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Economic Evaluation of Biotechnological Progress:

The effect of changing management behavior

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Abstract:

The paper assesses the welfare effects of biotechnological progress, as exemplified by tree improvements, using a partial equilibrium model. Timber demand is assumed to be stochastic and the distributions of the coefficients of the demand function are known. Assuming that timber supply is a log-linear function of timber price and forest inventory, we determine the coefficients of the supply function by maximizing the expected present value of the total surplus of timber production, both in the presence and in the absence of genetically improved regeneration materials. The supply functions are then used to estimate the expected present values of the total surplus in different cases through simulation. These estimates enable us to assess the direct effect and the total effect of the genetically improved regeneration materials on the expected present value of the total surplus. By taking the difference between these two effects, we obtain an estimate of the effect of changing harvest behavior induced by the use of genetically improved regeneration materials in forestry. The main results of the study are (1) the presence of genetically improved regeneration materials has significant impacts on the aggregate timber supply function; (2) application of genetically improved regeneration materials leads to a significant increase in the expected present value of the total surplus; (3) a considerable proportion of the welfare gain results from the change in timber harvest behavior; and (4) the use of genetically improved regeneration materials reduces the profits of timber production.

Additional keywords: timber market model, tree improvement, optimal harvesting decision, timber supply.

1. Introduction

Biotechnological progress in forestry has been relatively fast in the sense that the productivity of forest land has increased considerably in the past decades. In Sweden, for example, the current timber growth is 30% above what was considered to be the maximum level in the 1930s. The increase in forest growth is partly attributed to the improved silvicultural practices in general, but the use of genetically better materials in stand establishment is certainly one of the most important constituting factors.

Planting genetically improved trees is nowadays perceived as one of the most efficient methods to enhance timber yield and the income of forest owners (Simonsen et al. 2007). Genetically improved trees can for example better resist damages, increase growth, and produces wood of higher quality. A higher survival rate of seedlings and higher production can in addition reduce the costs for stand establishment, management, and harvesting. In general, the cost of producing traditional seed-orchard seeds is very low compared to the great benefits, making the use of seed-orchard seedlings highly profitable and attractive to most forest owners. The logistics of seedling distribution from a small number of forest nurseries adds to the potential of widespread use of genetically improved trees. In Sweden, 80 % of all Scots pine and 50 % of all Norway spruce seedlings originate from seed orchard seeds. In fact, all available seed-orchard seeds are used and new seed orchards are being established to cover the whole Swedish nursery market (Rosvall et al. 2002). By using currently producing seed orchards and those which will be available in the future from already decided investments, the total timber harvest in Sweden is expected to increase by 9% in the future (Skogsstyrelsen 2009). Rosvall (2007) estimates that future timber harvest can be increased by 14% through the use of new propagation techniques.

Research on economic valuation of new genetic materials in forestry started in the late 1960s. One of the first papers is Davis (1967), which focuses on the cost of producing genetically improved seeds through investment in loblolly pine clonal seed-orchard and on the increase in timber yield necessary to make the investment profitable. A number of similar studies were conducted in the early 1970s[1]. More recent empirical evaluations of different tree improvement programs include Fins and Moore (1984), Stier (1990), and Palmer et al. (1998). Löfgren (1985) investigates theoretically how different types of biotechnological progress affect optimal forest management and the economic value of forestry. Löfgren (1988, 1990, 1996) extend previous economic analyses of tree improvements by introducing a number of general results on the properties of the optimal value function, i.e., the economic value of the forest under best practice associated with different types of biotechnology. Specifically, these works show how the economic gains from genetic progress can be given upper and lower bounds that, to a considerable extent, can be calculated based on current management practices.

In a general equilibrium setting, i.e., when imbedded in the rest of the economy, the analysis shows how the valuation problem (the cost-benefit analysis) can be solved in a market economy under different institutional regimes (Löfgren 1990). Here the impacts of consumer preferences are accounted for, as well as the effects of different sectors of the economy. The value generated by genetic progress, in the natural

[1] See Dutrow (1974) for a review of the earlier studies.

resource sector, emerges in terms of cost-benefit rules which tell us which component have to be estimated empirically.

The purpose of this paper is to extend the previous economic analyses by explicitly considering the impact of accelerated forest growth, resulting from the use of improved seeds, on timber price and on harvesting decisions. We will draw heavily on a methodology developed in Gong (1994,1995) and use a stochastic partial equilibrium model of the Swedish forest sector. This allows for contra factual comparisons of old and new regeneration materials that are introduced gradually in the forest sector.

2. A conceptual description of the welfare effects of tree improvement

Tree improvement increases the productivity of forestland and, therefore, affects both forest owners and “timber consumers” (the timber processing industry and other users of timber). From the perspective of forest owners, access to genetically improved regeneration materials (IRMs) implies that forest stands established in the future will grow faster than the existing ones. This means that they will be able to produce a greater amount of timber in their forests, but timber prices are likely to be lower (than in the absence of the IRMs) in the future as a result of the increase in production. The financial consequences of tree improvement, for the forest owners, depend on the relative magnitudes of the increase in timber yield and the decrease in prices.

However, advances in tree improvement will increase the consumer surplus, since the increase in the productivity of forestland implies that the timber processing industry and other users of timber can purchase greater amounts of timber at lower prices.

When IRMs emerge, the anticipated changes in the productivity of forestland and in timber prices would probably lead to changes in silvicultural practices as well as changed rotation ages, both for existing stands and for stands to be established using the IRMs. This means that the relationship between timber supply and factors affecting the optimal harvest decisions may change. Under the assumption of rational behavior, forest owners will change their management decisions in order to increase their gains (or reduce their losses) resulting from the use of IRMs. Such changes in management behavior are likely to affect consumers negatively. However, if the market leads to a socially optimal allocation of the resources, the change in forest management behavior in response to the presence of IRMs would increase the social welfare.

Figure 1 illustrates the changes in welfare at time *t*, when forest owners start to use IRMs at time 0. To keep the figure simple, we assume here that the timber demand and supply functions are both linear. Further, we pretend that the total surplus at time *t* is equal to the area between the demand curve and the supply curve[2]. The supply curve $S^b(I^b, p)$ depicts the relationship between the optimal harvest level and timber

[2] This is incorrect in the context of multiple-period natural resource management problems.

price at time t, in the absence of IRMs, where I^b denotes the (mature) timber stock in the forests at time t. The supply curve $S^b(I^n, p)$ shows the amount of timber to be harvested at time t corresponding to different prices in the case where IRMs have been used, but there is no change in forest owners' management behavior. Thus, the shift of the supply curve from $S^b(I^b, p)$ to $S^b(I^n, p)$ is caused solely by the change in the growing stock of timber from I^b to I^n. It does not involve any change in the supply function itself. Finally, the supply curve $S^o(I^o, p)$ describes the relationship between the harvest and price at time t after the forest owners have changed their management behavior in response to the presence of IRMs. It gives the optimal harvest level corresponding to different prices at time t.

Figure 1 shows that the adoption of IRMs results in an increase in the welfare at time t by an amount equal to the area *ABEF*. This change in welfare can be decomposed into two parts: the direct effect (indicated by area *ABCD*), and the effect of changing management behavior (indicated by the area *DCEF*). The direct effect tells how much the total surplus would change, as a result of the adoption of IRMs, if forest owners manage their forests as they used to do (except that they use the IRMs to regenerate the harvested sites). The effect of changing management behavior refers to the additional change in welfare when forest owners adapt their management activities to the new biological and economic conditions resulting from the use of IRMs.

