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Allocating Land for an Ecosystem Service: A Simple Model of Nutrient Retention with an Application to the Chesapeake Bay Watershed

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*** All opinions expressed herein are those of the author alone, and do not necessarily reflect those of the United States Environmental Protection Agency.**

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Abstract: There has been great interest in recent decades in "ecosystem services". One of the services most often mentioned is the retention of nutrients. I construct a simple model of agricultural land use under a regulatory requirement that nutrient loading cannot exceed a fixed ceiling develop three propositions. First, when the regulatory constraint is relatively weak there will be a corner solution in which no land is set aside to provide the service of nutrient retention. Second, for any given regulatory constraint there is in general a minimum amount of land that would be set aside to provide ecosystem services, regardless of the efficiency with which preserved land provides the nutrient retention function. Third, there is sort of paradox of value: the more valuable it is to set *some* land aside for nutrient retention, the *less* land in total would optimally be preserved for this purpose. I illustrate the implications of this model with an application to the Chesapeake Bay watershed. Estimates reported in the literature suggest that land retained in natural cover could prove very effective in retaining reactive nitrogen and other nutrients. If so, there is a sort of "good news/bad news" scenario for conservation advocates touting the importance of ecosystem services. The good news is that the ecosystem service of nitrogen retention is, in fact, likely to be very valuable. The bad news is that "a little may go a long way": setting aside small areas of land may be sufficient.

Key words: reactive nitrogen; diamonds and water paradox; ecosystem services; constrained optimization; land use regulation; corner solution.

Subject Areas: Costs of Pollution Control, Land Use (in agriculture)

JEL classification: Q24; Q53; Q58

Introduction

The term "ecosystem services" is in vogue (see, e. g., MA 2005; Daily and Matson 2006; Daily and Turner 2008; Fisher *et al*. 2009; and the papers introduced by Kareiva and Ruffo 2009). The basic idea is that preserved or restored "natural"[1] ecosystems sustainably provide a suite of goods and services whose aggregate net present value exceeds that which would arise from managing the land more intensively. A large and growing literature promotes the vision that a society that recognizes the importance of ecosystem services will devote larger fractions of the landscape it manages to the preservation of natural areas.

Yet despite the burgeoning literature[2] on the topic, there are relatively few contributions that document a rigorous empirical case for the economic value generated by ecosystem services. Since "ecosystem services" can comprise an extraordinarily broad spectrum of goods and services (see, e. g., Daily 1997 and MA 2005 for representative lists),[3] it would be difficult, if not impossible, to conduct a point-by-point assessment of each and every component element. While some very trenchant criticisms have been offered of seminal work on water purification (see Sagoff 2002, who comments on Chichilnisky and Heal 1998, and Plummer 2009, who comments on Breaux *et al.* 1995), and pollination (see MccCauley 2006, who comments on Ricketts *et al*. 2004), there are whole topic areas awaiting both initial empirical estimates and careful peer review.[4]

While it is frustrating to be reduced to a piecemeal approach to such a wide topic area, there appears to be little alternative. Yet in considering specific ecosystem services, we may yet uncover, or, perhaps put more accurately, *confirm*, the importance of economic principles that will apply more broadly. This is my objective

One ecosystem service that is often mentioned is the capacity of natural ecosystems to retain and neutralize pollution, especially nutrients that would otherwise eutrophy (that is, over-fertilize) and disrupt aquatic ecosystems (see, e. g., Daily 1997; MA 2005; Breaux, *et al*. 2005; Plummer 2009). Such services could be of great value in many policy settings. Ribaudo *et al*. (2001) consider the economic implications of setting aside cropland for the retention of nitrogen and other nutrients.

This subject is also very topical. A recent Presidential Executive Order requires U. S. federal agencies to take more active steps to protect and restore the Chesapeake Bay.[5] A recent interagency report responding to the Executive Order concludes that "There is no more cost-effective strategy [for meeting environmental and other goals]. . . than conserving existing farms, forests, natural areas, habitat, and other vital resources" (FLC 2009). It is natural to ask, then, both how cost-effective such a strategy is, and, if it is cost-effective, how it might best be implemented.

The Chesapeake Bay example is very useful, as regulators have suggested a quantitative nutrient loading reduction goal: nitrogen loading to the Chesapeake Bay is to be reduced by 30% (EPA 2009). Thus I can largely sidestep the vexing issue of the valuation of natural habitats for their contribution to ecosystem services. Because nonmarket valuation methods are often imprecise and in some instances very controversial, estimates of value are unavoidably suspect. If, instead of needing to determine what level of nutrient loading would result in the greatest social value, I can ask what costs would be incurred to meet a particular standard, the analytical task is far simpler. I can, however, still talk about the "value" of natural ecosystems as the reduction in opportunity costs their preservation affords relative to alternative methods of complying with the regulatory requirement.

This perspective is useful, although the main message that emerges from employing it is that concentrating on the "value" afforded by natural ecosystems in their provision of the ecosystem service of nutrient retention may be misleading. I use a very simple but, I argue, canonical, model to demonstrate three key results. As much of the concern with nutrient reduction arises from the fertilizers employed in, and animal excrement that is a by-product of, agriculture, I employ the terminology of "farmland cultivated" and "farm earnings" in the model, although similar principles might also be applied to other sources of nutrient loading. The three results are:

1. When required nutrient reductions are modest, the optimal policy response is a corner solution in which nutrient inputs are reduced but all available land is cultivated.

2. When nutrient reduction targets are more aggressive, it will often be cost-effective to meet them by reserving some areas of natural habitat, but the areas whose preservation may be justified by their provision of the nutrient retention service may prove to be surprisingly small.

