Unintended Impacts of Public Investments on Private Decisions: The Depletion of Forested Wetlands

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By affecting relative economic returns, public infrastructure investments can induce major changes in private land use. We find that 30 percent of forested wetland depletion in the Mississippi Valley has resulted from private decisions induced by federal flood-control projects, despite explicit federal policy to preserve wetlands. Our model aggregates individual land-use decisions using a parametric distribution of unobserved land quality; dynamic simulations are used to quantify the impacts on wetlands of federal projects and other factors. (JEL 717)

Private land-use decisions can be affected dramatically by public investments in highways, waterways, flood control, or other infrastructure. The large movement of jobs from central cities to suburbs in the postwar United States and the current destruction of Amazon rain forests have occurred with major public investment in supporting infrastructure. As these examples suggest, private land-use decisions can generate major environmental and social externalities. Hence, the extent to which major investment programs create "secondary impacts" through their effects on private decisions is a matter of great public concern. In this paper, we demonstrate that the depletion of forested wetlands in the Mississippi Valley (an important environmental problem and a North American precursor to the loss of South American rain forests) has been and is currently exacerbated by federal water-project investments, despite explicit federal policy to protect wetlands.

We begin with a structural model of an individual landowner's decision of whether or not to convert a parcel of land from its natural, forested state to agricultural use. This problem can be characterized as an optimal stopping problem, and is similar to those investigated by Glenn Gotz and John McCall (1980 and 1984), Ariel Pakes (1986), John Rust (1987), and Mark Rosenzweig and Kenneth Wolpin (1988). Unfortunately, such models require individual data for estimation; but in the present context data on land-use status and other characteristics of individual parcels would be prohibitively expensive to obtain over an area large enough to contain significant variation in the extent of federal investment. Therefore, we need a model that will explain the proportion of some aggregate (counties, in our case) that will be converted; this leads to the problem of the appropriate aggregation of individual optimal decisions to the county level.

If the land in a county could be assumed to be homogeneous, then the required aggregation could be accomplished simply by modeling a "representative parcel" and assuming that variations within counties were purely random. Such an assumption, however, is untenable. Some land in a county is

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of higher (potential) agricultural quality and will therefore be developed first. If we ignore this reality and estimate a model on a panel of counties over time, any variable whose value is initially high, and then falls, will appear to cause conversion. More generally, if we are to predict, based on the past, what would happen if we change policy in the future, it is necessary to take into account the fact that the marginal acre today is different from the marginal acre of the past.

We solve the problem by positing a parametric distribution for the unobserved quality of land within a county. The parameters of this distribution are then estimated jointly with the parameters of the individual-level, structural model. This allows us to quantify the effects of federal programs and policies, via dynamic simulations with the estimated distributional and structural parameters.[1]

The first section of the paper describes the problem of wetland depletion. The second section develops the theoretical framework, including the modeling of unobserved heterogeneity of land parcels. Section III presents econometric results, used in Section IV to carry out dynamic simulations. Concluding comments are found in Section V.

I. Forested Wetlands and Public Policy

Forested wetlands are among the world's most productive ecosystems, providing improved water quality, erosion control, floodwater storage, timber, fish and wildlife habitat, and recreational opportunities. Their continuing depletion is a serious land-use problem; preservation and protection of wetlands have been major federal environmental policy goals for at least twenty years. The largest remaining wetland habitat in the continental United States is the bottomland hardwood forest of the Lower Mississippi Alluvial Plain. Originally covering 26 million acres in seven states, this resource was reduced to about 12 million acres by 1937. Since then, another 6.5 million acres have been cleared, primarily for conversion to cropland.

The owner of a wetland parcel faces an economic decision involving revenues from the parcel in its natural state (primarily from timber), costs of conversion (the cost of clearing the land minus the resulting forestry windfall), and expected revenues from agriculture. Agricultural revenues depend on prices, yields, and, significantly, the drainage and flooding frequency of the land. Needless to say, landowners typically do not consider the positive environmental externalities generated by wetlands; thus conversion may occur more often than is socially optimal.

These externalities are the motivation for federal policy aimed at protecting wetlands, as embodied in the Clean Water Act. Nonetheless, the federal government has engaged in major public investment activities, in the form of U.S. Army Corps of Engineers (Corps) and U.S. Soil Conservation Service (SCS) flood-control and drainage projects, which appear to make agriculture more attractive and thereby encourage wetland depletion. The significance of this effect is disputed by the agencies which construct and maintain these projects; they attribute the extensive conversion exclusively to rising agricultural prices (U.S. Army Corps of Engineers, 1981). Our approach allows us to sort out the effects of federal projects and other changing economic forces. As we will see, these public investments appear to have been a substantial factor causing conversion of wetlands to agriculture.[2]

[1]The problem of estimating a transition process for individuals on the basis of aggregate data arises in many areas. In natural resource economics, in particular, it has been identified as a major gap between the theoretical literature on optimal extraction and the empirical literature on resource depletion (Douglas Bohi and Michael Toman, 1984). Also related is work in demography (for example, Richard Gill, 1986) and technological diffusion (Zvi Griliches, 1957; Paul David, 1966; and Richard Pomfret, 1976).

[2]Theoretical models of wetland conversion are found in John Brown (1972) and Leonard Shabman (1980). Our empirical results should be compared with Randall Kramer and Leonard Shabman 1986, and U.S. Department of the Interior 1988.

II. The Privately Optimal Land-Use Decision and Its Implications for the Behavior of Heterogeneous Aggregates

The first step is the construction of a dynamic optimization model of forestry and agricultural production at the individual, landowner level. The solution of this model yields necessary conditions for conversion of individual forest parcels to agricultural production and for abandonment of parcels of cropland. An explicit model of the heterogeneity of land allows for the aggregation of the respective necessary conditions to the county level, so that an econometrically estimable model can be specified.

