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ACIDIFICATION AND TIMBER SUPPLY WITH ENDOGENOUS SOIL PROTECTION: A TWO-PERIOD MODEL*

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The paper considers the potential impacts on timber supply of forest damage due to acidic and other pollutants. In a two-period model of harvest timing and forest investment, tree mortality and site degradation are represented by changes in the standing stock and the growth function, respectively. An exogenous growth decline is first shown to increase short-run supply and discourage investment. Where salvage is not feasible, mortality in the standing stock tends to reduce the current supply and renders its overall change indeterminate. Endogenous soil protection is then introduced. It is shown that the anticipated damage justifies measures to alleviate site degradation. Consequently, short-run supply is ambiguously effected. The paper concludes by considering the impacts of pollution on the long-run steady state supply.

1. *Introduction*

The forest decline, or »novel» forest damage attributed to acid rain and other atmospheric pollutants, has become a major concern. Widespread damage has been reported especially in Central Europe, and it is estimated that over 20 per cent of the total timber inventory in Europe is suffering pollutant-induced damage (e.g. Forest... 1989, New forestry... 1990). As for Finland (see Kauppi et al. 1990), no large-scale forest dieback or growth decline due to pollution has been verified so far. However, warnings have been made (Hari et al. 1987) that changes in the concentrations of nutrients, toxic compounds, and soil acidity will result in a decline in forest growth in the next decades. Also, stands killed by a fungi disease have been recently reported in northeast Finland, a region with high depositions of e.g. sulphur.

The ultimate causes and mechanisms of the damage so far remain unknown, but for the present purpose the effects of pollution on the forests can be classified into two categories (e.g. European... 1986; Phillips & Forster 1987; Leuschner & Ferguson 1987; Kauppi et al. 1990).

First, there are direct effects on the trees through the needles or leaves by sulphur dioxide, oxides of nitrogen, and ozone. The consequences can range from minor foliage losses to a serious weakening of tree vitality. Eventually, this may lead to an increase in tree mortality and to what can be called »forest dieback» (often launched by an insect attack or fungi diseases). This will be characterized as mortality in the standing stock. Secondly, the

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accumulating pollutants have indirect, delayed effects through changes in the forest soil. Continued depositions of sulphur and nitrogen oxides, converting to acids, cause increased soil acidity and leaching of nutrient cations (in particular magnesium, calcium, and potassium). Moreover, increased concentrations of soluble aluminium and heavy metals have toxic impacts. The overall impact is site degradation, which will be modelled as a general decline in forest growth.

Regarding the consequences of the forest damage on the timber markets, the increased mortality of trees has been expected to increase timber supply in the short run through sanitation fellings. In the long term, the decline in soil productivity due to acidification would result in both reduced forest growth and sustainable harvest (e.g. European... 1986). However, there is little formal analysis on the topic.

The harvesting decision under pollution-induced changes in growth is considered in Ovaskainen (1987) and Lohmander (1989) using the optimum rotation model. Numerical scenarios on the market-wide consequences of forest damage in a global trade model have been presented by Dykstra and Kallio (1987) and Seppälä et al. (1990). Haynes and Adams (1990) analyze the latter problem in the TAMM framework. More generally, the problem is related to the literature dealing with renewable resources, mainly fisheries, and pollution control. One may refer to Tahvonen (1989) for a review. Despite the existing literature on each of the topics as such, only few studies (Tahvonen 1989 and references therein; McConnell & Strand 1989; Tahvonen & Kuuluvainen 1990) explicitly consider the case where pollution affects the productivity of renewable resources.

The aim of this paper is to gain a conceptual understanding of the potential effects of air pollution damage on timber supply using a simple intertemporal, two-period model of harvest timing and forest investment. The impacts of pollution are represented by changes in the initial stock (observed mortality) and growth function (anticipated growth decline). A »lumped-parameter», density dependent growth model is used, where pollution affects both the saturation level and the intrinsic growth rate of the stock. Throughout the study, pollution is assumed to be exogenous. While pollution itself can not be controlled, the paper considers a case where its negative impact on the forest can be reduced by certain forestry practices (especially liming).

The effects on short-term supply (i.e., current harvest) and silvicultural effort/soil protection are considered in Chapters 2 and 3. In Chapter 2, the model is introduced with an exogenous change in forest growth, while Chapter 3 introduces endogenous soil protection by taking the damage to the soil to be a function of measures alleviating soil acidification. In Chapter 4, the implications with respect to the long-run supply (steady state harvest) are discussed. Chapter 5 concludes the paper.

