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BY

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Efficient Management of Coastal Marine Nutrient Loads with Multiple Sources and Abatement Instruments

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Abstract Pollution management based on marginal abatement costs is optimal only if those abatement costs are specified correctly. Using the example of nitrogen pollution in groundwater, we show that the marginal abatement cost function for any given pollution source can be directly derived from a social-welfare maximization problem, wherein controls include both abatement instruments and inputs to pollution-generating production of a good or service. The solution to the optimization model reveals that abatement instruments for each source should be used in order of least marginal abatement cost, and the sources should in turn abate in order of least cost. The least-cost result remains optimal, even when the abatement target is exogenously determined.

JEL Classification Q10, Q25, Q53

Keywords Abatement costs, groundwater pollution, nutrient loading

1 Introduction

Pollution management proposals often describe control strategies in terms of abatement and associated costs without detailed explanations of exactly how the marginal abatement cost (MAC) functions are derived. Yet, such management strategies can only be welfare-maximizing if the MAC functions are themselves derived from an optimization problem which takes into account each source's costs—including reductions in benefits such as profits—of abating pollution. As an alternative to assuming a functional form for abatement costs, we show that the MAC function can be directly derived from a social-welfare maximization problem, wherein controls include both abatement instruments and inputs to pollution-generating production of a good or service. In doing so, we also describe a procedure for optimally managing pollution when multiple vectors of abatement are available, using the example of nitrogen pollution in groundwater. In some cases, however, quantification of environmental damages generated by the relevant sources of pollution is not feasible, thus rendering the described approach impracticable. We discuss an alternative target-setting approach, according to which abatement instruments should be implemented in the order of least-MAC to achieve the exogenously determined abatement target.

In recent years, nitrogen cycles in coastal marine areas have been transformed by the increased use of chemical fertilizers, fossil fuel combustion, and other anthropogenic activities (Galloway et al., 2008). During the 20th century, the rate of global reactive nitrogen creation increased by 33-55% (Howarth, 2008), and in the United States alone, nitrogen inputs from human activity doubled between 1961 and 1997 (Howarth et al., 2002). Nitrogen and phosphorus, which are required for protein synthesis, as well as for

DNA, RNA, and energy transfer, are the key limiting nutrients in most aquatic systems (Conley et al., 2009). Consequently, excess nitrogen creation has resulted in a marked increase in coastal eutrophication worldwide (Nixon, 1995; Howarth and Marino, 2006). Although the exact relationship between nitrogen concentration and eutrophication occurrence is difficult to quantify and varies by region, there is little disagreement that the negative effects of eutrophication on marine environments—hypoxia, anoxia, habitat degradation, changes to the food-web structure, loss of biodiversity, and algal blooms (Howarth, 2008)—can be substantial. Thus, the health of coastal ecosystems can benefit from further analyses of various nitrogen reduction measures.

In order to properly develop management strategies for the control of eutrophication, one must be able to identify the nitrogen sources and characterize the transport of nitrogen to receiving waters. Generally, three major sources contribute to nearshore nitrogen concentration: atmospheric deposition, fertilizers, and wastewater (Valiela et al., 1990; Valiela et al., 1992; Valiela et al., 1997; Valiela and Bowen 2002). In many cases, nitrogen from these sources enters the watershed away from the coast, and a considerable amount is lost to sorption and denitrification in transit to nearshore waters. In a study of Waquoit Bay, Massachusetts, for example, nitrogen losses within the watershed were estimated at 89%, 79%, and 65% for nitrogen originating from atmospheric deposition, wastewater disposal, and fertilizer use respectively (Valiela et al., 1997). Atmospheric deposition was the largest contributor to nitrogen delivered to the watershed but the smallest contributor of effective nitrogen arriving at receiving coastal waters, whereas wastewater was the largest source of nitrogen actually reaching the estuary (nearly 50% of the total nitrogen load to the bay). Clearly, optimal management decisions will depend on both the magnitude of nitrogen loads from each source to the near-shore waters and the efficiency of nitrogen transport.