A. *A Dynamic Optimization Model of Forestry and Agricultural Production*

Landowners observe a variety of economic, hydrologic, and climatic factors relevant to decisions regarding the use of their lands for forestry or agricultural production. Current and past values of variables presumably constitute the basis for expectations about future values of 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. A prime factor determining such suitability of land (in the geographic area of this study) is its wetness, that is, the degree of (natural and artificial) protection from flooding and poor drainage.

A landowner continually faces a decision of whether to keep land in its current state, to convert forested land to agricultural production,[3] or to abandon cropland and allow it to return to forest. A risk-neutral[4] landowner faced with the decision of how to utilize his land, given the alternatives of forestry and agriculture, may be expected to seek to maximize the present discounted value of the stream of expected future returns to his land:[5]

$$(1)\quad \max_{\{g_{ijt}v_{ijt}\}} \int_0^{\infty} \Big[\big[A_{it}q_{ijt} - AC_{it}\big]\big[g_{ijt} - v_{ijt}\big] - C_{it}g_{ijt} + f_{it}S_{ijt} + w_{it}g_{ijt} - D_{it}v_{ijt}\Big] e^{-r_t t}\, dt$$

subject to:

$$(2)\quad \dot{S}_{ijt} = v_{ijt} - g_{ijt}$$

$$(3)\quad 0 \le g_{ijt} \le \bar{g}_{ijt}$$

$$(4)\quad 0 \le v_{ijt} \le \bar{v}_{ijt}$$

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[6] of typical expected agricultural revenues per acre in the county;

[3]The potential sale of a parcel is economically irrelevant, since a new owner faces the same conversion/abandonment decision. The option of residential or commercial development is empirically insignificant. Finally, since land prices presumably reflect the present value of net revenues under optimal use, land-price data, if available, would provide an alternative means of examining the phenomena modeled here. See Richard Arnott and Frank Lewis (1979).

[4]Evidence on the risk aversion of farmers is not consistent (Douglas Young 1979; Bruce Gardner and Jean-Paul Chavas 1979; Rulon Pope 1981). Provision for risk-averse behavior in the objective functional would lead to the inclusion in derived necessary conditions of second-order moments of stochastic variables. Due to lack of sufficient data, however, only expected values are used in the empirical analysis: we assume risk neutrality and independence of relevant factors. Because flood protection projects may reduce the variance of returns (in addition to increasing average returns), the assumption of risk neutrality may lead to underestimation of the impacts of federal projects.

[5]Note that the term in the objective function which represents the (discounted present value of) expected future net revenue from agricultural production. $A_{it}q_{ijt} - AC_{it}$, is the price of farmland in a competitive market.

[6]Though a discrete-time formulation would be more realistic, the continuous-time approach is simpler and easier to interpret. The econometric specification implied by the discrete-time formulation is identical.

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 forested condition);
AC = expected costs 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);[7]
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 clearcut of forest (in the process of conversion);
D = expected present discounted value of loss of income due to the gradual regrowth of forest (harvesting does not occur until the year $t+R$, where R is the exogenously determined rotation length);[8]
$\bar{g}$ = maximum feasible rate of conversion, defined such that

$$(5) \qquad \int_t^{t+\Delta}[\bar{g}_{ij\tau}]\,d\tau = S_{ijt}$$

for arbitrarily small interval, Δ, over which $\bar{g}_{ij\tau}$ is constant;
$\bar{v}$ = maximum feasible rate of abandonment, defined such that

$$(6) \qquad \int_t^{t+\Delta}[\bar{v}_{ij\tau}]\,d\tau = T_{ijt} - S_{ijt} = AG_{ijt}$$

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.[9]

Note that only the control variables, the state variables, and the quality index, q, are specific to the individual land parcel. All of the revenue and cost variables are measured at the county level. This is a consequence of the data, and is indicative of the information available to landowners. Aggregation of first-order conditions for individual landowners to the county level will yield relationships among county-level variables and the distribution of q. The parameters of these relationships and of the underlying distribution can then be estimated econometrically.

The solution to the optimization problem is provided in a longer version of this paper (Stavins and Jaffe, 1988). To characterize that solution, the following notation is convenient:

$$(7) \quad X_{ijt} = A_{it}\cdot q_{ijt} - AC_{it} - C_{it} - FN_{it},$$

$$(8) \quad Y_{ijt} = \tilde{F}_{it} - A_{it}\cdot q_{ijt} + AC_{it},$$

where FN_{jt} is net forestry revenue, $F_{it} - W_{it}$; and $\tilde{F}_{it}$ is delayed net forest revenue, $F_{it} - D_{it}$.

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

[8]The inclusion of this term allows for a category of land which is neither productive farm nor mature forest, but evolving "bush." The expected present discounted value of loss of income due to gradual regrowth of forest, D_{it}, is:

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

where F_{it} is the present discounted value of an infinite future stream of net forest income, i.e. $F_{it}\cdot r = f_{it}$. If $R=0$, $D_{it}=0$ (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.)

[9]Some land in the thirty-six counties was withdrawn from availability to the private market during the study period as a result of designation of protected status by Federal and state authorities, including the U.S. Fish and Wildlife Service, the U.S. Forest Service, and state fish and game agencies.

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

(9) Conversion occurs if $X_{ijt} > 0$

and parcel is forested,

(10) Abandonment occurs if $Y_{ijt} > 0$

and parcel is cropland.

Letting the time interval Δ in equations (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, $v^*_{ijt} = AG_{ijt}$. 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.

B. *Modeling the Unobserved Heterogeneity of Land*

Equations (9) and (10) imply that all land in a county of a given quality will be in the same use in the steady state. We do not, however, observe counties as all forest or all farmland. Partly, this may reflect deviations from the steady state (on which more below), but to a great extent it reflects heterogeneity of land within a county. We can characterize this heterogeneity in terms of a probability density function $f_i\{q_{ijt}\}$, as pictured in Figure 1.

