Tellus
SERIES B CHEMICAL AND PHYSICAL METEOROLOGY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2009), 61B, 385–393
Printed in Singapore. All rights reserved

TELLUS

Leakage and spillover effects of forest management on carbon storage: theoretical insights from a simple model

By FEDERICO MAGNANI[1,*], RODERICK C. DEWAR[2]† and MARCO BORGHETTI[3],
[1]*Dipartimento di Colture Arboree, University of Bologna, via Fanin 46, I-40127, Bologna, Italy;* [2]*INRA, Unité EPHYSE, BP 81, Villenave d'Ornon CEDEX, F-33883, France;* [3]*Dipartimento Scienze dei Sistemi Colturali, Forestali e dell'Ambiente, University of Basilicata, viale dell'Ateneo lucano 10, I-85100, Potenza, Italy*

(Manuscript received 22 December 2007; in final form 18 September 2008)

ABSTRACT

Leakage (spillover) refers to the unintended negative (positive) consequences of forest carbon (C) management in one area on C storage elsewhere. For example, the local C storage benefit of less intensive harvesting in one area may be offset, partly or completely, by intensified harvesting elsewhere in order to meet global timber demand. We present the results of a theoretical study aimed at identifying the key factors determining leakage and spillover, as a prerequisite for more realistic numerical studies. We use a simple model of C storage in managed forest ecosystems and their wood products to derive approximate analytical expressions for the leakage induced by decreasing the harvesting frequency of existing forest, and the spillover induced by establishing new plantations, assuming a fixed total wood production from local and remote (non-local) forests combined. We find that leakage and spillover depend crucially on the growth rates, wood product lifetimes and woody litter decomposition rates of local and remote forests. In particular, our results reveal critical thresholds for leakage and spillover, beyond which effects of forest management on remote C storage exceed local effects. Order of magnitude estimates of leakage indicate its potential importance at global scales.

1. Introduction

Forests in the northern hemisphere currently act as a substantial carbon (C) sink, sequestering 0.6–0.7 Pg of C per year (Goodale et al., 2002) and thus contributing to the mitigation of climatic change. Forest management of established forests, afforestation and natural regeneration of forest following agricultural abandonment are among the dominant processes governing this sink activity (Houghton et al., 1999; Caspersen et al., 2000; UN ECE/FAO, 2000; Fang et al., 2001). Changes in local forest management aimed at increasing forest lifespan and standing biomass may also have a significant effect on the global C balance (Schulze et al., 2000; Magnani et al., 2007) and could have contributed to the sink activity observed in the northern hemisphere. Most forests are not at maximum C storage because of natural disturbance and harvesting, and could store more C if less intensively managed (Dixon et al., 1994).

A reduction in timber extraction from boreal and temperate forests has therefore been recommended by the Intergovernmental Panel on Climate Change (2007), which warned, however, that the expected local benefits in C storage could be partly offset by increased timber harvesting elsewhere in order to meet global timber demand, resulting in C 'leakage' on a global scale. Carbon leakage refers to "the situation in which a carbon sequestration activity on one piece of land inadvertently, directly or indirectly, triggers an activity which, in whole or part, counteracts the carbon effects of the initial activity" (Intergovernmental Panel on Climate Change, 2002). Thus, C leakage can reduce the effectiveness of international climate agreements (Kallbekken et al., 2007). Conversely, forestry activities may yield greater benefits than intended, resulting in C 'spillover'. For example, intensive plantation forestry could reduce the pressure on established forests through an increased flow of cheaper wood products. Spillover benefits might even outweigh the C stored in the plantations themselves and prove the most important contribution of intensive forestry to the global C cycle (Dixon et al., 1994).

The potential relevance of C leakage has been recognized in the Kyoto Protocol, with a call to consider it when afforestation and reforestation activities are accounted for in the computation of national C cuts (UN Framework Convention on

---

[*] Corresponding author.
e-mail: federico.magnani@unibo.it
†Now at: Research School of Biological Sciences, The Australian National University, Canberra ACT 0200, Australia
DOI: 10.1111/j.1600-0889.2008.00386.x

Climate Change, 2002). However, the subject currently lacks a theoretical framework from which the key factors determining leakage and spillover may be understood.

Here we explore the unintended leakage and spillover effects (U) induced by local changes in forest management, using an analytical model of C storage in managed forest ecosystems and their wood products (Dewar, 1990, 1991; Dewar and Cannell, 1992). We define U as the dimensionless ratio of remote to local changes in C storage; U can be negative (leakage) or positive (spillover). Our main objective is to identify the key ecosystem and management factors determining the sign and magnitude of U, rather than to provide accurate numerical estimates. Therefore, in order to gain analytical insights, we apply the C storage model to simple scenarios of forest management change within the hypothetical context of a fixed global timber demand. We also aimed to determine critical thresholds for leakage and spillover, beyond which effects on remote C storage exceed local effects (i.e. $U < -1$ or $U > +1$). Our analysis provides a prerequisite theoretical understanding of the problem in terms of which the results of more realistic numerical studies may then be interpreted.

2. Material and methods

2.1. Modelling carbon storage and wood production per hectare

A detailed description of the analytical C storage model used in the present paper is given elsewhere (Dewar, 1990, 1991; Dewar and Cannell, 1992). The key features are summarised here.

The model describes the per hectare C storage in the tree biomass, litter, soil and wood products of a managed forest ecosystem. A steady state is assumed in which the productivity of the site is constant over successive rotation cycles. Within any given rotation, the increase in woody biomass B (tree stems, branches and coarse roots, expressed as C equivalent) with stand age is described by a logistic function:

$$B\,(t) = \frac{B_m}{1 + b \cdot e^{-rt}}, \tag{1}$$

where t is time since planting, B_m is the biomass of undisturbed old-growth trees and b and r are empirical parameters (see Table 1 for symbol definitions, units and parameter values). Numerically similar results are obtained with other growth functions with the same general sigmoidal shape (Cooper, 1983). C storage in leaf and fine-root biomass is ignored in relation to B.