2. *Short-term timber supply and silvicultural effort under exogenous pollution damage*

The paper employs an extended version of the two-period model of short-term timber supply or harvest timing (e.g. Lohmander 1983; Koskela 1989 a, b; Kuuluvainen 1989), which in turn is basically the 'Fisherian' consumption-savings model (e.g. Sandmo 1985) augmented by a density dependent growth function. Because the level of forest investment is important to the long-run timber supply, management intensity is endogenously determined in addition to the current harvest (cf. Ovaskainen 1989). Perfect capital markets and certainty will be assumed, and no »stock benefits» (i.e., forest-related amenity values) will be considered.[1]

2.1 Basic assumptions

Suppose the forest owner wishes to maximize the utility of consumption over two pe-

[1] Literally, the density dependent growth function represents selective harvesting, but it is also approximate to even-aged management (clearcutting) if the »marginal» units are taken to be even-aged stands rather than individual trees. As the separation theorem holds, this particular case could be analyzed in terms of present-value maximization (cf. Hyde 1980; Chang 1983). However, the utility maximizing model has the advantage that cases can readily be considered where this no longer holds. An example of the potential extensions is the uncertainty of future damage/growth rates and tree mortality (cf. the risk from a wildfire; e.g. Caulfield 1988).

riods ('today' and 'the future'), with preferences represented by the additive separable utility function V,

(1) $V = u(c_1) + \beta u(c_2)$

where c_i is consumption in period i ($i = 1,2$), $\beta = (1+\rho)^{-1}$, and ρ is the rate of time preference. Further, it is assumed that $u' > 0$ and $u'' < 0$. Consumption in the first period is constrained by revenue from timber sales minus net saving and investment in silviculture,

(2) $c_1 = p_1 X - S - wE$

and in the second period by the sum of harvest revenue and past savings with the interest,

(3) $c_2 = p_2 Z + (1+r)S.$

The current harvest (short-term timber supply) is denoted by X, the future harvest by Z, and silvicultural effort by E. Further, p_i is the timber price in period i ($i = 1,2$), S denotes net savings (saving as $S > 0$ and borrowing as $S < 0$), r is the market rate of interest in a perfect capital market, and w is the unit cost of the silvicultural effort.

The future harvest possibilities are defined by

(4) $Z = Q(m) - X + F(Q(m) - X,\ E,\ g),$

where $Q = Q(m)$ is the initial stock of timber and m is the amount of agents causing tree mortality. $Q(m) - X = K$ thus denotes the post-harvest growing stock. $F = F(K, E, g)$ is a growth function, where g represents the level of site degradation.

The growth function $F(\cdot)$ is assumed to be strictly concave in (K, E) at any given levels of m and g. Let M and C denote the density of the maximum sustained yield and the saturation level, respectively. The following assumptions are made:

A.1

$F_K \gtreqless 0$ as $K \lesseqgtr M$;
$F_E > 0,\ F_g < 0,\ F_{KK},\ F_{EE} < 0,$
$F_{KK}F_{EE} - (F_{KE})^2 > 0,$
$F_{KE} > 0,\ F_{Kg} < 0,\ F_{Eg} < 0$

and consequently

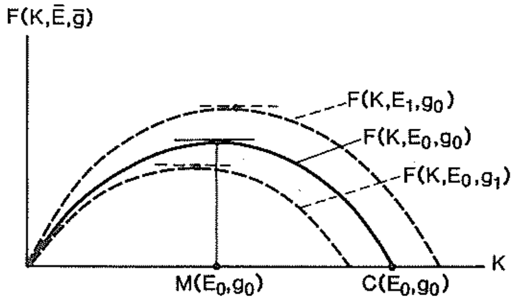

Figure 1. Forest growth as a function of stock at varied levels of effort and pollution ($E_1 > E_0$, $g_1 > g_0$).

A.1'

$F_m = F_K Q'(m) \gtreqless 0$ as $K \lesseqgtr M$,
$F_{Km} = F_{KK} Q'(m) > 0,$
$F_{Em} = F_{EK} Q'(m) < 0$

for all $K \in (0, C)$, $E > 0$ and $g \in (0, \bar{g})$.

