Journal of Environmental Management (1994) **40**, 341–355

Drainage Investment and Wetlands Loss: an Analysis of the National Resources Inventory Data

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Received 12 *February* 1993

The United States Soil Conservation Service (SCS) conducts a survey for the purpose of establishing an agricultural land use database. This survey is called the National Resources Inventory (NRI) database. The complex NRI land classification system, in conjunction with the quantitative information gathered by the survey, has numerous applications. The current paper uses the wetland area data gathered by the NRI in 1982 and 1987 to examine empirically the factors that generate wetland loss in the United States. The cross-section regression models listed here use the quantity of wetlands, the stock of drainage capital, the realty value of farmland and drainage costs to explain most of the cross-state variation in wetland loss rates. Wetlands preservation efforts by federal agencies assume that pecuniary economic factors play a decisive role in wetland drainage. The empirical models tested in the present paper validate this assumption.

Keywords: wetlands, non-market benefits, drainage, farmland realty.

1. Introduction

The economic forces that drive wetland drainage and conversion by farmers have been noted in empirical and theoretical settings (Heimlich, 1988; Douglas, 1989; Stavins and Jaffe, 1990). Farmland drainage is an investment activity whose principal motive is to increase the stock of private productive capital. However, because of the paucity of data on costs, drainage investment is not as amenable to empirical analysis as other types of farm investment (Heimlich, 1989). Moreover, omissions remain in the formal theory of drainage investment.

In this paper we look for patterns in recent data (U.S. Soil Conservation Service, 1991) that suggest that wetland loss in the United States is related to economic variables. In 1982, the United States Soil Conservation Service (SCS) made available data from an extensive survey of soil and land cover types for the contiguous 48 states (U.S. Soil Conservation Service, 1991). The survey was begun in 1980, but not completed until

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1982. The SCS database, called the National Resources Inventory (NRI), includes estimates of wetland areas. The theory of drainage investment may correctly depict the economic factors that generate investment in drainage equipment. However, these economic factors may have little relevance in explaining wetland loss data. We find the theory of drainage investment to be sharply relevant in explaining cross-sectional wetland loss data. However, intuition suggests that natural resources loss and degradation in less-developed parts of the world may be generated by social forces such as population change that are not likely to be affected by conventional economic policies.

There are various inter-related issues that can be examined with any given socio–economic data set. First, one can test hypotheses for some economic premise or model. Second, one can explore the relative explanatory power of two or more different socio–economic models. Third, one can examine the relative explanatory power of each of a group of socio–economic or policy variables. The current investigation, like many empirically-oriented socio–economic investigations, mixes and blends these activities.

We used regression models to quantify the relative explanatory power of per acre realty value and per acre farm income in explaining the variance in wetland loss rates. Farmland realty values reflect expected discounted per acre net income. There is a close connection between measured real income per acre and farmland realty values. The question of which of these two variables has greater explanatory power with regard to the variation in wetland loss rates across the contiguous 48 states is an empirical issue. However, the empirical analysis of the farm income and farmland realty variables also tests the explanatory power of the investment model. Suppose, for example, that neither the income nor the farmland realty variable has discernible statistical explanatory power for the data set in question. In that case, the theoretical model might be flawed.

Because real income per acre is sharply affected by various federal farm programs, both farm income per acre and farmland realty values are potential policy variables. Price support payments, for example, sharply impact farm income (Heimlich and Langner, 1986). Therefore, support payments indirectly affect farmland realty values. The data analysis clearly indicates that per acre farmland realty value is more closely related to wetland losses than is real farm income per acre. We suggest that farm realty prices can and should be used as a guide in wetlands acquisitions programs. This suggestion is prompted in part by our regression results and perusal of recent time-series data.

Stavins and Jaffe (1990) present a "bang-bang" control theory model of drainage investment for the case in which investment cost is a linear function of the rate of drainage. Stavins and Jaffe (1990) are particularly interested in the forested wetlands of the Mississippi River delta. Their model incorporates various economic factors for these wetlands, such as foregone income from timber sales, that are neglected in the current model. Bang-bang control theory models (Clark, 1976) can relate the optimal stationary state capital stock to various parameters. The mathematical simplicity of their model allows Stavins and Jaffe (1990) to examine the impact of a large number of variables on wetland drainage rates. However, the analysis is flawed. The rate of drainage investment is not determined by economic forces in a bang-bang model. The increasing marginal cost of investment case discussed here relates the level of investment to economic variables. The model demonstrates a functional relation between investment rates and the optimal capital stock, and relates the optimal stock to exogenous economic parameters. Thus, the control theory drainage investment model is a useful complement of an empirical analysis.

2. The theory of drainage investment

In this model, the marginal cost of draining a wetland is a monotonically increasing function of the rate of drainage investment. The marginal physical product of drained land is a monotonically decreasing function of the amount of land drained. The basic theory of drainage investment is complicated because the marginal product of the stock of capital must be compared with the cost of increasing the stock. The complicated intertemporal aspects of the analysis give rise to problems in control theory (Pontryagin *et al.*, 1962). The control theory problem of optimizing the net discounted revenues from wetland drainage can be solved with Pontryagin's maximum principle (Pontryagin *et al.*, 1962; Clark, 1976).