The function pictured has a point mass of probability at $q = 0$, corresponding to land of hydrologic condition which renders agriculture completely infeasible. The rest of the land in a county could be farmed, with agricultural yields being an increasing function of q, since q reflects primarily variations in frequency of flooding, drainage, and soil conditions. Thus it depends on the natural lay of the land, the type of soil, and importantly, the existence of man-made flood-control and drainage projects.

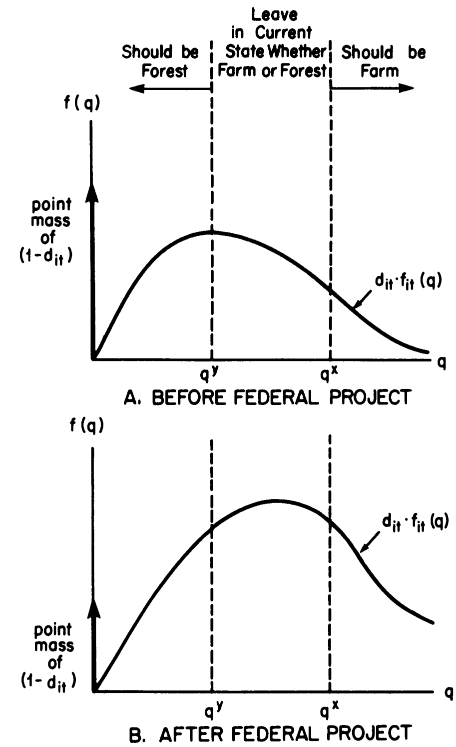

FIGURE 1. THE EFFECT OF FEDERAL FLOOD CONTROL AND DRAINAGE PROJECTS ON THE DISTRIBUTION OF UNOBSERVED LAND QUALITY

The two panels of Figure 1 demonstrate the effects of public projects. Conceptually, there are three such effects, but two are indistinguishable empirically. First, flood-control and drainage projects may render feasible for agriculture land that was previously infeasible; this is reflected as a transfer of probability mass from the point at zero to the rest of the distribution. Second, by improving drainage or reducing flooding, projects may shift the quality distribution for previously feasible land to the right.

Finally, projects may also change the distribution of q for agriculturally feasible land because the land which *was* infeasible that is rendered feasible may have an underlying or potential quality distribution that is different from the distribution for already feasible land. This effect could go in either direction. On the one hand, it could be that infeasible land, because it is low-lying and poorly drained, is likely to remain low quality even if given enough flood protection to be technically feasible. Alternatively, it could be that the soil on such land is of high quality and that, with flood protection, it is very good agricultural land. In the former hypothetical, projects would shift the quality distribution for feasible land to the left; in the latter to the right. Note that if *any* of the infeasible land is potentially of high quality, and if this is known in advance, then the government could increase the tendency for projects to be quality-improving by choosing preferentially to give flood protection to (potentially) high quality land. Thus, both the second and third effects are likely to result in an improvement in observed quality of feasible land, but these effects cannot be distinguished in the data.

We parameterize this model of the quality distribution as follows:[10]

$$\text{(11)}\quad \log(q_{ijt}) \sim N(\mu, \sigma^2) \quad \text{with probability } d_{it}$$

$$q_{ijt} = 0 \text{ with probability } (1 - d_{it})$$

where d_{it} is the probability that agricultural production is feasible.[11] The first effect identified above is incorporated by allowing d_{it} to be a function of the extent of federal projects:

$$\text{(12)}\qquad d_{it} = \left[\frac{1}{1 + \left[\frac{1}{e^{\pi(z)}}\right]}\right]$$

$$\text{(13)}\qquad \pi(z) = DRY_i + \beta_1 \cdot PROJ_{it}$$

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 and SCS projects, and β_1 is a parameter which indicates the impact of artificial flood protection relative to the impact of natural flood protection.[12]

The two effects of projects on the quality distribution for feasible land are incorporated by allowing the parameters of the lognormal distribution to depend on the project index as well:

$$\text{(14)}\quad \log(q_{ijt}) \sim N\left[\mu(1 + \beta_2 PROJ_{it}),\ \left[\sigma \cdot (1 + \beta_3 PROJ_{it})\right]^2\right] \text{ with prob. } d_{it}$$

$$q_{ijt} = 0 \text{ with probability } (1 - d_{it})$$

The effects of federal projects on land-use decisions are thus captured through the employment of three project-impact parameters —β_1, β_2, and β_3.

C. *Aggregation of Necessary Conditions for Forested Wetland Conversion*

Having posited the basic nature of the heterogeneity of land, the distributional model can now be used to aggregate the individual-landowner necessary conditions previously developed.[13] Equation (9), above, 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 q_{it}^x, above which the incentive

[10]We focus on the lognormal distribution because we believe that its general shape is appropriate for a distribution over quality of land. We experimented with other functional forms, and we discuss some of these results below.

[11]In the current application, individual county means and variances are not estimated. Note, however, that separate μ_i and σ_i parameters are identified and could therefore, in principle, be estimated, given sufficient data.

[12]The logistic specification is used to constrain d_{it} to values between zero and unity, because the empirical measures of Corps and SCS project impact areas and natural flood protection are only indexes of protection.