When the MAC and marginal damage cost (MDC) functions are given, it is straightforward to show that optimality requires reducing nitrogen until MAC and MDC are equal (e.g., Perman et al., 2003). For multiple nitrogen sources, equality of the aggregate MAC and the MDC determine the optimal total abatement and shadow price of nitrogen, which in turn determines source-specific abatement according to the individual MAC functions. Although theoretically convenient, ad hoc assumptions about the MAC curve's functional form (e.g. Hart and Brady, 2002; Laukkanen et al., 2009) are troublesome from an operational standpoint. We provide a method for deriving MAC curves as an intermediate step in solving a management problem, whose objective is to maximize profits, net of environmental damage and direct nitrogen abatement costs.[1]

Even with a means of deriving the MAC function, the optimum level of nitrogen abatement can only be identified if environmental damages associated with nitrogen loading can be quantified. When damages are difficult to quantify, the first-best management problem is transformed into a second-best constrained optimization problem, whose objective is to determine the most cost-effective means of achieving an exogenously determined target level of nitrogen reduction (e.g. Hart and Brady, 2002). We show that the same outcome can be achieved by abating in the order of least MAC among abatement instruments until the target level of reduction is met. The equivalency obtains because the MAC functions, which are derived from the welfare maximization problem, already incorporate net benefits to society.

[1] Goetz and Zilberman (2010) develop a similar management framework to address the problem of phosphorus runoff. They do not, however, derive or conjecture a MAC function in solving their model.

In the section that follows, we focus first on the optimal management of nutrient pollution generated from a single source. Three types of nitrogen abatement measures are considered: input substitution (cleaner fertilizer), output reduction (less fertilizer), and end-of-pipe technologies (nitrate barrier). Results from the theoretical model confirm that abatement instruments should be employed in order of least cost, and that the optimal total nitrogen abatement is determined where the marginal damage cost (MDC) and the aggregate marginal abatement cost (MAC) are equal. When additional sources are considered, the least-cost principle remains valid, and optimal total abatement is still determined by the equality of MDC and aggregate MAC, although the aggregate MAC is now generated by summing over all instruments and all sources. At the optimum, the MAC for each instrument, the aggregate MAC, and the MDC must be simultaneously equal. Otherwise, welfare could be improved by shifting some abatement to a lower cost source. In section 3, we discuss the implications of explicitly incorporating some dynamic aspects into the framework. Section 4 describes the alternative target-setting approach to pollution management. We conclude with a discussion of key results.

2 Optimal nutrient management

In this section, we derive MAC functions for several pollution-reduction instruments: input substitution, output reduction, and end-of-pipe technologies. We show that when pollution from a single source is considered, abatement instruments should be used in the order of least cost. Optimal total abatement is determined where the aggregate MAC intersects with the MDC.

2.1 Flow vs. stock pollution

Economists generally draw a line between flow and stock pollution. The former occurs when damage corresponds directly to the rate at which the pollutant is discharged, while the latter occurs when damage depends on the stock or concentration of pollution built up in the environmental system. Accumulation of a stock requires that the pollutant has a positive lifespan and that the rate of emissions exceeds the rate at which the environment can assimilate or breakdown the pollution (e.g. Perman et al., 2003). However, such delineation is not always apparent. In the case of nutrient loading, damages to an estuary or bay likely depend on the stock of nitrogen, but treating nitrogen pollution as a flow may make more sense for modeling and implementation purposes. If multiple flushing events occur within the bay annually and the time step of the model is one year, then it is sensible to treat nitrogen as a fund (flow) pollutant and damages as a function of nitrogen flow. Thus, a dynamic problem is transformed approximately into a static one, where the amount of environmental damage is related to the amount of nitrogen flowing into the receptor area in a given period.