3. There is an inverse relationship between initial value on the margin – that is, the benefit realized from setting aside the *first* hectare of habitat to provide ecosystem services – and the extent of habitat whose preservation can be justified by its provision of the nutrient retention service. The *least* preservation of natural habitats may be justified when the nutrient retention service provided by the first hectare preserved is *most* valuable.

These results can be explained by two principles. Both underscore the crucial economic role of scarcity. First, land is, in general, scarce. Farmers incur substantial opportunity costs if they forgo the cultivation of available land, or give up the option to employ it in uses that would not be compatible with conservation. In contrast, it is reasonable to suppose that, in the *status quo*, farmers employ polluting inputs until the marginal profit they can realize from further application vanishes. Under such circumstances, it is easy to see what a farmer would do in order to meet a requirement to *slightly* reduce the pollution her activities cause: reduce the employment of polluting inputs rather than setting aside more land to retain them.

I might characterize the other important principle as "the diamonds and water paradox on steroids". The diamonds and water paradox is the principle that things that may be immensely valuable in aggregate may be of negligible value on the margin. The "diamonds and water paradox on steroids" holds when marginal values are necessarily negligible as quantities increase. The ecosystem service with which we are concerned here is the retention of nutrients. Suppose that preserved areas of natural ecosystems are very effective in performing this function. If this proves to be the case, then "a little goes a long way". If the first hectare of land retains the lion's share of pollution, there will be little left for the second hectare of land to retain, and hence, little reason to preserve it. Conversely, if preserved land is *not* very effective in retaining nutrients, it will prove more cost-effective to forgo its preservation and reduce the application of nutrients.

Most of this paper will be devoted to establishing the results above and demonstrating the intuitions just outlined. The heart of the paper consists of formal, if schematic, modeling. Before launching into that venture, however, I present in the next section a description of an area in which the nutrient retention ecosystem service may prove to be very important: the Chesapeake Bay watershed. Following that I introduce a simple model, solve it, and demonstrate the first three results above. The fourth section of the paper calibrates the model to the circumstances of the Chesapeake Bay watershed. The fifth section considers the robustness of the results. The final section concludes with some conjectures regarding the application of similar methods to the allocation of land for the provision of other ecosystem services.

2. A motivating example: the Chesapeake Bay watershed

Several contributors to the literature on ecosystem services have included among the most important services treatment of pollution. Natural ecosystems filter and trap materials that would otherwise enter more sensitive receiving areas and cause greater damage. In some instances the ecosystem merely slows the transmission of pollutants, but in others pollutants may be detoxified or neutralized.

One interesting and, at this point, very topical, application of this pollution treatment function is found in the Chesapeake Bay watershed. Chesapeake Bay is the largest estuary[6] in the United States. Its watershed spans about 64,000 square miles in the states of Maryland, Delaware, Virginia, West Virginia, Pennsylvania, and New York, and the District of Columbia. While about 17 million people live within the watershed, some 25% of the land in the watershed is devoted to agriculture (FLC 2009).

The Chesapeake Bay is in poor condition. One of the largest problems is eutrophication. Eutrophication results when excessive nutrients are introduced into a water body. The nutrients stimulate the growth of organisms such as algae. When the algae die they sink to the bottom, and oxygen is depleted from the water in the process of their decomposition. This leads to hypoxic (low dissolved oxygen) or anoxic (no dissolved oxygen) conditions under which fish and other animals cannot survive.

The two most important nutrients in the Chesapeake Bay are reactive nitrogen and phosphorus.[7] I will concentrate on the former here. Reactive nitrogen can come from a variety of sources. Natural sources include lightning, fixation by microorganisms, and recycling via excretion of pre-existing reactive nitrogen. Man-made sources include combustion, sewage treatment plants, rural septic systems, storm runoff from urban areas, and agriculture. Some 284 million pounds of reactive nitrogen are now introduced into the Bay per year. Experts estimate that this will need to be reduced by about 30%, to 200 million pounds per year, if the Bay is to recover (EPA 2009).

About 46% of reactive nitrogen entering Chesapeake Bay comes from agriculture. Of the nitrogen of agricultural origin, about half results from the application of fertilizer to crops, the other half from farm animal excretion. While some of the reactive nitrogen employed in agriculture becomes airborne and reaches the Bay through deposition, the great majority runs off in surface or groundwater (EPA 2009).

It has proved particularly difficult to reduce reactive nitrogen loading to the Bay because most of it comes from "nonpoint sources": relatively small-scale operations whose use and emissions are difficult to monitor. However, many commentators hope that loading from agriculture can be reduced considerably. There are a number of ways in which this might be accomplished, other than by simply reducing the scale of agriculture. Farmers can adopt different tillage practices, target fertilizer applications, plant "cover crops" to reduce runoff when other crops are not present, modify animal feed, better manage manure, and/or better manage runoff water from their lands. Moreover, farmers (and other landowners) can preserve or restore elements of the natural landscape to intercept, retain, and, ideally, "denitrify" runoff.

Less intensively managed landscapes can reduce reactive nitrogen loading for a couple of reasons over and above the simple fact that no further nitrogen is applied to them. One factor is that water flows more slowly through such landscapes. Taller, denser vegetation forms a physical barrier to water flow. Root networks create channels into the soil into which water can percolate. More of the reactive nitrogen is then likely to be incorporated into plant growth. Of course, in steady state, this might lead only to a slower speed of transit from farm to Bay, rather than an actual reduction in flows.[8, 9] There are, however, natural processes by which reactive nitrogen is "denitrified"; this means that the various molecular forms of reactive nitrogen are broken down into other elements and N_2, the molecular form of the inert, "nonreactive" nitrogen that comprises nearly four-fifths of the atmosphere.[10]

The facts as I have laid them out can be used to structure a constrained optimization problem. Suppose that total reactive nitrogen loading is restricted to a set limit. What fraction of the landscape should be devoted to natural ecosystems so as to meet the loading constraint with the least sacrifice of other social benefits? I turn to the characteristics of a solution to such a problem next.