[13]One alternative research strategy would be to collect data on individual land parcels and estimate a model such as that developed by Rust (1987). In the present context, however, it would be prohibitively expensive to develop this data over an area large enough to identify the effects of interest.

for conversion manifests itself:

$$(15)\qquad q_{it}^{x}=\left[\frac{C_{it}+FN_{it}+AC_{it}}{A_{it}}\right].$$

If conversion cost is allowed to be heterogeneous across land parcels (within counties) and flood-control projects are believed to affect conversion costs as well as agricultural feasibility (yields), then the conversion cost term in equation (1) is replaced by the term $\alpha_1 \cdot q_{ijt}C_{it}g_{it}$, where α_1 is a parameter which captures the relative effect of heterogeneity on conversion costs, compared with the effect on agricultural yields. Next, allowing for the parametric effect of weather on conversion costs, q_{it}^{x} becomes

$$(16)\qquad q_{it}^{x}=\left[\frac{FN_{it}+AC_{it}}{A_{it}-\alpha_1 C_{it}\cdot\exp\{\alpha_2 PHDI_{it}\}}\right].$$

In either case, there is an incentive to convert parcel j (in county i at time t) from a forested condition to agricultural cropland if $q_{ijt}>q_{it}^{x}$. Therefore, the privately optimal (the desired or target) stock of converted land, expressed as a fraction of all land available for conversion, is

$$(17)\qquad \left[\frac{AG}{T}\right]_{it}^{*}=\left[1-\left[\frac{S}{T}\right]_{it}^{*}\right] = d_{it}\cdot\left[\int_{q_{it}^{x}}^{\infty}[f_i\{s\}]\,ds\right],$$

where $f_i\{\cdot\}$ is the lognormal density function. Therefore,

$$(18)\qquad \left[\frac{AG}{T}\right]_{it}^{*}=d_{it}\cdot[1-F_i[q_{it}^{x}]],$$

where $F_i[\cdot]$ is the lognormal cumulative distribution function, and

$$(19)\qquad \left[\frac{AG}{T}\right]_{it}^{*}=d_{it}\cdot[1-\mathbf{F}[[\log[q_{it}^{x}]-\mu]/\sigma]],$$

where $\mathbf{F}[\cdot]$ is the cumulative, standard normal distribution function.

There is an analogous equation for abandonment, which gives the target stock of forested land as a fraction of the total

$$(20)\qquad \left[\frac{S}{T}\right]_{it}^{*}=d_{it}\cdot[\mathbf{F}[[\log[q_{it}^{y}]-\mu]/\sigma]] + [1-d_{it}],$$

where q_{it}^{y} is the threshold value of q_{ijt} below which the incentive for abandonment manifests itself (see equation (8), above, and Table 1).

These relationships are shown graphically in Figure 1. The area to the right of q^x should be converted to farmland (if forested); the area to the left of q^y should be abandoned (if farmed). The area between q^y and q^x is worth farming if previously converted, but not worth converting if currently forested. Changes in the economic climate affect the position of the thresholds. For example, an increase in expected agricultural revenue will shift both the conversion threshold, q^x, and the abandonment threshold, q^y, to the left, thereby encouraging conversion of forested land to agricultural use.

III. Econometric Analysis

A. *Specification Issues*

Two specification issues must be addressed before the model embodied in equations (19) and (20) can be estimated. These are: (1) the possibility that adjustment toward optimal land use is not instantaneous; and (2) combining the conversion and abandonment models into one estimating equation.

All of the analysis to this point has assumed that conversion to optimal land use (conditional on current prices) occurs instantaneously. There are several reasons why this may not be true.[14] Although we estimate the

[14]These include: forest age distribution, liquidity constraints, uncertainty about the permanence of price movements, and decision-making inertia.

TABLE 1—ECONOMETRIC MODEL OF FORESTED WETLAND CONVERSION AND AGRICULTURAL CROPLAND ABANDONMENT

$$FORCH_{it} = FORCH_{it}^{c} \cdot D_{it}^{c} + FORCH_{it}^{a} \cdot D_{it}^{a} + \lambda_i + \phi_{it}$$

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

$$FORCH_{it}^{a} = \gamma_a \Big[d_{ii} \cdot \Big[\mathbf{F}\Big[\big[\log[q_{it}^{y}] - \mu(1+\beta_2 PROJ_{it})\big] / \sigma(1+\beta_3 PROJ_{it})\Big]\Big] + [1-d_{it}] - \left[\frac{S}{T}\right]_{i,t-1}\Big]$$

$$d_{it} = \left[\frac{1}{1+\left[\frac{1}{e^{\pi(z)}}\right]}\right], \text{ where } \pi(z) = DRY_i + \beta_1 PROJ_{it}$$

$$q_{it}^{x} = \left[\frac{FN_{it} + AC_{it}}{A_{it} - \alpha_1 C_{it} \cdot \exp\{\alpha_2 PHDI_{it}\}}\right] \qquad q_{it}^{y} = \left[\frac{\tilde{F}_{it} + AC_{it}}{A_{it}}\right].$$

"frictionless" model implied by equations (19) and (20), we also want to consider the possibility of partial adjustment in each observation period toward the optimal land use pattern. In the case of conversion, we have

$$(21)\quad \left[\frac{AG}{T}\right]_{it} + \left[\frac{AG}{T}\right]_{i,t-1} = \gamma_c \cdot \left[\left[\frac{AG}{T}\right]_{it}^{*} - \left[\frac{AG}{T}\right]_{i,t-1}\right] + \varepsilon_{jt}^{c}$$

where γ_c is the rate of partial adjustment, $[AG/T]^*$ is given by equation (19), and ε_{it}^{c} is an error term composed of a county-specific (time-invariant) component, λ_i, and a component, ϕ_{it}^{c}, which has mean zero, so that $\varepsilon_{it}^{c} = \lambda_i + \phi_{it}^{c}$. In abandonment situations, we have

$$(22)\quad \left[\frac{S}{T}\right]_{it} - \left[\frac{S}{T}\right]_{i,t-1} = \gamma_a \cdot \left[\left[\frac{S}{T}\right]_{it}^{*} - \left[\frac{S}{T}\right]_{i,t-1}\right] + \varepsilon_{it}^{a},$$

where γ_a is the rate of partial adjustment for abandonment, $[S/T]^*$ is given by equation (20), and ε_{it}^{a} is an error term composed of a county-specific component, λ_i, and a component, ϕ_{it}^{a}, which has mean zero. Since county-level stocks are aggregates of individual decisions, these adjustment parameters represent the probability that a landowner not in equilibrium in a given time period will switch to the optimal land use within the initial period.[15]

