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BENEFITS FROM RESTORING WETLANDS FOR NITROGEN ABATEMENT: A CASE STUDY OF GOTLAND

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Abstract

The values of nitrogen abatement by measures involving restoration of wetlands, sewage treatment plants and agriculture are calculated and compared. The analytical results show that the value of wetlands is likely to exceed the values of other measures due to the multifunctionality of wetlands and their self organizing abiblity. The multifunctionality implies that, in addition to nitrogen abatement, other outputs like buffering of water and biodiversity are produced and the self organizing feature reduces the rate at which future values of outputs are discounted. According to the empirical results applied to Gotland, a Swedish island in the Baltic with high concentrations of nitrate in the ground water, the imputed value of wetlands exceeds the corresponding values of the other nitrogen abatement measures by several hundred per cents.

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1. INTRODUCTION

In many countries, the emission of nitrogen has been an important cause of eutrophicated coastal waters and high concentrations of nitrate in ground water. In Sweden, like in several other countries, the search for measures mitigating these problems has mainly been focused on sewage treatment plants and agriculture. However, it is now recognized that quite other type of measures implying the use of nature's own nitrogen purification capacity, so called eco-technologies, can be considered as alternatives to the conventional nitrogen abatement measures. Due to the functioning of wetlands as nitrogen sinks, restoration of wetlands is regarded as an important ecological technology for nitrogen abatement. The purpose of this paper is therefore to calculate and compare the value of restored wetlands with the value of using conventional technologies involving sewage treatment plants and agriculture. The study is applied to Gotland, an island in the Baltic where the content of nitrate in ground water is high due to the load of nitrogen

The capacity of restored wetlands to purify water sheds from nitrogen and other pollutants has been pointed at in several studies carried out by natural scientists; see e.g. Mitsch & Gosselink (1986), Nichols (1983) and Fleischer (1991). There is today an ongoing debate on the efficiency of wetlands as nutrient sinks (Race, 1986). Economic studies of restoration of wetlands are much less frequent. Most of the economic studies have focused on the social costs associated with wetland degradation; see e.g. Bergström et al. (1990), Costanza et al. (1989), Turner (1990). To my knowledge, there is only one study where the cost for nitrogen abatement by restoring wetlands has been compared by the costs for using conventional abatement technologies (Andréasson-Gren, 1991).

There are some similarities in the methods used to find measurements of the value of restoring wetlands and of existing wetlands. A common feature is the difficulty to measure, not only the value of nitrogen abatement, but also the multifunctional value provided by the wetland such as a water buffering capacity and other several life supporting functions. There are, however, two further questions that must be explicitly addressed when assessing the value of restoring wetlands. When a certain function of the wetland is of interest, here nitrogen abatement, the value of restored wetlands is partly determined by the efficiency of nitrogen purification as compared to other abatement technologies. The other difference concerns the change during time in the capacity of restored wetlands to function as nutrients sinks. When measuring the value of existing wetlands it is usually assumed that the production of different environmental services does not change. However, the capacity of restored wetlands to provide for different services is increasing during a certain time interval before it reaches its mature state. In order to account for these factors an intertemporal model is used where the value of restored wetlands is derived from the values of the provided outputs (Mäler 1991 and 1992).

The paper is organized as follows. First, the intertemporal model is described. Next, the model is applied to Gotland, a Swedish island in the Baltic Sea, where the content of nitrate in ground water is high. The paper ends with a summary.

2. THE MODEL

As mentioned above, the purpose for restoring wetlands is to reduce the load of nitrogen to watersheds. Thus, one important output is improved water quality, which is denoted by W. The nitrogen abatement efficiency by restored wetlands depends on several climatic and hydrological factors, and on the stock of the wetland (Mitsch, 1990). However, in this simple model only the stock of wetlands is included. The production of water quality in each time period, W, is a function of nitrogen load, N, nitrogen abatement capacity at sewage treatment plants, P, and the impact of the stock of wetlands, S, which is written as

$$(1) \qquad W = g(N,P,S)$$

The load of nitrogen, N, is negatively related to the water quality. An increase in the capacity at the sewage treatment plants and in the stock of wetlands are supposed to improve the water quality. It should be noted that the variable S, stock of wetlands, is assumed to include both functional aspects of the wetland and the size as measured by, for example, the quantity of biomass. Needless to say, it is a difficult task to find a measurement of this variable.