3. A Simple Model and its Implications

In this section I present a very simple model. This model is not intended to represent real-world circumstance with any precision; rather, it is intended to illustrate possibilities. It can, however, be argued that model is relatively general.

Consider a production process. Let me call it "agriculture" for concreteness, although it could apply in other contexts, or to some aggregation of activities. Agriculture involves the combination of "inputs," which I will denote by a vector $\mathbf{x}$, with "land," A, to produce output, Q. Suppose also that this production process gives rise to a residual, which I will denote by R.[11] Now if $f(\mathbf{x}, A, R)$ is the production function describing the amount of output that can be produced using variable inputs $\mathbf{x}$ and some fixed amount of land, A, while generating a polluting residual of no more than R, we can say that profits are

$$\Pi(R, A) = \max_{\mathbf{x}} \; Pf(\mathbf{x}, A, r) - \mathbf{w}'\mathbf{x} \;\; \text{s. t. } r \leq R, \qquad (1)$$

where P is the price of output and $\mathbf{w}$ the price vector of the inputs.

While the first and second results I derive below can be demonstrated to be reasonably general, it is difficult, and not always very revealing, to work at a very high level of generality. Let us, then, consider what functional form might be adopted as a laboratory, as it were, in which to experiment with the properties of the function $\Pi(R, A)$. Reasonable desiderata for such a specification are, first, that profits be increasing over a range of values of R and A, second, that for a fixed area of land available, profits are a single-peaked function of R — that is, there is a point at which farmers reach diminishing returns in residual pollution; and third, that the profit function exhibits diminishing returns in R and A separately. It is also helpful to suppose that the profit function exhibits constant returns to scale in R and A: if we scaled up both land area available and the residuals permitted proportionately, profits would increase in the same proportion.

The reader may find this last assumption problematic, so I will digress momentarily to defend it on two bases. First, I will argue in more detail below that this assumption is conservative, and my results would hold *a fortiori* if I supposed – admittedly more realistically – that the existence of other fixed factors prevents perfect replication. Second, my intention here is to sketch a rather simple argument: that the amount of valuable land whose preservation can be justified to provide the ecosystem service of nutrient retention may be limited. This is not to say, of course, that the preservation of a lot of *cheap* land would not be a good idea. If copious quantities of cheap land were still lying about, however, there would be far less controversy about conservation policy. It is, then, useful to go through the exercise of seeing what happens in a homogeneous benchmark model in which all land is of equal potential value before thinking about special cases.

Finally, it seems reasonable to suppose that the release of some residual nitrogen would be essential: nothing can be produced without *some* pollution. In the case of nitrogen this is literally true. Even if one did not apply fertilizer, the very act of breaking ground results in the oxidization of some of the nitrogen trapped beneath it. Similarly, it is impossible to raise farm animals in numbers greater than the land's natural carrying capacity without feeding them from some outside source and, consequently, releasing nitrogen in their excretions.

A function satisfying these requirements is

$$\Pi(R, A) = \alpha R - \beta \frac{R^2}{A}, \tag{2}$$

where α and β are constants that could be calculated by calibrating the model to real-world data. Expression (2) has been chosen because of the strikingly simple form of the results that emerge from it. However, it is worth noting that expression (2) is a second-order approximation to *any* constant-returns to scale profit function in R and A in which R is essential. [12] While there could be infinite variations on the theme, I would argue that any results that arise from the use of expression (2) merit at least a rebuttal presumption of generality.[13]

Normalize the land area to one. Then setting $A_0 = 1$ (the subscript zero will relate to quantities that obtain in the absence of regulatory restrictions), profit is maximized in the absence of regulatory constraints when the derivative of (2) with respect to R is equal to zero, i. e., when

$$R_0 = \frac{\alpha}{2\beta}. \tag{3}$$

It will be convenient to note for later reference that earnings in the absence of any regulatory constraint (or, equivalently, the rent to land) are given by

$$\Pi_0 = \frac{\alpha^2}{4\beta}. \tag{4}$$

The ecosystem service of nutrient retention is provided when some portion of the landscape is preserved to provide ecosystem services rather than cultivated to produce more output. Suppose that a fraction D of the residual is "passed through" and deposited in a sensitive receiving area — in the motivating example, Chesapeake Bay — while the complementary fraction, $1 - D$, is retained so it cannot harm the receiving area. It seems natural to suppose that the fraction neutralized would increase in the amount of land retained for the provision of ecosystem services, but that the relationship would be concave: adding more land would result in a less-than-proportional overall reduction in the neutralization of residual pollution (this diminishing returns assumption is *not* crucial to the results; see section 5). Moreover, it is also reasonable to require that if no habitat were retained for this purpose, 100 percent of residual pollution would be passed directly from the agricultural sector into the receiving environment.

A function having these properties is

$$D(A) = \frac{1}{1+\phi(1-A)}, \tag{5}$$

where ϕ is also a constant. I will refer to this as the "deposition" function.