2.2 The marginal abatement cost function

In this section, we focus on deriving the MAC function of nitrogen from a single source: agriculture. Agricultural output can be produced from a combination of clean (x) and dirty (z) inputs. Nitrogen leaching into the groundwater can be reduced by substituting clean inputs for dirty ones. This might entail, for example, using a slow-release nitrogen fertilizer and applying it more frequently in smaller doses. Cleaner fertilizers tend to be more expensive, and improving the frequency and accuracy of applications increases labor costs. Nitrogen loading can also be decreased by reducing output. The decision to produce less, however, is inextricably tied to the choice of inputs. Lastly, loading can be controlled via a subsurface nitrate barrier (e.g. biofilm or woodchips) designed to remove nitrogen in groundwater as it flows subterraneously toward the bay (Robertson et al., 2007).

The planner's problem is to choose production inputs, and hence the quantity of crops as determined by the production function $F(x,z)$, and the amount of nitrate barrier to construct (b) to maximize societal benefits from landscaping, less the costs of nitrogen-induced damage (D) to the nearshore environment. We assume that the production function is increasing and concave in both inputs, while the damage function is increasing and convex in nitrogen. Mathematically, the problem can be stated as

$$(1) \qquad \underset{x,z,b}{Max} V, \qquad V = py - w_x x - w_z z - c_b b - D(N)$$

subject to

$$(2) \qquad y = F(x,z)$$

$$(3) \qquad N = T(x,z) - G(b),$$

where the unit crop price (p) is exogenous, output (y) is determined by the production function (F), w_x and w_z are the factor prices for the clean and dirty input respectively, and c_b is the unit cost of the nitrate barrier. The nitrogen load from fertilizer that ultimately enters the bay (N) is determined by the transport function (T) and the efficacy of the nitrogen barrier, as measured by the function G.[2]

[2] The transport function should theoretically include environmental variables such as porosity of the medium through which the water is flowing, velocity of the water, distance, slope, etc. However, in practice, scientific techniques such as isotope-tracing (e.g. Johnson et al., 2008; Knee et al., 2010) provide a

The maximization problem (1)-(3) can be simplified by substituting the equality constraints (2) and (3) into the objective function (1) as follows

(4) $\underset{x,z,b}{Max L}, \qquad L = pF(x,z) - w_x x - w_z z - c_b b - D[T(x,z) - G(b)].$

Then the necessary conditions are[3]

(5) $\frac{\partial L}{\partial x} = pF_x - w_x - D'(N)T_x \leq 0$ if < then $x = 0$

(6) $\frac{\partial L}{\partial z} = pF_z - w_z - D'(N)T_z \leq 0$ if < then $z = 0$

(7) $\frac{\partial L}{\partial b} = -c_b + D'(N)G'(b) \leq 0$ if < then $b = 0$.

Each abatement instrument should be used until the marginal cost of reducing nitrogen load by one unit is equal to the resulting marginal reduction in damage. For production inputs *x* and *z*, the marginal cost of reducing nitrogen is the decline in profits resulting from input substitution and the subsequent change in output. The marginal cost of end of pipe nitrogen reduction is the physical cost of the addition to the barrier (e.g. wood chips) required to reduce nitrogen by one unit.

Assuming that both inputs are essential for production and that the environmental damage from nitrogen is not severe enough to preclude production altogether, the input mix and total output will be chosen such that the marginal costs of nitrogen reduction, or the MACs, are equal across production inputs, and also equal to the marginal damage cost of nitrogen:

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means of estimating a simple empirical relationship between nitrogen inputs to the watershed and nitrogen flowing out at the coast.

[3] The necessary conditions are also sufficient, given our assumptions about the shape of the production and damage functions.

(8) $$D'(N) = \frac{pF_x - w_x}{T_x} = \frac{pF_z - w_z}{T_z}.$$

If this were not the case, one could decrease total environmental damage by substituting inputs, while maintaining the same level of profit. The marginal damage cost is measured in dollars per unit of nitrogen load. The numerator in each of the MACs measures the change in profit per unit of input, and the denominator converts those figures into dollars per unit of nitrogen load.