The properties of the growth function are illustrated in Figure 1. It is assumed that $F(\cdot) = 0$ as $K = 0$, $K = c$, $g = \bar{g}$ or $m = \bar{m}$ and $F(\cdot) > 0$ for all $K \in (0, C)$, $g \in [0, \bar{g})$, $m \in [0, \bar{m})$. That is, the growth function starts at the origin (negative growth at low stock levels would make no sense in the forest's case) and reaches zero at $C = C(E, g)$. An increase in silvicultural effort »stretches» the growth function so that both the saturation level and the intrinsic growth rate increase (cf. Tahvonen 1989), as does $M = M(E, g)$. In the case of Figure 1, the second-order cross-partial derivative F_{KE} is positive.

The impacts of exogenous pollution enter the expression (4) through two variables. First, $Q = Q(m)$ with $Q'(m) < 0$ defines the effective initial stock of standing timber of normal quality as a decreasing function of tree mortality. Thus, m represents the direct damage in the standing stock. Secondly, the growth function includes the argument g denoting the predetermined level of acidic and other depositions inducing site degradation (cf. Tahvonen 1989; McConnell & Strand 1989). This represents the indirect effect, or an anticipated decline in soil productivity. The impact of g is assumed to be identical to that of E in shape but opposite in sign (i.e., $F_g < 0$, $F_{Kg} < 0$)[2].

[2] *Note that g and E are separate arguments in the growth function. This assumption will be modified below by letting g = g(E).*

2.2 The impacts of exogenous damage on short-term timber supply and optimum effort

Solving S from eq. (2) and substituting into (3), the intertemporal budget constraint is obtained. Substituting this for c_2 and the expression in (4) for Z, the decision problem can be written as

$$\max_{\{c_1, X, E\}} \quad V = u(c_1) + \beta u\{p_2[Q-X+F(Q-X, E, g)] + (1+r)[p_1X-c_1-wE]\} \tag{5}$$

The first-order conditions for an interior maximum are

$$\begin{aligned} V_{c_1} &= u'(c_1) - \beta u'(c_2)(1+r) = 0 \\ V_X &= \beta u'(c_2)\{-p_2[1+F_K(\cdot)] + p_1(1+r)\} = 0 \\ V_E &= \beta u'(c_2)\{p_2F_E(\cdot) - w(1+r)\} = 0 \end{aligned} \tag{6}$$

An inspection of (6) reveals that the optimality conditions V_X, $V_E = 0$ for X and E are satisfied if and only if the expression in braces is zero in each of them, because β, $u'(c_i) > 0$ by assumption. This means that the harvesting and investment decisions are separable from the consumption decision. The second-order conditions $p_2F_{KK} < 0$ and $D = p_2^2[F_{KK}F_{EE} - (F_{KE})^2] > 0$ are fulfilled under the assumptions in A.1. Thus, the optimal current harvest X* and management intensity E* (and, by (4), Z as well)) are determined simultaneously by the two equations:

$$-p_2[1+F_K(Q-X, E, g)] + (1+r)p_1 = 0 \tag{7}$$

$$p_2F_E(Q-X, E, g) - (1+r)w = 0. \tag{8}$$

Condition (7) for optimal harvesting equates the marginal revenue and marginal cost of current harvest. This can also be expressed as the cutting rule $(p_2/p_1)[1+F_K(\cdot)] = 1+r$, which says that the marginal value growth rate equal the rate of interest (land rent considerations are omitted; cf. Hyde 1980). Condition (8) for silvicultural effort states that the marginal revenue and marginal cost of effort are equal at the optimum, i.e. $p_2F_E(\cdot)(1+r)^{-1} = w$.

Given that the growth function has a nonzero cross-partial derivative ($F_{KE} > 0$), there will be interaction effects between the decision variables. The comparative statics are solved from the set of two equations by totally differentiating (7) and (8) and using Cramer's rule. The results are indicated by the signs given below each exogenous variable:

$$\begin{aligned} X^* &= X^*(\underset{+}{p_1}, \underset{-}{p_2}, \underset{+}{r}, \underset{+}{w}, \underset{-}{m}, \underset{+}{g}) \\ E^* &= E^*(\underset{-}{p_1}, \underset{+}{p_2}, \underset{-}{r}, \underset{-}{w}, \underset{0}{m}, \underset{-}{g}) \end{aligned} \tag{9}$$

Apart from direct impacts of changes in the marginal revenue (cost) related to the decision variable under consideration, the results involve indirect effects due to the interaction between K and E. With $F_{KE} > 0$, the interaction effects, in most cases, work in the same direction as the direct ones and will not give rise to ambiguity or major changes in terms of qualitative results (cf. Kuuluvainen 1989; Ovaskainen 1990). Therefore, only the results for g and m are examined in more detail.

