13 Conflicting objectives while maximising carbon sequestration by forests

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INTRODUCTION

In the current debate on global climatic change, forests and forestry policies have gained much attention; in particular hope has been expressed that forestry policies have the potential to mitigate climatic change—at least partially (Sedjo and Solomon 1988; Sedjo 1989b; Johnson 1992; Kauppi 1992; Krapfenbauer 1992; Kurz et al. 1992; Marland and Marland 1992; Dewar 1993; King 1993; Turner et al. 1993; Wisniewski et al. 1993). Many issues however, are poorly understood and contradictory conclusions have been drawn by different authors (e.g., Harmon et al. 1990; Marland and Marland 1992). While some authors have demonstrated how much land would be needed, how great the economic costs of a full mitigation by such policies would be (Sedjo 1989a), and have even warned against costly premature actions (Sedjo 1989b), others have argued that any contribution is worthwhile (Marland and Marland 1992). Moreover, management options favouring carbon (C) sequestering are often discussed without considering potential conflicts with other objectives, such as wood production.

One study advocated a forestry policy which harvests wood at the maximum sustainable yield (MSY) while maximising a C flux from the forests to long-lived forest products. Marland and Marland (1992) found that a net gain in total C sequestered can be achieved with such a policy but admit that the needed growth rates and the assumed harvesting efficiencies may be difficult to put into practice. If such net gains could be obtained for average forests on the whole globe and not just in highly productive plantations, such a policy would be highly beneficial in many ways. Marland and Marland (1992) suggest that significant potential exists for sequestering C this way. Regardless of whether this is actually the case or not, such a policy relies heavily on a basic assumption—namely that it is possible to maximise C sequestration while still harvesting wood.

Other authors have derived differing conclusions and, in particular, have warned against turning mature forests into young, highly productive stands by asserting that no forestry policy could surpass the C sequestration potential of mature forests (Harmon et al. 1990). Similar findings were reported by other authors (e.g., Kurz et al. 1992; Fischlin and Bugmann 1994a, b), who found that an attempt to maximise C storage by a policy which maximises sustainable yield, and therefore optimally feeds the forest product sector, does increase total C-storage capacity, but not by large amounts. Again, regardless of whether or not this is actually the case, the main issue is: a policy which maximises C-storage risks running into conflict with harvesting of wood.

Thus the following questions arise: Is there really a basic conflict between harvesting of wood and C sequestration? Moreover, if this conflict exists, is it unrealistic to recommend

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cessation of all harvesting of wood—for most nations an unacceptable proposition—and would such a policy be in conflict with today's call for a more sustainable use of natural resources (which should result in the replacement of fossil-fuel dependent production systems with their detrimental effects to the environment)? Therefore, the question remains, are there circumstances under which these conflicts disappear or where there are acceptable compromises? For instance, how defensible is a policy of harvesting the replacement yield at sub-optimal levels instead of the MSY, in face of the C sequestration benefits? Could such policies be put into practice without resorting to highly unlikely prerequisites such as high mean growth rates or extremely high harvesting efficiencies?

In this study we used a simple forest growth model, similar to that by Marland and Marland (1992), which we combined with several management options to explore possible answers to the above questions. We assumed that the model, despite its primitive structure, properly reflects the important basic characteristics of a growing forest capable of producing wood for the forest sector while also providing woody reservoirs for C. Parameters are taken for northern mid-latitude species and growth conditions which can be found within a small area—specifically along an altitudinal transect through the Alps. We suggest that the forest types studied are typical for hard- and softwood forests, i.e., for northern mixed-deciduous and boreal like forests.