The nitrate barrier should be implemented only if the marginal cost of doing so is no greater than the marginal damage cost at the optimum. And if the end of pipe nitrogen reduction instrument satisfies this condition, it should be employed until its marginal cost is exactly equal to the optimal marginal damage cost:

(9) $$\frac{c_b}{G'(b)} = D'(N).$$

The denominator on the left hand side of (9) converts the nitrate barrier unit cost to dollars per unit of nitrogen load. At an interior solution, i.e. when all of the controls are positive, (8) and (9) both hold with equality, which implies that the marginal cost of nitrogen reduction is equal for changes in either of the production inputs and for the nitrate barrier. Moreover, the marginal costs are also equal to the marginal damage cost at the optimum.

Proposition 1: *If production is optimally positive, the end of pipe instrument is used only if its marginal cost of nitrogen reduction is equal to that of the production inputs.*

Proof: Suppose that $b > 0$ and that $\frac{c_b}{G'(b)} > \frac{pF_x - w_x}{T_x} = \frac{pF_z - w_z}{T_z} = D'(N)$. But that implies $-c_b + D'(N)G'(b) < 0$, which is consistent with condition (7) only if $b = 0$, a contradiction.

Suppose instead that $b > 0$ and $\frac{c_b}{G'(b)} < \frac{pF_x - w_x}{T_x} = \frac{pF_z - w_z}{T_z} = D'(N)$. But that implies $-c_b + D'(N)G'(b) > 0$, which is inconsistent with necessary condition (7).

That leaves only the possibility that $\frac{c_b}{G'(b)} = \frac{pF_x - w_x}{T_x} = \frac{pF_z - w_z}{T_z} = D'(N)$ for $b > 0$, which is consistent with (7). □

Viewing the reduction in damage or the MDC as a marginal benefit (MB), it is clear from conditions (5)-(7) that a particular abatement instrument is only used if the MB of doing so is equal to the cost. And since the MB of a unit of nitrogen abatement does not depend on the instrument employed, the least-cost instruments are optimally used first. Otherwise, the same MB could be obtained at a lower cost.

The optimal total nitrogen abatement is determined where the aggregate MAC intersects the MDC. Since we care about the marginal impact of a reduction (rather than an increase) in each production input, the changes in profit should be considered negative, rather than positive numbers. Similarly, the change in environmental damage for a marginal reduction in nitrogen is also negative, rather than positive. Therefore, supposing the necessary conditions hold with equality,

$$(10) \qquad \underbrace{\frac{c_b}{G'(b)}}_{MAC_b} + \underbrace{\left(-\frac{pF_x - w_x}{T_x}\right)}_{MAC_x} + \underbrace{\left(-\frac{pF_z - w_z}{T_z}\right)}_{MAC_z} = \underbrace{-D'(N)}_{MDC}.$$

Equivalently, the MDC is equal to the aggregate MAC, or the MACs summed over every abatement instrument. Figure 1 illustrates optimal total abatement and the decomposition for three abatement instruments.

2.3 An alternative derivation of the MAC

In the discussion that follows, we suppress factors of production, i.e. they are implicit in the level of expenditure. Farmers choose the amount of nitrogen to apply, calculated as a proportion of the total applied fertilizer. Applied nitrogen is broken down into effective nitrogen (N^{EFF}), which is absorbed by plants, and leached nitrogen (N^{LCH}), which infiltrates beneath the soil and is transported to nearshore waters. The iso-expenditure curves (IEC) in figure 1 give combinations of effective and leached nitrogen obtainable with exactly E_j dollars of expenditure on production inputs. The IECs are increasing and concave because leached nitrogen can only be reduced by decreasing effective nitrogen. The optimal quantities of nitrogen are determined where the IEC is tangent to a line with slope equal to the MDC of N^{LCH} divided by the value marginal product (VMP) of N^{EFF}. The slope is effectively the "price" of N^{EFF} in terms of N^{LCH}. Since each expenditure level corresponds to a unique point of tangency, there is an expansion path with an (N^{EFF}, N^{LCH}) pair for each E_j. The tangency condition can be described mathematically as

(11) $$\frac{\partial N^{EFF}}{\partial N^{LCH}} = \frac{MDC(N^{LCH})}{VMP(N^{EFF})}.$$

Next, we verify analytically that the tangency condition described in figure 2 is consistent with the social optimum. The social net benefit function is defined as total landscaping revenue less total nitrogen damage costs to the nearshore environment:

(12) $$B = pf(N^{EFF}) - D(N^{LCH}).$$

The objective function (12) is maximized when net marginal benefit is equal to zero, or equivalently when marginal benefit is equal to marginal cost. The net marginal benefit of effective N is

(13) $$MB = p\frac{\partial f}{\partial N^{EFF}} - D'(N^{LCH})\frac{\partial N^{LCH}}{\partial N^{EFF}}.$$

Setting MB=0 implies that

(14) $$\frac{\partial N^{EFF}}{\partial N^{LCH}} = D'(N^{LCH}) / p\frac{\partial f}{\partial N^{EFF}},$$

where the numerator on the right hand side is the marginal damage cost associated with leached nitrogen, and the denominator is the VMP of N^{EFF}. This is none other than the tangency condition (11).

To calculate the marginal cost of effective nitrogen at a particular point, we need to determine how much minimized expenditure would have to increase in order to increase N^{EFF} by one unit. If we suppose that each level of expenditure in figure 1 corresponds to a particular marginal cost (e.g. MC=1), then the MB corresponds to the increments of N^{EFF} and N^{LCH} required to move up the expansion path by one unit. Alternatively, one could fix the change in N^{EFF} at one unit. Then the MB of N^{EFF} is defined as in (13). In that case, MC is the increase in cost corresponding to moving up the expansion path such that the change in N^{EFF} is one unit. Because the factors of production are suppressed, the optimality conditions implicitly include expenditure minimization, i.e. types and quantities of fertilizer, as well as the application method are assumed chosen to minimize expenditure.

The marginal abatement cost specifies the loss in welfare (not including environmental damage) corresponding to a one unit decrease in leached nitrogen. From the expansion curve, we can calculate the reduction in effective nitrogen required to achieve that marginal change for every initial level of leached nitrogen. The reduction in N^{EFF} corresponds to both a decline in revenues and a change in expenditures on factors of production. The MAC is therefore defined as

$$(15) \qquad MAC \equiv p\frac{\partial f}{\partial N^{EFF}}.$$

Since the marginal damage cost of effective nitrogen is $D'(N^{LCH})[\partial N^{LCH} / \partial N^{EFF}]$, social optimality (condition 14) requires that MAC=MDC. If it were the case that MAC<MDC, social welfare could be increased by abating more nitrogen (reducing profits) and reducing total environmental damage costs. If instead MAC>MDC, abating less nitrogen would increase profits by more than enough to offset the additional environmental damages that would result.

2.4 Managing multiple sources

With multiple sources contributing to nitrogen loading, abatement instruments should still be used in the order of lowest cost. Optimality may entail using multiple abatement instruments for a single source or targeting a single instrument for each of multiple sources. Regardless of the decomposition, like in the single-source case, optimal total abatement is determined by the intersection of the MDC and the aggregate MAC, where the aggregate MAC is constructed by summing the MACs over all instruments for all sources. To ensure that there are no arbitrage opportunities, MACs should be equated across instruments for which positive abatement is optimal.

3 Some dynamic considerations

In this section, we examine the case where damage from nitrogen loading is still treated as a flow but demand is allowed to grow exogenously over time. We then discuss how climate change alters the optimal management strategy.

3.1 Exogenously growing demand

As discussed in the previous section, when multiple nitrogen sources and abatement instruments are present, the aggregate MAC is constructed by horizontally summing the individual MACs. The shadow price of nitrogen (λ), determined at the intersection of the MDC and the aggregate MAC, can be traced back to decompose abatement among the available instruments. If the MAC and MDC functions are constant, the shadow price of nitrogen today (period 0) is also constant, and the current level of nitrogen abatement for each source remains optimal over time. The MAC curves may be shifting over time, however, with exogenously changing demand for fertilizers. For example, if the demand for crops is increasing, then the cost of abatement in terms of lost profits to farmers is also increasing. Figure 3 shows that if the individual MACs, and therefore the aggregate MAC are shifting upward over time, then the shadow price of nitrogen is rising over time.