The entrepreneur maximizes the present value of his drainage investment. The rate of investment is $q(t) \geqslant 0$; the quantity of drained land is $E(t) \geqslant 0$. In the control theory literature $E(t)$ is called the state variable. The gross revenue stream from drained land is $\{p \times F[E(t)]\}$, where $p > 0$ is the fixed price of crop production. The cost of drainage investment is $C[q(t)]$. Drainage equipment depreciates (Pavelis, 1985; Economic Research Service, 1987). The type of depreciation introduced into the present model is exponential decay. Let $\omega > o$ be the rate of decay. Thus, the rate of change of the stock of drainage equipment is (dotted symbols denote time derivatives):

$$\dot{E} = q(t) - \omega \times E(t). \tag{1}$$

The entrepreneur chooses values for $q^*(t)$, the optimal instantaneous investment rate and a related optimal time path, $E(t) = E^*(t)$, that maximize the discounted future net income stream provided by the drained land. Let V be discounted net income:

$$V = \int_0^\infty \{p \times F[E(t)] - C[q(t)]\} \times e^{-\delta t}. \tag{2}$$

An equivalent model emphasizes the net returns from drained wetland acreage.

Let $A(t)$ be the number of drained acres, $a(t) \geqslant 0$ be the rate at which drainage occurs and $r > 0$ the rate at which drained areas reconvert to wetlands. The basic production and cost functions are $F_a(A)$ and $C_a(a)$, and:

$$\dot{A}(t) = a(t) - r \times [A(t)]. \tag{3a}$$

Let $k > 0$ be a constant:

$$E = k \times A,\ q = k \times a,\ \omega = r,\ F(E) = F_a(k \times A),\ C(q) = C_a(k \times a), \tag{3b}$$

and assume that the entrepreneur maximizes the net discounted returns from drained acreage. Then equations (1) and (2) follow from equations (3a) and (3b). The econometric implications of the approaches are identical if reconverted wetlands generate no pecuniary income (Stavins and Jaffe, 1990). The variable $q(t)$ is called the control variable because $q(t)$ determines the rate of change of the state variable. The function C is strictly by convex and C and its first derivative are continuous, differentiable and pass through the origin:

$$\text{for } q>0,\ \frac{\mathrm{d}C}{\mathrm{d}q}=C'(q)>0,\ \frac{\mathrm{d}^2C}{\mathrm{d}q^2}=C''(q)>0, \tag{4a}$$

$$C(0)=C'(0)=0. \tag{4b}$$

The function F is continuous, twice differentiable, strictly concave and passes through the origin:

$$F(0)=0;\ \text{for } +\infty>E\geqslant 0,\ F'(E)>0,\ F''(E)<0, \tag{5a}$$

$$F'(0)=+\infty,\ F'(\infty)=0. \tag{5b}$$

There is a fundamental non-negativity constraint that must be introduced into a realistic model of drainage investment. Let $A_o>0$ be the number of rural acres that can be drained. The maximum feasible quantity of wetlands that can be drained is the current stock of wetlands. However, the total maximum amount of land that can be drained is the sum of wetland acres plus the number of acres of undrained wet soils. A wetland has hydric soils, supports hydrophytes and is inundated during the growing season (Cowardin *et al.*, 1979). However, drainage investment in any poorly drained soil can result in substantial increases in productivity (Economic Research Service, 1987). The upper bound on the number of drained acres is the sum of the number of acres of wetland plus the number of rural (non-wetland) wet soil acres. Let $E^{**}>0$ be the optimal stationary level of wetland drainage, and $W_o=k\times A_o$. Equation (6) must hold then for each land parcel, and for aggregate drained acreage:

$$0<E^{**}\leqslant W_o<+\infty. \tag{6}$$

Aggregate drained acreage—the sum of the number of drained wet soil acres plus the number of drained wetland acres—cannot be greater than the total number of acres that can be drained.

The maximum principle (Pontryagin *et al.*, 1962) and a theorem by Seierstad and Sydsaeter (1987) provide a set of necessary conditions for maximizing V. The theorem in Seierstad and Sydsaeter (1987) extends the maximum principle so that it can be applied to problems in which non-negativity constraints such as equation (6) are imposed on the state variable. The unconstrained problem is solved first because the solution for the constrained problem can be obtained more easily after the unconstrained problem has been solved. A non-negative piecewise continuous function called the discounted Hamiltonian, and a non-negative piecewise continuous variable called the adjoint variable, are introduced to facilitate the statement of the necessary conditions (Clark, 1976). Let $\psi(t)\geqslant 0$ be the adjoint variable; the discounted Hamiltonian is:

$$H(E,q,\psi)=\{p\times F[E(t)]-C[q(t)]+\psi\times[q-\omega\times E(t)]\}e^{-\delta t}. \tag{7}$$

The maximum principle states that the optimal feasible time path, $[E^*(t),q^*(t)]$, must satisfy the non-negativity constraints $E(t)\geqslant 0$, $q(t)\geqslant 0$. Equation (1) must be satisfied by $[E^*(t),\ q^*(t)]$. The maximum principle derives its name from the fact that q^* must maximize the Hamiltonian for all $t\geqslant 0$. Also, q^* and ψ^* must satisfy a differential equation called the adjoint equation:

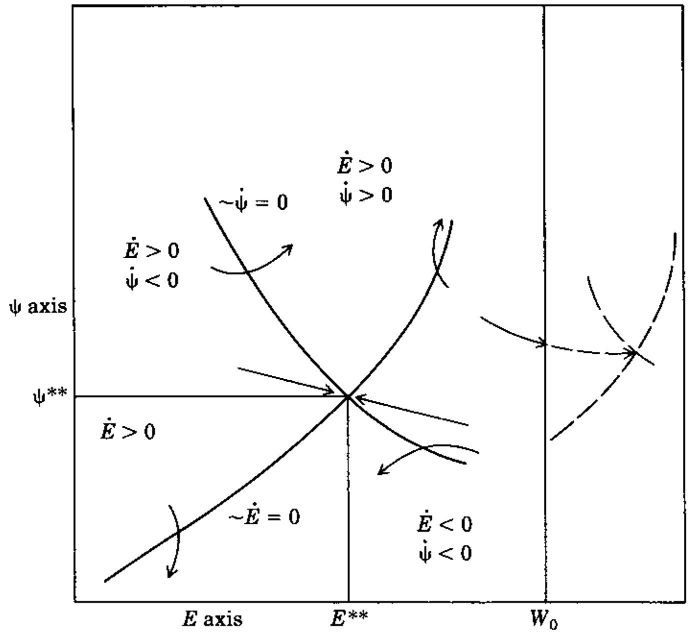

Figure 1. Solid curves illustrate the interior solution case: land-drained acreage is less than the total wetland acreage. The broken lines illustrate the boundary case in which the land-drained area equals the total wetland area.

$$\frac{d}{dt}[\psi(t) \times e^{-\delta t}] = -\frac{\partial H}{\partial E}, \tag{8}$$

and an endpoint condition called the transversality condition:

$$\lim_{t \to \infty}[\psi(t) \times e^{-\delta t}] = 0. \tag{9}$$

The conventional technique for solving control theory problems of this kind is to use the necessary conditions of the maximum principle to construct solutions to equations (1) and (8). The differential equations in equations (1) and (8) form a pair of autonomous differential equations in the (E,ψ) phase-plane (Clark, 1976). The motion of E and ψ are completely determined by the tuple (E,ψ). The behavior of this dynamic system can be analyzed by dividing the non-negative orthant into various subregions in the (E,ψ) plane (see Figure 1). The subregions are defined by a pair of curves, $R(E,\psi)$ and $S(E,\psi)$, in the (E,ψ) plane that satisfy equation (10):

$$\dot{E} = R(E,\psi) = 0, \ \dot{\psi} = S(E,\psi) = 0. \tag{10}$$

These curves are called isoclines (Clark, 1976). Points (E_s,ψ_s) in the plane that satisfy $R(E_s,\psi_s) = S(E_s,\psi_s) = 0$ are called rest points or stationary points (Clark, 1976). If there is a unique solution path that approaches a stationary point, the rest point is called a saddle-point, and the path is called a local saddle-point path. If the saddle-point path is defined for all $E \geqslant 0$, it is a global saddle-point path (Seierstad and Sydsaeter, 1987). Isoclines for equations (1) and (8) exist, and a unique rest point for the dynamic system also exists (see Figure 1). Uniqueness and existence for the rest point can be established with the aid of equation (22).

The first-order maximum condition for H is:

$$\frac{\mathrm{d}H}{\mathrm{d}q}=\psi-C'(q)=0. \tag{11a}$$

Therefore:

$$q=D(\psi);\ \frac{\mathrm{d}q}{\mathrm{d}\psi}=D'=\frac{1}{C''}>0. \tag{11b}$$

Eliminating q from equations (1) and (8):

$$\dot{E}=D(\psi)-\omega E, \tag{12}$$

$$\dot{\psi}=(\delta+\omega)\times\psi-p\times F'(E). \tag{13}$$

The isoclines for equations (12) and (13) are:

$$\psi=D^{-1}(\omega\times E),\ \frac{\mathrm{d}\psi}{\mathrm{d}E}=\frac{\omega}{D'}=(\omega\times C''>0, \tag{14}$$

and:

$$\psi=\frac{p\times F'(E)}{\omega+\delta},\ \frac{\mathrm{d}\psi}{\mathrm{d}E}=\frac{p\times F''}{\omega+\delta}<0. \tag{15}$$

The stationary point is a local saddle-point (Seierstad and Sydsaeter, 1987) if the eigenvalues of the matrix of first-order partial derivatives of the system are real and have opposite signs. Taking partial derivatives:

$$\frac{\partial\dot{E}}{\partial E}=-\omega<0,\ \frac{\partial\dot{E}}{\partial\psi}=D'(\psi)>0, \tag{16}$$

and:

$$\frac{\partial\dot{\psi}}{\partial E}=-p\times F''\{E\}>0,\ \frac{\partial\dot{\psi}}{\partial\psi}=(\omega+\delta)>0. \tag{17}$$