Note that

$$\lim_{y\to\infty} D(y) = 0; \tag{6}$$

if it *were* possible to put aside an arbitrarily large area to retain nutrients, all nutrients would be retained. Since the area available can be no greater than one by our choice of normalization, however,

$$D(0) = \frac{1}{1+\phi}, \tag{7}$$

and

$$D(1) = 1. \tag{8}$$

Moreover,

$$D'(A) = \frac{-\phi}{[1+\phi(1-A)]^2} = \frac{-\phi D(A)}{1+\phi(1-A)}. \tag{9}$$

Note that the deposition function is approximately exponential for values of *A* near one. Expression (9), like expression (2), was chosen for analytical tractability rather than verisimilitude. However, its "quasi-exponential" form means it comports reasonably closely with the description often encountered in the empirical literature on the nutrient-retention potential of natural ecosystems; that is, that a certain area of natural ecosystem will retain a certain fraction of incident nutrients (see, e. g., Mayers *et al* 2007).

The parameter ϕ can be regarded as a measure of the efficacy of preserved habitat in neutralizing pollution: fixing *A*, the *larger* is ϕ, the more pollution is retained, rather than being deposited in the receiving body.

Now suppose that agricultural production and the use of inputs therein is to be constrained so that the pollution "load" received in the sensitive area does not exceed some limit, $\overline{L}$. Thus

$$\frac{R}{1+\phi(1-A)} \leq \overline{L}\,. \tag{10}$$

I will assume that this loading constraint is binding, and treat (10) as an equality. Rearranging (10), we have

$$R = [1+\phi(1-A)]\overline{L}\,. \tag{11}$$

Substituting this expression in the profit objective, (2), the objective is to maximize by choice of the area of land cultivated, A,

$$\alpha[1+\phi(1-A)]\overline{L} - \beta\frac{[1+\phi(1-A)]^2\,\overline{L}^2}{A}\,. \tag{12}$$

The first-order condition for an optimum is that

$$-\phi\alpha\overline{L} + \beta\frac{2A\phi[1+\phi(1-A)] + [1+\phi(1-A)]^2}{A^2}\overline{L}^2 \geq 0\,. \tag{13}$$

The first-order condition is expressed as an inequality because, as we will see momentarily, corner solutions in which all land is cultivated obtain under some circumstances.

Assuming equality for now, simplifying and rearranging,

$$\alpha = \frac{\beta\overline{L}}{\phi A^2}\left[(1+\phi)^2 - \phi^2A^2\right], \tag{14}$$

or

$$A^2 = \frac{\beta\overline{L}(1+\phi)^2}{\alpha\phi + \beta\overline{L}\phi^2}\,. \tag{15}$$

Expression (15) can be simplified further if we make a substitution. Recall that, in the absence of regulation, the residual *R* would be produced in the quantity $R_0 = \alpha/2\beta$. As there would be no reason *not* to expand agriculture to the full area available for cultivation, A_0 =1 in the absence of regulation. Thus the pollution load received in the sensitive area would also be $L_0 = \alpha/2\beta$. I will now express the loading constraint, $\bar{L}$, as a fraction, ρ, of the unregulated loading, L_0. That is,

$$\bar{L} \; = \; \rho L_0 \; = \; \frac{\rho\alpha}{2\beta}. \tag{16}$$

Substituting this expression in (16), α and β cancel, leaving

$$A^2 \;\; = \;\; \frac{\rho(1+\phi)^2}{\phi(2 + \;\rho\phi)} \tag{17}$$

While it is an artifact of the approximation by which (2) was derived, expression (17) is conveniently compact. The area of land cultivated depends only on one parameter measuring regulatory stringency, ρ, and another indexing the effectiveness of preserved land in retaining nutrients, ϕ.

I can now demonstrate the three results summarized in the introduction.

Proposition 1: When the regulatory loading constraint is not very strict, there must be a corner solution in which all land is cultivated.

The area of land cultivated, *A*, will be less than one when

$$\rho(1+\phi)^2 \; < \; \phi(2 + \; \rho\phi) \tag{18}$$

or

$$\rho \; < \; \frac{2\phi}{1+2\phi}. \tag{19}$$

The fraction on the right-hand side of (19) is strictly less than one. For any finite ϕ, then there must exist values of ρ that are less than one for which *no land would be preserved for nutrient retention*. The objective would be entirely met by a reduction in input usage.

Expression (19) provides confirmation of a general proposition. Residuals will be generated until their marginal contribution to profitability is zero. If land is scarce, it is expensive, and so small reductions in loading are best achieved by reducing purchased inputs other than land.

Proposition 2: For any regulatory objective, there is a minimum area of land that will be cultivated, regardless of the effectiveness of land in retaining nutrients.

Expression (19) demonstrates that if ϕ were small enough, A would be one for any positive value of ρ. Intuitively, it makes little sense to set aside land for retaining nutrients if the land being set aside is not very effective for this purpose. It is also intuitive, though, that if ϕ where *large* enough, the area preserved to retain nutrients would be vanishingly small. This intuition is easily confirmed by applying L'hospital's Rule twice to expression (17):

$$\lim_{\phi \to \infty} \frac{\rho(1+\phi)^2}{\phi(2 + \rho\phi)} = \lim_{\phi \to \infty} \frac{2\rho(1+\phi)}{2(1 + \rho\phi)} = \lim_{\phi \to \infty} \frac{2\rho}{2\rho} = 1. \tag{20}$$

If vast quantities of nutrients could be neutralized by setting aside only a very small area of land, there would be no reason to forgo the cultivation of any more land than necessary.

So, if ϕ, which measures the effectiveness with which preserved areas of natural habitat retain nutrients, were very small we would have a corner solution at A =1, while if ϕ were very large, we would also approach the corner solution of A = 1. It is natural to ask, then, what the minimum value A attains might be.