Considering the optimal current harvest first, the impacts of changes in g and m are

$$X_g = D^{-1}p_2^2\{F_{Kg}F_{EE} - F_{Eg}F_{KE}\} > 0 \tag{10}$$

$$X_m = Q'(m) < 0 \tag{11}$$

First, it can be seen in (10) that the anticipated growth decline due to pollutants increases the optimal current harvest. A reduction in the marginal product of the growing stock ($F_{Kg} < 0$), hence in the marginal cost of the current harvest, gives rise to a positive direct effect. The indirect effect works in the same direction, as a reduction in the marginal revenue of silvicultural effort (as $F_{Eg} < 0$) implies less investment and, with $F_{KE} > 0$, a smaller growing stock. Secondly, (11) suggests that increased tree mortality in the standing stock reduces short-term supply. Because $F_{KK} < 0$, a reduction in growing stock implies an increase in its marginal product. Restoring the growing stock (of so far undamaged trees) at the optimal level requires that the current harvest be reduced.

The two assumptions underlying the latter result should be noted. The formulation $Q = Q(m)$ implicitly means that the dying/dead trees, at least part of them, are not salvagable. Therefore, rather than an increase in supply from salvage fellings, there is a negative stock effect as a fraction of harvestable inventory is lost. For salvage to be financially feasible, a sufficient volume per hectare is required (e.g. Leuschner & Ferguson 1987) and, although suitable for most industrial purposes when cut soon enough, the dead trees are no longer valid as commercial timber if the wood dries (European... 1986). On the other hand, the property $F_{Km}>0$ (by $F_{KK}<0$) suggests that even if some trees die, the growth and reactions of the rest of trees are undisturbed.[3]

The results are of interest when viewed against the standard contention that supply increases due to sanitation harvests. The point is that the overall effect of forest damages on short-term supply remains indeterminate *a priori* if the expected growth decline and observed mortality are operative concurrently. Much depends on the severity of the damage to the standing timber, the feasibility of salvage, and the susceptibility of dead trees to quality losses. The non-salvage assumption need not be too extreme, especially when individual trees are dying. In fact, there seems to be no evidence of major sanitation fellings and/or increased timber supply even if relatively large-scale forest dieback has been reported in Central Europe (European... 1986; Seppälä et al. 1990).

Turning to changes in optimum effort, the impacts of pollution are indicated by (12) and (13):

$$(12)\quad E_g = D^{-1}p_2^2\{-F_{KK}F_{Eg} + F_{Kg}F_{KE}\} < 0$$

$$(13)\quad E_m = 0$$

By (12), the optimum level of silvicultural effort is reduced by an anticipated decline in forest growth. Again, there is a direct effect from a reduction in the marginal product of effort ($E_{Eg}<0$). On the other hand, the reduced growth rate ($F_{Kg}<0$) implies a smaller optimum stock. Because $F_{KE}>0$, the indirect effect works in the same direction. Eq. (13) shows that damage in the initial stock does not affect the optimal effort.

The result of (12) may seem surprising, since it might be assumed that a threat to forest health justifies more effort. However, the result is logical given the assumption that site degradation is unaffected by the silvicultural measures. The point is that expectations of a future growth decline tend to discourage »conventional» forest investment by reducing the expected returns. However, it is possible that the impacts of pollutant deposition on forest soil can be reduced by certain sanitary measures. This case will be examined next.

3. *Short-term timber supply with endogenous soil protection*

It has been suggested that liming could be used as a means to alleviate the detrimental impacts of acidic depositions on the soil. In principle, liming could replace the leaching of calcium and magnesium, decrease soil acidity, and reduce the concentrations of harmful aluminium (e.g. Derome & Pätilä 1990; Hari et al. 1990). This possibility is now taken into account by introducing soil protection into the model as an endogenous factor. This involves interpreting »silvicultural effort» as liming or another kind of a sanitary fertilization with Mg, Ca, and K.