Let $\bar{M}$ be the matrix of first-order partial derivatives; the eigenvalues of $\bar{M}$ must satisfy the determinant equation:

$$\mathrm{Det}\left|\bar{M}-\lambda\bar{I}\right|=\mathrm{Det}\begin{vmatrix}\left(\frac{\partial\dot{E}}{\partial E}-\lambda\right) & \frac{\partial\dot{E}}{\partial\Psi}\\ \frac{\partial\dot{\Psi}}{\partial E} & \left(\frac{\partial\dot{\Psi}}{\partial\Psi}-\lambda\right)\end{vmatrix}=0. \tag{18}$$

Expanding equation (18):

$$\lambda^2-\lambda\delta+p\times D'\times F''-\omega(\omega+\delta)=0. \tag{19a}$$

The roots of equation (19a) are real and have opposite signs because:

$$p\times D'\times F''-\omega(\omega+\delta)<0. \tag{19b}$$

A theorem by Hartman (Hartman, 1964; Seierstad and Sydsaeter, 1987) proves that the local saddle-point for this dynamic system is a global saddle-point. Any path that lies above the saddle-point path (see Figure 1) can eventually be improved upon. Any path that lies below the saddle-point path eventually violates the non-negativity constraint for ψ. The saddle-point path cannot be improved upon, and satisfies all of the feasibility and necessary conditions. Because the Hamiltonian is strictly concave in q and E, the maximum of H with respect to q is unique and is also concave in E. Therefore, the necessary conditions are also sufficient conditions (Seierstad and Sydsaeter, 1987). A theorem in Seierstad and Sydsaeter (1987) proves that the portion of the saddle-point path that lies to the left of the vertical line $E=W_0=k\times A_0$ is the optimum path if the constraint $E\leqslant W_0$ is binding (Figure 1).

The necessary conditions for a constrained optimum require the introduction of a non-negative function, $L\{[E(t), q(t), \psi(t)], \eta(t)\}$:

$$L[H(E,q,\psi),\eta]=H(E,q,\psi)+\eta\times(W_0-E)\times e^{-\delta t}. \tag{20}$$

If $[E^*(t),q^*(t)]$ is an optimal path, q^* must maximize L for all $t\geqslant 0$. If:

$$(W_0-E)>0,\ \text{then}\ \eta=0;\ \text{if}\ (W_0-E)=0,\ \eta\geqslant 0. \tag{21a}$$

The adjoint variable must satisfy equation (21b):

$$\frac{d}{dt}[\psi(t)\times e^{-\delta t}]=-\frac{\partial L}{\partial E}=-\left(\frac{\partial H}{\partial E}-\eta e^{-\delta t}\right). \tag{21b}$$

By equations (21a), (21b) and the maximum principle, the adjoint equation for the constrained maximum is identical with the adjoint equation of the unconstrained maximization problem on the interior of the non-negative orthant. The net investment equation is equation (1) for the constrained and unconstrained problems. Therefore, the portion of the saddle-point path that lies to the left of $E=W_0$ is the optimum path for the constrained maximization problem (Seierstad and Sydsaeter, 1987). For any quantity of initial drained acreage that satisfies $k\times A_0=W_0\geqslant E(0)=E_0\geqslant 0$, with $W_0>0$, there is some optimal investment path $[E^*(t),q^*(t)]$ that maximizes V. There is always an optimal stationary value for $E=E_s=E^{**}\geqslant 0$ for the unconstrained maximum problem. If $E_s\leqslant W_0$, then the optimal stationary value for the constrained maximum problem is $E_s=E^{**}\leqslant W_0$. This optimal stationary value is approached asymptotically along the optimal investment path. If, however, $E_s>W_0$, the optimal stationary value is reached in finite time, and $E^{**}=W_0$. In this model, it is impossible for $E_0=E(0)>W_0$. If $W_0>E_0>E^{**}>0$, the optimal path lies on the portion of the saddle-point path that is between the vertical line $E=W_0$ and the saddle-point.

It is useful to eliminate ψ from equations (14) and (15) at the stationary point in order to derive comparative statics propositions and to demonstrate the fact that a stationary point always exists. A new parameter, $\sigma > 0$, is introduced into the analysis to express the effect of exogenous increases or decreases on the marginal cost of drainage. Thus, total cost is $[\sigma \times C(q)]$, and:

$$\sigma \times C'(\omega E_s) = \frac{p \times F'(E_s)}{\delta + \omega}. \tag{22}$$

The left-hand side of equation (22) is a strictly increasing function of E_s. The right-hand side of equation (22) is a monotonically decreasing function of E_s. Therefore E_s is unique; moreover, E_s always exists because some real number, $E_s, 0 < E_s < +\infty$, solves equation (22). The left-hand and right-hand sides of equation (22) take on all non-negative real values. Let E^{**} be the optimal stationary stock of drained wetlands, and e^{**} represent the optimal stationary level of drainage investment. If the non-negativity constraint is binding, the optimal stock of drained acreage is not determined by a functional relation between E^{**} and the economic variables that appear in equation (22). But, because there are millions of undrained acres of rural wetlands (Heimlich and Langner, 1986; Heimlich, 1988), E^{**} is assumed to be determined by equation (23):

$$G(E^{**};p,\delta,\omega,\sigma) = \sigma(\delta + \omega) \times C'(\omega \times E^{**}) - p \times F'(E^{**}) = 0. \tag{23}$$

