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AGRICULTURAL VERSUS URBAN INTERESTS IN GROUNDWATER QUALITY

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Concerns over water quality are playing an increasingly important role in agriculture throughout the United States, Europe and many other parts of the world. As progress has been made in curbing industrial and municipal emissions, agricultural sources are contributing growing shares of nutrients (nitrogen, phosphorus) and other pollutants such as pesticides and sediment. Population growth and the spread of urbanization increase the social costs of this pollution by increasing demand for recreation, fishery productivity and drinking, and thus demand for water in terms of both quality and quantity. As a result, urban and agricultural interests are increasingly in conflict over water.

Groundwater provides a good case in point. The quality of groundwater supplies has become a growing cause of concern throughout the United States. Surveys at the federal, state, and local levels (Office of Technology Assessment) indicate that many aquifers used for drinking water supplies contain chemicals that are documented or suspected human health hazards. Agriculture, in particular, has become a focus of concern over contamination of groundwater with nitrate and pesticides. A recent Environmental Protection Agency (EPA) survey found that 52 percent of community water system wells and 57 percent of rural domestic wells contained measurable amounts of nitrate, while 10 percent of community water system wells and 4 percent of rural domestic wells contained measurable amounts of pesticides (U.S. Environmental Protection Agency).

Groundwater is a critical source of drinking water in both rural and nonrural areas: Over 97 percent of rural drinking water comes from underground aquifers, while 50 percent of the U.S. population overall relies on groundwater (Office of Technology Assessment). Population growth in many areas has resulted in the conversion of many former rural areas to residential use.

Groundwater is the chief source of drinking water in these areas, as evidenced by the rapid growth of groundwater withdrawals in these areas (Aldrich). This increased reliance on groundwater has led to increased demand for nitrate- and pesticide-free water, which has led in turn to growing political pressure for curtailing leaching from agriculture, for example, via mandatory use of manure storage systems, more stringent restrictions on pesticide use and other regulations on agricultural production.

This emphasis on pollution control is somewhat one-sided. Since Coase, economists have understood that pollution problems exhibit joint dependence on the behaviors of emitters and receptors of pollution, that is, on polluter and pollution victims. Polluters can alter emissions by changing their production practices or by installing pollution control equipment. Victims can engage in averting behavior to reduce the level of damages suffered; moreover, the level of damage suffered will depend on the locational choices of victims. In general, it will be efficient for both parties to bear some of the cost of pollution, so that both will have incentives to reduce damages (Olson and Zeckhauser), although under certain conditions there may be nonconvexities that make it optimal to require only one party to bear the full cost (Shibata and Winrich, Oates).

This paper examines theoretically and empirically the potential roles of pollution control and mitigation by victims for the case of groundwater contamination, taking into account both efficiency and equity concerns. We begin with a simple model of the minimum cost allocation of effort between pollution control by farmers and mitigation by urban residents. We then examine the impacts of exogenous urbanization on this division of effort and on the total and marginal costs of managing agricultural pollution. We consider two types of urban growth, conversion of agricultural land to residential uses at existing population density and increases in population density with no changes in land use, a dichotomy that corresponds to recent growth control proposals. We then consider a simple financing scheme to implement the optimal mix of pollution control and mitigation in an equitable manner. We assume that the distribution of property rights to groundwater implies that farmers and the urban population should pay specific shares of the total cost of pollution control plus mitigation, and that those costs are defrayed from a central fund raised by levying per acre taxes on agricultural and residential land, a scheme corresponding to a form of political-economic equilibrium (Zusman) and which is also attractive on practical grounds. We examine the impacts of different patterns of growth on the rate of taxation of urban and agricultural land and discuss implications for further growth and political conflict.