To answer this question, first differentiate expression (17) with respect to ϕ

$$2A\frac{\partial A}{\partial \phi} = \frac{2\rho(1+\phi)}{\phi^2(2 + \rho\phi)^2}[(1-\rho)\phi - 1]. \tag{21}$$

Thus $\partial A/\partial\phi = 0$ when the term in square brackets is zero:

$$\phi^* = \frac{1}{1-\rho}. \tag{22}$$

This is the only extreme point on the interval $1 \geq \rho \geq 0$ and, as I will now show that it leads to a value of A that is not greater than one, it must identify a unique minimum. Substituting from (22) into (17),

$$A^* = \sqrt{1-(1-\rho)^2}. \tag{23}$$

The *minimum* amount of land area cultivated varies from none, when nutrient loadings are to be totally eliminated, to one, when the *status quo* is preserved. In between, however, land cultivated is a convex function of the regulatory constraint, ρ, with A^* greater than ρ for all values of the latter between zero and one.

The optimal reduction in land area is often much less than proportionate to the reduction in loading required. For example, the *maximum* reduction in land area cultivated that would be required to meet a 28% reduction in loading would be 4%.

Proposition 3: The more preserved land is "worth" ab initio*, the less land should be preserved.*

Much of the literature on ecosystem services has focused on the question of whether land would be worth more preserved in, or restored to, natural habitat, as opposed to in more intensive managed use. The goal of such exercises is to determine whether *some* land, or a particular parcel of land, should be devoted to providing ecosystem services. It is also important to know, however, *how much* land should be devoted to providing ecosystem services. It may seem natural to suppose that if *some* land could be shown to be extremely valuable in the provision of an ecosystem service, then *a lot* of land out to be set aside for that purpose. That is not generally correct, however.

Note first that when there is an interior solution – that is, when the area of land cultivated is strictly less than the total area of land available for cultivation – the marginal value of land preserved for nutrient retention would be exactly equal to the marginal value of cultivated land.

Let us, then, conduct a thought experiment. Suppose that the regulatory constraint, (10), must be met *without reducing the amount of land cultivated* below its normalized *ex ante* value, 1. It would then follow from (10) that

$$\overline{R} \;=\; \overline{L}\,, \tag{24}$$

where I denote by $\overline{R}$ the residual permitted while meeting the loading constraint. This, in turn, implies that

$$\overline{\pi} \;=\; \left[\alpha - \beta\overline{R}\right]\overline{R} \;=\; \rho(2-\rho)\pi_0\,, \tag{25}$$

where the second equality follows from (4) and (16), and π_0 is land rent in the absence of regulation.

Now let's ask by how much would overall earnings from agriculture increase if one hectare of land were removed from production and restored to provide the nutrient retention ecosystem service?

To answer this question, we need to return to the first-order condition, (13), and evaluate it at $A = 1$. It will be useful to rearrange (13) as

$$\frac{d\pi}{dA} \;=\; \left(\alpha - 2\beta\frac{R}{A}\right)\frac{dR}{dA} + \beta\frac{R^2}{A^2}\,. \tag{26}$$

The second term on the right-hand side of equation (26) is the direct effect of cultivating more land – it is the marginal increase in profit resulting from employing more land. The first term on the right-hand side of (26) is the indirect effect induced by affording the possibility of producing more residuals since such residuals can be partially offset by the ecosystem services provided by preserved habitats. Differentiating the regulatory constraint, (11), with respect to A,

$$\frac{dR}{dA} = -\phi\bar{L} \,. \tag{27}$$

Substituting (27) into (26) and evaluating (26) at $A = 1$

$$\frac{d\pi}{dA} = -\phi\bar{L}\left[\alpha - 2\beta R\right] + \beta R^2 \,. \tag{28}$$

Since $\bar{L} = R = \rho R_0$ when evaluated at $A = 1$, and combining (3) and (4) to note that $\pi_0 = \beta R_0^2$, we have

$$\frac{d\pi}{dA} = -2\phi\rho(1-\rho)\pi_0 + \rho^2\pi_0 \tag{29}$$

Note that $d\pi/dA < 0$ when evaluated at $A = 1$, so the optimal solution requires $A < 1$, only if condition (19) is met. When the optimal solution requires $A < 1$, we might refer to the negative of the first term of (29), which I earlier characterized as the indirect effect of cultivating the marginal hectare of land, as the value of the *first* hectare of land preserved in terms of increased profit afforded by more intensive application of other inputs (and gross of the opportunity cost of leaving such land idle, as represented by the second term in (29)). Note that this value is increasing in ϕ, the effectiveness with which preserved land fulfills the nutrient retention function.

As expression (19) demonstrates that the area cultivated approaches the limit of land available as ϕ grows large, I have established Proposition 3 for this case: the value of the first hectare of land preserved is greatest when the overall amount of land preserved would be least.

This derivation has been somewhat convoluted, so let me provide some further context. Much of the literature on ecosystem services has asked “When is land more valuable for providing ecosystem services than it would be if employed in production directly?” It seems entirely appropriate to conclude that preserving land for the provision of ecosystem services would make sense in many circumstances. My point, however, is that a demonstration that *some* land could be extremely valuable for the provision of ecosystem services says nothing about *how much* land should be devoted to this purpose. I am suggesting that the demonstration that preserving *some* land to provide ecosystem services makes sense may, in fact, set up a sort of good news/bad news scenario for those who appeal to ecosystem services to motivate conservation more generally. The good news is that the argument to set *some* land aside may be logically impeccable. The bad news is that demonstrating very high values associated with setting *some* land aside may necessarily imply that very little land in total should be preserved for that purpose.