When restoring wetlands secondary benefits may be obtained which include primary production, secondary production of fauna, food chain and habitat diversity, aesthetic and recreational values for human use (Knight, 1992). All these ancillary benefits are here aggregated into one output, E, and the associated production function is given a very simple specification. It is assumed that E is a function of the stock of wetlands.

(2) $$E = f(S)$$

Restoration of wetlands, R, is here defined as an increase in the stock of wetlands during the time period when the restoration activity takes place. Thus, according to this definition, a restored wetland is not completely restored in the sense that it has passed through different succession stages and reached its mature state.

In general, the most important production factors required for restoration are land and labour. The combination of these factors depends on type of restored wetland. For example, when the water from dammed ditches is allowed to overflow surrounding land only land is needed. The required area of land may be smaller for other types of wetlands where it instead may be necessary to use labour for harvesting plants. Sometimes capital resources are needed such as excavators and reaping machines. For a review of alternative methods for restoring and creating wetlands see Kusler and Kentula (1990). However, the requirement of capital resources is relatively small for the type of wetlands that are under consideration in Sweden (Fleischer, Ekwall pers. comm.) The production function for restoration of wetlands therefore includes land, A^R, and labour, L^R, according to

(3) $$R = r(L^R, A^R)$$

The total growth in the stock of wetlands, dS/dt, is here supposed to consist of natural growth and of restoration. Natural growth includes succession and self-organization and depends on several climatic and hydrological factors. It is assumed that the natural growth can be expressed as a function of the stock of wetlands, k(S), which is written as

(4) $$dS/dt = k(S) + R$$

When building sewage treatment plants and/or expanding existing plants the most important production factors are capital and labour. Nitrogen purification by sewage treatment plants, T, is thus a function of labour and capital, L^T and P respectively, which is written as

(5) $$T = h(L^T, P)$$

The change during time in the nitrogen abatement capacity at the sewage treatment plants, dP/dt, is the investment I^T minus the depreciation, which is written as

(6) $$dP/dt = I^T - \rho^T P$$

where ρ^T is the rate of depreciation.

In order to simplify the analysis all market goods are aggregated into one output, Q. The production of this compounded good is a function of the inputs of labour, L, land, A, capital, K, and nitrogen emissions, N, according to

(7) $$Q = q(L, A, K, N)$$

The rate of change in the stock of capital of the production sector, dK/dt, is the investment, I^K, minus the depreciation. The rate of depreciation is ρ^K. The change in the capital stock is thus

(8) $$dK/dt = I^K - \rho^K K$$

It is assumed that the region can export the good, X, as much as it wants at the given export price. The import, M, is assumed to depend on the relation between the import price and the domestic price, e, which is written as

(9) $M = m(e)$

The market clearing condition for the aggregated good is then

(10) $C + I + X - M = Q$

Consumption is limited by the budget restriction which is formulated as a function of the total production according to (11).

(11) $C = n(Q,R,T)$

Additional restriction are put on the total use of labour, L, and on land, A which is written as

(12) $L \leq L^Q + L^R + L^T$

(13) $A \leq A^Q + A^R$

Note that it is assumed that the use of land by sewage treatment plants is negligible. However, since only restored wetlands are considered, the area of land is limited by the size of wetlands converted into arable land, A*, according to

(14) $A^* \leq A^R$

The objective function to be maximized over current and all future time periods includes the utility of the consumer good, water quality and other secondary environmental services provided by wetlands, which is written as