3.1 The formulation

The growth function is reformulated by taking the negative impact of pollution on soil fertility and forest growth to be a decreasing function of the level of protective measures rather than exogenously given. Let site degradation be represented by G, which is defined as

$$(14)\quad G = \gamma g(R),\ g' < 0,\ g'' > 0.$$

In (14), soil protection is denoted by R (for »replacement»), and $g = g(R)$ is a function relating the rate of growth losses to the intensity of the protective measures. Finally, γ is a positive shift parameter depicting exogenous

[3] *Leuschner and Ferguson (1987, p. 15) suggest that the mortality of individual trees may not reduce stand yield at harvest at all, as other trees grow into the space vacated by the killed trees. Here, the total volume from current and future harvest will decrease ($X_m<0$, while $Z_m=0$).*

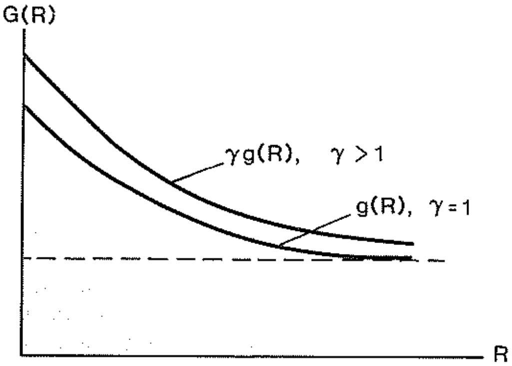

Figure 2. The degradation of growth conditions (G) as a function of protection measures.

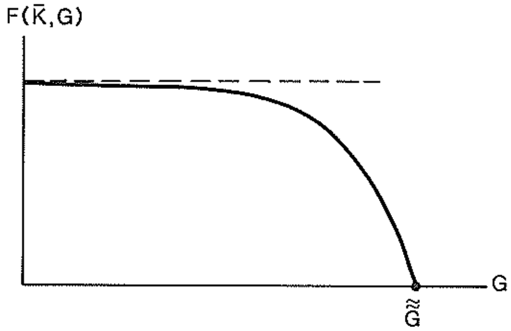

Figure 3. The effect of soil degradation (G) on forest growth (at a fixed level of growing stock).

changes in the level of pollution relative to a basic level ($\gamma = 1$).

The growth function is now written as

(15) $F = F(K, G)$

where $K = Q(m) - X$ as before. The growth function is assumed to have the following properties:

A.2

$$F_K \gtreqless 0 \text{ as } K \lesseqgtr M; \quad F_G < 0,$$
$$F_{KK}, F_{GG} < 0, F_{KG} < 0,$$
$$F_{KK}F_{GG} - (F_{KG})^2 > 0,$$

and, consequently,

A.2'

$$F_\gamma = F_G g(R) < 0, \; F_{K\gamma} = F_{KG} g(R) < 0$$
$$F_R = F_G \gamma g'(R) > 0, \; F_{R\gamma}$$
$$= [F_{GG} \gamma g(R) + F_G] g'(R) > 0$$
$$F_{RR} = F_{GG} \gamma^2 g'(R)^2 + F_G \gamma g'' < 0,$$
$$F_{KR} = F_{KG} \gamma g'(R) > 0$$
$$F_m = F_K Q'(m) \gtreqless 0 \text{ as } K \lesseqgtr M,$$
$$F_{Km} = F_{KK} Q'(m) > 0,$$
$$F_{Rm} = F_{GK} Q'(m) \gamma g'(R) < 0$$

for all $K \in (0, C)$, $G \in (0, \tilde{\tilde{G}})$, $R > 0$ and $\gamma > 1$.

The general shape of the growth function continues to be similar to that in Figure 1, with the roles of E and g interchanged with R and γ, respectively. That is, $F(\cdot) = 0$ as $K = 0$, $K = C$ or $G = \tilde{\tilde{G}}$, and $F(\cdot) > 0$ for all $K \in (0, C)$, $G \in [0, \tilde{\tilde{G}})$, where $C = C(R, \gamma)$.