The decomposition of abatement between instruments is detailed in figure 4 for a hypothetical scenario. We suppose that the manager can reduce nitrogen from any of three sources—agriculture (A), wastewater (W), and invasive plants (I)—and that nitrogen from each source can be abated with its own exclusive instrument. As depicted in Figure 4a, the shadow price of nitrogen is initially relatively low so that only farmers reduce nitrogen by substituting for cleaner fertilizers. The shadow price rises over time, however, due to increasing demand for crops until at some point (figure 4b) optimal abatement switches from targeting agriculture alone to both wastewater denitrification and fertilizer substitution. In the stage 3, the shadow price is so high that all forms of abatement become optimal (figure 4c). Although the stages are depicted discretely, one can imagine a smooth and continuous transition of optimal abatement, wherein one or more MAC curve is shifting in a given period, as is the shadow price of nitrogen.

3.2 Climate change

Climate change accelerates the optimal avoidance plan because it tends to shift the MDC curve upward. For a given nitrogen load in the bay, the damage is even higher. Consequently, the shadow price of nitrogen rises more rapidly, as does the need for abatement measures (figure 5).

4 Target-setting approach

In some instances, cultural significance of a resource is viewed as an important component of societal welfare, even though its value is extremely difficult to quantify. Or for some other reason, available information may be insufficient to even roughly estimate an environmental damage cost function. Since the socially optimal level of nitrogen abatement can only be identified when environmental damage is quantifiable, such circumstances require modification of the first-best management problem. One approach is to exogenously decide on the target level of nitrogen (e.g. through community and stakeholder meetings), and then determine the most cost-effective means of achieving the objective (e.g. Hart and Brady, 2002). Mathematically, the second-best problem can be written by replacing the damage function in the first-best problem (4) with the constraint that nitrogen load to the bay is equal to some constant $\overline{N}$:

$$(16) \quad \underset{x,z,b}{Max}\overline{L}, \qquad \overline{L} = pF(x,z) - w_x x - w_z z - c_b b + \lambda\left(\overline{N} - [T(x,z) - G(b)]\right).$$

The necessary conditions for (16) are identical to (5)-(7), except with the MDC replaced by the shadow price of the nitrogen constraint (λ). The implication is that one should abate using each instrument until the marginal cost of doing so is just equal to λ. In other words, following the least-cost abatement principle ensures welfare maximization, whether the nitrogen target is determined exogenously or endogenously by the damage cost function.

5 Conclusion

Inasmuch as the functional forms of pollution abatement cost functions are often assumed rather than derived, we develop a method for constructing MAC functions, using information from an optimization problem, whose objective is to maximize social benefits from production, net of environmental damage costs generated from those production activities. Using the example of nitrogen pollution in groundwater, we derive the MAC function for a single pollution source when multiple abatement instruments are available. The optimal solution is characterized by ordering instruments in reverse order of their MAC, which implies that multiple controls are implemented simultaneously only when their MACs are equal to each other, as well as to the MDC. The general result of least-MAC first extends to both the problems of optimally abating with multiple instruments across multiple pollution sources, as well as maximizing social net benefits when the pollution target is exogenously determined.

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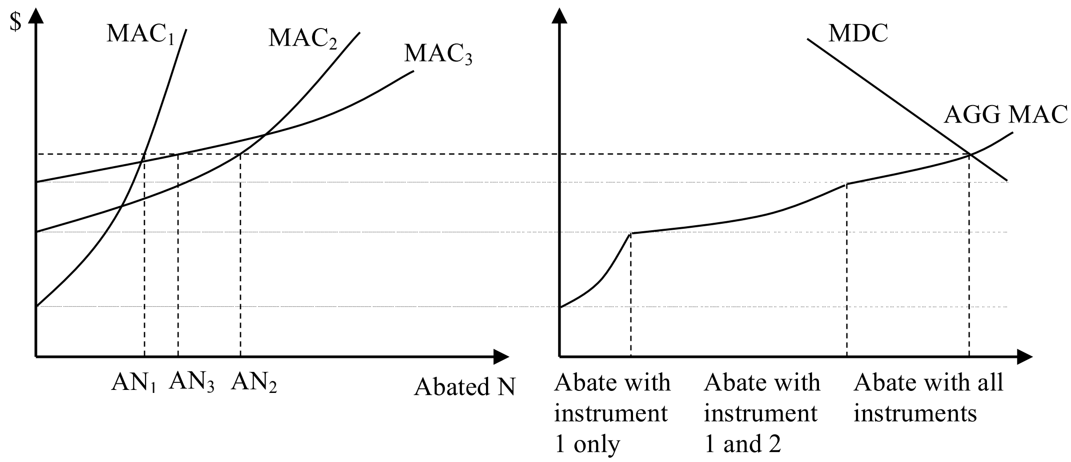