(15) $$\int_0^\infty e^{-rt}U(C,W,E)dt$$

where r is the discount rate. Applying the Maximum Principle, the current value Hamiltonian, H, is maximized according to

(16) $$\text{Max} \quad H = U(C,W,E) + v^S(k(S)+R) + v^P(T-\rho^T P) + v^K(I-\varepsilon^K K)$$

s.t. (1)-(14) except (4), (6) and (8)

Assuming that the appropriate constraint qualifications are satisfied, the first-order conditions for maximum are obtained by putting the derivatives with respect to the control variables equal to zero. The variables of main interest here are the three nitrogen abatement measures: reductions in the emissions of nitrogen, N, an increase in the nitrogen abatement capacity of sewage treatment, T, and restoration of wetlands, R. The corresponding derivatives are

(17) $$U_W g_N = p^Q q_N$$

(18) $$cn_T + v^P = p^T$$

(19) $$cn_R + v^S = p^R$$

where subscripts denote partial derivatives and p^Q, p^T, p^R and c are the Lagrange multipliers for the restrictions on the production technologies and on the consumption possibilities, i.e. on (7),(3),(5) and (11). As will be shown below, the costate variables v^P and v^S can be interpreted as the values of a marginal increase in the capacity of sewage treatment plants and in the stock of wetlands respectively.

From the left-hand sides of (17)-(19) the marginal values of using either of the three measures can be identified. The right-hand sides can then be regarded as the associated marginal costs. Thus, the sector producing the good Q should reduce the emissions of nitrogen to the level where the marginal utility of the improvement of water quality is equal to the marginal cost which corresponds to the decrease in the value of output. The values of a marginal increase in T and R include the associated impacts on the consumption possibilities, cn_T and cn_R, and the stock effects, v^P and v^S.

In optimum, the value of a marginal increase in the stock of wetlands, v^S, in time t includes the associated current and future streams of utility. This can be seen by solving for v^S in the maximized Hamiltonian which gives

$$(20) \qquad v^S(t) = \int_t^\infty e^{-(r-k')(\tau-t)}(U_W g_S + U_E f_S)d\tau$$

The first term within the parentheses on the right-hand side, $U_W g_S$, measures the utility of a marginal improvement of the water quality and the second term, $U_E f_S$, corresponds to the utility of a marginal increase in ancillary benefits. Thus, according to (20), the *present value of a marginal increase in the stock of wetlands in time t* includes current and all future streams of utility from the corresponding increase in water quality and ancillary environmental services. Due to the growth in the capacity of wetlands to provide for these services, the associated utilities available in the future grow at the rate k'. Note that the future utilities are discounted by the discount rate, r, minus the growth of wetlands, k'.

The corresponding value of an increase in the stock of sewage treatment plants in time t, $v^P(t)$, is

$$(21) \qquad v^P(t) = \int_t^\infty e^{-(r+\rho)(\tau-t)}(U_W g_T)d\tau$$

By comparing (20) and (21) we note that v^S is likely to exceed v^P due to two factors. First, future values of a marginal increase in the stock of sewage treatment plants are discounted at a higher rate than the values of an increase in the stock of wetlands, i.e.

$(r+\rho)>(r-k')$. The second factor is the inclusion of the utility of secondary environmental services provided by wetlands, $U_E f_S$. It should however be noted that v^P exceeds v^S if the marginal product of nitrogen abatement at the sewage treatment plants is sufficiently high. According to several studies this is not likely to occur. Instead it is shown that the marginal cost for reducing the load of nitrogen in sewage treatment plants is higher than the corresponding cost for wetlands (Andréasson-Gren et al., 1991).