The assumptions $g'(R) < 0$, $g''(R) > 0$ mean that protection measures will reduce the growth losses, but at a decreasing marginal rate (the negative marginal impact decreases in absolute value). For example, there may be a given minimum level of damage that cannot be avoided at any R (Figure 2). Further, we have $F_{GG} < 0$, i.e. the negative marginal impact of G increases in absolute value with no marked growth losses at low levels of pollution but a sudden drop after some critical level (cf. Figure 3). Taken together, the assumptions imply that soil protection shows diminishing marginal returns as indicated by $F_{RR} < 0$. Note that the initial stock $Q = Q(m)$ is unaffected by R. This suggests that while site degradation (and future growth losses in trees with minor damage so far) can be reduced by intensified protection, the currently dying trees can not be rescued.[4]

3.2 Short-term supply and optimal protection

Solving the maximization problem again yields a separation result, with the optimal

[4] *There would be other ways to introduce the damage as dependent on forest management. In particular, tree age is an important determinant of resilience to acidic conditions. The over-aging and over-stocking of forest stands increase their susceptibility to damage (e.g. New forestry... 1990), so that the damage in standing timber could be reduced to some extent by applying shortened rotation periods and intensified thinnings. This case will not be considered here.*

current harvest and protection effort determined by the conditions

$$(16)\quad -p_2[1+F_K(\cdot)]+(1+r)p_1=0$$

$$(17)\quad p_2F_G(\cdot)\gamma g'(R)-(1+r)w=0.$$

The second-order conditions $p_2F_{KK}<0$ and $D=\gamma p_2^2\{\gamma(g')^2[F_{KK}F_{GG}-(F_{KG})^2]+F_{KK}F_Gg''\}>0$ are always fulfilled under the assumptions in A.2 and (14), according to which $[\cdot]>0$ and $g''>0$. Compared to (8), the second condition now defines the optimal protection effort by equating its marginal cost with the marginal revenue, i.e. the value of the marginal growth loss ($F_G<0$) avoided by increased soil protection ($g'(R)<0$).

The comparative statics results are summarized as follows:

$$(18)\quad \begin{array}{l} X^*=X^*(p_1,\ p_2,\ r,\ w,\ m,\ \gamma) \\ \qquad\qquad\ \ +\quad -\quad +\ +\quad -\quad ? \\ R^*=R^*(p_1,\ p_2,\ r,\ w,\ m,\ \gamma) \\ \qquad\qquad\ \ -\quad +\quad -\ -\quad 0\quad + \end{array}$$

While other properties of the short-term supply function remain qualitatively similar to those under exogenous damage, the impact of the pollution level γ turns out to be *a priori* indeterminate in sign. Also, most of the results for optimal protection effort R are qualitatively similar to those for silvicultural investment. However, the positive impact of a marginal change in pollution makes a difference.

It can be shown that the effects of increased mortality in the standing timber (m) are as before, i.e., $X_m=Q'(m)<0$ and $R_m=0$. Looking more closely at the impacts of an expected growth decline, the result for the optimal current harvest can be written as follows by using A.2':

$$(19)\quad X_\gamma=D^{-1}p_2^2[F_{K\gamma}F_{RR}-F_{KR}F_{R\gamma}]\gtreqless 0$$

The first term in square brackets depicts the direct effect of an anticipated decline in forest growth: as increased acidification reduces the marginal product of growing stock ($F_{K\gamma}<0$), the optimal stock decreases and consequently more timber is optimally harvested today. The second term in (19) represents an indirect effect through changes in optimal protection. A marginal increase in pollution increases the marginal return of protection ($F_{R\gamma}>0$), thereby justifying more protection effort. Given $F_{KR}>0$, this increases the optimal growing stock *ceteris paribus*. That in turn tends to reduce the optimal current harvest, so the total effect remains ambiguous. Note that the indirect effect is opposite to that under conditions of exogenous damage.

For optimal protection under increased pollution, the result can be written as follows by using A.2':

$$(20)\quad R_\gamma=D^{-1}p_2^2[-F_{KK}F_{R\gamma}+F_{K\gamma}F_{KR}]$$

Again, there are two effects with opposite signs. The first term in brackets represents a positive direct effect arising from $F_{K\gamma}>0$, i.e., the higher marginal product of protection measures, which justifies more effort on protection. But there is also an indirect effect through a change in optimum stock. With an increase in γ, F_K, and thereby the optimal stock, will decrease ($F_{K\gamma}<0$), which also tends to decrease the optimum effort, given $F_{KR}>0$. However, the expression can be rewritten and signed by using the information in A.2 and A.2':

$$(20')\quad \begin{array}{l} R_\gamma=-D^{-1}p_2^2g'(R)\{\gamma g(R)[F_{KK}F_{GG} \\ \quad -(F_{KG})^2]+F_{KK}F_G\}>0. \end{array}$$

This shows that the positive effect dominates. In other words, an anticipated growth decline due to pollution unambiguously justifies increased investment in measures to protect future soil fertility and tree health.