To combine equations (21) and (22) into one relationship, we define the net change in the forested fraction of the county between

[15]It might seem that a superior approach would be to incorporate adjustment costs or lags into the original optimization problem, but this cannot be done in a way which yields necessary conditions which can be aggregated across heterogeneous parcels to the county level. Any such mechanism must depend on deviations of *individual* parcels from optimality. Estimating a model with adjustment costs requires observing the relationship between the magnitude of deviations from equilibrium and the rate of movement. Since we do not observe individual parcels, this cannot be done, so any adjustment mechanism built into the *individual* model could not be estimated with county data. One could specify a version of equation (1) with adjustment costs at the county level, but that would be equivalent to a representative-firm assumption. Thus, a fully dynamic optimal model can only be implemented with individual data.

periods t-1 and t as

$$(23)\quad \left[\frac{AG}{T}\right]_{it}-\left[\frac{AG}{T}\right]_{i,t-1} = \left[\frac{S}{T}\right]_{i,t-1}-\left[\frac{S}{T}\right]_{it} = (-1)\cdot FORCH_{it}.$$

Under the assumptions of the model, conversion and abandonment will never occur simultaneously in the same county, so we can write

$$(24)\quad FORCH_{it} = -D_{it}^{c}\gamma_c\left[\left[\frac{AG}{T}\right]_{it}^{*}-\left[\frac{AG}{T}\right]_{i,t-1}\right] + D_{it}^{a}\gamma_a\left[\left[\frac{S}{T}\right]_{it}^{*}-\left[\frac{S}{T}\right]_{i,t-1}\right]+\varepsilon_{it},$$

where D_{it}^{c} and D_{it}^{a} are dummy variables[16] for the conversion and abandonment regimes; $[AG/T]^*$ and $[S/T]^*$ are the corresponding target stocks; and ε_{it} is a composite error term, defined by $\varepsilon_{it}=\varepsilon_{it}^{c}+\varepsilon_{it}^{a}=\lambda_i+\phi_{it}^{c}+\phi_{it}^{a}=\lambda_i+\phi_{it}$.

The county-specific components of the error term, λ_i, are treated as fixed-effect parameters and the ϕ_{it} are assumed to be independently distributed across i and t, but not necessarily homoscedastic.[17] Thus, equation (24) is a single-equation, fixed-effects model, the parameters of which can be estimated by nonlinear least squares, with county dummy variables employed to eliminate any bias due to the county fixed effect (Table 1).

B. *Parameter Estimation of Alternative Specifications*

Using data for 36 counties in Arkansas, Louisiana, and Mississippi, during the period 1935–1984,[18] the parameters of the model embodied in equations (24), (Table 1) were estimated econometrically. Panel data were incorporated into the estimation process by stacking the data for 36 counties for each of ten (five-year[19]) time periods, for a total of 360 observations.

The results of six versions of the model are presented in Table 2. 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 percent, 95 percent, or 99 percent level. Also, both parameter and standard error estimates are quite robust with respect to modifications of the specification. Thus, the basic structural model of changes in forested acreage being a function of expectations regarding relative economic returns from agriculture and forestry is strongly supported.[20] In addition, the fixed-effects approach is clearly superior to a totally pooled model, as indicated by the appropriate likelihood ratio tests.[21]

Column 1 of Table 2 restricts flood-control and drainage projects to affecting only agricultural feasibility, while columns 2 and 3 also allow for effects on quality. The estimated partial adjustment coefficients on conversion, γ_c, and abandonment, γ_a, indicate that about 60 percent of the targeted de-

[16]The dummies are endogenous variables. We first estimate separately the conversion and abandonment equations, and thus predict values for conversion and abandonment. The two equations are then combined as in equation (24) with dummies constructed on the basis of the predicted conversion or abandonment.

[17]Heteroscedasticity-consistent standard errors were calculated according to Halbert White (1980), and are reported in the table of econometric results. The possibility of serial correlation in ϕ_{it} was explored. Neither J. Durbin's (1970) test nor that suggested by T. S. Breusch (1978) and L. G. Godfrey (1978) indicated significant serial correlation.

[18]The nature and sources of data employed are briefly described in the Appendix, which also provides basic statistics for all variables.

[19]Limitations on the availability of data on the dependent variable (forested acreage) necessitated the use of a quinquennial as opposed to an annual model.

[20]The possibility exists of including in the model a measure of individuals' expectations regarding future construction of flood-control and drainage projects, proxied by project authorizations. Given relatively constant real conversion costs, however, no incentive exists for landowners to convert their parcels prior to project construction (and consequent flood protection).

[21]For example, in the $L1$ specification, the likelihood ratio (LR) statistic is 69.9; the appropriate χ^2 critical value is 58.6 at the 99 percent confidence level.