3. APPLICATION TO GOTLAND

The most serious environmental problem in Gotland is insufficient supply of drinking water with acceptable quality. The average content of nitrate is high, 40 mg N03/l, as compared to the rest of Sweden, 10 mg N/l. In some wells the content of nitrate exceeds 100 mg N03/l. The main sources of nitrogen is the instantaneous leakage of nitrogen from drained mires and farmers´ application of nitrogen fertilizer and manure. Although the average application rate of nitrogen is modest, about 100 N kg/ha, the leakage of nitrogen is high. This is due to the bedrock structure. The bedrock in Gotland is mainly limestone which is porous thus making it easy for nitrogen to infiltrate and reach the ground water. The bedrock also contains widespread cracks so that nitrogen is quickly spread from one area to another. For this reason and also due to lack of data the spatial allocation of nitrogen emission sources is neglected. The ground water basin in Gotland is thus treated as a single recipient.

The largest single source of nitrogen load in Gotland is farmers´ use of nitrogen. Their nitrogen use corresponds to about 80 % of the total load in Gotland including nitrogen fertilizers and manure. This can be seen from Table 1.

Table 1: Nitrogen sources and their emissions, tons of N/year

Agriculture	8510
Sewage treatment plants	170
Air deposition:	
Sources in Gotland	775
Imports	2325
Total	11780

Source: Andréasson (1989a)

From (17)-(19 it can be seen that the value of improved water quality is included in all equations. A money measure of water quality is obtained from a Swedish study where the contingent valuation method was used to estimate the willingness to pay for a certain reduction in the content of nitrate in drinking water (Silvander, 1991). According to the results, the willingness to pay for a reduction from 50 mg NO3/l to 30 mg NO3/l is SEK 600/person/year (1 USD = SEK 5.80). This value is used as the upper limit value of the valuation function which is then assigned a quadratic form in the content of nitrate.

In order to estimate the production function for water quality, i.e. equation (1) in the foregoing section, a hydrological model of Gotland is used (Spiller, 1978). According to the simulation results of this model, the relation between the load of nitrogen and the content of nitrate can be described by a linear function. The production function is therefore given a linear form. The load of nitrogen includes the emission sources presented in Table 1 minus the nitrogen abatement carried out by the wetlands.

The nitrogen purification by wetlands on the water quality is calculated by means of a Swedish study, according to which the denitrification of mature wetlands varies between 100 and 500 kg N/ha/year depending on type of wetland and on the location (Leonardsson, 1991). However, the maximum abatement capacity of restored wetlands is achieved after about 3-5 years (see e.g. Kusler and Kentula, 1990). In order to account for this delay a relatively low level of nitrogen purification is assumed, 200 kg N/ha/year.

However, as mentioned in earlier sections restoration of wetlands implies not only improved water quality but also secondary benefits. In the model described in the foregoing section these ancillary benefits were aggregated into one variable. In order to find a measurement of the value function of this variable the results from a study of the life supporting values of a mire in Gotland is used (Folke, 1990). Several life support functions were included in the study such as nitrogen abatement, water buffering, supply of energy and provision of habitat. The life support functions were evaluated at their replacement costs. For example, the buffering capacity of ground water was valued at the cost for a water plant to supply the same amount of drinking water. Excluding the value of nitrogen abatement, the total value of the life support functions was estimated to range between SEK 9600-25000/ha/year. However, since this value was estimated for a mature wetland it is assumed that the corresponding value for restoring wetland is half of the lowest value, i.e. SEK 4800/ha/year. It is further assumed that the production function for secondary benefits, i.e. equation (2) in the foregoing section, is linear in the stock of wetlands.

Restoration of wetlands is a recently established area of research and few experimental results are available which can be used in this model. It is therefore simply assumed that the rate of natural growth in the stock of wetlands, k'/S is constant and amounts to 0.01/year. In order to estimate the values of a marginal investment in sewage treatment plants and wetlands it is further assumed that the real discount rate , r, is 0.03 and that the economic length of life of a sewage treatment plant is 50 years which implies that the rate of depreciation, ρ^r, is 0.02.

It should be noted that the values of water quality and secondary benefits are assumed to be separable and are added in the objective function. This is a strong simplification since the peoples´ valuation of these function are related. Further, the production of the functions are interrelated such that a large scale use of wetlands as nitrogen abatement may preclude some life supporting functions. Another simplification is the assumption that the growth of the nitrogen abatement and environmental services is the same and amounts to the same rate as the growth in stock of wetlands.