4. *The impacts of pollution on the long-run timber supply*

Next, the consequences of pollution on the long-run timber supply are considered. As opposed to short-term supply which refers to the optimal harvest from a given inventory of mature timber, the notion of long-run supply deals with the steady state harvest constrained by the forest's long-run growth potential.

The two-period model can be taken to represent adaptive decision-making. The harvest timing and investment decisions are revised every period in the light of the most recent information on timber prices, interest rates, the standing stock, etc. The cutting rule in (7) or (16) requires that the increase in value growth due to the marginal unit of growing stock equals the interest rate. That is, the harvesting decision is defined in terms of an optimal level of growing stock K*, to which an arbitrary initial stock Q is adjusted by cutting if $Q > K^*$ (by refraining from cutting if $Q < K^*$).[5]

By assuming unchanging conditions over time, the optimal steady state harvest can be considered. Suppose timber price, cost, interest rate, as well as the growth function and level of pollution, remain unchanged from period to period ($p_2 = p_1 = p$, etc). The optimality conditions (7) and (8), considering the exogenous damage first, take the form $F_K(\cdot) = r$ and $pF_E(\cdot) = (1+r)w$. With all the exogenous factors constant, the marginal products of growing stock and silvicultural effort, and thus their optimal levels K* and E*, must remain as constants over time. The first period's optimal decision then defines the steady state levels of the growing stock and effort. Consequently, the optimal policy after the initial period is to harvest the steady state growth every period, so that

$$h = F(K^*, E^*, g). \tag{21}$$

That is, the long-run steady state harvest per period, h, equals the steady state growth at the optimum level of growing stock and effort.[6]

As the supply decision follows from a similar optimization problem for any period, the qualitative properties of the long-run supply function are obtained from the above results by noting that $K^* = Q(m) - X^*$ and inserting the reaction equations $X^* = X^*(p, r, w, g, m)$ and $E^* = E^*(p, r, w, g, m)$ into the growth function in (21). If only the pollution impacts are of interest, h can be written as $h = F(Q(m) - X^*(m, g), E^*(m, g), g)$. From there we obtain

$$\begin{aligned} h_m &= F_K(\cdot)[Q'(m) - X_m] + F_E(\cdot)E_m = 0 \\ h_g &= F_g(\cdot) - F_K(\cdot)X_g + F_E(\cdot)E_g < 0 \end{aligned} \tag{22}$$

as $F_K(\cdot) = r > 0$, $F_E(\cdot) > 0$, and $X_m = Q'(m)$, $E_m = 0$ by (11) and (13).

This suggests that the mortality of some trees has no effects beyond the short-term supply reduction. As part of the trees die ($Q'(m) < 0$), the current harvest is reduced ($X_m > 0$) to restore the growing stock to the optimal level. The long-run growth and harvest remain unaltered, since the two reactions cancel (in brackets) and the optimal effort is unaffected by m. On the other hand, acidification and other pollutants will unambiguously reduce the long-run steady state harvest through site degradation and declining soil productivity. The direct negative effect $Fg(\cdot)$ and the indirect impacts from changes in the decision variables all work in the same direction (increased harvesting reduces the growing stock, and »ordinary» investment is discouraged).