Differentiating:

$$\frac{\partial G}{\partial E^{**}} = \sigma\omega \times (\delta + \omega) \times C'' - p \times F'' > 0, \tag{24}$$

$$\frac{\partial G}{\partial \omega} = \sigma C' + \sigma(\delta + \omega) \times E^{**} \times C'' > 0, \tag{25}$$

$$\frac{\partial G}{\partial \delta} = \sigma C' > 0, \tag{26}$$

$$\frac{\partial G}{\partial p} = -F' < 0, \tag{27}$$

$$\frac{\partial G}{\partial \sigma} = (\delta + \omega) \times C' > 0. \tag{28}$$

The function G has continuously differentiable first-order partial derivatives, and continuous second-order partial derivatives. The implicit function theorem can therefore be applied to G. Because the partial derivatives of F are single-signed throughout the entire non-negative orthant, there is a continuous function $g(p, \delta, \omega, \sigma)$ that associates a single value of E^{**} with each vector $(p, \delta, \omega, \sigma)$. From equations (24)–(28):

$$E^{**} = g(p,\delta, \omega, \sigma); \tag{29}$$

$$\frac{\partial E^{**}}{\partial p} = g_p > 0, \frac{\partial E^{**}}{\partial \delta} = g_\delta < 0; \tag{30}$$

and:

$$\frac{\partial E^{**}}{\partial \omega} = g_\omega < 0, \; \frac{\partial E^{**}}{\partial \sigma} = g_\sigma < 0. \tag{31}$$

In many empirical settings (Griliches, 1960) the current level of investment is assumed to be a monotone increasing function of the optimal stock of capital, but a monotone decreasing function of the current stock of capital. Such an assumption is perfectly compatible with the control theory model, and this assumption is incorporated into the empirical analysis. The theory of drainage investment presented here is strikingly validated by the close relation between components of the pecuniary returns on drainage investment and wetland losses. The model explains the NRI data so well that the distinction between testing the model and looking for interesting empirical relations is moot.

Space limitations preclude extensive discussion of the empirical implications of the model. The following two points are, however, worth noting in detail. First, equations (22) and (23) imply that as marginal gross income from drainage increases, the rate of drainage investment increases. Second, equations (22), (23) and (30) imply that any increase in the productivity of drained wetland will increase $[F'(E)]$ as well as the rate of investment and the equilibrium stock of drained acreage.

A change in farm income per acre, the discount rate or the productivity of drained wetland acreage will affect the level of drainage investment. Per acre farm incomes for the states are recorded, and correspond to variation in the numerator of the right-hand side of equation (22). Cross-section differences in farmland realty values capture variation in both the numerator and the denominator of the right-hand side of equation (22) because farmland realty values are closely linked to discounted expected income. Equations (22) and (23) suggest that farm income and farm realty values should explain some of the variation in farmland investment levels. It is reasonable to assume that the larger the stock of wetlands in a state, the greater the variation in the net returns from draining wetlands. The variation is induced by heterogeneity in both costs and productivity. Thus, a state with a large stock of undrained wetlands should have more acres of potentially highly productive, easily drained wetlands than a state with relatively few wetland acres. Wetland acreage, then, may be a surrogate for the net rate of return on drainage investment. This factor may account for part of the powerful impact of wetland acreage on wetland drainage rates in the regression models.

3. Non-market benefits and wetland drainage data

The regression models presented here feature wetland loss rates and wetland loss rates per acre of extant wetlands as cross-section variables. The observations of state wetland loss that are used as the dependent variables in the regressions were not provided on the original NRI data tapes (U.S. Soil Conservation Service, 1991). The 1982 and 1987 NRI data tapes contain county-level estimates of wetland areas. The 1982 county wetland area estimates were made from a survey that was started in 1980 and finished in 1982. The wetland area estimates were redone in a 1985–1987 survey; we often refer to the 1982 and 1987 surveys as the 1980 or 1985 surveys. The 1987 NRI data base was based on fewer observation points than the original—roughly 300 000 data points for the later survey versus over 1 000 000 data points for the 1982 database. However, the later database features a revised wetland definition, and revised 1982 wetland area estimates by counties. We made internally consistent county wetland loss rate estimates from the 1987 tape for the 1982–1987 period. State wetland loss estimates for 1982–1987 were derived by aggregating the county wetland losses. These state wetland loss estimates serve, directly or indirectly, as the dependent variable in the regressions listed here. The 1987 data tape is available on request from SCS (U.S. Soil Conservation Survey, 1991).

The 1978 area drained data used here was published as a separate volume (U.S. Bureau of the Census, 1981) as part of the *1978 Census of Agriculture*. The data on farm realty values is published in a set of annual compilations (Economic Research Service, 1992) with the generic title of *Agricultural Resources, Agricultural Land Values and Markets: Situation and Outlook Report*. The source for the non-farm socio-economic data are editions 110–111 of the annual statistical compilations entitled the *Statistical Abstract of the United States* (U.S. Bureau of the Census, 1990, 1991). These volumes also contain useful agriculture summary statistics, including data on farm income, and excellent references to other U.S. Department of Agriculture data sources.