A central parameter of forest management is rotation length T, the interval between successive harvests of the same plot. From eq. (1), the rotation-average woody biomass C storage of a plot managed with rotation length T is

$$B = \frac{\int_0^T B(t)\mathrm{d}t}{T} = B_m \cdot \left[1 + \frac{1}{rT} \cdot \ln\left(\frac{1 + b \cdot e^{-rT}}{1 + b}\right)\right] \tag{2}$$

For a uniform age-class distribution, eq. (2) also gives the landscape-average C storage in woody biomass. The landscape-average wood production (which includes exported wood products and woody slash debris left on site) is then equal to the rotation-average wood production (P) given by

$$P = \frac{B(T)}{T}, \tag{3}$$

where $B(T)$ is forest woody biomass at harvest age T.

Branch and coarse root litter production rates (L_b and L_w, respectively) are assumed to be proportional to tree biomass ($L_i = \alpha_i \cdot B$, for $i = b, w$). In contrast, foliage litter production L_l reaches a maximum earlier in the life of the stand (at canopy closure), as described by the saturating function

$$L_l = L_l^m \cdot (1 - e^{-t/a}), \tag{4}$$

where a is a measure of the time to canopy closure. The average rate of foliage litter production over a rotation period T is then

$$\bar{L}_l = L_l^m \cdot \left[1 - \frac{a}{T} \cdot (1 - e^{-T/a})\right]. \tag{5}$$

Fine root litter production L_f is assumed to be proportional to foliage litter production ($L_f = \gamma \cdot L_l$). Litter production enters various forest floor litter pools, fractions of which then decompose to CO_2, the residuals being transferred to a soil organic matter (SOM) pool which also subsequently decomposes. Decomposition is described by first-order kinetics, with specific rates k_i for each litter pool ($i = b$, branch; w, coarse root; l, foliage; f, fine root) and a specific rate k_m for SOM. If β_i denotes the fraction of decomposed litter from pool i that enters the SOM pool (the remainder being lost as CO_2), then for the C which enters litter pool i, its total residence time D_i within the litter–soil system is

$$D_i = \frac{1}{k_i} + \frac{\beta_i}{k_m} \qquad (i = l, f, b, w). \tag{6}$$

Additional inputs to forest floor litter occur at harvesting, as described by the fractions of woody biomass $B(T)$ left on site as branch and coarse root slash (the latter including stumps; h_b and h_w, respectively). The remaining fraction $(1 - h_b - h_w)$ of woody biomass is exported from the forest and enters the wood chain as timber and other wood products.

Because C in harvested wood is not immediately lost to the atmosphere (Borden et al., 2000), the total amount of C stored by wood products depends on product lifetime. The decomposition of wood products is represented by an exponential decay function, with an average life-time D_p which may range from zero for slash-and-burn agriculture to less than 1 yr for newspapers and packing material, and up to 15–50 yr for building material. A lifetime of 30 yr is assumed in our simulations, representative of furniture (Skog and Nicholson, 1998). A more refined treatment would account for C losses along the wood-chain, as well

Table 1. Parameter values used in the simulation of C storage in fast-, medium- and slow-growth forests, represented, respectively, by an industrial plantation of *Pinus radiata* in New Zealand, a *Picea abies* forest in temperate Central Europe, and a *Picea abies* forest in the Boreonemoral zone of Russia. Parameters were derived from the literature (Nabuurs and Mohren, 1995), assuming a moderate fertility and average rates of litter production throughout the rotation. Values of humification coefficients β_i and debris fractions h_i were also derived from the literature (Dewar 1991; Andrén et al., 1997)

		Value			
Symbol	Units	Boreal	Temperate	Plantation	Definition
A_1	yr	162.7	137.2	95.8	Coefficient in eq. (8)
A_2	–	1.22	1.19	1.14	Coefficient in eq. (8)
A_3	yr	57.1	44.2	34.8	Coefficient in eq. (8)
b	–	21.6	25.7	12.3	Empirical parameter in eq. (1)
B_m	Mg C ha^{-1}	110	205	175	C content of old-growth trees
D_b	yr	120.3	77.3	46.1	Branch litter lifetime
D_f	yr	96.3	60.4	39.1	Fine root litter lifetime
D_l	yr	96.3	60.4	39.1	Foliage litter lifetime
D_p	yr	30	30	30	Wood product lifetime
D_s	yr	120.3	77.4	46.1	Stem litter lifetime
D_w	yr	120.3	77.4	46.1	Woody root litter lifetime
h_b	–	0.2	0.2	0.2	Fraction of felled biomass left on site as branch debris (including stem residues)
h_w	–	0.1	0.1	0.1	Fraction of felled biomass left on site as coarse root debris
k_b	yr^{-1}	0.03	0.05	0.1	Fractional decomposition rate of branch litter
k_f	yr^{-1}	0.17	0.33	0.33	Fractional decomposition rate of fine root litter
k_l	yr^{-1}	0.17	0.33	0.33	Fractional decomposition rate of foliage litter
k_m	yr^{-1}	0.002	0.003	0.004	Fractional decomposition rate of soil organic matter
k_w	yr^{-1}	0.03	0.05	0.1	Fractional decomposition rate of coarse root litter
$L_l{}^m$	Mg C ha^{-1} yr^{-1}	0.77	0.80	0.45	Maximum rate of foliage litter production
r	yr^{-1}	0.05	0.07	0.15	Initial relative growth rate of C storage in trees
T^*	yr	85	60	23	Rotation length for maximum wood production (mean annual increment)
α_b	yr^{-1}	1.5×10^{-3}	1.9×10^{-3}	2.4×10^{-3}	Annual biomass fraction lost as branch litter
α_w	yr^{-1}	3.6×10^{-4}	4.9×10^{-4}	5.7×10^{-4}	Annual biomass fraction lost as coarse root litter
β_i	–	0.16	0.16	0.16	Fraction of C loss from pool i that is transferred to soil organic matter
γ	–	0.7	1.3	1.4	Ratio of fine root to foliage litter production

Note: Calculated values of D_i ($i = l, f, b, w$), τ, A_2 and A_3 are also shown.

as a combination of different uses and decay rates for different plant parts (Liski et al., 2001). However, a full life-cycle analysis of wood and alternative products lies beyond the scope of the present paper.