A Simple Model of Land Use and Pollution

Consider the case of a region where agriculture generates a pollutant that is harmful to urban users, for example, nitrate in groundwater used for drinking water. Let all of the land in a region, A_T, be used either for agriculture or urban uses. Let A_F denote land used for agriculture, so that urban land is A_T-A_F. Let emissions of this pollutant be proportional to agricultural acreage, eA_F. Farmers can reduce emissions by engaging in pollution control, for example, storing manure and using it in place of chemical fertilizers, reducing chemical fertilizer applications, using time-release formulations of fertilizers, using cover crops during the off-season to soak up excess nutrients, and so on. Let the fraction of emissions controlled be denoted α, and let the total cost of controlling emissions by an amount $E = \alpha e A_F$ be a convex function $C(\alpha e A_F)$. The convexity of the cost function captures diminishing marginal productivity of pollution control both at the farm and regional levels. On a single farm, the marginal cost of pollution control $C_E(\alpha eA_F)$ may be rising because reducing emissions by a larger amount requires larger investment in pollution control or impairs farm productivity more. At the regional level, the marginal cost of pollution control may be rising because achieving greater reductions in emissions requires controlling emissions on farms that emit less or have higher pollution control costs due to scale economies.

Let the urban population of the region be $P = \rho(A_T-A_F)$, where ρ is urban population density. Uncontrolled emissions from agriculture are $(1-\alpha)eA_F$. Assume that the pollutant is mixed uniformly in the environment, so that all urban users are affected equally by total emissions. Let the fraction of these uncontrolled emissions removed by mitigation efforts on the part of urban residents be β, and assume that the cost of these mitigation efforts is $K(\beta(1-\alpha)eA_F,\rho(A_T-A_F))$, a function of the amount of pollution removed, $B = \beta(1-\alpha)eA_F$, and the size of the urban population, $\rho(A_T-A_F)$. We assume that the marginal cost of mitigation, K_B, is positive and increasing ($K_B > 0$, $K_{BB} > 0$) and that mitigation exhibits increasing returns to population ($K_P > 0$, $K_{PP} > 0$, $K_{BP} < 0$). For example, mitigation may involve installing filtration systems or drilling new wells to obtain cleaner water, both of which have lower marginal costs with higher population because of high fixed costs.

Suppose that pollution control effort α and mitigation effort β are chosen to minimize the total cost of meeting a quality standard N such as the EPA standard for nitrate in drinking water. The regional optimization problem is:

$$\min \quad C(\alpha e A_F) + K\big(\beta(1-\alpha)eA_F, \rho(A_T - A_F)\big)$$
$$s.t. \quad (1-\beta)(1-\alpha)eA_F \le N.$$

Assuming an interior solution, the necessary conditions can be written:

$$\begin{aligned} C_E - \beta K_B - (1-\beta)\lambda &= 0 \\ K_B - \lambda &= 0 \\ (1-\beta)(1-\alpha)eA_F &= N. \end{aligned}$$

The fact that λ, the (absolute value of the) shadow price of the pollution standard N, equals the marginal cost of mitigation effort K_B implies that the necessary conditions can be written in more simplified form as:

$$\begin{aligned} C_E - K_B &= 0 \\ K_B - \lambda &= 0 \\ (1-\beta)(1-\alpha)eA_F &= N. \end{aligned}$$

The first two of these conditions are the familiar requirements that (1) the marginal costs of pollution control and mitigation must be equal and (2) both must equal the marginal cost of the standard, λ.[1]

These necessary conditions are sufficient when:

$$\begin{aligned} e^2A_F^2C_{EE} + \beta^2e^2A_F^2K_{BB} &\ge 0 \\ (1-\alpha)^2e^2A_F^2K_{BB} &\ge 0 \\ \left(e^2A_F^2C_{EE} + \beta^2e^2A_F^2K_{BB}\right)(1-\alpha)^2e^2A_F^2K_{BB} - \beta^2(1-\alpha)^2e^4A_F^4K_{BB}^2 = (1-\alpha)^2e^4A_F^4C_{EE} &\ge 0, \end{aligned}$$

all of which hold when our assumptions about pollution control and mitigation technology are met.