TABLE 2—ECONOMETRIC ESTIMATION RESULTS—LOGNORMAL, NORMAL, AND UNIFORM DISTRIBUTIONS OF LAND QUALITY

Parameter	Alternative Specifications[a]					
	$L1$	$L2$	$L3$	$L4$	$N1$	$U1$
γ_a Abandonment	0.37618	0.32360	0.36717	–	0.41883	0.18288
Partial Adjustment	(0.190)[b]	(0.177)	(0.184)		(0.190)	(0.075)
γ_c Conversion	0.44875	0.69352	0.64826	–	0.62814	0.29872
Partial Adjustment	(0.142)	(0.156)	(0.154)		(0.150)	(0.114)
μ Mean of Unobserved	0.74095	0.83464	1.11650	1.41950	2.26650	–
Quality Distribution	(0.368)	(0.290)	(0.364)	(0.354)	(0.419)	
σ Standard Deviation	0.38182	0.44438	0.43848	0.56324	0.43538	–
of Quality Distrib.	(0.087)	(0.069)	(0.067)	(0.021)	(0.067)	
ω Upper Limit of	–	–	–	–	–	4.64270
Quality Distribution						(2.173)
θ Range of Unobserved	–	–	–	–	–	1.34980
Quality Distribution						(0.855)
β_1 Project Impact on	9.20170	8.83060	8.93700	8.37430	8.69140	8.94940
Agric. Feasibility	(3.216)	(2.309)	(2.465)	(1.768)	(2.394)	(3.705)
β_2 Project Impact on	–	1.07240	0.77193	0.36821	0.24691	–
Heterogeneity Mean		(1.467)	(0.774)	(0.449)	(0.317)	
β_3 Project Impact on	–	0.53757	0.42799	0.36451	0.39361	–
Heterogeneity S.D.		(0.229)	(0.183)	(0.133)	(0.176)	
α_1 Relative Conversion	1.58160	1.02070	–	–	–	–
Cost Impact	(0.923)	(1.169)				
α_2 Weather Impact on	–	–	1.59720	1.59410	1.41720	1.58600
Conversion Cost			(0.304)	(0.296)	(0.193)	(0.302)
Goodness-of-Fit[c]	0.6719	0.6743	0.6747	0.6681	0.6738	0.6742
Log Likelihood Value	786.07	790.62	791.70	788.23	791.57	787.89
Degrees of Freedom	318	316	316	318	316	318

[a]All versions also contain 36 county dummies. $L1$, $L2$, $L3$, and $L4$ (frictionless model) employ lognormal distributions of land quality; $N1$ employs a normal distribution; and $U1$ employs a uniform distribution.

[b]Robust standard error estimates appear below parameter estimates.

[c]This dynamic goodness-of-fit statistic is equal to one minus Theil's U-statistic, based on comparing predicted and actual net rates of conversion.

crease in forested acreage (increase in agricultural cropland) and about 36 percent of the targeted abandonment occur in the initial five-year period.

The distribution of heterogeneity is nondegenerate: the standard deviation, σ, of the lognormal distribution of agricultural quality is significant quantitatively and statistically. Likewise, two of the three parameters capturing the impact of federal projects on conversion and abandonment are significant: direct impact on agricultural feasibility, β_1; and impact on the standard deviation of agricultural quality, β_3. The impact on the mean of agricultural quality, β_2, is positive but not significant.[22] The average direct impact of artificial flood protection on agricultural feasibility, β_1, is about nine times that of "natural flood protection."

[22]Note that the model is parameterized such that projects affect the mean and variance of the log of q. The expectation of q itself is

$$\exp\left\{\mu(1+\beta_2 PROJ)+0.5\sigma^2(1+\beta_3)^2\right\},$$

so both β_2 and β_3 indicate increasing agricultural quality due to projects.

It was not possible, due to limitations of the data, to estimate the equation with both a parameter for the effect of conversion costs relative to other benefits and costs, α_1, and a parameter for the effect of weather on conversion costs, α_2, although the parameters of such a specification are theoretically identified. The specification with α_1 ($L2$) appears inferior to the one with α_2 ($L3$), and the estimate of α_1 is not significantly different from 1.0. The impact of weather on conversion costs, α_2, is very significant.

Columns $L4$, $N1$, and $U1$ explore the sensitivity of the results to dynamic and distributional assumptions. $L4$ assumes instantaneous rather than partial adjustment to the optimal state. This constraint is rejected by the data,[23] but most parameters remain qualitatively similar. The dynamic goodness-of-fit, calculated as suggested by Henri Theil (1961), shows only slight decline compared to the partial adjustment case ($L3$).[24] Assuming a normal ($N1$) or uniform ($U1$) distribution of unobserved land quality also yields results that are qualitatively similar, with slight decrease of dynamic goodness-of-fit.

Although the results in Table 2 exhibit the significance of prices, costs, and government projects in conversion and abandonment decisions, these results say little about the relative importance of these influences. Due to the nonlinear, dynamic form of the model, the importance of the various factors can be discerned only through a series of dynamic simulations.

IV. Dynamic Simulation Results

To provide a benchmark for comparison, the extent of conversion or abandonment is simulated using the econometrically estimated parameters and the actual, historical values of all variables ("factual simulation"). Then, in a series of "counterfactual simulations," the extent of conversion or abandonment is simulated using various assumed counterfactual values for certain exogenous variables, while maintaining all other variables at their actual levels. Finally, the simulated changes in forested wetland acreage in each counterfactual simulation are compared to the factual simulation changes. Any difference represents an estimate of the land-use change that can be attributed to a change in an exogenous variable from the counterfactual value of the variable to its actual historical pattern of values.

The simulation results utilizing model $L3$ are summarized in Table 3. Column 1 shows the total (net) conversion of forested wetlands to farmland through 1984. In the factual simulation, this is 3.68 million acres. (The true historical conversion was 3.64 million.) Because of the partial adjustment mechanism, conversion will continue into the future, even if all exogenous variables remain unchanged. To capture this effect, column 2 extends the simulations through 1999, keeping all (factual) variables at their 1984 values. Thus, we predict that a total of 3.83 million would be converted by the end of the century if 1984 conditions were to prevail. The target stock based on 1984 values corresponds to net conversion of 3.84 million acres, so the 1999 simulations come very close to the steady state.

The second row in the table shows that simulated wetland depletion through 1999 if *no* federal projects had been built is about 32 percent less than factually simulated depletion. For comparison, the third row shows simulated depletion if flood protection provided by natural topography and the Missis-

[23] Individually, the Wald statistics for constraining the model to instantaneous adjustment are 5.2 for conversion and 11.8 for abandonment, compared with a 99 percent critical (χ^2) value of 6.6; the joint test yields a statistic of 12.1, compared with a 99 percent critical value of 9.2.