For a given rotation length (T), the total C stored in tree biomass, litter, soil and wood products under steady-state conditions can then be expressed analytically as the sum of three contributions, from (i) decomposing foliage and fine roots; (ii) live and decomposing woody biomass (branches, stems and coarse roots) and (iii) decomposing wood products and woody slash debris (Dewar, 1991):

$$C = (A_1 \cdot \bar{L}_l) + (A_2 \cdot \bar{B}) + (A_3 \cdot P), \tag{7}$$

where the composite parameters A_1, A_2 and A_3 are given by

$$\begin{aligned} A_1 &= D_l + \gamma \cdot D_f \\ A_2 &= 1 + \alpha_b \cdot D_b + \alpha_w \cdot D_w \\ A_3 &= D_p + h_b \cdot (D_b - D_p) + h_w \cdot (D_w - D_p). \end{aligned} \tag{8}$$

2.2. Scenarios of forest management change

We examined the C leakage and spillover effects induced by two scenarios of forest management change: decreased harvesting intensity and afforestation. In accordance with the aim of our theoretical study, for each scenario we considered a simple, hypothetical system consisting of two areas of forest with contrasting growth rates. We adopted the very simplistic assumption of a fixed total timber demand, as a first-order approximation to more sophisticated economic models (e.g. Sohngen and Mendelsohn, 2003).

In the first scenario we considered two areas consisting of established medium- and slow-growth forests, respectively, and we studied the unintended leakage effect ($U < 0$) of decreasing the harvesting intensity in one area on the C storage of the other area. In the second scenario, we studied the unintended spillover effect ($U > 0$) of establishing new fast-growth plantations in one area on the C storage of an established medium- or slow-growth forest in the other area.

To illustrate our theoretical results numerically, we chose to represent the fast-, medium- and slow-growth forest types by, respectively, an industrial plantation of *Pinus radiata* in New Zealand, a temperate *Picea abies* forest in Central Europe, and a boreal *P. abies* forest in the Boreonemoral zone of Russia. Moderate fertility was assumed in all three cases. Parameter estimates for each forest type were derived from the literature (Dewar, 1991; Nabuurs and Mohren, 1995; Andrén and Katterer, 1997) and are given in Table 1. In the first scenario, the effect of management change on global (i.e. whole-system) C storage was illustrated by assuming medium- and slow-growth forest areas of 297 and 746 million ha with a fixed total timber demand of 0.62 Pg C yr^{-1}, based on data of productive temperate and boreal forests in the northern hemisphere (Dixon et al., 1994; UN ECE/FAO, 2000). The hypothetical nature of these scenarios should be stressed; the numerical examples here serve only to suggest an order of magnitude for the leakage effects that could arise on global scales, and should not be interpreted otherwise.

3. Results and discussion

3.1 *Carbon storage versus wood production per unit area*

As an introduction to the analysis of leakage and spillover, this section analyses some key properties of the relationship between per hectare C storage (*C*, eq. 7) and wood production (*P*, eq. 3), predicted by the C storage model as the rotation length (*T*) is varied.

Figure 1 illustrates the *C–P* relationship for fast-, medium- and slow-growth forests, in response to changes in rotation length (*T*). Superimposed on each curve, dots indicate the rotation length T^* for maximum wood production (maximum mean annual increment). The point where each curve crosses the vertical axis represents the hypothetical limiting case of an unmanaged old-growth forest ($T = \infty$). In the case of medium- and slow-growth forests this point corresponds to maximum C storage. In contrast, the fast-growth plantation maximises its C storage at a finite rotation length that is close to T^*. This contrast reflects the relative magnitudes of the wood product lifetime D_p (=30 yr in this example) and T^* (Table 1); for the fast-growth forest ($D_\mathrm{p} > T^*$) the relative contribution of wood products to total C storage is much greater than for medium- and slow-growth forest ($D_\mathrm{p} < T^*$), with the consequence that management of the fast-growth forest for maximum *C* almost coincides with management for maximum *P* (Dewar, 1990, 1991; Dewar and Cannell, 1992); this point is analysed further below. These results have been confirmed by more detailed models (Harmon et al., 1990; Liski et al., 2001; Pussinen et al., 2002).

Figure 1 reveals three contrasting phases in the *C–P* relationship: (i) as *T* decreases below T^* towards zero (increasing harvest frequency), *P* and *C* both decrease towards zero, reflecting reductions in both standing biomass and litter input to the soil (Dewar, 2001); this phase is of no relevance to the present study and will not be discussed further; (ii) *C* is highly sensitive to small changes in *P* when forests are managed close to their maximum *P* (high-sensitivity phase) (iii) the *C–P* relationship becomes linear when rotation length exceeds T^* by about 30% (linear phase); for the type of wood products considered in this example (furniture, with a lifetime of 30 yr), the slope of the linear phase is positive for fast-growth forests only (as noted above).