The magnitude of the effect of changing management behavior depends on the difference between the two supply curves $S^b(I^n, p)$ and $S^o(I^o, p)$. If the use of IRMs does not induce any change in the relationship between the optimal harvest level and the factors that determine the optimal harvest decision, the supply curve $S^b(I^n, p)$ would be identical to $S^o(I^o, p)$. Consequently, there would not be any effect from changing management behavior. On the other hand, if the supply function changes significantly when IRMs are used, the effect of changing management behavior on welfare could be large.

It should be pointed out that the direct effect as well as the effect of changing management behavior is likely to vary with time. Thus, one cannot examine the welfare effects of tree improvement by examining the change in the total surplus (the sum of producer surplus, i.e. forest owners' profits and consumer surplus) at a single point in time. Rather, one should examine the sum of properly discounted changes in total surplus at different points in time. Figure 1 describes a situation where both types of effects are positive. However, it is possible that the emergence of IRMs causes the total surplus to increase at some points in time, but decrease at others. Because of the complex interactions between optimal forest management decisions, timber supply, and the dynamics of the forests, numerical analyses are required to determine the sign and assess the magnitudes of the direct effect and the effect changing management behavior at different points in time.

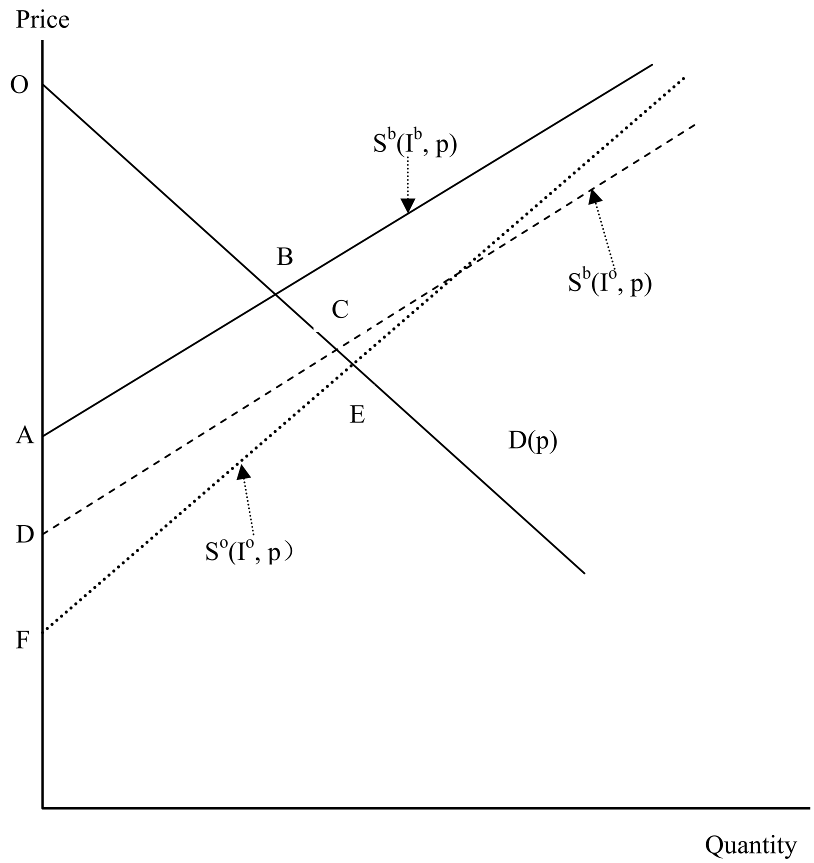

Figure 1. A graphical description of the welfare effects of tree improvement.

3. Methods

In order to assess the effect of changing management behavior on the welfare changes resulting from tree improvement, we need to know the "optimal" supply function both in the absence and in the presence of IRMs. We use the word "optimal" to emphasize that the supply function should describe the relationship between the optimal harvest level and its determining factors.

Our task is to conduct counterfactual comparisons and this has shown to be very difficult, in particular if one bases the approach on relationships estimated using historical data. This insight was forcefully introduced in a paper by Robert Lucas in 1976 where he showed how policy based on parameters that are not policy invariant, i.e. they change whenever the policy/experiment changes, could potentially be very misleading. An example would be a general equilibrium macroeconomic model where certain parameters, estimated from historical data, change whenever fiscal or monetary policy changes. This argument questioned the large scale econometric models that lacked foundations in dynamic economic theory. Lucas suggested that, if we want to conduct a counterfactual experiment, we should model the "deep" parameters relating to underlying preferences, technology and resource constraints.

Our counterfactual experiment will use a slightly different approach based on an idea suggested by Gong (1994, 1995) to handle "the Lucas critique". Here we model the shapes of the demand and supply functions that are determined by their respective parameters[3]. The parameters of the stochastic demand function are calibrated from previous econometric estimates of its position and its elasticity, while the optimal total surplus is determined by optimizing with respect to the parameters of the supply function conditional on the demand function. The underlying resource constraints pertain to the state of the forest, its age structure and its growth function. Our experiment is to compare the impact on the optimal value function (total surplus) associated with different growth functions.

[3] This can be made in a very general manner by introducing parameters related to a Taylor expansion, but here we restrict the optimal controls/parameters to three.

In other words, we determine the theoretically optimal timber supply function both in the absence and in the presence of the new and better regeneration materials. These supply functions are then used to estimate the direct effect and the effect of changing management behavior on the total surplus following the introduction of new and better regeneration materials.

3.1 Overview of the method

Conceptually, the timber supply function gives the optimal amount of timber harvest in each time period conditional on the current state of the forest and market conditions. This means that one can, in principle, identify the timber supply function based on the characteristics of the optimal harvest decisions. When considering a particular forest, the optimal harvest decision maximizes the value of a properly defined objective function that represents the preferences of the forest owner. Accordingly, the timber supply function at the first-property level could be determined by maximizing the forest owner's objective function (Gong 1994, 1995). In a perfectly competitive market, the time path of the aggregate supply of timber (the sum of optimal harvests from all forests in each time period) is characterized by maximization of the present value of the total surplus (Lyon and Sedjo 1983, Gong and Löfgren, 2003). Therefore, we can determine the market supply function by maximizing the present value of the total surplus.

In this paper, we consider the case when the timber demand function is stochastic. We assume that all forest owners are risk neutral, and determine the market supply function by maximizing the EPV of the total surplus over time. Specially, we choose a functional form of the timber supply function $S(X_t, p_t; A)$ and determine the parameters (A) of the supply function by solving the following maximization problem:

$$\max_A \quad E[TS(A)] = E\left[\sum_{t=1}^{\infty}\left(\int_0^{Q_t} P(q; B_t)dq - C(X_t, Q_t)\right)e^{-rt}\right] \tag{1}$$

$$\begin{aligned} p_t &= P(Q_t; B_t) \\ Q_t &= S(X_t, p_t; A) \end{aligned} \tag{2}$$

$$X_{t+1} = G(X_t, Q_t) \tag{3}$$

$$X_1 = X_0 \tag{4}$$

where E is the expectation operator,

$P(Q_t; B_t)$ = the inverse timber demand function at time *t*. The functional form of $P(Q_t; B_t)$ as well as the probability distributions of the random parameters (B_t) are assumed to be known.

