APPENDIX: NONPOINT POLLUTION MODEL

Following Horan et al. (1998, 2002), consider a model in which a natural resource such as lake or river is damaged by a single residual (e.g. nitrogen or phosphorous) from nonpoint agricultural emissions sources. The ambient concentration of the pollutant is given by $A = a(r_1, r_2, \ldots, r_n, b, w, \gamma)$, where r_i ($i = 1, 2, \ldots, n$) is emissions from nonpoint source (farm) i, n is the total number of farms, b is natural generation of the pollutant, w is a vector of stochastic environmental conditions (e.g. timing and intensity of precipitation) that influence transport and fate of the pollutant, and γ is a vector of natural resource characteristics and parameters (e.g. soil types, topography). Emissions from any farm contribute to the ambient concentration ($\partial a / \partial r_i > 0$), although the contribution can vary from one farm to another depending on variables such as distance from the lake or river.

Nonpoint emissions cannot be observed directly and are random because of stochastic environmental conditions. As a result, farms can only influence the distribution of their emissions through their management decisions. Emissions by farm i are given by $r_i = r(x_i, z_i, v_i, \alpha_i)$, where x_i is a vector of m_x inputs into production that may also influence emissions, z_i is a vector of m_z inputs into pollution remediation/clean-up after production has occurred, v_i is a vector of stochastic environmental drivers at the farm's site, and α_i is a vector of natural resource characteristics at the farm's site. Pollution remediation inputs reduce emissions ($\partial r_i / \partial z_{ik} < 0$, $k = 1, 2, \ldots, m_z$). Production inputs could in general increase, reduce or have no impact on emissions, depending on the input, the quantities used of that input and other production and remediation inputs, and natural resource characteristics. Emissions are zero if no production inputs are used, $r(0, z_i, v_i, \alpha_i) = 0$.

Farm decision-making

Farm i's profits for any choice of inputs are $\pi_i = h(x_i, v_i, \alpha_i) - \rho(z_i, \alpha_i) = h_i - \rho_i$, where $h_i = h(\cdot)$ represents economic returns from production activities and $\rho_i = \rho(\cdot)$ captures the costs of pollution remediation. Profits are random because of the stochastic environmental drivers v_i. Returns from production activities are zero if no inputs are used, so that $h(0, v_i, \alpha_i)$ = 0, and pollution remediation costs are zero if no remediation inputs are used, i.e. $\rho(0, \alpha_i) = 0$. Farms are risk-averse and have utility functions of the form $u_i = u(\pi_i, \beta_i)$, where β_i is a vector of farm-specific parameters influencing utility (e.g. farm household size and composition), with $\partial u_i / \partial \pi_i > 0$ and $\partial^2 u_i / \partial \pi_i^2 < 0$. Farms maximize expected utility $E(u_i)$. Because pollution remediation inputs do not contribute to production, they will not be used ($z_i = 0$) in the absence of environmental policies that require or incentivize their use.[1]

The n farms are assumed for simplicity to have no collective influence on input or output prices, so that input and output markets are unaffected by environmental policies directed at this natural resource. Input and output markets are also assumed to be free from distortions, so that environmental policies do not affect social costs indirectly by augmenting or reducing these distortions. The economic cost of damages caused by pollution is $D(A, u)$, where u is a random variable that captures uncertainty about the consequences of agricultural pollution for the economy, human health, and ecosystems.

Information sets

The random variables in the model are assumed to be jointly distributed with a density function $f(v, w, \eta | \Gamma)$, where v is a matrix containing the vectors v_i, $i = 1, 2, \ldots, n$, and Γ is the set of all available information about natural and economic processes. In practice, neither the regulatory agency responsible for environmental policies nor individual farms have full information. Let the regulatory agency's information set be Ω and let the information set for farm i be Ω_i. One common assumption in the nonpoint pollution literature is that the regulatory agency has better information than farms about natural and economic processes at an aggregate level (represented by w and η), while each farm has better information about its own circumstances (represented by v_i) than the regulator. The union of the

[1] If nonpoint emissions or ambient concentrations entered directly into the farm's utility function (e.g. pollution of drinking water consumed by a farm household), this statement would not necessarily hold.

regulatory agency and farm-specific information sets, along with relevant information possessed by anyone else, constitutes the full information set Γ.

Regulatory agency decision-making

The regulatory agency has a social objective function $W = w(u_1, u_2, \ldots, u_n, D)$ that depends positively on the utility of each farm ($\partial W / \partial u_i > 0$) and negatively on damages from pollution ($\partial W / \partial D < 0$). There are diminishing returns to utility ($\partial^2 W / \partial u_i^2 < 0$) and increasing marginal costs to damages ($\partial^2 W / \partial D^2 < 0$). The agency seeks to maximize the expected value of this objective function.

The first-best, ex ante efficient solution to this problem involves the regulatory agency choosing the quantities of the production and remediation inputs for every farm using the full information set Γ. The choices are subject to non-negativity constraints on the inputs. With appropriate continuity and convexity assumptions, first-order necessary conditions for the first-best solution are:

$$E\left(\frac{\partial W}{\partial u_i} \frac{\partial u_i}{\partial \pi_i} \frac{\partial h_i}{\partial x_{ij}} \middle| \Gamma \right) + \lambda_{ij} = -E\left(\frac{\partial W}{\partial D} \frac{\partial D}{\partial A} \frac{\partial A}{\partial r_i} \frac{\partial r_i}{\partial x_{ij}} \middle| \Gamma \right) \;\; \forall\, i, j \qquad (1)$$

$$E\left(\frac{\partial W}{\partial u_i} \frac{\partial u_i}{\partial \pi_i} \frac{\partial \rho_i}{\partial z_{ik}} \middle| \Gamma \right) - \mu_{ik} = E\left(\frac{\partial W}{\partial D} \frac{\partial D}{\partial A} \frac{\partial A}{\partial r_i} \frac{\partial r_i}{\partial z_{ik}} \middle| \Gamma \right) \;\; \forall\, i, k \qquad (2)$$

$\lambda_{ij} \geq 0$ is the Lagrangian multiplier associated with the constraint $x_{ij} \geq 0$, with $\lambda_{ij} = 0$ when $x_{ij} > 0$, and $\mu_{ik} \geq 0$ is the Lagrangian multiplier associated with the constraint $z_{ik} \geq 0$, with $\mu_{ik} = 0$ when $z_{ik} > 0$. For inputs whose quantities are greater than zero, (1) and (2) state that the expected marginal net benefit of each input must equal the expected marginal damage cost from that input. Expected marginal net benefit and expected marginal damage cost are negative for production inputs that reduce emissions and for remediation inputs.