Urban Growth and the Division of Effort between Agriculture and the Urban Population

Consider the impact of urbanization on the optimal division of effort between pollution control in agriculture and mitigation conducted by the urban population. We distinguish two types of urban growth. The first, extensive growth, we characterize by examining conversion of agricultural land to urban uses holding population density constant. This corresponds to growth patterns where agricultural land is zoned for low density residential development. The second, intensive growth, we characterize by examining increases in population density holding agricultural land use constant. This corresponds to a situation where growth is restricted to existing urban corridors, and agricultural land is zoned to prohibit its conversion to residential use.

This dichotomy springs from current debates over land use planning in areas like the Northeastern United States. In Maryland, for example, agricultural land in the Baltimore-Washington corridor is being converted to urban uses at a relatively rapid rate. Existing zoning regulations favor low-density development, which results in extensive growth. Recently, the governor of the state proposed a new land use planning framework in which the state would pre-empt local control and restrict urban growth to specific corridors. This new framework would channel development into intensive growth patterns.

It is straightforward to show the following:

Proposition 1. Conversion of agricultural land to urban uses will result in an increase (decrease) in pollution control in agriculture if it reduces the marginal cost of pollution control more quickly (slowly) than the marginal cost of mitigation. Mitigation by urban users will increase (decrease) if population growth makes the marginal cost of mitigation rise more slowly (quickly) than the marginal cost of pollution control in agriculture.

Proof. Differentiating the simplified system of necessary conditions totally and using Cramer's rule yields:

$$\frac{\partial \alpha}{\partial A_F} = \Delta^{-1}(1-\alpha)eA_F(\alpha eC_{EE} + \rho K_{BP} - (1-\alpha)eK_{BB})$$
$$\frac{\partial \beta}{\partial A_F} = \Delta^{-1}(1-\beta)eA_F(eC_{EE} + \rho K_{BP})$$

where $\Delta = -(1-\alpha)eA_F[C_{EE} + K_{BB}] < 0$.

Consider first the impact of conversion of agricultural land on pollution control effort α. A reduction in agricultural land reduces emissions from agriculture and thus the marginal cost of pollution control in agriculture by αeC_{EE}. It has two effects on the marginal cost of mitigation by urban residents: (1) a direct decrease of $(1-\alpha)eK_{BB}$ and (2) a decrease of ρK_{BP} due to the increase in the urban population. If the reduction in the marginal cost of pollution control is greater, then pollution control will increase, and vice versa.

Mitigation by urban residents, on the other hand, will increase whenever the decrease in the marginal cost of pollution control in agriculture, eC_{EE}, is greater than the decrease in marginal mitigation cost due to the increase in the urban population, ρK_{BP}. This means that three different situations can occur. First, the decrease in the marginal cost of pollution control may be greater than both the total decrease in marginal mitigation cost and the decrease in marginal mitigation cost due to increased population, i.e., $\alpha eC_{EE} > (1-\alpha)eK_{BB} - \rho K_{BP} > -\alpha\rho K_{BP}$. In this case, conversion of agricultural land to urban uses will lead to an increase in pollution control in agriculture and a decrease in mitigation by urban users. Second, the decrease in the marginal cost of pollution control may be less than both the total decrease in marginal mitigation cost and the decrease in marginal mitigation cost due to increased population, i.e., $(1-\alpha)eK_{BB} - \rho K_{BP} > -\alpha\rho K_{BP} > \alpha e C_{EE}$. In this case, conversion of agricultural land to urban uses will lead to an decrease in pollution control in agriculture and a increase in mitigation by urban users. Third, the decrease in the marginal cost of pollution control may be less than the total decrease in marginal mitigation cost but greater than the decrease in marginal mitigation cost due to increased population, i.e., $(1-\alpha)eK_{BB} - \rho K_{BP} > \alpha e C_{EE} > -\alpha\rho K_{BP}$. In this case, conversion of agricultural land to urban uses will lead to decreases in both pollution control in agriculture and in mitigation by urban users. In the first two cases, the reduction in agricultural land leads to reductions in emissions that alter the comparative advantage of pollution control vis-a-vis mitigation. In the third case, the reduction in emissions of the pollutant is sufficiently large to permit meeting the environmental quality standard N with an overall reduction in both types of effort.

Proposition 2. Restricting urban growth to existing urban areas will result in decreased pollution control in agriculture and increased mitigation by urban residents.