$C(X_t, Q_t)$ = forest management and harvest costs as a function of the state of the forest and the harvest level.

Q_t = the market supply of (and demand for) timber at time *t*.

p_t = the market price of timber at time *t*.

X_t = the state of the forest at time *t*.

X_0 = the initial state of the forest.

r = discount rate

$G(X_t, Q_t)$ = the growth function of the forest.

Constraint (2) is the market clearing condition. Constraint (3) is the dynamics of the forests. Equation (4) gives the initial state of the forests. Of course, the total harvest at each point in time cannot exceed the total growing stock of timber in the forests. This constraint is embedded in the supply function.

Except in some trivial cases, it is impossible to derive a closed form expression of the EPV of the total surplus given in Equation (1). Solution of the above optimization problem will have to rely on numerical approximations of the objective function. In the current case, stochastic variations in the total surplus originate from uncertainty in the coefficients of the timber demand function. Given a timber supply function, a simple way to estimate the EPV of the total surplus is to take the average of the present values of the total surplus associated with a large number of randomly drawn timber demand scenarios.

Let $\left[B_1^k, B_2^k, ..., B_T^k\right]$ denote the coefficients of the demand function in years 1 to T in scenario k, where B_t^k is a random sample drawn from the distribution of B_t. A numerically tractable version of the optimization problem (1)-(4) can be formulated as:

$$\max_A \quad E[TS(A)] = \frac{1}{N}\sum_{k=1}^{N}\left[\sum_{t=1}^{T}\left(\int_0^{Q_t^k} P(q; B_t^k)dq - C(X_t^k, Q_t^k)\right)e^{-rt} + R(X_{T+1}^k)e^{-r(T+1)}\right] \quad (5)$$

$$\begin{array}{l} p_t^k = P(Q_t^k; B_t^k) \\ Q_t^k = S(X_t^k, p_t^k; A) \end{array}, \quad \text{for } t = 1\ldots T;\ k = 1\ldots N \tag{6}$$

$$X_{t+1}^k = G(X_t^k, Q_t^k), \quad \text{for } t = 1\ldots T;\ k = 1\ldots N \tag{7}$$

$$X_1^k = X_0, \qquad \text{for } k = 1\ldots N \tag{8}$$

where N is the number of demand scenarios used to estimate the EPV of the total surplus; T is the time horizon within which the annual harvest of timber is determined using the supply function; Q_t^k is the market supply (and demand) of timber in year t in scenario k; p_t^k is the market price of timber in year t in scenario k; X_t^k is the state of the forest in year t in scenario k; and $R(X_{T+1}^k)$ is the value of the forest in year T+1. To be specific, the term $R(X_{T+1}^k)$ represents the sum of the discounted total surplus the forest will generate from year T+1 and onwards. That is:

$$R(X_{T+1}^k) = E\left[\sum_{t=T+1}^{\infty}\left(\int_0^{Q_t} P(q; B_t)dq - C(X_t, Q_t)\right)e^{-rt}\right]$$

By constructing a special rule of determining the harvest volumes Q_t for t = T+1 to infinity we will be able to estimate the value of the forest at time T+1. This is needed for estimating the EPV of the total surplus associated with a given timber supply function.

The optimization model (5)-(8) can be used to determine the coefficients of the timber supply function both in the absence and in the presence of IRMs. In terms of the optimization model, the two cases differ from each other only in the growth function of the forests. Let $G^b(X_t, Q_t)$ and $G^n(X_t, Q_t)$ denote the growth functions of the forests in the absence and in the presence of the IRMs, respectively. Then, by solving the optimization model (5)-(8) using the growth function $G^b(X_t, Q_t)$ we obtain the coefficients of the timber supply function and the EPV of the total surplus in the absence of IRMs. Denote this optimal solution by A^b and $E[TS^b(A^b)]$. Similarly, if the growth function $G(X_t, Q_t)$ in Equation (7) is replaced by $G^n(X_t, Q_t)$, then the optimal solution of problem (5)-(8) gives us the coefficients of the timber supply function and the EPV of the total surplus in the presence of IRMs. Denote this optimal solution by A^n and $E[TS^n(A^n)]$.

Relating to Figure 1, the EPV of the total surplus in the absence of IRMs, $E[TS^b(A^b)]$, corresponds to the area AOB. The EPV of the total surplus in the presence of IRMs, $E[TS^n(A^n)]$, corresponds to the area FOE. The difference between $E[TS^n(A^n)]$ and $E[TS^b(A^b)]$ is, hence, the total welfare effect of using the IRMs.

We can decompose the total welfare effect into the direct effect and the effect of changing harvest behavior by estimating the EPV of the total surplus in the following situation: IRMs are used in forest regeneration, but the forest owners do not change their harvest behavior. The use of IRMs means that the dynamics of the forests should be described by the growth function $G^n(X_t, Q_t)$. Since the forest owners do not change their harvest behavior, the timber supply function remains as $S(X_t, p_t; A^b)$. The EPV of the total surplus in this case, denoted by $E[TS^n(A^b)]$, is estimated using the following set of equations:

$$E[TS^n(A^b)] = \frac{1}{N}\sum_{k=1}^{N}\left[\sum_{t=1}^{T}\left(\int_0^{Q_t^k} P(q;B_t^k)dq - C(X_t^k, Q_t^k)\right)e^{-rt} + R(X_{T+1}^k)e^{-r(T+1)}\right] \quad (9)$$

$$\begin{aligned} p_t^k &= P(Q_t^k; B_t^k) \\ Q_t^k &= S(X_t^k, p_t^k; A^b) \end{aligned}, \text{ for } t = 1\ldots T;\ \text{k}=1\ldots\text{N} \quad (10)$$

$$X_{t+1}^k = G^n(X_t^k, Q_t^k) \quad \text{for } t = 1\ldots T;\ k=1\ldots N \quad (11)$$

$$X_1^k = X_0 \quad \text{for } k=1\ldots N \quad (12)$$

The EPV of total surplus $E[TS^n(A^b)]$ corresponds to the area DOC in Figure 1.

The direct effect of using IRMs on welfare is:

$$E[TS^n(A^b)] - E[TS^b(A^b)]$$

The effect of changing harvest behavior is:

$$E[TS^n(A^n)] - E[TS^n(A^b)]$$

This term measures the result of an attempt to avoid the "Lucas critique".

3.2 Specification of the model

This section describes in detail the specific version of model (5)-(8) we used in our numerical assessment of the effect of using IRMs. To make the presentation easier and less messy, we skip the demand scenario index k in all variables and parameters. Superscripts are still used, but for other purposes.

3.2.1 The state of the forests

The forestland is divided into two parts, productive land and less productive land. In each part, there can be two types of stands - the initially existing stands (old stands) and stands which will be established using IRMs after the old stands have been harvested. The new stands are expected to grow faster and provide larger timber yields than the old stands on similar land, and hence should be separated from the old ones in the model. The state of the forest in each time period is described by the age-distribution of each of the four types of stands (old stands on productive land, old stands on less productive land, new stands on productive land, and new stands on less productive land). For simplicity we call each type of stand a forest. The state of the i-th forest is denoted by

$$X_t^i = (x_{t,1}^i, x_{t,2}^i, ..., x_{t,M}^i),$$

where $x_{t,a}^i$ (i =1…4; t = 1…T; a = 1…M) is the total area of a-year old stands in forest i in time period t, T is the simulation time horizon, and M is the maximum age of the stands.