MATERIAL AND METHODS

The model is basically a logistic growth model (Equation 1) of aboveground biomass Q_j (i.e., stem, branches, and foliage) combined with discrete-event harvesting (Equations 2–4).

$$\frac{dQ_j(\mathrm{t})}{dt} = r_j \cdot \frac{K_j - Q_j(\mathrm{t})}{K_j} \cdot Q_j(\mathrm{t}) \qquad [1]$$

where

t = continuous time (yr)
j = type of forest: A = Beech forest, B = Montane spruce, or C = Subalpine spruce
Q_j = dry weight (DW) of aboveground biomass (including wood) (Mg ha^{-1})
r_j = maximum relative growth rate (yr^{-1})
K_j = carrying capacity (Mg ha^{-1})

By harvesting wood the biomass Q_j is reduced by the harvested amount H_j (Equation 2)

$$Q_j(\mathrm{t}) = Q_j(\mathrm{t}^-) - H_j(\mathrm{t}^-) \qquad [2]$$

Woody slash is assumed to decay quickly, and only the fraction μ of the harvested biomass H_j is transferred to durable wood products P_j (Equation 3).

$$P_j(\mathrm{t}) = P_j(\mathrm{t}^-) + \mu H_j(\mathrm{t}^-) \qquad [3]$$

where:

P_j = biomass stored as durable wood products (Mg ha^{-1})
μ = fraction of harvested biomass ending up in durable wood products (%)

The management options investigated represent a small spectrum of basic options (Table 13.1). To establish a reference point for C sequestration similar to that used by Harmon et al. (1990) one extreme option (u) was to harvest no wood at all. Other options are clear-cutting (cC) and selection cutting (or plenter) management (p) as currently practised in many European countries.

Table 13.1. Management options used in all simulations. The output variables of interest are C^* (mean total C sequestered in forests and forest products) and W^* (mean annual wood production).

MANAGEMENT	DESCRIPTION	EQUATION	OUTPUTS
u	Unused forests without any harvesting	1	C^*, –
cC	Clear cutting	1–3,4,5,6	C^*, W^*
p	Selection cutting (plenter management)	1–3,4',5',6	C, W^*

Conventional harvesting, i.e., clear-cutting, is modelled as a sequence of three cuts with typically 8 year separations, initiated as soon as Q_j reaches a specified fraction θ_c , say 90%, of K_j (Equation 4). For each type of forest the harvest H_j can be represented as a sequence of three state events occurring at the cutting times $t^- = t_h$, t_{h+8} , and t_{h+16} , where the level of harvest removal from the forest is h_i = 30, 50 and 70% (respectively) of the current Q_j (Equation 5):

$$H_j(t^-) = \left\{ \begin{array}{lll} h_i \cdot Q_j(t^-) & t^- = t_h + i \cdot 8 & i = 0,1,2 \\ 0 & \text{else} & \end{array} \right. \qquad [4]$$

where

$$t_h = t|_{Q_j(t) = \theta_c \cdot K_j} \qquad [5]$$

and

H_j = harvested biomass (DW) (Mg ha^{-1})
h_i = fraction of harvested wood in percentages of currently present biomass Qj (%)
t_h = harvesting time or time of first cut in a sequence of 3 cuts (yr)
t^- = continuous left-hand side of time before, and up to, the discrete event harvest (yr)

Alternatively, selective cutting takes place whenever Q_j exceeds the fraction θ of K_j by the tolerance ε_j. The amount harvested is assumed to be $2 \times \varepsilon_j$ (Equation 4', 5'):

$$H_j(t^-) = \left\{ \begin{array}{ll} 2 \cdot \varepsilon_j & t^- = t_h \\ 0 & t^- \neq t_h \end{array} \right. \qquad [4']$$

where

$$t_h = t|_{Q_j(t) = \theta \cdot K_j + \varepsilon_j} \qquad [5']$$

ε_j = harvested biomass (DW) (Mg ha^{-1})

A simple equation of exponential decay (Equation 6) is used to model the slow decomposition of durable wood products P_j :

$$\frac{dP_j(\mathrm{t})}{dt} = -d_j \cdot P_j(\mathrm{t}) \qquad [6]$$

where

d_j = relative decay rate (yr^{-1})

The model parameters, including those used in the sensitivity analysis (see below), are listed in Table 13.2.