The principal shortcoming of the available current data on wetland loss and drainage investment is the paucity of information on wetland drainage costs. Recent research by Stavins and Jaffe (1990) suggests that a measure of soil moisture content, the Palmer hydrological drought index (PHDI), is a useful surrogate for per acre drainage investment costs. It is prohibitively expensive to use conventional statistical sampling techniques to estimate drainage costs because of the large sample variances (Heimlich, 1989). The Z-index and PHDI proper are two distinct measures of soil moisture content. The Z-index is an index of plant root zone moisture content, and the PHDI is a measure of moisture content for deeper subsurface layers. The two measures listed here were the average values for the 1980–1987 period. The Z-index performed a bit better than the PHDI. State data on the PHDI and the Z-index can be obtained on disks provided by the National Climatic Data Center in Asheville, North Carolina.

The nation's wetlands were long regarded as an impediment to economic activity and agricultural productivity (Douglas, 1989). But wetlands provide an array of non-market goods and services, including opportunities for scientific research, aesthetic benefits, climatological stabilization, erosion control, flood control, groundwater recharge and storage, sediment trapping, contaminant removal, geochemical cycling, fish and wildlife habitat, and outdoor recreation sites. The social value of these outputs has not been completely documented (Douglas, 1989). However, the social value of wetlands in providing waterfowl habitat (Hammack and Brown, 1974) and waterfowl hunting sites (Miller and Hay, 1981) has been carefully quantified. Drained wetlands can be used for various market activities. Thus, there is a potential divergence between the socially optimal use of rural wetland acreage and private market oriented uses of these wetlands. Non-market benefits provided by wetlands have generated considerable interest in the social forces that induce on-farm wetland drainage.

The U.S. Department of Agriculture (U.S. Soil Conservation Service, 1991) estimated that there were 78·4 million acres of remaining non-federally owned wetlands in 1982, but 96 million acres of uncropped wet soils. Heimlich (1988) reported that 40% of the wet soils that were cropped in 1982 were also classified as wetland. Tiner (1984) estimates the current wetland acreage of the lower 48 states to be about 99 million acres, whereas Alaska has 200 million wetland acres. Tiner (1984) asserts that agricultural drainage is the major cause of wetland loss, accounting for 84% of the lost wetland acreage in recent years.

Heimlich's (1988) analysis of the empirical factors that drive on-farm wetland drainage provides evidence on government farm program impacts on wetland conversions. In particular, Heimlich (1988) suggests that the "swampbuster" provisions of the Food Security Act of 1985 may not be effective in slowing down on-farm wetland conversion. These provisions stated that any farmer who drains a wetland cannot enroll in any government farm programs during any year in which he plants a crop on the drained acreage (Heimlich, 1988). Heimlich's (1988) discussion suggests that 17 million of the remaining 78·4 million non-federal wetland acres in 1982 had a high likelihood of being converted to cropland. Heimlich (1988) states that the swampbuster provisions of the Food Security Act of 1985 should effectively diminish the likelihood of drainage on 6 000 000 of these wetland acres.

4. Factors omitted from the model

There are two principal types of drainage capital (Donahue *et al.*, 1983), namely surface drainage installations and sub-surface drainage installations. Surface drainage systems include drainage ditches, drainage-by-beds and open-W (Donahue *et al.*, 1983). Subsurface drainage systems include tile, plastic tube, mole, sump-and-pump and various vertical systems (Donahue *et al.*, 1983). Subsurface drainage capital is more costly and more durable than surface drainage capital. The U.S. Department of Agriculture (Economic Research Service, 1987) uses 25 years as the mean service time of subsurface drainage, and 15 years as the average lifetime of surface drainage equipment in constructing estimates of the quantity and value of the stock of drainage equipment.

Certain features that are difficult to model are omitted from the current model of wetland drainage. Three of these omitted factors are: (1) investment in social overhead drainage capital; (2) non-pecuniary returns to drainage investment; and (3) drainage of wetland soils. Wetlands are widely regarded as a nuisance. For example, insects use wetlands as a breeding place. Wetland drainage generates non-pecuniary private returns, but data on these returns is not available on the scale needed for the current study. Past investment in social overhead capital can shift the returns to current investment levels. Such investment need not always directly increase the number of acres drained (Stavins and Jaffe, 1990). However, data on social overhead capital is difficult to obtain. Stavins and Jaffe (1990) deal only with federal project impacts in the delta region, yet omit the mainline levee system as an explanatory variable in their regressions because of data limitations.

Another economic variable that is related to wetland drainage investment is drainage investment in wet soils. Wet soil drainage drives a wedge between drainage investment and wetland loss. Wet soil drainage investment for poorly draining soils may also increase cropland productivity (Donahue *et al.*, 1983). The paucity of data on wet soil drainage precludes empirical exploration of this subject. Drainage investment often occurs in conjunction with cropland irrigation because irrigated soils often drain poorly (Donahue *et al.*, 1983).