Table 1. The four forests included in the model.

Identification number	Description of the forest
$i = 1$	old stands on less productive land
$i = 2$	old stands on productive land
$i = 3$	new stands on less productive land
$i = 4$	new stands on productive land

The age-distributions enable us to describe and simulate the dynamics of the forests more precisely than highly aggregate forest state variables (such as the timber inventory). However, it is neither practical nor desirable to include directly the age-distributions as arguments of the supply function. In the supply function, the state of the forests in each time period *t* was described by one aggregate state variable, the inventory of mature timber stock. Let $V^i(a)$ be the per unit area timber stock of the *a*-year old stands in forest *i.* Given the age-distributions of the forests in period *t*, the mature timber stock (I_t) is:

$$I_t = \sum_{i=1}^{4} \sum_{a=m}^{M} V^i(a) x_{t,a}^i \,, \tag{13}$$

where *m* is the lowest stand age at which harvest of the stand is allowed.

3.2.2 Demand and supply functions

The inverse demand function in time period *t* is

$$P(Q_t, B_t) = \beta_t^1 (Q_t)^{\beta_t^2} \tag{14}$$

where β_t^1 and β_t^2 are stochastic coefficients. We assume that β_t^1 as well as β_t^2 for $t = 1 \ldots T$ are independent and identically distributed normal variables. Furthermore, in each time period *t* the two parameters β_t^1 and β_t^2 are independent.

The supply function is modeled as:

$$S(I_t, p_t; A) = e^{\alpha_1} (I_t)^{\alpha_2} (p_t)^{\alpha_3} \,, \tag{15}$$

where $A = (\alpha_1, \alpha_2, \alpha_3)$ is a vector of the supply function coefficients to be determined through optimization[4].

Substitute the demand function (14) and the supply function (15) into Equation (6), the market clearing condition is specified as:

$$\begin{aligned} p_t &= \beta_t^1 (Q_t)^{\beta_t^2} \\ Q_t &= e^{\alpha_1} (I_t)^{\alpha_2} (p_t)^{\alpha_3} \end{aligned}, \quad \text{for } t = 1 \ldots T \tag{16}$$

3.2.3 The harvest areas in different stands

The set of equations (16) enable us to determine the total harvest volume and timber price in each time period corresponding to each state of the forests. In order to determine the management and harvest costs, as well as the age-distributions of the forests in the next time period, we need to decide which forest stands should be harvested to obtain the market clearing amount of timber. The decision on the stands to be harvested in each period is made based on estimates of the expected gain of delaying the harvest by one year. The expected gain from delaying the harvest of an a-year old stand in forest i is defined as:

$$E[g^i(a)] = \left((p_t - C_h)V^i(a+1) + L^i\right)e^{-r} - (p_t - C_h)V^i(a) - L^i \tag{17}$$

where p_t is the timber price in period t, C_h is the per cubic meter timber harvest cost, and L^i is the expected value of bare land in forest i, which is determined using the

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[4] Defining the constant term in the supply function as the base e raised to the power of α_1 helps to improve the precision of the numerical solution.

long-run steady state expected timber price[5]. In each period t, stands were selected for harvesting in the order of increasing expected gain from delaying the harvest. That is, one starts by harvesting the stands that have the lowest expected gain from delaying the harvest, then continue to harvest the stands that have the second lowest expected gain and so on until a specific amount of timber has been obtained. This rule of selecting the stands to harvest is, in principle, the same as the rule of harvesting in the order of decreasing age of the stands.

Let $h_{t,a}^{i}$ (i =1…4; t = 1…T; a = m…M) denote the area of the a-year old stands in forest i to be harvested in time period t. The rule of prioritizing the stand for harvest implies that

$$\text{If } h_{t,a}^{i} > 0 \text{ then } h_{t,b}^{j} = x_{t,b}^{j} \text{ for all } j \text{ and } b \text{ such that } E[g^{j}(b)] < E[g^{i}(a)] \tag{18a}$$

where $g^{i}(\cdot)$ is the expected gain function. The harvest areas in different stands should also satisfy the following conditions:

$$\sum_{i=1}^{4}\sum_{a=m}^{M} V^{i}(a)h_{t,a}^{i} = Q_t , \tag{18b}$$

$$h_{t,a}^{i} \le x_{t,a}^{i} , \quad i =1\ldots4,\ a = m\ldots M, \tag{18c}$$

Equation (18b) means that the total amount of timber harvested from the forests should equal the amount delivered to the market. (18c) says that the harvest area in each stand cannot exceed the total area of the stand. The three conditions (18a)-(18c) enable us to determine the area to be harvested in each stand conditional on the state of the forests and the total amount of timber to be harvested.

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[5] The expected timber price associated with the long-run steady state of the forests.

We assume that the harvested area is regenerated immediately, but ignore all other management activities. Thus the state of the forests in each time period has no direct effect on the management and harvest costs[6]. The total harvest area in forest *i* in period *t* is:

$$HA_t^i = \sum_{a=m}^{M} h_{t,a}^i, \quad i = 1 \ldots 4.$$

3.2.4 Harvest and regeneration costs

The total regeneration area in each of the forests depends on whether IRMs are available. In the absence of IRMs, the area of the "new forests" is always zero and the harvested area in each of the "old forests" remains in the same "old forest". The total regeneration area in each forest in period *t* is:

$$\begin{aligned} RA_t^i &= HA_t^i = \sum_{a=m}^{M} h_{t,a}^i, \quad i = 1, 2 \\ RA_t^i &= 0, \qquad\qquad\qquad i = 3, 4 \end{aligned} \tag{19a}$$

In the presence of IRMs, we assume that all harvested areas will be regenerated with the new materials[7]. This means that, after regeneration, the harvested area in each of the "old forests" moves to the corresponding "new forest". The total regeneration area in each forest in period *t* would be:

[6] The state of the forests affects the management and harvest costs indirectly through its impact on the total harvest volume and on the harvest area in each forest.

[7] It is more likely that only part of the harvested area in each forest will be regenerated with the new materials, at least in the early phase after the new materials are introduced.

$$RA_t^i = 0, \qquad\qquad i = 1, 2$$
$$RA_t^i = HA_t^{i-2} + HA_t^i = \sum_{a=m}^{M} h_{t,a}^{i-2} + \sum_{a=m}^{M} h_{t,a}^i, \qquad i = 3, 4 \tag{19b}$$

Given the total regeneration area in each forest, the management and harvest costs in period t are:

$$C(X_t, Q_t) = C_h * Q_t + \sum_{i=1}^{4} C_r^i * RA_t^i \tag{20}$$

where C_r^i is the per ha regeneration cost of forest i.

3.2.5 Forest growth

Forest growth was modeled by tracing the changes in the age-distributions of the forests over time. For each forest i (i = 1…4) and time period t (for t = 1…T):

$$x_{t+1,M}^i = x_{t,M}^i - h_{t,M}^i + x_{t,M-1}^i - h_{t,M-1}^i, \tag{21a}$$

$$x_{t+1,a}^i = x_{t,a-1}^i - h_{t,a-1}^i, \text{ for } a = m+1 \ldots M\text{-}1, \tag{21b}$$

$$x_{t+1,a}^i = x_{t,a-1}^i, \quad \text{for } a = 2 \ldots m, \tag{21c}$$

$$x_{t+1,1}^i = RA_t^i, \tag{21d}$$

The regeneration areas RA_t^i are determined by equations (19a) or (19b), depending on whether IRMs are available.