Table 13.2. Parameters used in Equations 1–6 to model forest growth and harvesting. p_o: mean or reference value used to calculate deviations, i.e., $\Delta p'$, in the sensitivity analysis (parameters r, K, d vary depending on the forest type j = A, B, or C; forest types are characterised by the dominant species). The parameters represent average growing conditions of mid-northern latitudes and were determined from yield tables of central Europe. DW: dry weight. For management options see Table 13.1.

		REFERENCE VALUE, p_o				
PARAMETER p	MEANING	($j = A$)[a]	($j = B$)	($j = C$)	UNIT	MANAGEMENT OPTION
r	Growth rate	0.04	0.05	0.05	yr^{-1}	u, cC, p
K	Carrying capacity (DW)	550	600	170	$\mathrm{Mg\ ha}^{-1}$	u, cC, p
d	Decay rate of wood	0.025	0.037	0.037	yr^{-1}	cC, p
μ	Harvesting efficiency	40	40	40	%	cC, p
θ	Fraction of K at which selection cutting starts	50	50	50	%	p
ε	Tolerance by which Q_j may exceed θK_j before selection cut occurs	40	80	25	$\mathrm{Mg\ ha}^{-1}$	

[a] Parameter j is forest type: A: Beech forest; B: Montane fir-spruce; C: Subalpine spruce.

All basic management options can be modified by changing the parameters listed in Table 13.2. For instance the parameter θ determines the age at which harvesting starts, expressed in terms of the biomass Q held by a stand, while the parameter μ determines how efficiently C is transferred from the forest into long-lived wood products.

Background information on the model formalisms and details on the simulation technique can be found in Fischlin et al. (1994) and copies of the model can be obtained from the author. All simulations needed for this study were made with ModelWorks and the RAMSES software on Apple Macintosh IIfx and Quadra 950 computers (Fischlin 1991; Fischlin et al. 1994).

The model system provides two outputs of main interest in this study: First, the mean total C sequestered in forests and long-lived forest products, C^* (Figure 13.1a), and second, the mean annual wood production, W^* (Table 13.1). C^* is computed from C, i.e., the total C currently sequestered within the forest biomass and the forest products. W^* is computed from W which is at any time the annually harvested wood taken from the forest according to the currently employed management option. W is calculated from H_j assuming a linear relationship. Since harvesting has been formulated as a discrete event, both variables C and W tend to fluctuate strongly (Figure 13.1b). To represent large areas—the model just represents a single stand—we integrated C and W over time and divided by the elapsed simulation time to calculate C^* and W^*, respectively. The first 100 years of simulation time were always discarded (i.e., $t < t_o = 100$ years), since this period is a transient, primary successional mode (Figure 13.1a).

The sensitivity of C^* and W^* to changes in the model parameters (Table 13.2) was analysed by sampling normally distributed variates p according to a normal distribution with an expected value of p_o and a coefficient of variation of 10%, i.e., $p \sim N(p_o, 0.1p_o)$. Using the reference values p_o , the corresponding steady-state outputs C^*_o and W^*_o (at year 500, Figure 13.1) and the deviations $\Delta C^* = C^* - C^*_o$ and $\Delta W^* = W^* - W^*_o$, respectively, were computed and correlated with the parameter changes $\Delta p = p - p_o$ (Figure 13.2a, Table 13.3). Parameters were only changed independently from each other, i.e., while a variate for parameter p was sampled, all other parameter values were kept at their reference value p_o.

To assess sensitivities (where the correlation was significant) the slopes of linear regressions between ΔC^* and ΔW^* with Δp were calculated. The sample sizes were 30 per forest type (*A*, *B*, and *C*, Table 13.2) amounting to 90 simulation runs per regression (Table 13.3) or a total of 990 runs for the entire sensitivity analysis.