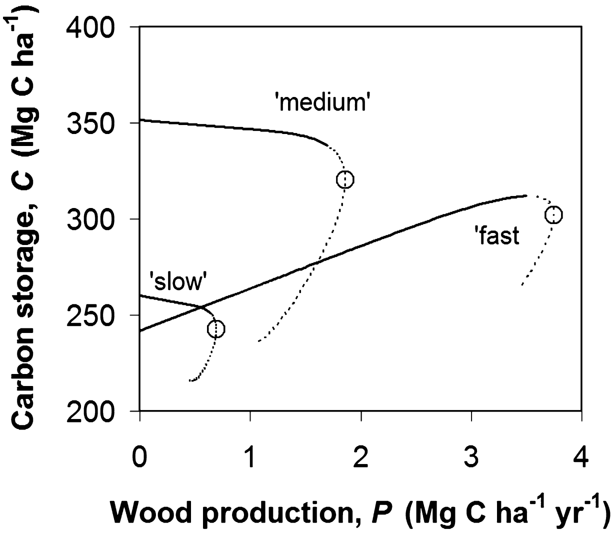

Fig. 1. The relationship between the per hectare C storage (*C*, eq. 7) and wood production (*P*, eq. 2) of fast-, medium- and slow-growing forests, obtained by varying the rotation period (*T*). C storage includes living trees, litter, soil and wood products. As the rotation period (*T*) increases through and beyond the age of maximum wood production (T^*, circles), a phase of high sensitivity of *C* to *P* (dotted line) is followed by a linear phase (continuous line) with a positive slope for fast-growing plantations only.

We can gain some theoretical insight into the slope of the linear section by taking the limit of large *T* in eqs (1)–(3). From eqs (1) and (3) we have $P \approx B_m/T$ in this limit, so from eq. (2) we find an approximately linear relationship between $\bar{B}$ and *P*:

$$\bar{B} = B_m \cdot \left[1 + \frac{1}{rT} \cdot \ln\left(\frac{1}{1+b}\right)\right] = B_m - \tau \cdot P, \tag{9}$$

where the time constant τ is given by

$$t = \frac{\ln(1+b)}{r}. \tag{10}$$

A numerical analysis of the logistic equation reveals that $T^* \approx 1.39\tau$ over a realistic range of parameter values ($25 < b < 1000$ and $0.01 < r < 2$). From eq. (1) and the values of B_m in Table 1, we see that τ corresponds to the age at which tree biomass is approximately half its old-growth value B_m. In this approximation, eq. (7) then becomes

$$C \approx (A_1 \cdot \bar{L}_l + A_2 \cdot B_m) + (A_3 - A_2 \cdot \tau) \cdot P. \tag{11}$$

The first term is equal to the total ecosystem C storage of the old-growth forest obtained when P is zero (no harvesting). Within this term, the rotation-average foliage litter production ($\bar{L}_l$) is largely insensitive to rotation length (and hence P) beyond the age of maximum P, because canopy closure occurs much earlier in the life of the stand. The sensitivity of C to changes in P is therefore almost constant, and given in terms of stand growth and decomposition parameters by

$$\frac{\mathrm{d}C}{\mathrm{d}P} = A_3 - A_2 \cdot \tau. \tag{12}$$

This expression is the slope of the linear phase of the C–P relationship (Fig. 1), and can be positive or negative.

As a simple hypothetical example to illustrate this result, let us ignore coarse woody litter production ($\alpha_b = \alpha_w = 0$) and assume whole-tree harvesting ($h_b = h_w = 0$). Eq. (12) then becomes $\mathrm{d}\,C/\mathrm{d}\,P = D_p - \tau$. In this example, therefore, the slope of the linear phase in Fig. 1 can be interpreted as the difference between the timescales for C release from wood products (D_p) and for C accumulation in living trees (τ). Albeit unrealistic, this example serves to demonstrate analytically how the sign of the slope of the linear phase depends on the relative magnitudes of D_p and T^*. The results presented in Fig. 1, based on model simulations assuming realistic values for woody-litter and brash production (see Table 1), demonstrate the general validity of this conclusion: assuming a common value of 30 yr for wood product lifetime, the slope of the C–P relationship can be seen to increase substantially as τ declines from 62 ('slow' forest) to 44 ('medium' forest) to 18 yr ('fast' forest plantation).

3.2. *Leakage induced by decreased harvesting frequency*

We now consider the first management change scenario, in which we assume two areas consisting of established medium-growth and slow-growth forest, respectively. For brevity, in the following we will refer to these as 'temperate' and 'boreal' forests, respectively, although the analytical results derived below apply to any two forest types with contrasting growth rates.

Figure 2 illustrates the individual area-integrated C--P relationships for each forest type derived from scaling eqs (7) and (3) by the respective forest areas (297 and 746 million ha, respectively). The figure shows the high-sensitivity and linear phases only; obviously the slope of the linear phase of the area-integrated C–P relationship is the same as that of the corresponding plot-scale curve in Fig. 1. Points B and C$'$ are defined as the transition points between the high-sensitivity and linear phases of the temperate and boreal forests, respectively. Points A and D$'$ correspond to intensive management for maximum production of each forest. Pairs of points A–A$'$, B–B$'$, etc. correspond to a fixed, combined (global) wood production of $P_g = 0.62$ Pg C yr^{-1}.