3.2.6 The end value

In order to estimate the value of the forests remaining at the end of the simulation time horizon, we assumed that these forests will be converted to the long-run "optimal steady state" by keeping the periodic harvest area in each forest at a constant level. The long-run optimal steady state is defined conditional on the assumption that the forests will be managed according to the Faustmann rule. It is determined using the following conditions:

(a) The total area of each forest is equally distributed among stands in different ages from 1 to the optimal rotation age.

(b) Only the stands that have reached the optimal rotation age are harvested and regenerated in each period.

By keeping the harvest area in each forest at a constant level, the forests remaining at the end of time period T will be converted to the optimal steady state after one rotation. During the transition period, the expected consumer and producer surplus in each year are implicitly determined by the age-distributions of each forest. Thereafter the expected consumer and producer surplus will remain constant.

3.3 Data

The total forest area covered in the analysis is 20 million ha (which includes all the productive forests in Sweden under the age of 120 years), divided into two soil productivity classes of approximately equal size (see Table 2). All the existing forests are classified as "old forests". The current age-class distributions of these forests are determined based on data from national forest inventory (Figure 2). In the numerical analysis, each time period consists of one year. When determining the initial state of the forests, we assume that the forest stands within each age-class are uniformly distributed among different ages within that age-class.

The “new forests” in Table 2 refer to those that will be established using IRMs. It is assumed that the forests established using IRMs grow 40% faster (measured in terms of the maximum mean annual increment, MAI) than the existing ones with the same site productivity.

Table 2. Total area and productivity of the forest land and regeneration costs.

	Old forests		**New forests**	
Site productivity	Low	High	Low	High
MAI (m3/ha/yr)	3.5	5.5	4.9	7.7
MAI max age (yrs)	120	100	110	90
Regeneration cost (SEK/ha)	6500	8500	6600	8600
Total area (million ha)	10.522	9.524	0	0

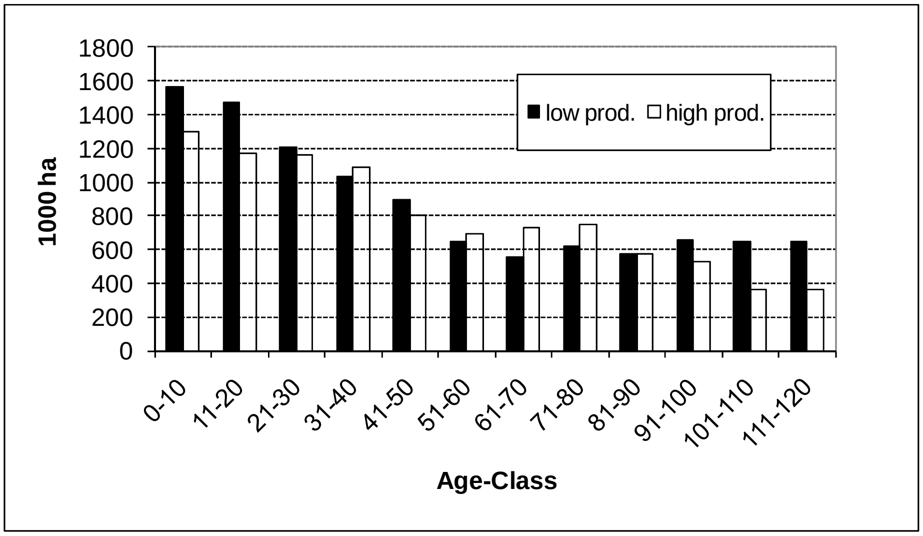

Figure 2. The age-class distribution of the existing forests.

Timber yields (m^3/ha) in different stands were estimated using a modified version of the production function of Fridh and Nilsson (1980).

$$V^i(a) = A^i * Y^i * 1.6416 * (1 - 6.3582^{-a/A^i})^{2.8967}(1 - e^{-0.02a}) \tag{29}$$

where Y^i is the maximum MAI, and A^i is the stand age at which the MAI reaches its maximum (see Table 2). The term within the last pair of parentheses of yield function (29) is an age-dependent conversion factor. This is used to calculate the equivalent volume of timber of some standard grade corresponding to the growing timber stocks at different ages. The purpose of measuring timber yields in a standardized volume is to avoid the need for explicitly dealing with the dependence the yields of timber, of different grades, have on stand age and the dependence of the price on the grade of timber.

For all the forests, the maximum stand age recognized in our analysis was 120 years and the lowest harvest age was 60 years.

The mean values and standard deviations of the inverse timber demand function used in this study are presented in Table 3. Based on the results of earlier empirical studies (Brännlund et.al. 1983, Brännlund 1988), we assume that the average price elasticity of timber demand is -0.6, which gives us the mean value of β^2. The mean value of β^1 was determined based on the mean value of β^2 and the annual total supply and price in recent years. The standard deviations of the two parameters were set to 10 % of their mean values.

Table 3. Mean and standard deviation of the demand function coefficients.

Coefficient	Mean	Standard deviation
β^1	473610.0	47361.0
β^2	-1.67	0.167

The harvest cost is 95 SEK/m^3, and a real interest rate of 3% was used throughout the analysis. The simulation time horizon was set to 200 years (T = 200). 100 randomly generated demand scenarios were used in the optimization of the supply function coefficients (N = 100).

3.4 Solution methods

The optimization problem (5)-(8) was solved as an unconstrained minimization problem – we solved the problem by finding the values of the supply function coefficients *A* that minimize the negative of the EPV of total surplus, and the constraints (6)-(8) were used to determine the value of the objective function. Figure 3 describes the procedure for estimating the EPV of the total surplus associated with different values of the coefficients of the supply function. The solution method we used was a combination of gradient descent and Powell's method (Powell, 1964). Given an initial guess of the values of *A*, we used the gradient decent method to find an optimal solution with low precision, from where we continued the search for the optimal solution using Powell's method.

When optimizing the values of the supply function coefficients, the EPV of total surplus was estimated using 100 demand scenarios, both in the absence and in the presence of IRMs. After the optimal values of the supply function coefficients have been determined for the respective cases, extended simulations using different sets of demand scenarios were carried out to estimate the EPV of the total surplus in different situations. Optimizations of the supply function coefficients as well as the simulations were implemented in Turbo Pascal[8].

4 Results

[8] The program is available from the authors upon request.

4.1 Timber supply function

It is well known that a nonlinear optimization problem may have multiple local optimal solutions. In an attempt to find the global optimal solution, we solved the optimization problem repeatedly using different starting points, both for the benchmark case and the case when IRMs are used in forest regeneration. The starting points were generated randomly within some specified intervals (the initial values of α_1 and α_3 were chosen from the interval [0.6, 0.7], and the initial value of α_2 was chosen from the interval [0.06, 0.16]).