For the optimisation of C sequestration and wood production, a brute-force method was used: Parameters were simply sampled from normally distributed variates $p \sim N(p_o, 0.1p_o)$. However, in contrast to the sensitivity analysis, parameter values were changed simultaneously, which required further simulations to a total of 4320 runs.

RESULTS AND DISCUSSION

Figure 13.1 shows the reference simulation results obtained while using the reference parameter values p_o (Table 13.2). The differences between the three management options (Table 13.1) become obvious: in the case of unused forests (u) total C sequestered (*C*), as well as its mean over time, C^*, are solely determined by the amount sequestered within the forest or the standing biomass, Q_j. C^* reaches a maximum determined by the carrying capacity *K*. Under the clear cutting regime (cC), the forest biomass Q_j fluctuates strongly together with *C*. Long-lived forest products P_j are incremented step-wise as a result from the cuts. They decay subsequently till the next cut. *C* fluctuates strongly which is similar to the selection cutting regime (p) although in the latter case the amplitude is smaller. *C* is irregular and difficult to assess unless pooled and averaged over time which yields C^*; it represents the long-term benefit and is of greater use to evaluate a particular management option than the variable *C*.

The sensitivity analysis showed that for most parameters the output deviations ΔC^* and ΔW^* were significantly ($2\alpha = 0.1$) correlated with the parameter deviations Δp (Figures 2a–c; Table 13.3). Among the most sensitive parameters were the carrying capacity *K* and θ (note, both parameters are related, since the latter is the fraction of *K* at which selection cutting starts). However, due to the non-linear relationship between $\Delta\theta$ and the deviations in the mean annual wood production ΔW^* (Figure 13.2d), the correlation between these two variables were not always significant (Table 13.3, last row, last two columns).

The more sensitive ΔC^* or ΔW^* are to a particular parameter change, the easier it is to modify the system behaviour in a desired direction by changing this parameter. Any management policy which can increase a positively correlated parameter or which can decrease a negatively correlated parameter leads to a higher C sequestration.

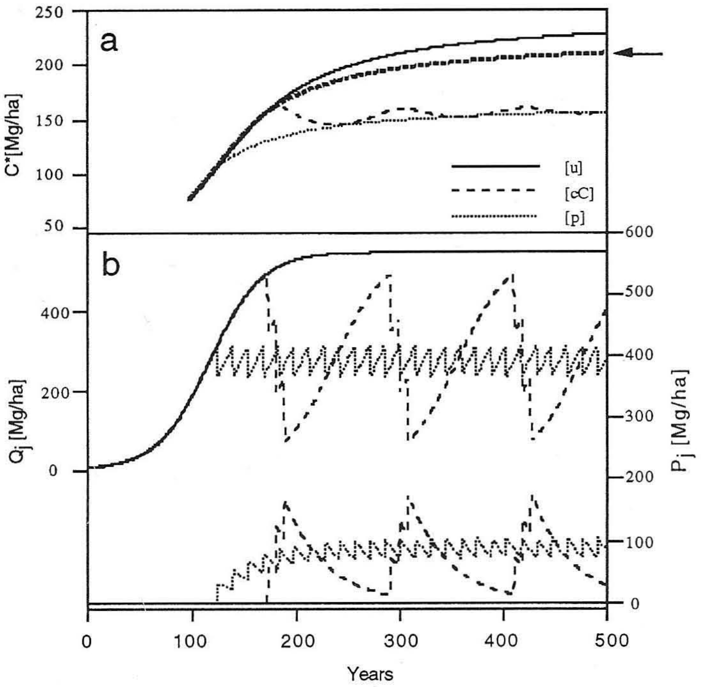

Figure 13.1. Typical simulation result obtained with the forest/forestry model used in this study. (a) Total C sequestered averaged over 400 years (C^*), for the standard parameters and three management options, respectively, for optimised $\theta = 0.8$ at arrow (see Figure 13.3, bar 8). (b) top: Forest biomass (Q_j) in beech forest ($j = A$); bottom: Beech wood in long-lived forest products (P_j). Management options applied are: unused forest (u); clear cutting (cC); selection cutting (p).