Remember from the foregoing section that the marginal values of nitrogen abatement by sewage treatment plants and restored wetlands includes not only the value of water quality and ancillary benefits but also the net impact on the consumption possibilities, i.e. cn_T and cn_R from equations (18) and (19) respectively. In order to estimate the changes in total income, or consumption possibilities, a very simple equilibrium model of the Gotland economy is constructed. A formal description of this model is given in Appendix A. A very brief description is therefore given here.

In the equilibrium model of Gotland, nitrogen abatement by sewage treatment plants and restored wetlands are treated as sectors producing the goods water quality and secondary environmental benefits as described in the foregoing Section 2. In addition, 5 other production sectors are included; animal, vegetable, food, other production, and service production. The production functions are characterized by an input-output technology. The output prices are assumed to be given. The difference in prices between the produced good and the imported good is assumed to correspond to the cost for transporting the good from the mainland. In the objective function total income is maximized, where total income is defined as total value added. All values inserted in the model are given in Appendix B.

Given all above-assumptions, the total value of a marginal increase in restoration of wetlands, p^R, in the capacity at the sewage treatment plant, p^T, and a marginal decrease in farmers′ use of nitrogen, $p^Q g_N$, are calculated according to (17)-(19) in Section 2. All values are estimated at their current activity levels of the abatement measures. The results are therefore interpreted as the value of a marginal increase today in either of the three nitrogen abatement measures. The marginal value of water quality is then calculated at the optimal emissions of nitrogen as estimated by the equilibrium model which gives SEK 5/kg of nitrogen abatement (see Appendix A and Appendix B, Table B4 for the value function of water quality). The results as expressed in SEK/kg nitrogen abatement for the different measures are presented in Table 2.

Table 2: Marginal values of nitrogen abatement, SEK/kg N-reduction

	Income effects	Water quality	Secondary benefits	Total
Restoration of wetlands	7	259	600	866
Sewage treatment plants	28	104		132
Agriculture		5		5

According to the results presented in Table 2, the value of a marginal increase in nitrogen abatement by wetlands is considerably higher than the corresponding values of the other measures. This is partly explained by the value of the secondary benefits which account for about 2/3 of the total marginal value of restoring wetlands. Another reason is the differences in the rates at which future values are discounted. This can be seen from the value of water quality. Remember that the marginal value of water quality is SEK 5, which is total value of nitrogen abatement for the agricultural sector. The difference in the values of water quality in the Table 2 is pertinent to the differences in discounting factors, 0.02 and 0.05 for wetlands and sewage treatment plants respectively.

It should be noted that the marginal value of nitrogen abatement in the agricultural sector includes only flow effects. This may be a reasonable assumption for reductions in the use of nitrogen fertilizers. If other mitigation measures are considered such as a change in land use from grain production to energy forestry stock effects occur. Furthermore, ancillary benefits are provided by the functioning of energy forests as carbon sinks.

4. SUMMARY

The purpose of this paper has been to identify and measure the value of restoring wetlands for nitrogen purification. For this purpose an intertemporal model was constructed. The objective function included the utility of consumer goods, water quality and other environmental services provided by wetlands. It was conceptually shown that the marginal utility of applying restoration of wetlands is higher than a marginal investment in sewage treatment plants mainly due to two factors; i) wetlands provide secondary benefits and ii) an investment in a self organizing system gives rise to a natural growth in future values while an investment in sewage treatment plants is subjected to depreciation. Future values of a marginal increase in the stock of wetlands are thus discounted at a lower rate than future values of a marginal increase in the stock of sewage treatment. According to the empirical results, the estimated marginal value of restoring wetlands was considerably higher than the marginal value of increasing the nitrogen abatement capacity at the sewage treatment plants, SEK 866 and SEK 132 respectively.