Proof. Differentiating the simplified system of necessary conditions totally and using Cramer's rule yields:

$$\frac{\partial\alpha}{\partial\rho} = -\Delta^{-1}(A_T - A_F)(1-\alpha)eA_F K_{BP} \leq 0$$
$$\frac{\partial\beta}{\partial\rho} = \Delta^{-1}(A_T - A_F)(1-\beta)eA_F K_{BP} \geq 0.$$

Intuitively, an increase in population density decreases the marginal cost of mitigation by urban residents while leaving the marginal cost of pollution control unaffected. As a result, mitigation effort must increase, while pollution control effort falls.

Together, propositions 1 and 2 indicate that different patterns of growth (and, by implication, different growth control policies) can have very different implications for least cost pollution control strategies. Zoning regulations that favor low density development may increase emphasis on either pollution control or mitigation. If they lead to large enough reductions in emissions, they may even permit reductions in both pollution control and mitigation. Strategies that seek to channel urban growth into a few restricted areas, and thus increase density, will lead to a greater emphasis on mitigation and reduced emphasis on pollution control.

Urban Growth and the Total Cost of Pollution Management

These two different approaches to growth control also have different consequences in terms of the total and marginal costs of pollution management, that is, the total and marginal costs of pollution control in agriculture plus mitigation by urban users. They thus have different implications for public finance and government budgets.

It is straightforward to show the following.

Proposition 3. Conversion of agricultural land to urban uses will increase (decrease) the total cost of pollution management if the direct reduction in the costs of pollution control and mitigation due to lower emissions are less (greater) than the increase in mitigation cost due to higher population.

Proof. Differentiating the total cost of pollution management $C(\alpha^* eA_F)+K(\beta^*(1-\alpha^*)eA_F,\rho(A_T-A_F))$ using the envelope theorem yields:

$$\frac{\partial(C+K)}{\partial A_F} = \alpha e C_E + \beta(1-\alpha)eK_B - \rho K_P.$$

Converting an acre of agricultural land to urban uses has two effects. First, it reduces emissions by e and thus the cost of pollution control by αeC_E and the cost of mitigation by $\beta(1-\alpha)eK_B$. Second, it increases need for mitigation because of urban growth, thereby increasing the cost of mitigation by ρK_P. If the cost reduction due to lower emissions is greater, then the total cost of pollution management will fall, and vice versa.

Proposition 4. Restricting urban growth to existing areas will increase the total cost of pollution management.

Proof. Differentiating the total cost of pollution management using the envelope theorem yields:

$$\frac{\partial(C+K)}{\partial \rho} = (A_T-A_F)K_P > 0.$$

The increase in the size of the urban population increases the need for mitigation and thus its cost. But because agricultural land remains constant, emissions and thus the costs of pollution control, pollution control effort α and the level uncontrolled emissions $\beta(1-\alpha)eA_F$ remain the same. As a result, the total cost of pollution management C+K rises.

Taken together, Propositions 3 and 4 imply that growth control policies will affect expenditures on pollution management in different ways. Restricting urban growth to existing urban areas will necessarily result in greater expenditures on pollution management, while permitting conversion of agricultural land to urban uses, i.e., low density development, may allow expenditures on pollution management to fall. High density development increases the need for pollution management without altering emissions from agriculture; thus, expenditures on pollution management must rise. Low density development reduces emissions at the same time as it increases the need for pollution management. If the decrease in emissions is sufficiently large, pollution management expenditures may actually fall.

Proposition 5. Conversion of agricultural land to urban use and restricting urban growth the existing urban areas both decrease the marginal cost of pollution management.