Figure 3 shows the effect of actively decreasing the wood production of the temperate forest (A → B → C → D) on the

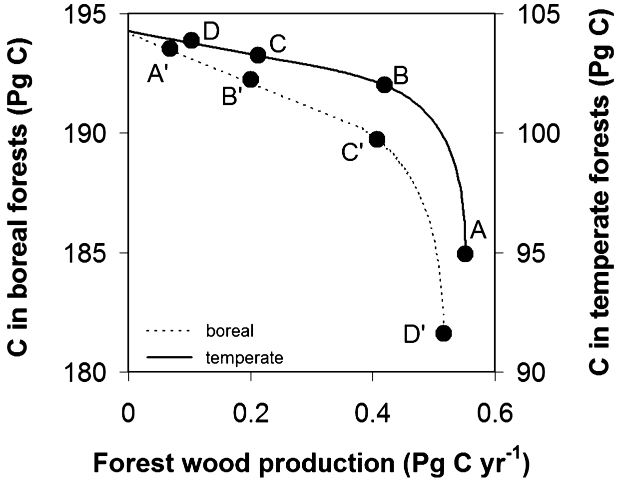

Fig. 2. The relationship between the area-integrated C storage ($C \cdot S$) and wood production ($P \cdot S$) of temperate (medium-growth) and boreal (slow-growth) forests, obtained by scaling the corresponding C–P relationships in Fig. 1 by the respective forest areas ($S = 297$ and 746 million ha, respectively). Only the high-sensitivity and linear phases are shown, with a transition between the two phases at points B and C$'$ in medium- and slow-growth forests; note the steeper slope of the linear phase for slow-growth forests. Combinations A–A$'$, B–B$'$, etc. satisfy a fixed global demand for timber ($P_g = 0.62$ Pg C yr^{-1}); A–A$'$ indicates the situation when medium-growth forests are exploited for maximum wood production, with only a small contribution from slow-growth forests. Point D–D$'$ indicates the reverse situation.

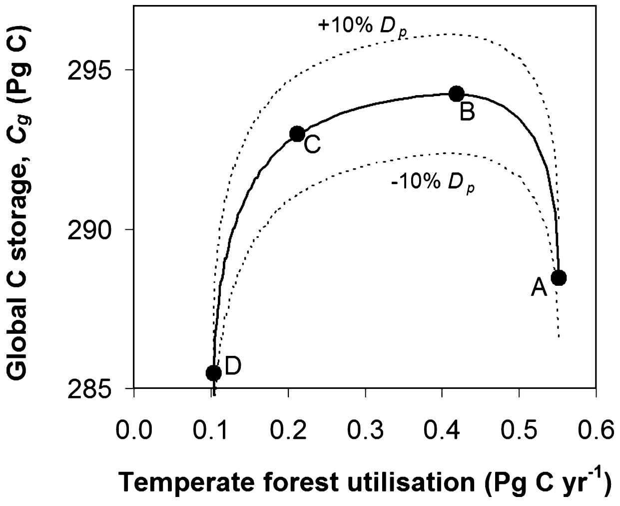

Fig. 3. Response of global C storage (temperate and boreal forests combined) to changes in the area-integrated wood production of temperate forests, under the constraint of a fixed global timber demand ($P_g = 0.62$ Pg C yr^{-1}). The continuous line corresponds to a forest product lifetime (D_p) of 30 yr, whilst the dotted lines represent the effects of a ±10% change in D_p. In regions A–B and C–D, the global response reflects the high-sensitivity phase of temperate and boreal forests, respectively (Figs. 1 and 2). In the intermediate region B–C, both forest types lie in the linear phase, and the global response depends on the difference between their growth rates, as explained in the text.

combined (global) C storage of the two areas (C_g), under the constraint $P_g = 0.62$ Pg C yr^{-1} which induces an equal increase in the wood production of the boreal forest (Fig. 2, $\mathrm{A}' \rightarrow \mathrm{B}' \rightarrow \mathrm{C}' \rightarrow \mathrm{D}'$). A 10% increase in wood product lifetime (D_p) results in a greater C storage in this compartment and in higher global C stocks, but does not change the shape of the relationship (Fig. 3).

If the temperate and boreal forests are initially intensively managed and largely untouched, respectively (Fig. 2, A–A$'$), global C storage follows three distinct trends as the temperate harvesting frequency is subsequently reduced (Fig. 3). Firstly (A–A$'$ → B–B$'$), when temperate forests are in the high-sensitivity phase and boreal forests are in the linear phase, the global C response is positive and dominated by the large C gains in temperate forests; this response corresponds to a C leakage U between 0 and -1 since temperate C gains are only partially offset by boreal C losses. Second (B–B$'$ → C–C$'$), when both forest types are in the linear phase, the global C response becomes negative as temperate C gains are more than offset by boreal C losses, reflecting the more sensitive boreal *C–P* relationship; this response corresponds to a C leakage of $U < -1$ whose numerical value throughout this phase is a constant which depends on the parameters A_2, A_3 and τ of each forest type (see eq. 15 below). Third, as the rotation length of boreal forests decreases to values close to the maximum in wood production (C–C$'$ → D–D$'$), boreal forests enter the high-sensitivity phase while temperate forests remain in the linear phase, resulting in a more rapid decline in global C storage (U becomes more negative). In this example, therefore, global C storage is maximised not by abandonment of temperate forests (C or D) but rather by actively managing them for timber production (point B) and protecting boreal forests instead (point B$'$); small changes in temperate harvesting frequency about point B have no effect on global C storage (corresponding to a C leakage of $U = -1$).

More generally, whether global C storage is maximised by managing or abandoning local forests (i.e. whether the peak in Fig. 3 lies at point B or C, respectively) depends on whether the slope of the linear BC portion of Fig. 3 is negative or positive. Thus we can use our previous analysis of this linear phase (Section 3.1, eq. 12) to gain theoretical insight into the key factors determining both the local and the global response in this portion.