5. Statistical analysis of the NRI data

The basic goal of the statistical study was to discover relationships between economic variables and wetland loss rates, and to note the relevance of various social forces in explaining wetland loss rates. Various measures of wetland loss were used as dependent variables, including the following:

Y_1 = wetland loss for 1982–1987 in acres for each state.

Y_2 = wetland loss for 1982–1987 for each state as a percentage of state 1982 wetlands acreage.

The set of physical explanatory variables includes:

X_s = area of state.
X_{c2} = long-term average, Z-index.

The set of socio–economic explanatory variables includes:

Z_{i1} = state farm income per acre in 1980.
Z_{v1} = realty value of farmland per acre in 1980.
Z_a = area of land drained in state in 1978.
Z_{r1} = state non-federal rural wetland area in 1980.

The actual data set was much larger than the variables list suggests. We experimented with more economic and non-economic variables than the list indicates. The quantity of wetlands variable—state wetland rural acreage—explained more of the variance in the wetland loss rate than any other variable. The sign of the coefficient of this variable was always positive, as the theory of drainage investment suggests it should be. The estimated coefficient is the elasticity of the dependent variable with respect to the independent variable with the log–log specification. The estimated response to a 10% increase in wetlands ranged from a 8·4% increase in acres drained in equation (32), to a 9·9% increase in the wetlands loss rate in equation (34).

The second most useful and consistent explanatory variable was farmland realty value. The farmland realty per acre value was almost always statistically significant if the $r^2 \geqslant 0{\cdot}60$ for the equation. The realty value of farm acreage performed somewhat better than per acre farm income. If both variables were included in an equation, the coefficient of the realty value variable had a positive sign, and the coefficient of the farm income per acre variable was negative. The realty value of farmland variable does not include the value of farm buildings. In equation (32), a 10% increase in per acre realty value generates a 3·8% increase in drained wetland acreage; in equation (34) it generates a 12% increase in the rate at which wetlands are drained.

Land drained, a measure of the quantity of drainage investment, performed well in equations in which the dependent variable was wetland loss rates rather than lost wetland acreage. When acres of wetland lost is the dependent variable of the regression model, the coefficient of land drained was positive in the regression equations. A similar difficulty occurred if the soil moisture content is used as an explanatory variable. There is a basic difference between the regression model estimated in equation (32) and the model underlying equations (33) and (34). Equation (32) assumes that the rate of wetland loss is a function of economic variables and the quantity of remaining wetlands. Equations (33) and (34) assume that the rate of wetland loss is the same across units, except for variation in socio–economic variables. The stock of wetlands could be a surrogate for the rate of return on wetland drainage in equations (33) and (34). Equation (32) and equations (33) and (34) are linear transformations of each other—dividing one variable by another before taking logarithms is equivalent to subtracting the logarithms of the variables.

In equation (32), the dependent variable is the natural logarithm of wetland loss between 1982 and 1987:

$$\log(Y_t) = K + \beta_1 \times \log(X_s) + \beta_2 \times \log(Z_{r1}) + \beta_3 \times \log(Z_{v1}) \tag{32}$$

and

Coefficient	$K = -8{\cdot}27$	$\beta_1 = 0{\cdot}199$	$\beta_2 = 0{\cdot}836$	$\beta_3 = 0{\cdot}384$
T-value	$-4{\cdot}72$	$1{\cdot}99$	$13{\cdot}34$	$2{\cdot}37$
Two-tailed α	$0{\cdot}000$	$0{\cdot}053$	$0{\cdot}000$	$0{\cdot}022$
		$r^2 = 0{\cdot}849$	$r_a^2 = 0{\cdot}839$	

In equation (32), the logarithms of state area, wetland area and per acre farm realty value are the independent variables. With a two-tailed t-test (Fomby *et al.*, 1984), state area is not a statistically significant explanatory variable for $\alpha = 0{\cdot}05$. Note that r_a^2 is the adjusted multiple correlation coefficient (Kvalseth, 1985). In equation (33), the explanatory variables are the three key economic variables including land drained, wetland area and per acre farm realty value. The dependent variable is the natural logarithm of the percentage of state 1980 wetlands drained during the 1980–1985 period. The three variables have t-values that are significant for $\alpha = 0{\cdot}01$:

$$\mathrm{lof}(Y_2) = K + \beta_1 \times \log(Z_a) + \beta_2 \times \log(Z_{r1}) + \beta^3 \log(Z_{v1}) \tag{33}$$

Coefficient	$K = -10{\cdot}95$	$\beta_1 = -0{\cdot}333$	$\beta_2 = 0{\cdot}988$	$\beta_3 = 1{\cdot}18$
T-value	$-12{\cdot}70$	$-6{\cdot}75$	$14{\cdot}70$	$9{\cdot}12$
Two-tailed α	$0{\cdot}000$	$0{\cdot}000$	$0{\cdot}000$	$0{\cdot}000$
		$r^2 = 0{\cdot}878$	$r_a^2 = 0{\cdot}870$	

Note that the soil moisture variable was averaged for the 1980–1987 period while the other explanatory variables use only a single 1982 or 1978 observation:

$$\log(Y_2) = K + \beta_1 \times \log(Z_a) + \beta_2 \times \log(Z_{r1}) + \beta_3 \times \log(Z_{v1}) + \beta_4 \times \log(X_{c2}) \tag{34}$$

