of private groups such as the Nature Conservancy in their purchases for purposes of protection of specific wetland habitats.

[36]Gross agricultural revenue minus agricultural production costs minus net forest revenue foregone minus costs of conversion.

[37]The so-called "swampbusting provisions" of the 1987 Farm Act constitute a move in the right direction, although it is not yet clear whether the U.S. Department of Agriculture's interpretation and execution of the law will be consistent with its intent.

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