In general, we have $C_g = C_{\rm loc}S_{\rm loc} + C_{\rm rem}S_{\rm rem}$ and $P_g = P_{\rm loc}S_{\rm loc} + P_{\rm rem}S_{\rm rem}$, where $C_{\rm loc}$ and $C_{\rm rem}$ are the per hectare C storage of the (local) area directly affected by management changes, and of the (remote) area indirectly affected through the constraint of a fixed global timber demand; $P_{\rm loc}$ and $P_{\rm rem}$ are their per hectare wood productivities; and $S_{\rm loc}$ and $S_{\rm rem}$ are their surface areas. Assuming no changes in $S_{\rm loc}$ and $S_{\rm rem}$, changes in global C storage (C_g) occur only through changes in $C_{\rm loc}$ and $C_{\rm rem}$:

$$\Delta C_g = \mathrm{d}C_{\rm loc} \cdot S_{\rm loc} + \mathrm{d}C_{\rm rem} \cdot S_{\rm rem}. \qquad (13)$$

The constraint of a fixed global demand for wood products ($\Delta P_g = \mathrm{d}P_{\rm loc}S_{\rm loc} + \mathrm{d}P_{\rm rem}S_{\rm rem} = 0$) implies that a reduction in the wood production of the local forest must be compensated by an equal increase in that of the remote forest:

$$\mathrm{d}P_{\rm rem}S_{\rm rem} = -\mathrm{d}P_{\rm loc}S_{\rm loc}. \qquad (14)$$

By combining eqs (12) and (14) it follows that the leakage factor (U), defined as the ratio of the total change in remote C storage ($\Delta C_{\rm rem} = \mathrm{d}C_{\rm rem} \cdot S_{\rm rem}$) to the total change in the C stored locally ($\Delta C_{\rm loc} = \mathrm{d}C_{\rm loc} \cdot S_{\rm loc}$) is given (within the linear BC portion of Fig. 3) by

$$U_{\rm BC} \equiv \left.\frac{\Delta C_{\rm rem}}{\Delta C_{\rm loc}}\right|_{\rm BC} = -\frac{A_3^{\rm rem} - A_2^{\rm rem}\tau_{\rm rem}}{A_3^{\rm loc} - A_2^{\rm loc}\tau_{\rm loc}}. \qquad (15)$$

The parameters $A_2^{\rm loc}$, $A_2^{\rm rem}$, etc. refer to the parameters defined by eq. (8), evaluated for the local (loc) and remote (rem) forests. eq. (15) implies that $U_{\rm BC} \le -1$ when

$$A_2^{\rm rem}\tau_{\rm rem} - A_3^{\rm rem} \ge A_2^{\rm loc}\tau_{\rm loc} - A_3^{\rm loc}. \qquad (16)$$

When this parameter condition holds as an equality (critical threshold), the slope of the linear BC portion of Fig. 3 is zero.

Also, the slope of the linear BC portion of Fig. 3 is the ratio of the change in global C storage (ΔC_g) to the total change in local wood production ($\Delta P_{\rm loc} = \mathrm{d}P_{\rm loc}S_{\rm loc}$). Using eqs (12), (13) and (15) we find

$$\left.\frac{\Delta C_g}{\Delta P_{\rm loc}}\right|_{\rm BC} = \left(A_2^{\rm rem}\tau_{\rm rem} - A_3^{\rm rem}\right) - \left(A_2^{\rm loc}\tau_{\rm loc} - A_3^{\rm loc}\right) \qquad (17)$$

Note, as expected, that $\Delta C_g/\Delta P_{\rm loc}|_{\rm BC} = 0$ when the critical threshold condition (equality in eq. 16) is satisfied, corresponding to $U_{BC} = -1$.

As demonstrated by the numerical analysis in Fig. 3, maximum global C storage is achieved by actively managing whichever is the faster-growing forest at the transition point between its high-sensitivity and linear phases (point B). Reducing harvesting of the faster-growth forest beyond this point (Fig. 3, B → C) would have an adverse effect on the global C storage, because it would result in a greater (albeit sustainable) exploitation of the slower-growth forest.

We can illustrate in a more intuitive form these general results in the simplified case of no woody litter production ($\alpha_b = \alpha_w = 0$) and whole-tree harvesting ($h_b = h_w = 0$). Assuming that wood product lifetime (D_p) is the same for local and remote forests, eq. (15) gives $U_{\rm BC} = (D_p - \tau_{\rm rem})/\left(\tau_{\rm loc} - D_p\right)$ for the leakage factor. Thus, if $\tau_{\rm loc}$ and $\tau_{\rm rem}$ are both greater than D_p then any local C management project will inevitably result in some C leakage ($U_{\rm BC} < 0$). Moreover, eq. (16) gives $\Delta C_g/\Delta P_{\rm loc}\,|_{\rm BC} = \tau_{\rm rem} - \tau_{\rm loc}$ for the slope of the BC portion of Fig. 3. As a result, when $\tau_{\rm loc} < \tau_{\rm rem}$ we have $U_{\rm BC} < -1$ (total leakage, Fig. 4). In this case, a local problem would only be moved elsewhere and magnified.

Conversely, if boreal harvesting is reduced at the expense of temperate harvesting (corresponding to C → B in Fig. 3), so that

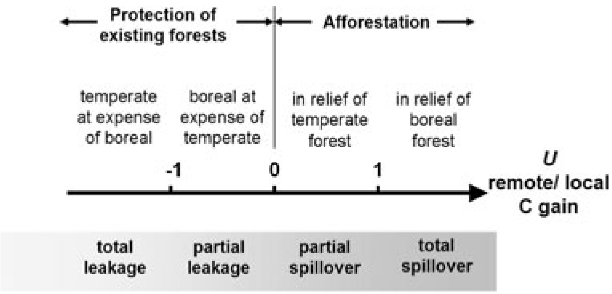

Fig. 4. Summary of leakage and spillover effects of forest management changes within the linear phases of Fig. 1. Reduced exploitation of medium-growth ('temperate') forests at the expense of slower-growing ('boreal') forests (Fig. 2, $B\text{–}B' \rightarrow C\text{–}C'$) induces a global C loss (total leakage, remote/local C gain $U < -1$). Leakage induced by the reduced exploitation of boreal forests (Fig. 2, $C\text{-}C' \rightarrow B\text{–}B'$) is only partial ($-1 < U < 0$). The global C gain from afforestation always exceeds local C gains (partial or total spillover, $U > 0$); for afforestation in relief of slow-growth boreal forests, remote C gains exceed local C gains in the plantation itself (total spillover, $U > 1$).

we have $D_p < \tau_{\text{rem}} < \tau_{\text{loc}}$, then global C storage will increase, leakage in this case being only partial ($-1 < U_{\text{BC}} < 0$).