Figure 1. Decomposition of optimal abatement

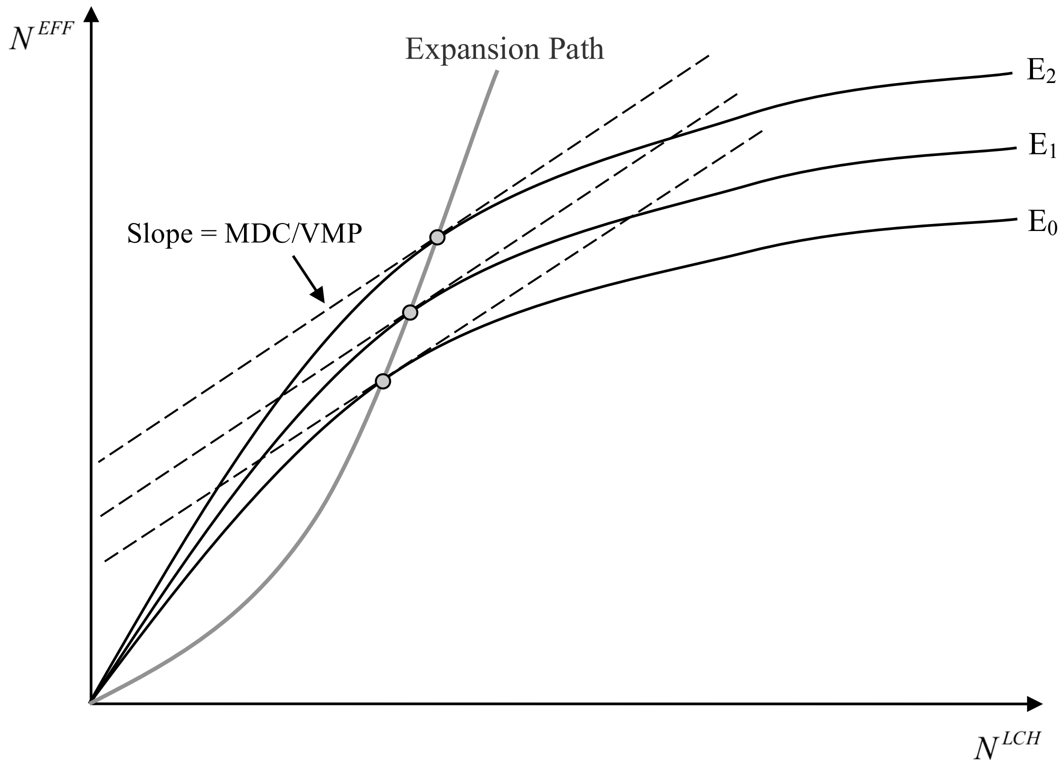


Figure 2. Optimal nitrogen expansion path

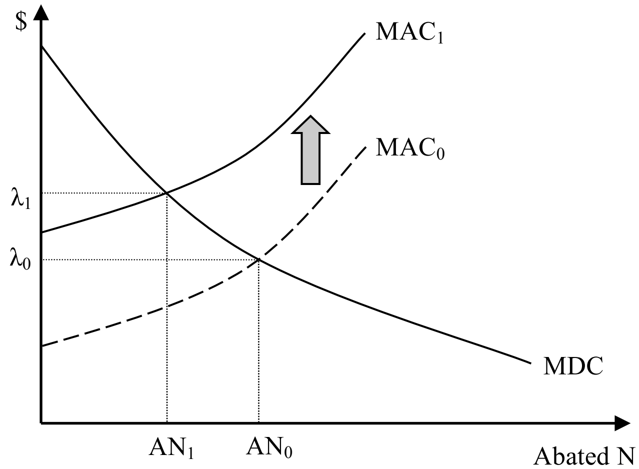
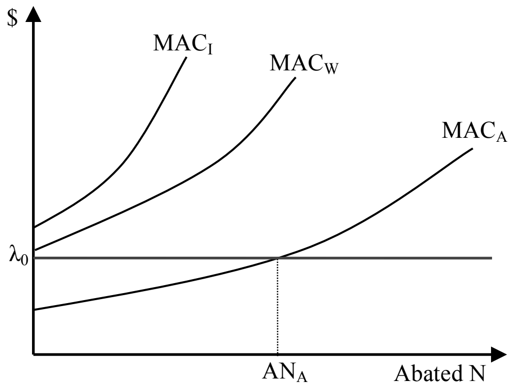
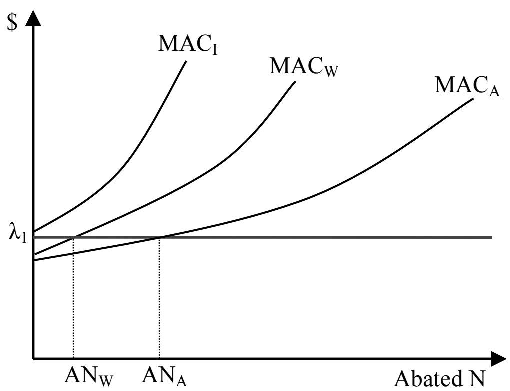


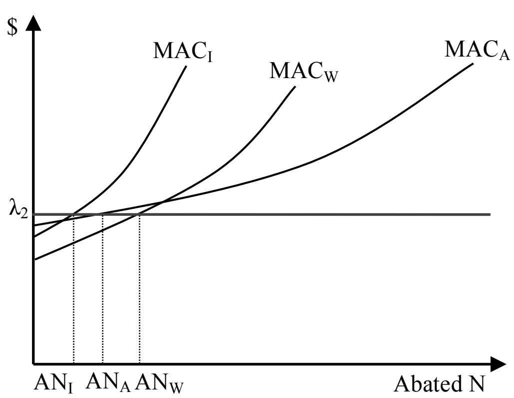
Figure 3. Shadow price of N increases as MAC shifts due to growing demand



(a) The shadow price of nitrogen is initially relatively low, and abatement is only optimal for agriculture.