4. A Calibration Exercise

In this section I calibrate the model presented above to data from the Chesapeake Bay watershed. As I have suggested above, and will document further in the next section, a multitude of caveats should accompany any such exercise. I will not repeat them here, but say only that it is useful to perform an exercise under the benchmark assumptions of a homogeneous landscape in order to develop a rough idea as to likely real-world outcomes.

With no further ado, then, let us begin with the facts that the current annual loading of reactive nitrogen received in the Bay is about 284 million pounds. It is felt that this loading must be reduced to 200 million pounds per year if the Bay is to be restored. This represents a reduction of about 30%. Of the total nitrogen loading, nearly half – 131 million pounds per year – is attributed to agriculture. Draft plans call for a reduction of loading from this sector by some 44%, to 73 million pounds per year (EPA 2009).

The scientific literature on the effectiveness of riparian buffers for nutrient removal reports a range of estimates of the relationship between the area of land set aside and their effectiveness (Rupprecht, *et al.*, 2009). It seems, however, that buffers are often very effective in removing nitrogen. A recent meta-analysis of 88 studies finds that four meter (13 feet) wide buffers remove half of incoming nitrogen, effectiveness climbs to 75% as width expands to 49 meters (160 feet), and at a width of 149 meters (485 feet) 90% of nitrogen is removed (Mayer, *et al*., 2007). While individual studies do, of course, vary widely, it seems safe to conclude that the general finding of such studies is that relatively small areas can remove substantial fractions of nitrogen, but that, beyond a certain size, little nitrogen remains to be retained (see, e. g., Dillaha et al. 1989; Palone and Todd 1997; Mayer et al. 2005).[14]

The Chesapeake Bay Watershed encompasses an area of 64,000 square miles (FLC 2009). About 115,000 miles of streams run through the watershed (GFIS 2001). Let us suppose, then, that the density of streams in the watershed is 115,000 miles/64,000 square miles = 1.8 miles of stream per square mile. Let us suppose, in what seems a somewhat conservative interpretation of the data as summarized in the Mayer, *et al.* (2007) and Rupprecht *et al*. (2009) reviews, that a riparian buffer extending 50 feet from each bank of a stream is sufficient to remove 50% of the nitrogen that would otherwise flow into it. This corresponds to a total area of 1.8 miles of stream per square mile of area × (2 sides of each stream × 50 feet of buffer on each side)/(5,280 feet per mile) = 0.034 of the area available for cultivation. From the deposition function, (8), we have

$$\frac{1}{2} = \frac{1}{1 + 0.034\phi}, \tag{33}$$

or

$$\phi = \frac{1}{0.034} = 29.4. \tag{34}$$

Using this figure and the regulatory objective of $\rho = 0.56$ in (17),the cost-effective strategy would call for the cultivation of

$$A = \sqrt{\frac{0.56(1+29.4)^2}{29.4(2 + 0.56 \cdot 29.4)}} = 97.6\% \tag{35}$$

of land available, with the preservation of only 2.4%. This figure would correspond to buffers of about 35, rather than 50, feet on each side of streams.

It is, on a moment's reflection, obvious why relatively little land should be devoted to the provision of the nutrient retention ecosystem service. The policy objective only requires that nitrogen loading be reduced by 44%. If buffers extending 50 feet on either side of streams would reduce loading by 50%, the objective could obviously be met with narrower buffers.

In fact, it would appear that the objective could be met largely by requiring modest buffers with little need to modify other practices. It is easily shown that the ratio of residual nitrogen under the cost-effective solution to that in the status quo is, from (10) and (16),

$$\frac{R}{R_0} = [1 + \phi(1 - A)]\rho = [1 + 29.4(1 - 0.976)]0.56 = 94.8\%. \tag{36}$$

As an aside, note that farm earnings under the regulatory constraint would be

$$\Pi(R, A) = 0.948\left(2 - \frac{0.948}{0.976}\right)\pi_0 = 0.975\pi_0; \tag{37}$$

The regulatory constraint might be imposed with a relatively mild effect on the farming sector.

Let me conclude this section with an illustration of the "diamonds and water paradox on steroids". Recall from expression (29) that the value of the first hectare set aside to provide nutrient retention would be (the negative of)

$$\frac{d\pi}{dA} \; = \; -2\phi\rho(1-\rho)\pi_0 + \rho^2\pi_0$$

Using the values $\phi = 29.4$ and $\rho = 0.56$, the first term in expression is some 14.5 times profits in the absence of regulation, while the second term is only about a third of profits in the absence of regulation. These relative magnitudes confirm that it would be a very, very good idea to set aside some land to provide an ecosystem service, nutrient retention.

However, such land quickly becomes superfluous. Recall from expression (22) that the area of land preserved would be maximized if the effectiveness parameter were

$$\phi^* \; = \; \frac{1}{1-0.56} \; = \; 2.3 \tag{38}$$

Under these circumstances the amount of land cultivated would be

$$A^* \; = \; \sqrt{1-(1-0.56)^2} \; = \; 89.8\% \, . \tag{39}$$

of the land available. Over four times *more* land would optimally be devoted to the provision of the nutrient retention service if preserved land were some 12 times *less* effective in providing this service.

5. Caveats

I have employed a very simple model to generate results. This begs the question of whether the results I have derived are general, or if they are just artifacts of the specific functional forms chosen. A couple of concerns can be dismissed quickly. The first result, that a corner solution will obtain when the regulatory constraint is weak relative to the pre-regulatory *status quo*, is general so long as land is scarce in the absence or regulation. The second result, that there is necessarily a minimum area of land that will be cultivated for any specific level of regulatory stringency and regardless of the effectiveness of preserved land in performing this function is also general. Obviously, it can never be optimal to devote *all* land to the retention of nutrients, as there would then be no land employed in farming, no fertilization of crops, no importation of animal feed, and consequently, no excess nutrients to be retained.