Proof. The marginal cost of pollution management is the Lagrange multiplier λ. Differentiating the simplified set of necessary conditions totally and using Cramer's rule yields:

$$\frac{\partial \lambda}{\partial A_F} = \Delta^{-1}(1-\alpha)e^{2}A_F^2 C_{EE}(\rho K_{BP}-K_{BB}) < 0$$
$$\frac{\partial \lambda}{\partial \rho} = -\Delta^{-1}(1-\alpha)e^{2}A_F^2 C_{EE}(A_T-A_F)K_{BP} < 0.$$

Intuitively, converting agricultural land to urban uses decreases total emissions and thus the effective stringency of the standard. As a result, the marginal cost of pollution management, λ = d(C+K)/dN, falls as well. Increasing population density leaves emissions unaffected but decreases the marginal cost of pollution management because it decreases the marginal cost of mitigation ($K_{BP} < 0$).

Proposition 5 suggests that, from a cost-benefit point of view, urban growth should be accompanied by stricter environmental quality standards. Both types of growth control lead to lower marginal costs of pollution management. If the pollution standard is set to maximize net benefit, then the marginal benefit of pollution management should also be lower, implying that the level of pollution management should be greater, i.e., the standard itself should be stricter. Thus, urban growth in an agricultural area should be expected to produce heightened conflicts over the quality of water supplies and other resources.

Equity and the Division of Costs

The preceding discussion has focused on the minimum cost division of effort between pollution control by farmers and mitigation by urban users. Once known, optimal pollution control and mitigation can be implemented by imposing regulations specifying that farmers and urban users undertake the optimal levels of effort α and β or by imposing Pigouvian taxes on emissions and unmitigated pollution.[2] A more difficult question is that of assigning responsibility for pollution management: How much of the total cost of pollution management should be underwritten by farmers, who generate the pollution, and how much by urban users, the victims? As Coase pointed out, the solution to this equity problem depends on the distribution of property rights among polluters and victims. If farmers own the rights to use groundwater to dispose of nutrient and pesticide wastes, then urban users should bear the costs of attaining acceptable pollutant concentrations. If urban users own the rights to clean groundwater, farmers should pay. If both parties own some rights, then both should pay shares corresponding to the relative sizes of their rights.

Unfortunately, property rights in groundwater are undefined, and are typically undefinable or unenforceable. Groundwater is generally subject to open access. All agents owning land overlying an aquifer or groundwater deposit are considered to have equal rights to exploit the water. For farmers, this exploitation has historically included waste disposal, in the sense that contaminants leached from crops or livestock were freely disposed of via percolation into groundwater. As urban use has grown, the rights of urban users to use that water have increasingly come into conflict with the rights of farmers to use the water for waste disposal.

Even if property rights in groundwater were assigned, they could easily be unenforceable because of the difficulty of demonstrating violations. It is extremely difficult to trace contaminants to a single source. One may be able to show with some degree of confidence that a portion of, say, the nitrate found in drinking water wells is attributable to agricultural activity in the recharge zone of the well, for example, but demonstrating that the nitrate comes from a specific field or livestock operation is usually out of the question.[3] In cases where causal effect cannot be demonstrated to the satisfaction of a court, it is impossible to use legal remedies to enforce property rights. Thus, unless farmers are presumed to own all rights to groundwater quality, demarcation of property rights offers little hope for solutions to conflicts over groundwater quality. The basis for Coasian bargaining does not exist because cheating is, effectively, undetectable, rendering moot the outcome of any bargaining process.[4]

Under such conditions, the extent to which each party should bear the costs of pollution management will tend to be decided through the workings of political-economic markets (Stigler, Peltzman). in which the relative political strengths of farmers and urban water users determine their relative shares of the cost of pollution management. Assume that the pollution standard is set exogenously; for example, drinking water standards for nitrate and pesticides are set by the Environmental Protection Agency rather than state or local agencies, and are thus exogenous to state and local decisions. Zusman has shown that the political-economic process can be modeled as a cooperative game in which the bargaining solution is found through a two-step procedure: (1) minimize the total cost of meeting the standard and (2) apportion shares of the total cost of pollution management according to the relative political strengths of the two parties. This equilibrium can be implemented by a two-part procedure. First, impose direct regulations requiring farmers and urban users to engage in the least-cost levels of pollution control and mitigation; second reimburse farmers and urban users fully for their expenditures using a fund financed by local taxes apportioned on agricultural and urban land according to the relative shares determined by their political strengths in the Nash equilibrium. A two-part policy of this kind is attractive from a practical point of view, too, since it is straightforward to implement and is easily understood by policy makers and the general public.