The most sensitive parameter is K (Table 13.3). However, K is a parameter which is largely determined by site conditions such as climate and soil characteristics and is therefore rather difficult or expensive to modify via a particular management. Of course, increasing the carrying capacity via fertilisation or manipulating age structure, preserving existing forests, are all management options which directly or indirectly modify K and lead to a higher C sequestration. If K is interpreted globally as the mean carrying capacity per ha, analogous arguments are even applicable for afforestation and reforestation.

θ was found to be the second most sensitive parameter. In contrast to K, θ is relatively easy to change in practice. ΔC^* is positively correlated, while ΔW^* is negatively correlated, with $\Delta\theta$ (Figure 13.2d). Thus, while optimising C^*, θ has to be increased as much as possible. However, this leads inevitably also to a decrease of mean annual wood production W^*.

Maximum annual wood production W^*, i.e., MSY, was found as expected with $\theta = \theta_0$ i.e., 0.5 (Figure 13.3, bar 4). The widely practised clear-cutting regime (cC) using only reference parameters is clearly sub-optimal, both in C sequestration as well as wood production (Figure 13.3, bar 1).

In terms of C sequestration, the best results can be obtained only under the management option of selective cutting (p). This is mainly because unused forests can store more C than

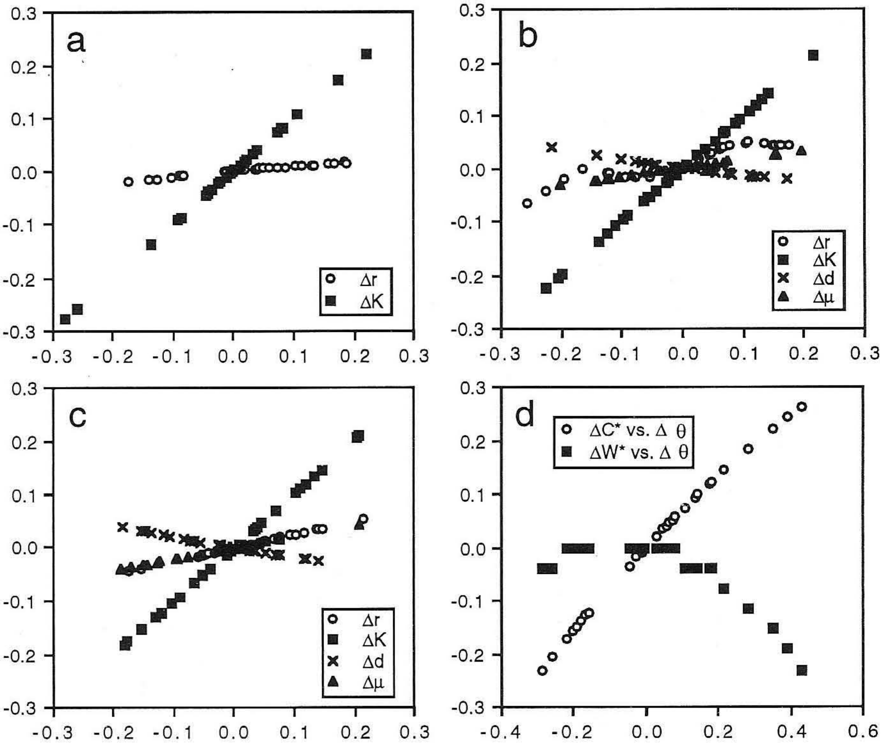

Figure 13.2. (a)–(c) Sensitivity analysis for beech forests using scatter grams drawn from a total of 990 simulation runs. Deviation of simulated $\Delta C^* = C^* - C_o^*$ (mean total C sequestered in forests and forest products) shown as a function of random variations in five selected model parameters $\Delta p = p - p_o$ ($p \sim N(p_o, 0.1p_o)$). (a) unused forest (u); (b) clear cutting (cC); (c) selection cutting (p). (d) Optimisation of beech forests. Deviation of simulated variables ΔC^* and ΔW^* (mean annual wood production) as a function of random deviations in parameter $\Delta\theta = \theta - \theta_o$ ($\theta \sim N(\theta_o, 0.1\theta_o)$) using data from 4320 simulation runs. ΔW^* decreases while ΔC^* is maximised, thus leading to a fundamental conflict between optimal wood production and maximum C sequestration.