APPENDIX A: A simple equilibrium model of Gotland

Value added for each production sector is v^iQ^i, where v^i is the value added per unit of output. The value of improved water quality is measured as a quadratic function of the leakage of nitrogen, N. and the value of the life supporting functions provided by wetlands is assumed to be proportional to the level of restoration, dR.

Total income, i.e. the sum of value added, plus the value of water quality and of environmental services are then maximized with respect to a set of restrictions. The total demand including intermediate goods, $\Sigma a_{ij}Q^j$, consumption, C^i, investment, I^i, public, G^i, exports, X^i, and imports, M^i. The consumption of each good is proportional to the total consumption, c^iC. The total consumption is further assumed to be a certain share, n, of total incomes. Each production sector faces a certain capacity limit, Q^{i*}.

For each production sector, the use of labour and land amounts to l^i and b^i respectively per unit of output. The area of land available for wetland restoration is A* and the capacity limits for the expansion of nitrogen abatement at the sewage treatment plants is T*.

The leakage of nitrogen is g^i per unit of output. The reduction in nitrogen leakage is g^T per unit of output from the sewage treatment and g^R per unit of restoration. Note that

T and R are measured as their total cost.

The maximization problem is thus formulated as

$$\text{(A1)} \qquad \text{Max} \quad \Sigma_i v^i Q^i + v^T T + v^R R - bN^2 + d(R+S)$$

s.t.

$$\Sigma a_{ij} Q^j + C^i + I^i + G^i + X^i - t^i M^i = Q^i$$

$$C^i = c^i \Sigma C^i$$

$$\Sigma C^i = n(\Sigma v^i Q^i + v^T T + v^R R)$$

$$\Sigma l^i Q^i + l^T T + l^R R \leq L$$

$$\Sigma b^i Q^i + b^R R \leq A$$

$$\Sigma g^i Q^i + g^T T + g^R (R+S) = N$$

$$Q^i \leq Q^{i*}$$

$$T \leq T^*$$

$$b^R R \leq A^R$$

APPENDIX B: Tables

The calculations of the input-output coefficients presented in Table B1 and the final demands and capacity limits shown in Table B3 are based on Andréasson (1984). It is then assumed that the coefficients, the consumption shares and the shares of investment and public demand as related to total income are the same in 1990 as in 1984.

Table B1: Coefficient matrix

	Anim.	Veget.	Food	Other prod.	Service	Sewage plants	Rest. wetl.
Animal prod.			0.47				
Vegetable prod.	0.14	0.04					
Food	0.20				0.01		
Other prod.	0.12	0.10	0.03	0.05	0.06	0.10	0.05
Services	0.06	0.14	0.01	0.02	0.23		

Source: Andréasson (1984)

Table B2: Resource coefficients

	Labour/mill. of SEK	Nitrogen kg N/SEK	Land ha/SEK
Animal[1]	4.27	0.005	
Vegetable[1]	8.72	0.02	0.00037
Food[2]	0.94		
Other production[2]	1.37	0.001	
Services[2]	5.63		
Sewage treatment plants[3]	4.50	-0.0018	
Restoration of wetlands	8.72	-0.0667	0.0005
Households[3]		0.0002	

Source: 1. Yearbook of Agricultural Statistics, Sweden
2. National Resource Accounts, Sweden
3. Yearbook of Environmental Statistics: The natural environment in figures., Statistics, Sweden

Table B3: Final demand and production capacity limits

	Consumption as a percentage of total consumption	Investment+ public demand mill. of SEK	Capacity limits mill. of SEK
Animal production	4	7	657
Vegetable production		6	238
Food	20	21	1050
Other production	3	254	1560
Services	36	397	1450
Sewage treatment plants			20
Restoration of wetlands			30

Source: National Resource Accounts, Statistics Sweden and Andréasson (1984)

Table B4: Value functions

Value of water quality	$0.00000022*N^2$
Value of secondary benefits	$1.6*R$

Source: Silvander (1991) and Folke (1990)

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