I have, however, characterized the second result as saying that not only is there a minimum area of land that would be cultivated given the level of regulatory stringency, but that minimum may be rather large. “Rather large” in this context means that the fraction of land cultivated relative to the pre-regulatory *status quo* is considerably greater than the fraction of the pre-regulatory loading allowed under regulation (in my notation, $A >> \rho$). As it is difficult to derive this result for a general model, I can only say that my numerical experiments with other functional specifications for the profit function such as Cobb-Douglas and translog variants, as well as with alternative exponential, linear, and hybrid specifications of the deposition function have yielded more, rather than less, dramatic results than emerge from the analytically tractable model I have employed above.[15] This has also been the case with the third result. Substitution of alternative functional forms makes the analytical derivation of results more complex, but does not eliminate the ostensibly paradoxical result that *less* land would be preserved when the effectiveness of nutrient retention renders the value afforded by the first hectare preserved *greater*.

In short, then, numerical results support the contention that the results outlined above are robust.

The next question to ask, then, is whether the ways in which I have structured the general problem are unduly restrictive and, if so, if they bias results. Is it unreasonable to suppose there are constant returns to scale in production, and hence that the profit function if homogenous of degree one in R and A? Yes, it probably is. "Land" is not homogeneous, and consequently, agricultural operations cannot be replicated perfectly on less-advantaged land. However, the clear implication of this observation is that the opportunity cost of withdrawing land from production is increasing in the area of land preserved. Thus my results should be strengthened under alternative assumptions.

It may also be unreasonable to suppose that the perfectly competitive conditions required to derive the reduced-form profit function of expression (1) obtain over large landscapes. As land is withdrawn from production and residual nutrients decreased agricultural production would decline. This, in combination with less-than-perfectly elastic demand for output would mean, again, that the opportunity cost of withdrawing land from production would change as the amount of land withdrawn increases. At the same time, however, the prices of less-than-perfectly-elastically supplied inputs would fall. It seems reasonable to conclude, however, that the net effect of such offsetting factors could be regarded as close to neutral (for a study that carefully considers the general equilibrium effects of land preservation policies designed to address nutrient retention, see Ribaudo *et al*. 2001).

Another concern that might be raised with the modeling assumptions I have adopted is that it is unreasonable to suppose that land available for farming is strictly fixed. Several justifications might be offered for the simplifying assumption that it is, however. First, the total amount of land available for all purposes in a particular region is, of course, fixed. Land not devoted to farming or preserved in natural areas would likely be devoted to some combination of activities that would themselves involve the laying down of impermeable surfaces, combustion, occupation by people who produce more sewage, and other activities that also increase reactive nitrogen residuals. Second, inasmuch as the supply of land to agriculture is determined by the demand for residential and commercial purposes, that supply may be relatively inelastic. Finally, and apropos of the subject of the next paragraph, while agriculture might well expand into the still-plentiful forested upland areas of the watershed, the more relevant question for our purposes concerns the division of land use between cultivation and preservation in the often-more-valuable downstream areas.

The largest problem with the modeling approach I have adopted is that it presumes all land is homogeneous. The simple model I have developed would be of little, if any, use in determining exactly which parcels of land would best be devoted to the retention of nutrients. Such micro level, on-the-ground planning will remain the province of more careful modelers who will compensate for the idiosyncrasies of topography, soil chemistry, hydrology, native vegetation, and the like in making their determinations of which specific areas should be farmed and which preserved to provide ecosystem services such as nutrient retention.

It is, however, worth emphasizing that if it were widely accepted that a fortuitous but strong inverse correlation existed between a parcel's value in agriculture and its effectiveness in retaining nutrients, the problems of excess nitrogen loading in water bodies like Chesapeake Bay would have been solved long ago. Over half of the land in the Chesapeake watershed is currently in forests (FLC 2009). If these forests are effective in retaining nutrients and they were in the "right places" for that purpose, there might well be no problem with excessive nutrient loading. If there is a problem, it must be because the opportunity cost of setting aside natural areas to retain nutrients *in the areas in which they would do the most good* are considerable. The question I have been asking, then, is whether appeal to the ecosystem service of nutrient retention would motivate the preservation (or, more likely, restoration) of a great deal of additional natural habitat. The principles illustrated by my simple model suggest that it might not.

6. Conclusion: Implications for the Ecosystem Services Framework

Let me return in closing to the "good news/bad news" message of this paper. The good news, from an ecosystem conservation perspective, is that the preservation of natural ecosystems is likely to comprise a critical part of a cost-effective strategy for nutrient management. My modeling effort, simple and schematic though it may be, would appear to confirm the conclusion noted above: "There is no more cost-effective strategy . . . than conserving existing farms, forests, natural areas, habitat, and other vital resources" (FLC 2009).

The "bad news", however, may be that the provision of this ecosystem service does not necessarily create a compelling argument for larger-scale conservation. Precisely because preserved natural ecosystems perform their functions so cost-effectively, "a little may go a long way".