can be transferred and kept in long-lived forest products. Note, there is a management option which gets very close to the potential of an unused forest (Figure 13.3, bar 9): Its sequestration potential (97.4%) is almost as high as that which can be achieved in the case of a management without any harvesting (u, 100%, Figure 13.3, bar 10). Its characteristics are selection cutting, little disturbance in the age structure, i.e., leaving the forest at a high mean age, but with a short rotation period. In addition, in this case (9) we assumed also first a very high harvesting efficiency (μ), similar to that assumed by Marland and Marland (1992), and second a maximum transfer into long-lived forest products.

However, we believe that the latter assumptions are unrealistic and require C flows into long-lived wood products, which can probably not be put into practice. More realistic is a lower harvesting efficiency ($\mu_O = 0.4$), similar to that shown in bar 8 of Figure 13.3, which reaches 91.8% (Figure 13.1a, see arrow) of the achievable, maximum C sequestration of 229.1 Mg ha^{-1}, which is remarkably high compared to only 68.4% obtained while harvesting at MSY ($\theta_o = 0.5$).

Table 13.3. Results of sensitivity analysis. Model parameters p were sampled from a normal distribution $N(p_o, 0.1p_o)$ and the sensitivity of the output variables C^* (mean total C sequestered in forests and forest products) respectively W^* (mean annual wood production) computed. Sensitivities were assessed by the slopes from linearly regressing deviations in the output variables, i.e., ΔC^* and ΔW^*, *vs.* the deviations in the respective parameter Δp. Note, ΔW^* is independent of Δd and $\Delta\mu$ (Equations 4 or 4'). p_o - mean model parameter of r, K, d, μ, or θ (Table 13.1); u, cC, p - management option (Table 13.1); L.R. - linear regression. All slopes based on 90 simulation runs (cf. Figure 13.2). r^2 - square of correlation coefficient. MIN(r^2), MAX(r^2) are minimum, maximum respectively of r^2 found in any of the three forest types.

Output variable	Parameter p	Management	Mean slope sensitivity L.R.	Min(r^2)	Max(r^2)
ΔC^*	Δr	u	0.08	0.98	0.98
		cC	0.24	0.87	0.89
		p	0.23	1.00	1.00
	ΔK	u	1.00	1.00	1.00
		cC	0.99	1.00	1.00
		p	1.00	1.00	1.00
	Δd	cC	-0.15	0.99	0.99
		p	-0.19	0.99	0.99
	$\Delta\mu$	cC	0.15	1.00	1.00
		p	0.20	1.00	1.00
	$\Delta\theta$	p	0.76	1.00	1.00
ΔW^*	Δr	cC	1.20	0.74	0.85
		p	1.07	0.98	1.00
	ΔK	cC	1.05	1.00	1.00
		p	1.05	0.98	1.00
	$\Delta\theta$	p	-0.10	0.03[a]	0.46

[a] Correlation not significant, since estimated r^2 is less than $r^2_{2\alpha=0.1;\nu=28} = 0.0937$.