Specifically, let t_F and t_R be the taxes levied respectively on each acre of agricultural and residential land. Let farmers be responsible for a share γ of the total cost of pollution management, so that urban users pay the remaining share $1-\gamma$. The appropriate taxes on agricultural and urban land will then be determined by

$$t_F A_F = \gamma\Big(C(\alpha^* e A_F) + K\big(\beta^*(1-\alpha^*)eA_F, \rho(A_T-A_F)\big)\Big)$$
$$t_R(A_T-A_F) = (1-\gamma)\Big(C(\alpha^* e A_F) + K\big(\beta^*(1-\alpha^*)eA_F, \rho(A_T-A_F)\big)\Big),$$

where α^* and β^* are the cost-minimizing levels of pollution control and mitigation effort.

Suppose that population growth leaves the relative political power of farmers and urban users unchanged, or, equivalently, that the terms of the initial cost allocation are adhered to despite any changes in relative political power. so that γ is unaffected by urban population growth. Assume also that the tax is small enough to have no effect on land use, pollution control or mitigation decisions. It is straightforward to show the following.

Proposition 6. Conversion of agricultural land to urban use will result in a decrease (increase) in the tax rate on agricultural land if the change in the cost of pollution management paid by farmers is greater (less) than the tax rate on agricultural land. The tax rate on urban land will decrease (increase) if the change in the cost of pollution management paid by urban users is greater (less) than the inverse of the tax rate on urban land.

Proof. Differentiating the definitions of the tax rates with respect to A_F and rearranging yields:

$$\frac{\partial t_F}{\partial A_F} = \frac{1}{A_F}\left[\gamma\frac{\partial(C+K)}{\partial A_F} - t_F\right]$$

$$\frac{\partial t_R}{\partial A_F} = \frac{1}{A_T-A_F}\left[(1-\gamma)\frac{\partial(C+K)}{\partial A_F} + t_R\right]$$

Intuitively, conversion of agricultural land to urban uses has two effects on agriculture. On the one hand, it reduces the agricultural tax base, implying that the tax rate on remaining agricultural land should rise. On the other hand, it changes both emissions and the need for mitigation and thus the total cost of pollution management. If the total cost of pollution management falls, the tax rate on remaining agricultural land should fall as well. If the total cost rises, so should the tax rate. Thus, if conversion of agricultural land to urban uses increases the total cost of pollution management, the tax rate on remaining agricultural land will rise. The tax rate will fall only if conversion of agricultural land decreases the total cost paid by farmers by more than the tax rate.

The opposite occurs for urban users. Conversion of agricultural land to urban uses increases the urban tax base and thus exerts downward pressure on the tax rate. If the cost of pollution management paid by urban users falls as well, then the tax rate on urban land will fall. The tax rate on urban land will increase only if conversion of agricultural land increases the need for mitigation so much that the cost paid by urban users rises by more than the tax rate on urban land.

Proposition 7. Restricting urban growth to existing urban areas will lead to increases in the tax rates on both agricultural and urban land.

Proof. Differentiating the definitions of the tax rates yields:

$$\frac{\partial t_F}{\partial \rho} = \frac{\gamma}{A_F}\frac{\partial(C+K)}{\partial \rho} > 0$$
$$\frac{\partial t_R}{\partial \rho} = \frac{1-\gamma}{A_T-A_F}\frac{\partial(C+K)}{\partial \rho} > 0.$$

As noted in the proof of proposition 4, an increase in urban population density increases the need for mitigation but leaves emissions unchanged, implying an increase in the total cost of pollution management. That increased cost will be shared by both farmers and urban landowners.

Together, propositions 6 and 7 indicate that extensive and intensive growth strategies can have very different impacts on local government finances and thus on the political acceptability of efficient pollution management strategies. Intensive growth, because it leads to higher costs of pollution management and thus higher taxes over time, is likely to cause increased political friction. Extensive growth, by contrast, may permit reductions in pollution management tax rates over time for farmers, urban users or both. Should that happen, political conflict over water quality is likely to decrease over time.