Table 4 presents 10 optimal solutions in the benchmark case (when IRMs are not available), in the order of a decreasing objective function value. These solutions were obtained using the same set of timber demand scenarios. This makes the objective function values associated with the different solutions directly comparable. To be more certain about the relative performances of the different supply functions, we estimated the EPV of the total surplus associated with each of the supply functions in Table 4 using 10 different sets of timber demand scenarios, where each set consists of 1000 scenarios. The results for the first two supply functions are presented in Table 5. The last column in Table 5 shows the difference in the EPV of the total surplus between the first and the second solution presented in Table 4. The results in Table 5 show clearly that the first solution is superior to the second one[9]. The simulations

[9] A simple t-test would show that the difference in the EPV between the two solutions is statistically

showed that the first solution led to significantly larger EPV than each of the other 9 solutions. Therefore, we chose the first solution in Table 4 as the global optimum for the benchmark case. That is, the optimal market supply function in the absence of IRMs is:

$$S^b(Q_t, p_t) = e^{-19.759881}(Q_t)^{1.975686}(p_t)^{1.720915} \tag{30}$$

Table 4. Optimal values of the supply function coefficients and the expected present value of the total surplus (billion SEK) in the absence of regeneration materials.

Solution nr	α_1	α_2	α_3	$E[TS^b(\alpha^b)]$
1	-19.759881	1.975686	1.720915	22475.4805
2	-0.733306	0.091132	0.774019	22438.4648
3	0.214024	0.100281	0.602536	22432.5384
4	0.394788	0.041671	0.643698	22431.2745
5	0.399262	0.052216	0.629837	22431.2237
6	0.589985	0.043376	0.608511	22429.8152
7	0.613215	0.009356	0.648415	22429.7295
8	0.616827	0.065843	0.575978	22429.4367
9	0.652272	0.039568	0.602555	22429.3543
10	0.677073	0.048903	0.586619	22429.0750

Table 5. Estimates of the expected present values of total surplus (billion SEK) associated with the first two solutions presented in Table 4. Each estimate is the

significant.

average of 1000 random samples.

Simulation Nr	Solution Nr 1	Solution Nr 2	Difference
1	22440.3458	22403.50	36.8456
2	22483.4690	22446.63	36.8342
3	22480.0278	22442.80	37.2307
4	22491.9954	22454.33	37.6694
5	22480.3823	22443.20	37.1823
6	22486.3847	22449.45	36.9347
7	22446.8810	22409.81	37.0710
8	22490.5597	22453.59	36.9697
9	22471.9369	22435.02	36.9169
10	22483.7921	22446.44	37.3521
Average	22475.5775	22438.48	37.1007

Following the same procedure, we obtained the optimal supply function in the presence of IRMs:

$$S^n(Q_t, p_t) = e^{-27.798934}(Q_t)^{2.497689}(p_t)^{2.511081} \tag{31}$$

What may appear remarkable about the supply functions is that the inventory elasticity and the price elasticity are abnormally high. It should be emphasized that most of the solutions we obtained do have "normal" inventory and price elasticity (see Table 4 for the benchmark case). Yet, these solutions lead to a lower EPV of the total surplus, which implies that these supply functions do not provide better descriptions of the relationship between timber supply and the explanatory variables.

The inventory elasticity of timber supply depends partly on the definition of inventory and the assumption about the area of forestland. For example, a change in the mature timber stock would have a larger impact on supply than a change in the total timber inventory in the forest. One can also imagine that the effect of increasing timber stock caused by an increase in the share of older stands in a forest would be larger than when the timber stock increase is caused by an expansion of the forest area. Likewise, the price elasticity of timber supply may depend on the age-class distribution of the forests. In this study, we used the mature timber stock (timber inventory in stands which are older than 60 years) as an independent variable in the supply function. The total area of forestland was fixed, which, together with the ranking rule used to select the stands to harvest, imply that the mature timber stock changes only through the change in the area of the oldest stands in the forests. The initial mature timber stock is over 2 000 million m^3, which is about 20 times larger than the annual harvest volume. With this background, it is not surprising that the inventory elasticity of supply is very high. The existence of this enormous mature timber stock is also the reason why the price elasticity of timber supply is high. When there is a large amount of timber in old stands, a small increase in timber price would cause a considerable change in the harvest volume.

4.2 Welfare effects

In order to obtain reliable estimates of the welfare effects of using IRMs, we repeatedly estimated the EPV of the total surplus in each of the three cases (the benchmark case, the case with the new forest growth function and the benchmark supply function, and the case with the new growth function and new supply function). We used 20 different sets of demand scenarios, where each set consists of 1000 demand scenarios.

Table 6 presents the EPVs of producer surplus (forest management profits), consumer surplus, and the total surplus in the benchmark case. The huge EPVs of consumer surplus and total surplus are mainly the results of the iso-elastic demand function. One should keep in mind that it is the changes in the consumer surplus and in the total surplus that are important. The absolute values of the consumer surplus and the total surplus are not directly relevant.

Table 6. The expected present values of producer surplus, consumer surplus, and total surplus in the absence of IRMs (unit: billion SEK).

Simulation Nr	producer surplus	consumer surplus	total surplus
1	623.73	21816.61	22440.35
2	626.51	21856.96	22483.45
3	627.85	21852.18	22480.03

4	628.72	21863.28	22492.00
5	626.43	21853.95	22480.38
6	626.57	21859.81	22486.38
7	624.24	21822.65	22446.88
8	627.12	21863.44	22490.56
9	625.81	21846.13	22471.94
10	627.31	21856.48	22483.79
11	629.26	21883.17	22512.43
12	623.78	21818.19	22441.97
13	627.61	21850.39	22478.00
14	627.60	21859.93	22487.54
15	631.29	21890.95	22522.24
16	624.20	21823.23	22447.43
17	626.57	21845.96	22472.53
18	627.15	21851.37	22478.52
19	629.64	21884.78	22514.42
20	624.79	21825.45	22450.24
Mean	626.81	21851.25	22478.06

The EPV of forest management profits also appears to be very large. The actual profit from timber production in Sweden during 1987-2006 was, on average, 11.85 billion

SEK per year (see Table 7). If we assume that the profit will remain at this level in the future, then with an interest rate of 3% the present value of all future profits would be 395 billion SEK, which is about 60% of the EPV shown in Table 6. In our analysis, we included timber harvest and regeneration costs, but not the costs of e.g. forest road construction and maintenance, drainage, pre-commercial thinning etc. The costs that were neglected in our analysis are about 1.5 billion SEK per year. The present value of these costs is in the order of 50 billion SEK. Another simplification, which leads to overestimation of the EPV of future profits, is that we ignore thinning in our analysis. A considerable portion of the existing forests have been thinned before. The assumption of a thinning-free management regime led to an overestimation of the mature timber stock in the existing forests by about 800 million m^3. Very roughly, this means that the EPV of forest owners' profits was overestimated by 100 billion SEK[10]. After these two biases are deducted, our estimate of the EPV of forest owners' profits reduces to 476 billion SEK, which is 20% higher than the value estimated based on the actual profits.

When determining the aggregate timber supply function, we assumed that the timber market is perfectly competitive and ignored the impact of timber harvest on the non-timber benefits of the forests. Most forest owners in Sweden have multiple objectives and do not maximize solely the profits from timber production (Carlen 1990, Andersson and Gong 2009). Moreover, the timber market in Sweden is not fully

[10] Using the first year timber price net of harvest cost as a rough approximation of the marginal value of mature timber stock.

competitive on the demand side, which further reduces the profits of timber production (Brännlund et al. 1983, Brännlund 1988). The EPV of the forest owners' profits associated with the optimal supply function ought to be higher than the actual profits. There is no precise estimate of the potential increase in the timber production profits in Sweden that can be used to verify our results. However, it is not unrealistic that the present value of future profits can increase by 20% if the timber market is perfectly competitive, and the forest owners manage their forests to maximize the profits from timber production.