The magnitude of C leakage in the BC portion of Fig. 3 is far from negligible. Because temperate forests are generally managed for maximum profit rather than production, present conditions correspond approximately to the maximum global C storage at point B rather than point A. Outright abandonment of temperate forests in the northern hemisphere (B → D) would then result in a net loss of 9.5 Pg C below this level. As an order of magnitude estimate of the possible global impact of C leakage, this C loss represents a net transfer of C to the atmosphere that is comparable to the cumulative effect over 100 yr of a 10% reduction in the current annual rate of C sequestration by northern hemisphere forests (Dixon et al., 1994), or a 1.5% increase in current net anthropogenic annual C emissions (Schimel et al., 2001).

3.3. Spillover induced by afforestation

The same general framework can be used to understand the global effects of afforestation projects. The establishment of new plantations has a twofold effect. On the one hand, C is stored locally in the plantation itself (and its wood products). On the other hand, the increase in timber supply permits a longer rotation period in existing forests, resulting in additional non-local C gains (spillover).

In contrast to C storage in existing forests, local C storage ($C_{\text{loc}} S_{\text{loc}}$) will vary in proportion to the area afforested (S_{loc}), because plantations are assumed to be managed for maximum C storage in forest and wood products ($T \approx T^*$; see Fig. 1). Changes in global C storage C_g can therefore be expressed as:

$$\Delta C_g = C_{\text{loc}} \cdot \mathrm{d}S_{\text{loc}} + \mathrm{d}C_{\text{rem}} \cdot S_{\text{rem}}. \tag{18}$$

The first term is the change ($\Delta C_{\text{loc}} = C_{\text{loc}} \cdot \mathrm{d}S_{\text{loc}}$) in the total C stored locally due to afforestation (assuming fixed C storage per hectare), and the second term is the change ($\Delta C_{\text{rem}} = \mathrm{d}C_{\text{rem}} \cdot S_{\text{rem}}$) in the total C stored remotely (the same as appears in eq. 14). The constraint of fixed global timber demand now implies that $P_{\text{loc}} \mathrm{d}S_{\text{loc}} = -\mathrm{d}P_{\text{rem}} S_{\text{rem}}$. In this case, eqs (11), (12) and (18) imply that the spillover fraction is given by

$$U \equiv \frac{\Delta C_{\text{rem}}}{\Delta C_{\text{loc}}} = \frac{A_2^{\text{rem}} \tau_{\text{rem}} - A_3^{\text{rem}}}{A_3^{\text{loc}} - A_2^{\text{loc}} \tau_{\text{loc}} + \frac{B_{\text{loc}}^m}{f_{\text{loc}}^c \cdot P_{\text{loc}}}}. \tag{19}$$

Here B_{loc}^m is C storage in old-growth trees for the local forest type and f_{loc}^c is the fraction of old-growth C storage in living trees relative to that in the entire old-growth ecosystem; thus $B_{\text{loc}}^m / . f_{\text{loc}}^c$ is the ecosystem C storage of old-growth forest, given by the first term in eq. (11). We can simplify eq. (17) further by noting that wood production of the local forest can be expressed as:

$$P_{\text{loc}} = \frac{B_{\text{loc}}(T^*)}{T^*} = \frac{\mu \cdot B_{\text{loc}}^m}{T^*}, \tag{20}$$

where parameter $\mu = B_{\text{loc}}(T^*)/B_{\text{loc}}^{\text{m}}$. From a numerical analysis of the logistic equation using a realistic range of model parameters ($25 < b < 1000$ and $0.01 < r < 2$), we find that $0.78 < \mu < 0.94$ (and in addition, $T^* \approx 1.39\ \tau$, as noted previously). Equations (19) and (20) then give

$$U \equiv \frac{\Delta C_{\text{rem}}}{\Delta C_{\text{loc}}} > \frac{A_2^{\text{rem}} \tau_{\text{rem}} - A_3^{\text{rem}}}{A_3^{\text{loc}} + \tau_{\text{loc}} \left(\frac{1.39}{f_{\text{loc}}^c \cdot 0.78} - A_2^{\text{loc}} \right)}. \tag{21}$$

The spillover resulting from the establishment of new plantations under a range of conditions is demonstrated in Fig. 5, using a representative value of $T^* = 23$ yr for fast-growing plantations (see Table 1). The magnitude of the spillover effect can be seen to be maximum when the new plantation alleviates wood prouction from slow-growing forests, and when forest harvesting is aimed at the manufacturing of short-lived products. As an example, managing boreal forests for paper production is expected to result in large overall C losses (see Dewar, 1991), and the alternative wood production from new plantations could achieve the greatest effect.

In the case of slow-growing (boreal) forests, the magnitude of the spillover effect can even exceed the local C gains (Fig. 5). Afforestation and preservation of existing boreal forests should therefore be viewed as cooperative rather than competing mechanisms of climate change mitigation (Schulze et al., 2000).