[24] A frequently used measure of dynamic performance is the root-mean-squared (RMS) error, but this measure suffers from the limitation that its magnitude is not standardized. An alternative is Theil's inequality coefficient (Theil, 1961). The numerator of this statistic is the RMS error, and the scaling of its denominator ensures that values fall within the bounds of zero and unity, where zero indicates a perfect dynamic fit. In keeping with the ordering of most goodness-of-fit measures, the final comparative statistic shown in Table 2 is equal to one minus the Theil coefficient, so that a perfect fit is evidenced by a value of 1.0.

TABLE 3—SIMULATED CHANGE IN STOCK OF FORESTED WETLANDS UNDER ALTERNATIVE SCENARIOS
LOGNORMAL DISTRIBUTION OF LAND QUALITY

	Change[a] in Forested Wetland Acreage		65-Year Period 1935–1999	
Simulation	50-Year Period 1935–84	65-Year Period 1935–99	Percentage of Factually Simulated Depletion	Share of Depletion Due to This Factor[b] in percent
	(1)	(2)	(3)	(4)
(1) Factual	−3.677	−3.834	(100)	(0.0)
(2) No Federal Flood-Control or Drainage Projects	−2.527	−2.612	68.1	31.9
(3) No Flood Protection from Natural Topography and Mainline Levees	−2.831	−2.984	78.8	21.2
(4) Conversion Costs Set to Zero	−4.354	−4.526	118.0	−18.0
(5) Net Forestry Revenue Set to Zero	−4.259	−4.419	115.3	−15.3
(6) Agricultural Prices Kept at 1934 Levels	−3.641	−3.818	99.6	0.4

[a]Millions of acres, based upon parameter estimates from specification $L3$, reported in column 3 of Table 2.
[b]Difference between counterfactual simulation and factual simulation, divided by factual simulation.

sippi mainline levee system[25] were eliminated. This has less effect than elimination of federal projects, reducing depletion by 21 percent. Rows 4 and 5 show that conversion costs and forestry revenues were significant forces restraining conversion. Simulated conversion is 18 percent more if conversion is costless, and 15 percent more if forestry yielded no net revenue.

Finally, the last row of Table 3 explores the hypothesis (maintained by the Corps of Engineers and others) that rising agricultural prices drove wetland depletion, by simulating conversion if farm prices had held at their 1934 levels (in real terms). Net depletion is about 1 percent less than when factually simulated. Thus, there is no evidence that rising agricultural prices were a significant factor driving conversion. Even with the depressed farm prices of 1934, economic incentives favored conversion of many acres.

The simulations in Table 3 were also carried out with the frictionless, normal, and uniform models ($L4$, $N1$, and $U1$ in Table 2). Although the changes attributed to specific factors vary somewhat, the ranking of factors by importance is the same in all versions. Two differences, however, are worth noting. The frictionless model, by assumption, does not predict continued conversion after 1984 based on 1984 conditions. In fact, it predicts slightly less net conversion by 1984 (3.586 million acres). As noted above, the optimal stock corresponds to net conversion of 3.84 million acres, so the partial adjustment model run out to 1999 would appear to be a better indicator of the ultimate conversion. At the other extreme, the uniform model predicts net conversion of 4.065 million acres by 1999, more than twice

[25]"Effect of natural topography" refers to DRY_i ($=1 - FLRISK_i$), a measure of natural flood-proneness of counties (prior to construction of flood-control and drainage projects). The "mainline levee system" (MLS) along the Mississippi River, which was in place virtually from the beginning of the study period, may also have had an impact on wetland depletion. Data on the area protected by the MLS are not available. The protected area is approximately proportional to the area affected by the great flood of 1927, but flood data are highly correlated with natural topography, and so multicollinearity prohibits estimation of the effects of natural topography and the MLS in the same equation. With the omission of the MLS proxy variable, the *FLRISK* variable accounts for both phenomena. Thus, the reported impact of Federal projects on conversion refers exclusively to interior levee development and underestimates the impact of all projects.

as much conversion between 1984 and 1999 as is simulated using the preferred, lognormal model. Not surprisingly, the impact of distributional assumptions becomes greater as we move into the tails of the distributions.

V. Conclusions and Policy Implications

The statistical analysis leads to several conclusions. First, landowners responded to economic incentives in their land-use decisions. Second, construction of federal flood-control and drainage projects caused a higher rate of conversion of forested wetlands to croplands than would have occurred in the absence of projects. Third, federal projects had this impact because they made agriculture feasible on land where it had previously been infeasible, and because, on average, they improved the quality of feasible land. Fourth, adjustment of land use to economic conditions was relatively gradual. On average, about 65 percent of forested acres which "should" have been converted to agriculture were converted in initial five-year periods; and about 38 percent of agricultural land which "should" have been abandoned were abandoned over initial five-year periods.

Simulations with estimated parameters show the quantitative importance of these effects. If there had been no federal flood-control or drainage projects constructed in the 36-county area after 1934, approximately 1.15 million fewer acres of forested wetlands would have been converted, 31 percent of total depletion. Long-term (steady state) depletion due to federal projects (constructed through the year 1984) is estimated to amount to more than 1.23 million acres, about 32 percent of estimated long-term depletion. Since the total acreage protected by projects was about 5.3 million acres, the results imply an average "propensity to convert" protected acres of about 0.22.

Of the factors considered in the econometric model, flood protection and drainage provision afforded by federal projects had the largest impact on net changes in forested acreage. The joint effect of natural topography and the mainline levee system was of secondary importance; and net forestry revenues and conversion costs exerted substantial restraints on wetland clearing.