The biases should not have any significant impact on the estimated effect of IRMs on the EPV of forest owners' profits, as the other management costs and thinning were ignored in both the absence and presence of IRMs.

Table 7. Annual revenues, costs and profits of timber production in Sweden during 1987-2006 (billion SEK at 2006 price level). Source: Statistical Yearbook of Forestry.

	Mean	Min	Max	std
Gross revenue	23.47	18.75	28.76	2.66
Harvest cost	8.79	6.66	13.40	1.85
Regeneration cost	1.36	0.96	2.13	0.37
Other costs[a]	1.47	0.97	2.17	0.38
Profit	11.85	8.81	16.86	1.91

[a] *Include construction and maintenance of forest roads, drainage, pre-commercial thinning etc.*

Table 8 presents the EPV of the total surplus associated with different supply functions, in the presence of IRMs. Column C1 gives the estimates of the EPV of the total surplus when IRMs are used but the forest owners do not change their harvest behavior. The figures in Column C2 are the differences between the EPV estimates in column C1 and the corresponding estimates in the benchmark case (shown in the last column of Table 6), i.e. the *direct* effect on welfare of IRMs. Column C3 presents the estimates of the EPV of the total surplus when IRMs are used *and* the forest owners change their harvest behavior accordingly. The resulting changes in the EPV of the total surplus (column C4) are, therefore, estimates of the total welfare effect of IRMs. The last column of Table 8 shows the effect of changing harvest behavior.

From Table 8, we see that the direct effect of using IRMs on the EPV of the total surplus is 27.41 billion SEK, and the total effect is 33.61 billion SEK. Accordingly, the effect of changing harvest behavior is 6.2 billion SEK, or about 18% of the total effect.

Table 9 summarizes the effects of IRMs on the EPVs of forest owners' profits and consumer surplus. The results show that access to IRMs causes the profits of timber production to decrease and the consumer surplus to increase. Once IRMs become available, they will be applied on large scales. This is simply the result of the force of competitive markets. As long as no single forest owner can influence the price of timber, it is better for the forest owner to use IRMs irrespective of whether the other forest owners use them or not. Widespread application of IRMs would cause timber supply to increase and timber price to decrease. If the price elasticity of timber demand is sufficiently large, the price effect would overweigh the effect of increasing the harvest on the forest owners' profits.

In a competitive market, forest owners behave as price takers. From the point of view of an individual forest owner, using the IRM would increase future timber yield but would not affect the evolvement of timber prices. In other words, for each forest owner, the access to IRMs implies that the value of forest land and, hence the opportunity cost of keeping the existing stands growing, increases. Therefore, the presence of IRMs would cause a forest owner to harvest the existing stands at lower ages. Simulations using the benchmark supply function do not capture this response by the forest owners, and therefore do not provide us with an estimate of the full welfare effect of IRMs.

Figure 4 presents the expected annual supply of timber both in the absence and in the presence of IRMs, over a time period of 200 years. Figure 5 presents the expected timber prices corresponding to the time paths of supply presented in Figure 4. These two figures are helpful in understanding the difference between the direct effect and the total effect of using IRMs on the EPV of the total surplus. When simulated using the benchmark supply function, the presence of IRMs has no effect on the expected timber supply and the price during the first 60 years, and causes the timber supply to increase and the price to decrease thereafter. The reason is that, without considering the change in harvest behavior, IRMs would affect the supply and the price only through the impact on the mature timber stock. The mature timber stock is not affected by the use of IRMs before the first stands regenerated using the IRMs have reached a mature age. Simulation results using the optimal supply function, in which the change in the harvest behavior is embedded, show that the timber supply would increase and the price decrease immediately after IRMs become available. As a result, the mature timber stock in the initially existing forests is depleted at a faster rate in the presence of IRMs, which has a negative effect on future supply. As time passes, the effect on timber supply of the decrease in the mature timber stock becomes greater and would eventually outweigh the positive effect of the change in harvest behavior. When the stands regenerated using the IRMs have reached a mature age, the mature timber stock starts to increase and so does the aggregate supply of timber.

Table 8. The expected present values of the total surplus in the presence of IRMs, estimated using different supply functions (unit: billion SEK).

Simulation Nr	Benchmark supply function		Optimal supply function		Effect of changing harvest behavior
	ETS	***change***	ETS	***change***	
	C1	C2	C3	C4	C4-C2
1	22467.78	***27.43***	22473.94	***33.60***	*6.17*

2	22510.82	***27.35***	22516.96	***33.49***	*6.14*
3	22507.44	***27.41***	22513.60	***33.57***	*6.16*
4	22519.50	***27.50***	22525.74	***33.74***	*6.24*
5	22507.70	***27.32***	22513.86	***33.48***	*6.16*
6	22513.92	***27.53***	22520.05	***33.66***	*6.13*
7	22474.24	***27.36***	22480.48	***33.60***	*6.24*
8	22517.91	***27.35***	22524.08	***33.52***	*6.17*
9	22499.25	***27.31***	22505.40	***33.46***	*6.15*
10	22511.14	***27.35***	22517.39	***33.60***	*6.24*
11	22539.87	***27.44***	22546.10	***33.67***	*6.23*
12	22469.40	***27.43***	22475.56	***33.59***	*6.16*
13	22505.44	***27.43***	22511.69	***33.69***	*6.26*
14	22514.89	***27.35***	22521.14	***33.60***	*6.25*
15	22549.66	***27.42***	22555.89	***33.65***	*6.23*
16	22474.79	***27.36***	22481.03	***33.60***	*6.24*
17	22499.92	***27.40***	22506.18	***33.65***	*6.25*
18	22506.01	***27.49***	22512.25	***33.73***	*6.24*
19	22541.88	***27.46***	22548.13	***33.71***	*6.25*
20	22477.69	***27.45***	22483.85	***33.61***	*6.16*
Average	22505.46	27.41	22511.67	33.61	*6.20*

Table 9. The expected present values of producer surplus and consumer surplus in the presence of IRMs (unit: billion SEK).

	Producer surplus	change[a]	Consumer surplus	change[a]
Benchmark supply function	596.72	-30.10	21908.75	57.50
Optimal supply function	583.35	-43.45	21928.31	77.06

[a] Compared with the case where IRMs are not available.

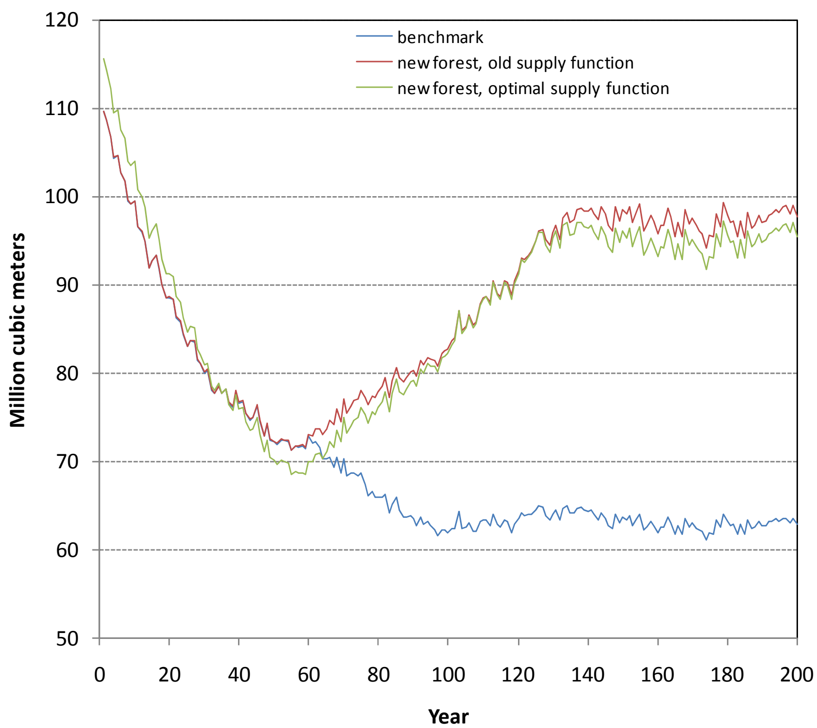

Figure 4. Expected timber supply in the absence and in the presence of IRMs.