Growth that leads to increases in pollution management taxes over time is likely to affect both land use decisions and political decision making. Rising tax rates will increase financial pressure on urban users, farmers or both groups. Suppose that pollution management tax rates become high enough to affect land use decisions. Farmers with less profitable operations will find the idea of selling their land to developers increasingly attractive, leading to increases in the supply of land offered for development or, equivalently, decreases in farmers' reservation prices for selling land. Development, too, will be less profitable, though, because of the increased cost of owning urban land. Demand for land for development will thus fall. Over time, then, one would expect growth to come to an end.

A second consequence could easily be that one or both groups will turn to political action to attempt to renegotiate the terms of pollution management financing. Under either form of growth, the urban population will increase relative to the farm population, so that the political power of the former is likely to increase as well. One would thus expect growing pressure to increase farmers' share of the total cost and consequently the tax rate on agricultural land. Such a process would accelerate increases in the supply of agricultural land by reducing the profitability of farming further. In this case, though, demand for development would increase because of reductions in the tax rate on urban land. One would thus expect increased conversion of agricultural land to urban uses; unless the total cost of pollution management falls, conflicts over water quality will escalate as well.

Extensions of the Model

The model used for the preceding analysis makes several implicit assumptions that are not plausible in all cases. One is that urban growth always occurs on agricultural land with the highest marginal cost of pollution control, so that low-density growth always reduces the marginal cost of pollution control. In fact, farms closer to urban areas tend to be smaller in size and typically engage in less intensive farming. On the other hand, these farms may specialize in activities that generate more pollution. Furthermore, smaller operations tend to have higher per acre costs of pollution control. For example, in Maryland, farms closer to urban areas are less likely to grow corn, which is widely believed to be a major source of nutrient pollution in both surface and ground waters; they do, however, tend to specialize in livestock (horses, dairy) or vegetables, both of which are positively correlated with higher nitrate concentrations in community water system wells (Lichtenberg and Shapiro). Pollution control measures like construction of manure storage facilities for dairies exhibit decreasing average cost per cow as herd size increases. In sum, one cannot say a priori whether or not urban growth takes place on agricultural land with the highest marginal cost of pollution control.

The model is easily extended to the case where urban growth does not occur on land with the highest marginal pollution control cost. When inframarginal agricultural land is converted to urban use, urban growth has no effect on the marginal cost of pollution control, C_E. Low-density growth with thus have the same qualitative effects on pollution control and mitigation as high-density growth: Conversion of agricultural land to urban uses will result in decreased pollution control in agriculture and increased mitigation by urban users. However, the total cost of pollution management may still fall because of decreased emissions, so that the implications of low-density growth on taxation and future development will remain qualitatively the same. The marginal cost of pollution management, λ, will remain unchanged.

The model also assumes that urban areas contribute nothing to total pollution. Yet leaky septic systems are often significant sources of nitrogen to ground and surface water supplies. Emissions from urban sources can be incorporated into the model by letting mitigated and unmitigated emissions be, respectively:

$$\beta\big((1-\alpha)eA_F + \xi(A_T-A_F)\big)$$
$$(1-\beta)\big((1-\alpha)eA_F + \xi(A_T-A_F)\big).$$

In this case, conversion of agricultural land to urban uses may actually increase total emissions, because emissions from urban sources may be greater than emissions from agriculture; Lichtenberg and Shapiro present some evidence indicating that this occurs. It thus becomes possible that low-density growth will result in increases in pollution control in agriculture, mitigation by urban users and the total cost of pollution management, so that low-density growth would have the same effects on further growth and taxation as high-density growth.

Conclusion

Conversion of rural land to urban uses is a major source of conflicts over water quality. Urbanization has led to growing use of water for drinking, recreation, fisheries and other uses that place a greater premium on high quality than farming. Ground and surface waters that functioned as sources of free disposal for agricultural wastes (nutrients, pesticides) have become sources of conflict between urban users and farmers as urban demand for them has increased.