Coefficient	$K = -11{\cdot}53$	$\beta_1 = -0{\cdot}323$	$\beta_2 = 0{\cdot}967$	$\beta_3 = 1{\cdot}20$	$\beta_4 = -0{\cdot}215$
T-value	$-13{\cdot}44$	$-6{\cdot}81$	$14{\cdot}89$	$9{\cdot}68$	$-2{\cdot}26$
Two-tailed α	$0{\cdot}000$	$0{\cdot}000$	$0{\cdot}000$	$0{\cdot}000$	$0{\cdot}029$
		$r^2 = 0{\cdot}891$	$r_a^2 = 0{\cdot}881$		

The dependent variable in these regressions is the total annual wetland acreage loss or it is the total annual percentage wetland loss rate for the 5-year period. The wetland area and farm value variables for 1985 did not perform as well as the 1980 values for these variables. The absolute magnitudes of the t-values of the explanatory variables are high but uniformly smaller for the 1985 observations. The capital stock variable is the area drained in 1978. Thus, the decline in the explanatory power of the model may be closely related to flaws in the capital stock data. Neither population change nor change in farmland area were useful explanatory variables.

6. Putting the statistical results in context

There was a shrinkage in the total value of farm real estate during the early 1980s. This decline might be a major causal factor of the sharp downturn in wetland loss rates estimated by the NRI (U.S. Soil Conservation Service, 1991). Freyer *et al.* (1983) estimated that 11 million wetland acres were lost between 1950 and 1970. The mean annual estimated wetland loss rate for the period was more than 500 000 acres per annum (Freyer *et al.*, 1983). The NRI (U.S. Soil Conservation Service, 1991) estimates that wetland loss rates for the 1982–1987 period were roughly 120 000 acres per annum. Recall that Heimlich (1988) asserts that 17 million of the remaining 78·4 million non-federal wetland acres are likely to be converted to farmland in the future. Hence, a "no productive wetlands remain" hypothesis is not the principal explanation of the slowdown in wetland drainage.

Further perusal of recent data indicates that the real aggregate farm income of farm operators declined between 1980 and 1984, but rose above 1980 levels during 1985–1988 (U.S. Bureau of the Census, 1990). The constant dollar value of aggregate farmland rose by 86% between 1970 and 1980; the mean per acre real value of farm real estate, including land and buildings, increased by 97% (U.S. Bureau of the Census, 1990, 1991). The average per acre value of farm real estate (land and buildings) in constant 1982 dollars peaked in 1980 at $954·76, and declined steadily between 1981 and 1986. Per acre farm real estate values began to rise in 1987, but in 1989 the average value was still only 58% of the 1980 mean value (U.S. Bureau of the Census, 1991). However, aggregate farmland acreage declined steadily between 1960 and 1989, and in 1989 was only 90% of the 1102 million acres farmed in 1970 (U.S. Bureau of the Census, 1991). Thus, until the early 1980s, increases in the value of farm real estate generated wetland losses during a period of declining farmland acreage.

7. Some policy reflections

Our results indicate that pecuniary factors explain a large fraction of the variance in drainage rates across states. One interesting implication of this finding is that policies that change the net returns to drainage investment will have major impacts on wetland losses. A major weakness of the swampbuster legislation is that participation in federal farm programs is highly volatile, and declines as farm income rises (Heimlich, 1988). An increase in demand for farm products increases farm income, hence induces higher wetland loss rates. Nevertheless, as farm income rises, participation in federal farm programs decreases, thereby debilitating the deterrent effect of the swampbuster legislation.

There are federal wetland acquisition programs in which the federal government pays farmers to leave their on-farm wetlands intact. Linking the level of the payments and acquisitions to cyclical fluctuations in farm income and farmland realty prices exploits fluctuations in realty prices. The acquisition programs could use the close relation between wetland loss rates and farm realty prices documented here to allow the federal government to acquire wetlands in a cost-effective manner. The Food Security Bill of 1985 contained provisions aimed at acquiring wetlands and upland habitat from financially distressed farmers. Similar provisions are part of the Food, Agriculture, Conservation and Trade Act of 1990. The 1990 Food, Agriculture, Conservation and Trade Act also contains provisions for partial reimbursement of farmers for wetland restoration costs incurred for on-farm wetland reconversions of cropland.

We suggest that resource management agencies place greater emphasis and funding in wetland acquisition programs, and less reliance on the penalty-oriented wetland preservation programs such as "swampbuster". The magnitude of recent downturns in wetlands loss rates and farm realty values is a major stimulus for the policy suggestion. When farm realty values are low, wetland loss rates are likely to be low. If farm realty values decline, the long-run problems associated with preserving wetlands may well be perceived as being more benign than they really are. However, wetland acquisition prices are likely to be low when farm realty values are low. Thus, there could be considerable social value in creating long-run, price-sensitive wetland acquisition programs. One strength of the current wetland acquisition programs, particularly the loan set-aside program, is that the natural resource agency becomes the ally of farmers and distressed farm communities. A weakness of the acquisition programs is that they require co-ordination between agriculture and natural resource management agencies.

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