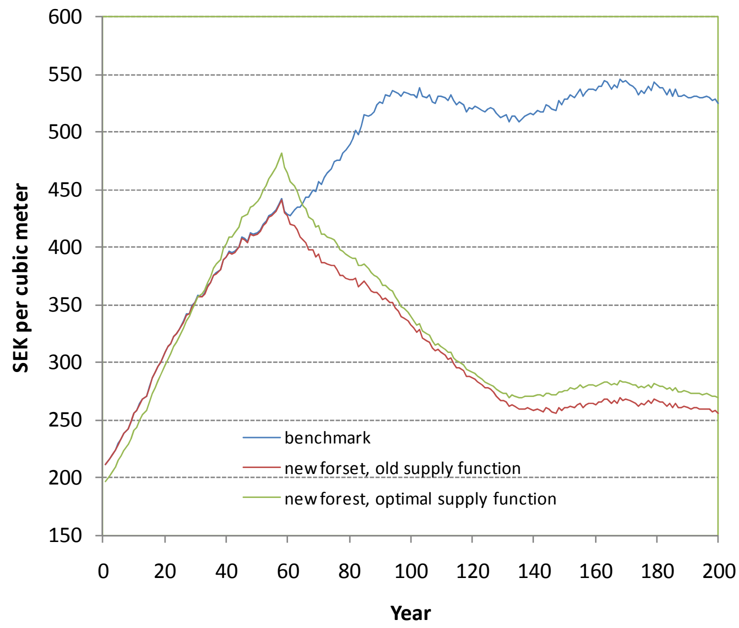

Figure 5. Expected timber price in the absence and in the presence of IRMs.

5. Summary and conclusions

The main results of the study are (1) the presence of IRMs has significant impacts on the aggregate timber supply function; (2) the use of IRMs leads to a significant increase in the EPV of the total surplus; (3) a considerable proportion of the welfare gain from the use of IRMs results from the change in management behavior; and (4) the use of IRMs reduces forest owners' profits from timber production.

If IRMs are available, they will be applied on large scales even though forest owners' profits may decrease. This is simply the result of the force of competitive markets. As long as none of the forest owners alone can influence the price of timber, it is better for each forest owner to use the new materials irrespective of whether other forest owners use them or not. On the other hand, we cannot conclude from the results of this study that forest owners' profits will decrease as a result of the emergence of IRMs. Firstly, the effect of large scale application of IRMs on forest owners' profits depends on the price elasticity of timber demand. If timber demand is perfectly elastic, for example, then the use of IRMs will increase the output without affecting the price and will thus increase the profits. Secondly, because not all forest owners are risk neutral, uncertainty in the growth effect of new regeneration materials would certainly slow down the speed of forest regeneration using IRMs. Thirdly, the emergence of IRMs might stimulate the demand for timber/biomass, which would affect forest owners' profits positively.

The results reported in this paper depend on the numerical assumptions. It is, nevertheless, safe to conclude that analyses that neglect the change in management behavior could lead to significant underestimation of the welfare effect of IRMs or other shocks to the supply and/or demand side of the timber market. Accordingly, the Lucas critique is not only of theoretical interest, it also has important implications from the point of view of empirical assessment.

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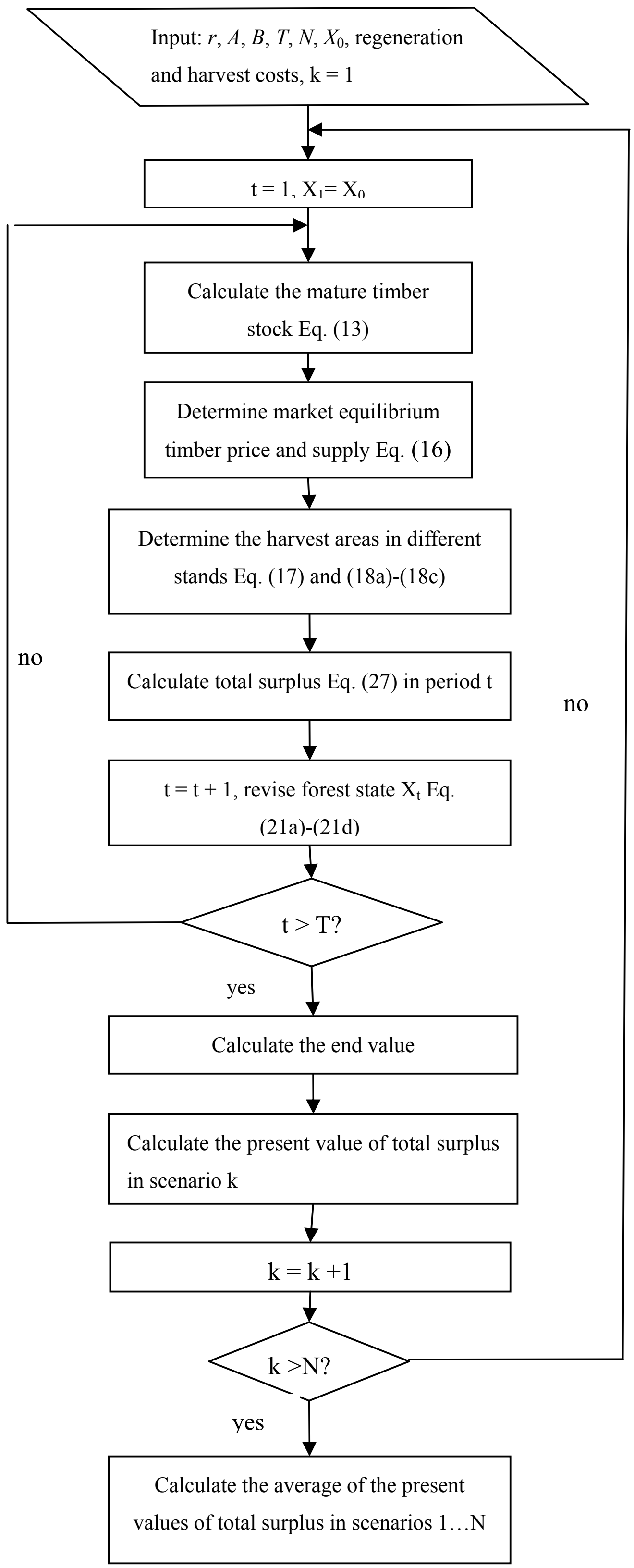

Figure 3. Estimation of the expected present value of total surplus