There has been growing political pressure to alter farming methods to curtail emissions of water pollutants. It has long been known, however, that efficient responses to pollution problems generally include both the control of emissions and mitigation efforts on the part of receptors of pollution, in this case, combinations of on-farm runoff and leaching control with mitigation efforts by urban users such as installing filtration systems, drilling new wells or developing new sources of surface water supply. Equity considerations are important, too. On the face of it, both farmers and urban users have some claim to ownership of rights in water quality, farmers because of historical usage and urban users because of the general social bias against permitting pollution.

Institutional mechanisms for dealing with urban-rural water quality conflicts should address both the efficiency and equity aspects of the problem. This paper investigates the implications of different patterns of urban growth for designing such mechanisms. We examine the impacts of urbanization on (1) the optimal division of effort between on-farm emission reductions and urban mitigation efforts, (2) the total and marginal costs of pollution management overall and (3) the use of taxation to achieve an equitable division of cost through the financing of pollution control and mitigation efforts. We consider two types of urbanization, low- and high-density.

High-density growth leads to increased emphasis on mitigation and decreased emphasis on pollution control, a higher total cost and lower marginal cost of pollution management and higher taxes on both urban and agricultural land. This implies that conflicts over water quality should escalate with urbanization, particularly because of growing dissatisfaction on the part of urban water users whose burden grows over time. Farmers, too, are likely to become increasingly dissatisfied because of the growing tax burden.

Low-density growth, on the other hand, has ambiguous effects on the division of effort between on-farm pollution control and urban mitigation measures. This type of growth has two opposing effects. On one hand, it reduces emissions by taking land out of production, thereby reducing the marginal and total costs of both pollution control and mitigation. On the other hand, it increases the affected population and thus the need for mitigation, making increases in both pollution control and mitigation possible. It is thus possible to find on-farm pollution control increasing and urban mitigation decreasing, urban mitigation increasing and on-farm pollution control decreasing, or both on-farm pollution control and urban mitigation decreasing as agricultural land is converted to urban uses. Similarly, the total cost of pollution management may increase or decrease. (The marginal cost, though, will always fall.) If the total cost of pollution management falls, tax rates on urban and agricultural land will fall, too, leading to reduced conflicts over water quality.

Urbanization that leads to rising costs of pollution management over time and thus rising tax rates may have two types of general equilibrium effects, one on land markets and the other on political-economic markets. Increases in farmers' tax rates should increase their willingness to sell for development. Increases in urban tax rates should reduce demand for development, leading to reductions in growth along with falling land prices. Alternatively, increases in tax rates may lead to increasing conflict over taxation. The growth of the urban population is likely to lead to shifting more of the burden onto farmers, which will lead to increases in the supply of land for development simultaneously with increases in demand and thus greater growth. In either case, the period of adjustment is likely to be long and conflicts over water quality may well get worse before they get better.

Footnotes

1. If for some reason the marginal cost of pollution control always exceeds the marginal cost of mitigation, then it will be efficient to use only mitigation to meet the standard N. If the marginal cost of mitigation always exceeds the marginal cost of pollution control, then it will be efficient to use only pollution control.

2. Pigouvian taxes may be difficult to implement because agricultural emissions are typically unobservable. In most cases, farmers do not know how much nutrients, pesticides or soil is running off their land into ground and surface waters. Monitoring is expensive, because pollutants run off a large number of sites on each farm. Thus, uncertainty about emissions is generally large. Furthermore, emissions are highly variable because of their dependence on weather; large storms typically produce emissions that are many times greater than those in average weather. When damage is produced mainly by random rare events, direct regulations tend to perform better than taxes (Weitzman).

3. In fact, it may not be possible to demonstrate even just a linkage between any class of nonpoint source polluters and existing pollution with the degree of reliability required for legal proof, since judges typically have much more stringent standards of reliability than can be attained through statistical methods.

4. Even if it were possible to demonstrate some linkages to the satisfaction of the court, uncertainty about emissions creates a moral hazard problem in that it creates a positive probability that emissions will not be detected. In such cases, direct regulation performs better than use of legal liability (Shavell).

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