Turning to long-run steady state supply with an endogenous protection effort, the expression $h = F(K^*, G(R^*)) = F(Q(m) - X^*, \gamma g(R^*))$ is used with $X^* = X^*(m, \gamma)$ and $R^* = R^*(m, \gamma)$ as given in Ch. 3. By rearranging,

$$\begin{aligned} h_m &= F_K(\cdot)[Q'(m) - X_m] \\ &\quad + F_G(\cdot)\gamma g'(R)R_m = 0 \\ h_\gamma &= F_G(\cdot)g(R) - F_K(\cdot)X_\gamma \\ &\quad + F_G(\cdot)\gamma g'(R)R_\gamma \lesseqqgtr 0 \end{aligned} \tag{23}$$

As before, tree mortality has no long-run effects. On the other hand, the overall effect of growth decline remains indeterminate *a priori*, since there are repercussions arising from the endogenous protection effort. The first term in h_γ represents the direct negative effect of γ. But the last term shows an opposite reaction: with γ, the marginal revenue and thereby the optimal level of protection increase ($F_{R\gamma} > 0$, $R_\gamma > 0$). Consequently, G decreases, and the negative effect tends to can-

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[5] An interior solution with $X^* > 0$ is assumed throughout the paper. A corner solution with $X^* = 0$ is possible if the initial stock is so small that approaching the optimum stock requires waiting for the stock to grow. At an interior optimum $F_K(\cdot) < 0$ as $p_2 > (1+r)p_1$ ($F_K(\cdot) \geq 0$ otherwise), so a zero first-period harvest is more likely when timber prices are expected to rise very quickly.

[6] This is a discrete-time counterpart of the »bang-bang» adjustment and steady state rule for continuous-time models of renewable resources (e.g. Johansson & Löfgren 1985).

cel out. Also, the second term is indeterminate due to the ambiguity of X_γ.

5. Conclusion

The present paper deals with the effects of pollution on short-term timber supply, management intensity and, finally, long-run supply. Two different cases (exogenous damage vs engogenous protection), as well as the different aspects of pollution damage, have been considered separately. Therefore, it is useful to conclude by summarizing the overall pollution impacts on the long-run steady state harvest.

As the results suggest that the steady state harvest is unaffected by tree mortality, the long-run impacts reduce to those of the decline in soil productivity. The direct effect on growth is negative in both cases, as is probably the effect through the growing stock. However, the impacts through management intensity differ. In the case of exogenous growth losses, steady state growth was shown to be affected negatively, as forest investment is discouraged by decreasing returns. Instead, the anticipated damage will call for specific measures to alleviate soil degradation (which, in a sense, tend to replace conventional investments). Thus, the net impact on the long-run timber supply depends on the effectiveness of the sanitary fertilization.

Intuition suggests that the negative impacts of accumulating pollutants on soil fertility can be offset only partially. Liming, for example, is known to possess some desirable impacts, but also side effects such as a short-term growth slow-down and other imbalances (Derome & Pätilä 1990). Hari et al. (1987), while reporting the estimated amounts of nutrients required to correct for leaching, also emphasize the toxic effects of pollutants and increased risk of damage by fungi and insects. Thus, continued pollution is bound to reduce the sustainable harvest even though the impact can be weakened by protective measures.

Timber prices were assumed to be independent of the quantity sold. Given a downward-sloping market demand curve timber prices would react to nonmarginal supply shifts. In the short run, increased supply from sanitation fellings would reduce timber prices, thereby affecting supply from »undamaged» forests and reducing changes in aggregate harvest levels. In the long run, the contracting supply would induce timber prices to rise. This in turn might encourage investment in timber production and forest protection over time, and reduce the long-run reaction.

These views (cf. Ovaskainen 1987, 1990) are in line with scenarios by Seppälä et al. (1990), which suggest rather modest reactions in the timber markets. In fact, major sanitation fellings or increased timber supply have not been observed (European... 1986; Seppälä et al. 1990) despite the forest dieback reported in Central Europe (i.e., a kind of substitution by sanitary fellings for normal ones seems to have taken place). Also Haynes and Adams (1990) conclude that the impacts are slow to develop, as they depend on changes in timber inventories.

Nevertheless, increased pollution would induce a long-term welfare loss for reduced production and higher prices in the forest sector (Haynes & Adams 1990; Ovaskainen 1990). The incidence of losses depends on the relative steepness of the long-run supply and demand functions. Using U.S. sample data, Haynes and Adams (1990) suggest that due to the inelastic demand for timber, and thereby higher prices for timber and timber products, consumers and producers of forest industry products would lose the most, while forest owners would be least affected. Moreover, when concluding that reactions in the timber market may be rather small and sluggish, no suggestion is made that the forest decline as a whole is a minor problem. For one thing, the damage may have serious welfare effects through losses of other forest benefits not considered here (amenity values, e.g. recreation and scenic beauty, wildlife, and watershed effects; see Leuschner & Ferguson 1987).

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