(b) Exogenous demand growth for crops shifts the MAC for agriculture and hence the aggregate MAC. As a result, the shadow price of nitrogen rises, and it becomes optimal to abate from wastewater sources as well.



(c) Eventually, the aggregate MAC shifts enough to make abatement from all three sources optimal.

Figure 4. Ordering of abatement from multiple sources

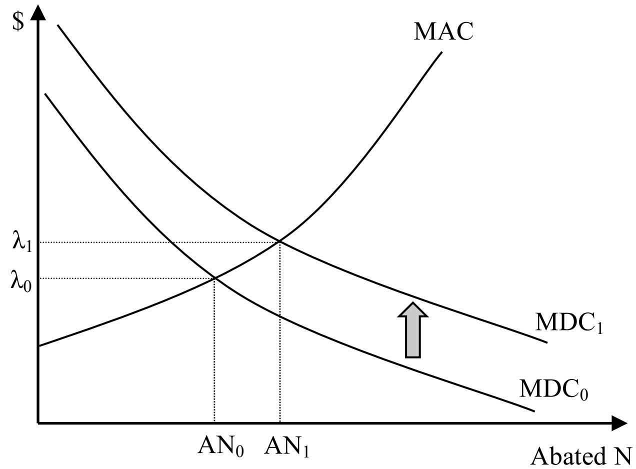


Figure 5. A higher MDC induced by climate change increases optimal abatement