In terms of public policy, the evidence highlights a striking inconsistency in the federal government's approach to wetlands. In articulated policies, laws, and regulations, the government recognizes the large positive externalities associated with wetlands; the Bush Administration has endorsed a "zero net-loss of wetlands" policy. But public investments in wetlands (in the form of flood-control and drainage projects) create major incentives to convert these areas to alternative uses. Clearly, the overall justification for these federal programs ought to be reexamined, and stringent tests of public need should be applied to both public and private actions which have direct or indirect effects on wetland resources.

The conclusion that major public infrastructure investments affect private land-use decisions (often thereby generating negative externalities) may not be a surprise to many readers of this journal, but the analysis described here provides evidence which contrasts sharply with the accepted wisdom among policymakers. It is hoped that the quantification of these effects will give these realities a more prominent role in policy debates. As wetlands, tropical rain forests, barrier islands, and other sensitive environmental areas become more scarce, their marginal social value rises. If induced land-use changes are not considered, we will engage in more and more public investment programs whose net social benefits are negative.

DATA APPENDIX

The data used in this study were collected as part of a previous research effort, sponsored by the U.S. Department of the Interior and carried out on behalf of the Environmental Defense Fund. For complete citations of sources of data and more information regarding the construction of requisite variable series, see Stavins 1986 and 1988. Also, a more comprehensive data appendix is available on request from the authors of the present paper.

Land-Use Patterns: The U.S. Forest Service periodically measures land use at sample sites, using a sampling procedure based upon aerial photographs. Sample locations are classified on a forest/non-forest basis, and these 0–1 observations are then converted into estimates of acreage of county land which is forested, S_{it}.

TABLE A1—SUMMARY STATISTICS FOR MAJOR VARIABLES[a]
1939 and 1984

Variable[b] Name	1939 Minimum	1939 Mean	1939 Maximum	1984 Minimum	1984 Mean	1984 Maximum
a	64.00	147.12	221.83	201.29	246.70	318.21
ac	62.41	155.38	197.51	117.92	180.97	295.46
ACCU	0.000	0.002	0.057	0.000	0.271	0.963
C	4.77	4.77	4.77	22.76	22.76	22.76
DRY	0.142	0.529	0.823	0.142	0.529	0.823
fn	−0.03	0.59	2.03	3.56	11.81	27.38
$\tilde{f}$	1.50	4.00	8.57	5.32	14.80	25.92
FORCH	−0.072	−0.020	0.080	−0.144	−0.023	0.016
PHDI	−2.150	−1.054	−0.020	−1.050	0.738	1.690
S	44.7	165.8	367.8	11.5	73.2	277.2
SCCU	0.000	0.000	0.000	0.000	0.100	0.864
T	129.9	360.4	590.7	110.9	354.6	590.7

[a]All monetary figures are real 1984 dollars.
[b]Variables are defined as follows:
a = annual agricultural revenue (dollars per acre);
ac = annual agricultural costs of production (dollars per acre);
ACCU = share of county protected by Army Corps of Engineers projects;
C = cost of conversion (dollars per acre);
DRY = share of county naturally protected from flooding;
fn = annuity of net forestry revenue minus windfall from clearcut;
$\tilde{f}$ = annuity of delayed net forestry revenue (dollars per acre);
FORCH = change in forestland as a share of total county over 5 years;
PHDI = Palmer hydrological drought index;
S = stock of forestland (thousand acres);
SCCU = share of county protected by USDA SCS projects; and
T = total county area (available for conversion, thousand acres.

Total county land available for conversion (not conserved by government) is represented by T_{it}. The net change in forest land as a share of all available county land is $FORCH_{it}$.

Agricultural Revenue: The average (gross) real agricultural revenue per acre, a_{it}, is a weighted average for four crops (soybeans, cotton, rice, and corn), based upon agricultural prices, production levels, yields, and acreages. Data on crop acreages, production levels, and prices come from the U.S. Census of Agriculture plus state publications. A weighted average of production costs, ac_{it}, was developed from state documents; costs considered were case expenses, which include variable plus fixed expenses (general farm overhead, taxes and insurance, and interest), but not capital replacement nor allocated returns to owned inputs.

Forestry Revenue: Annual forestry net revenue per acre, fn_{it}, consists of two components: the difference between the (annualized) revenue stream generated by periodic harvesting of limber and the (annualized) one-time revenue received from a clearcut of the forest prior to conversion. Thus, real forestry net revenue per acre is a weighted average of annual revenues from sawlogs and pulpwood minus the annuity of a windfall which is gained from a clearcut of timber if conversion is carried out. If farmland is abandoned and allowed to return to its forested state, there is a delay equal to the rotation length before harvests can commence. The annuity of delayed net forestry revenue is $\tilde{f}_{it}$ (see equation (8) in text).

Cost of Conversion: The time-series, C_t, is the average cost of conversion of wetlands to cropland. Because geographic variance in the cost of conversion is largely a function of soil moisture, a panel of conversion cost estimates were developed by allowing for the interaction of C_t and $PHDI_{it}$, as described above.

Artificial Flood Protection and Drainage Provision: Projects of the U.S. Army Corps of Engineers and the Soil Conservation Service were considered. In both cases, the primary measure of project impact was the "protected acreage" of projects, hydrologically defined as the area which experiences some reduction in the extent and frequency of flooding as a result of project construction. The respective Corps and SCS variables are $ACCU_{it}$ and $SCCU_{it}$, the sum of which is $PROJ_{it}$.

Natural Flood and Drainage Conditions: A measure of the average natural probability of flooding of sample counties, $FLRISK_i$, was developed from the National Resources Inventory, conducted by the Soil Conservation Service. The relevant variable for the analysis is the quantity, $DRY_i = 1 - FLRISK_i$.

Weather Conditions: The Palmer Hydrological Drought Index, estimated by the National Climatic Data Center, is related to precipitation, runoff, evapotranspiration, recharge, and soil water loss. Monthly drought index data were aggregated into quinquennial averages by county, $PHDI_{it}$.

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