No management scenario yielded C sequestrations above that of an unused forest, in contrast to the findings by other authors (Marland and Marland 1992). This is not a true contradiction, since the differences can be explained by the different growth rates. Our growth rates (r in Table 13.2) were taken from European data (Fischlin and Bugmann 1994a; Fischlin and Bugmann 1994b) which represent average growing conditions, easily surpassed by intensively managed forests or tree plantations as assumed by Marland and Marland. Our rates are also very comparable to those reported by other authors (Sedjo 1989a, b) who listed for similar latitudes and conditions, i.e., for the U.S., average C accumulation rates of 0.82 Mg C ha^{-1} yr^{-1}; in our model these amounted to 0.83–0.84 Mg C ha^{-1} yr^{-1}. (Carbon accumulation rates in units of C ha^{-1} yr^{-1} is computed as $1.6 \times 0.5 \times e^r$, where 1.6 is the ratio between stemwood growth and other C pools such as branches, roots, debris etc., and 0.5 is the ratio between dry weight and C mass.)

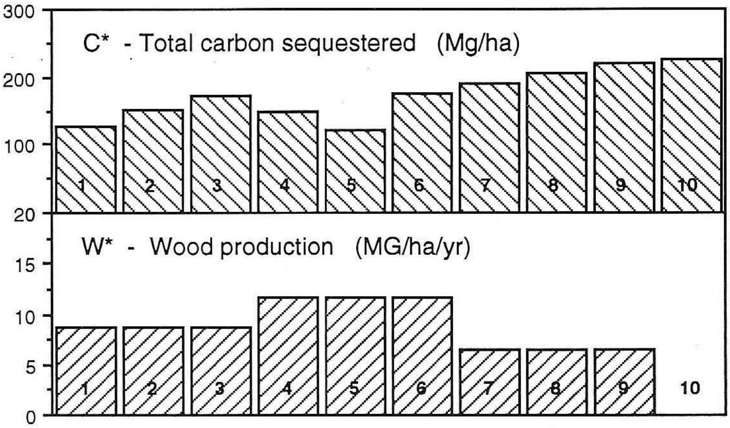

Figure 13.3. Comparison of total C-storage capacity C^* (forests plus long-lived forest products—top bars) and mean annual wood production W^* (bottom bars) for a set of management options and changed model parameters. Unless the value used is given together with the changed parameter in the following list, all other parameters were kept at their reference value p_0. For the management options see Table 13.1.: 1 - cC, d = 0.6 / 2 - cC / 3 - cC, $\mu = 0.75$ / 4 - *p* / 5 - p, d = 0.6 / 6 - p, $\mu = 0.75$ / 7 - p, $\theta = 0.8$, d = 0.6 / 8 - p, $\theta = 0.8$ / 9 - p, $\theta = 0.8$, $\mu = 0.75$ / 10 - u.

CONCLUSIONS

The following main conclusions were drawn from the presented findings:

- The greatest C sequestration is obtained in unused forests.
- The second greatest C sequestration is not with storing C in long-lived wood products while harvesting at MSY, but with augmenting standing crops while selectively cutting (plenter management). The period length should be relatively short and stands should be kept at a high mean age, i.e., with a biomass close to the carrying capacity.
- Objectives to maximise C sequestration conflict with wood production (e.g., MSY *vs.* maximum standing crop)
- Since the wood production is not independent of the state of a forest, strategies solely maximising harvest must be put in balance relative to optimal C storage strategies.

Obviously there are irresolvable conflicts between a management policy maximising wood production and that maximising C sequestration, which are too often overlooked. In its extremist form a policy of maximising C sequestration would even require protecting forests by fighting insects and fires, but completely C sequestration as a tool to mitigate climatic change, and may therefore inadvertently release C to the atmosphere. Since there is no single optimal solution (cf. Figure 13.3), the conflicting objectives have to be valued against each other. I believe, in a democratic society people have to make the decision how to weigh the conflicting objectives and accordingly choose management regimes between the two extremes. By doing so it may be helpful to recognise that solutions between these two extremes exist, solutions where wood production is not at its maximum, i.e., MSY, but harvesting is still possible while C sequestration is nearly optimal. Given the currently wide-spread, sub-optimal clear-cutting practices, such policies might also be economically more acceptable than appears to be the case at first glance.

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