Natural ecosystems provide a host of services, however, and economic theory suggests that they should be preserved so long as the *sum* of the values of the incremental benefits their preservation generates exceeds the opportunity costs of preservation. The incremental benefits of the full suite of services remain to be established. Many of the benefits of ecosystem services may be of a similar character to those of nutrient retention, however. Many of the services of natural ecosystems are valuable precisely because they protect or augment the value, or mitigate the impact, of the decidedly *unnatural* systems of homes, agriculture, and industry of the areas they adjoin. There will, then, generally be an interior solution to the land allocation problem characterized by a tradeoff between the benefits of expanding areas preserved and the opportunity cost of forgoing intensive use of such areas. The "diamonds and water paradox on steroids" that motivates my results could prove to be general. If natural ecosystems are not sufficiently productive in generating ecosystem services, they may not provide enough value to justify the opportunity costs of their preservation. If, however, they prove *too* effective in providing ecosystem services, we may conclude that a little goes a long way, and not decide to save *much* of them.[16]

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End notes

[1] The quotation marks around "natural" are intended to suggest the difficulty of defining what comprises a "natural" as opposed to an "artificial" or "managed" system. See, e. g., Charles Mann's fascinating book *1491* (2007) for examples of how ostensibly "natural" systems may reveal hints of long and careful management. For the purposes of this paper, it may be better to distinguish "more intensively managed"

from “less intensively managed” systems, and consider the assertion that the latter are more effective than the former in supplying certain socially valuable goods and services.

[2] Fisher and Turner document exponential growth in the number of publications dealing with “ecosystem services,” beginning from essentially none in the early 1980’s to more than 250 in 2007, the last year for which they had data.

[3] It should also be noted that the term “ecosystem services” is used in different ways by different authors. For example, the nutrient recycling function performed by microorganisms in the soil is certainly an “ecosystem service,” but its provision does not depend on the preservation of large areas of pristine habitat (I am grateful to Andy Manale for providing this example and emphasizing its importance).

[4] I might also add to this list the work of Simpson *et al*. 1996, which suggested that the value of biodiversity in new product research had been overstated, although that work, and the earlier papers to which it responded, was completed before the term “ecosystem services” came into vogue. New-product sourcing continues to be listed in compendia of ecosystem services, however (see, e. g., MA 2005).

[5] Executive Order 13508, Issued 12 May 2009. http://www.gpoaccess.gov/presdocs/2009/DCPD-200900352.pdf.

[6] An estuary is a body of water in which fresh and saltwater mix.

[7] I will not consider phosphorus or sediments, which are also major problems in Chesapeake Bay, further here. However, reactive nitrogen, phosphorus, and sediments tend to arise from similar activities, and to be retained in roughly proportionate quantities by preserved or restored natural ecosystems.

[8] We should not, however, completely dismiss timing-of-load issues. If reactive nitrogen is greatly slowed in its transmission to the Bay, it could arrive in a Bay less stressed by other nitrogen sources and perhaps better situated to deal with more nitrogen. In particular, it is hoped that native oysters might be reestablished in the Bay. The current oyster population of the Chesapeake is believed to be less than one percent of its historical level. Widely cited figures claim that, when oysters were healthy, they could filter the entire water mass of the Bay in a period of three or four days. Doing so now would take over a year (FLC 2009).

[9] The processes of nitrogen retention may become very complex. Plants also bind nitrogen in complex organic molecules from which it cannot easily escape, and which may, depending on the attributes of the ecosystem in which they are growing, sequester it for long periods of time.

[10] This is a desirable end over and above its eutrophication consequences. Among the various nitrates, oxides, and other compounds containing reactive nitrogen are toxins and potent greenhouse gases.

[11] I could generalize to suppose that Q and R are also vectors, but there seems to be no real gain from doing so.

[12] The assumption of constant returns implies that

$$\Pi(R, A) = \pi(R/A)A.$$

The assumption that R is essential means

$$\pi(0) = 0.$$

To a second-order approximation of $\pi(R/A)$ around $R = 0$, then,

$$\Pi(R, A) \approx \left[\pi(0) + \pi'(0)R/A + \frac{1}{2}\pi''(0)R^2/A^2\right]A \cdot$$

The first term in square brackets is zero by assumption. Setting $\alpha = \pi'(0)$ and $\beta = -\frac{1}{2}\pi''(0)$, we have expression (2).

[13] Another convenient, if less general, way in which to motivate equation (5) is to suppose that $R - \gamma R^2/A$ is a constant-returns-to-scale production function in a single input polluting input R purchased at price w. If P is the price of output, then $\alpha = P - w$ and $\beta = P\gamma$.

[14] It should also be noted, however, that the literature warns against generalization. The amount of nitrogen that will be delivered to a water body depends not only on the size of the area through which it will be filtered and retained, but also the properties of soils, the slope of the terrain, the type of vegetation covering it, and other factors. Moreover, more nitrogen will be flushed out during storms than during more tranquil periods, so such studies implicitly (or, occasionally, explicitly; see, e. g., . Finally, nitrogen may be retained to different degrees and with differing levels of certainty depending on whether it is fully denitrified (converted back into atmospheric nitrogen, N_2) or bound into complex organic molecules which may or may not remain in the soil after the plants that produced them die.

It is also worth noting in passing that the literature generally reports nitrogen retention efficiency as a fraction of the inflow, rather than as an absolute amount.

[15] It is worth noting an interesting curiosum here. Substituting the linear deposition function

$$L = R - \phi(1 - A)$$

for equation (5) yields *exactly* the same expression for the minimum possible value of A as in (23). This is one among many indications of the robustness of the results.

[16] I hesitate to state such a conclusion without positing some final caveats and qualifications. One is that *my* understanding of ecology, at least, is not such as to suggest that we can confidently suppose that arbitrarily small ecosystems could sustainably provide arbitrarily large benefits. Put in the parlance of production theory, there may well be nonconvexities arguing for the preservation of ecosystems of at least a minimum scale. The other obvious caveat here is that some of the most important reasons for preserving nature are probably the least tangible and effable. Economists considering ecosystem services might do well to contemplate the musings of John Stuart Mill, which he may have been wise not to have attemped to quantify:

> Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture ploughed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture. (1848).