4. Conclusions

The potential global effects of a change in forest management intensity have been explored through a simple analytical model. In particular, the impact of a change in rotation length has been studied. The long-term effects of outright forest abandonment, which could result in the onset of natural successional cycles, have not been considered. The potential of forest biomass

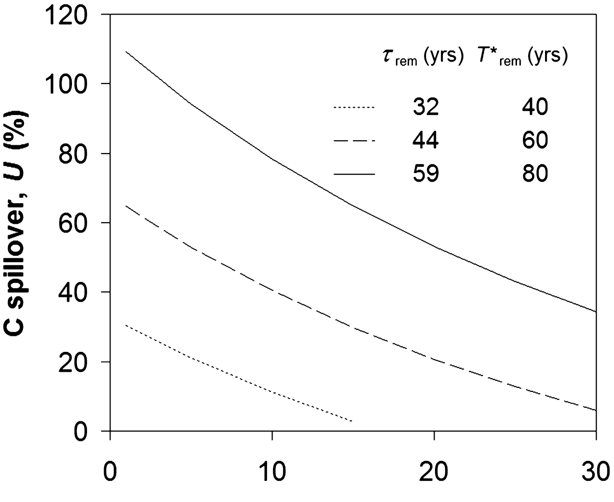

Fig. 5. Magnitude of the C spillover effect resulting from the establishment of new plantations. The spillover effect (U,%) resulting from the establishment of forest plantations with a representative rotation length $T^* = 23$ yr is presented, when wood from the new forest is used for products with increasing lifetime (D_p) in substitution of timber from remote forests of different growth rates (τ).

production for fossil fuel substitution has also been excluded from the present analysis.

Our study demonstrates that the full impact of forest management choices becomes apparent only at the global (whole-system) level, because of unintended leakage and spillover effects. The hypothetical case studies discussed, albeit oversimplified, clearly demonstrate that the potential magnitude of these effects cannot be neglected in the discussion of future strategies for C storage through the adaptive management of existing forests and afforestation.

The key analytical results of our study, eqs (15) and (21), reveal how leakage and spillover depend on the parameter combinations A_2 and A_3 and the characteristic growth timescale (τ) of each forest type. Through eq. (8), we conclude that specific factors to take into account are woody litter production (α_b and α_w) and decomposition (D_b and D_w), slash management (h_b and h_w), and wood product lifetime (D_p). Our analysis reveals how the relative magnitude of D_p and τ for local and remote forests plays a key role. These results provide a prerequisite theoretical understanding of the problem on the basis of which more realistic numerical studies may be interpreted.

5. Acknowledgments

The current study was supported by the Italian MIUR project 'CarboItaly', by the Società Produttori Sementi (Fondazione Cassa di Risparmio in Bologna) through the 'Selvicoltura' project and through the French CarboFor project ('Sequestration of carbon in the major forest ecosystems of France'; GICC, GIP-Ecofor).

References

Andrén, O. and Kätterer, T. 1997. ICBM: the introductory carbon balance model for exploration of soil carbon balances. *Ecol. Appl.* **7**, 1226–1236.

Borden, J. H., Marland, G., Schlamadinger, B. and Matthews, R. 2000. "Kyoto Forests" and a broader perspective on management. *Science* **290**, 1895–1896.

Caspersen, J. P., Pacala, S. W., Jenkins, J. C., Hurtt, G. C., Moorcroft, P. R. and co-authors. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. *Science* **290**, 1148–1151.

Cooper, C. F. 1983. Carbon storage in managed forests. *Can. J. Forest Res.* **13**, 155–166.

Dewar, R. C. 1990. A model of carbon storage in forests and forest products. *Tree Physiol.* **6**, 417–428.

Dewar, R. C. 1991. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. *Tree Physiol.* **8**, 239–258.

Dewar, R. C. and Cannell, M. G. R. 1992. Carbon sequestration in the trees, products and soils of forest plantations. An analysis using UK examples. *Tree Physiol.* **11**, 49–71.

Dewar R. C. 2001. The sustainable management of temperate plantation forests: from mechanistic models to decision-support tools. In: *Models for the Sustainable Management of Temperate Forest Plantations* Volume 41 (eds J.-M. Carnus, R. C. Dewar, D. Loustau and M. Tomé). *Eur. For. Inst. Proc.,* 119–137.

Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler, M. C. and co-authors. 1994. Carbon pools and flux of of global forest ecosystems. *Science* **263**, 185–190.

Fang, J., Chen, A., Peng, C., Zhao, S. and Ci, L. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* **292**, 2320–2322.

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S. and co-authors. 2002. Forest carbon sinks in the Northern Hemisphere. *Ecol. Appl.* **12**, 891–899.

Harmon, M. E., Ferrell, W. K. and Franklin, J. F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* **247**, 699–702.

Houghton, R. A., Hackler, J. L. and Lawrence, K. T. 1999. The U.S. carbon budget: contributions from land-use change. *Science* **285**, 574–578.

Kallbekken, S., Flottorpa Line, S. and Rivea, N. 2007. CDM baseline approaches and carbon leakage. *Energ. Policy* **35**, 4154–4163.

Intergovernmental Panel on Climate Change. 2002. *Climate Change 2001: Mitigation*. Cambridge University Press, Cambridge, 762 p.

Intergovernmental Panel on Climate Change. 2007. *Mitigation of Climate Change*. Cambridge University Press, Cambridge, 896 p.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R. and Karjalainen, T. 2001. Which rotation length is favourable to carbon sequestration? *Can. J. Forest Res.* **31**, 2004–2013.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F. and co-authors. 2007. The human footprint in the carbon cycle of temperate and boreal forests, 2007. *Nature* **447**, 849–851.

Nabuurs, G. J. and Mohren, G. M. J. 1995. Modelling analysis of potential carbon sequestration in selected forest types. *Can. J. Forest Res.*, **25,** 1157–1172.

Pussinen, A., Karjalainen, T., Mäkipää, R., Valsta, L. and Kellomäki, S. 2002. Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. *Forest Ecol. Manage.*, **158**, 103–115.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P. and co-authors. 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature*, **414**, 169–172.

Schulze, E.-D., Wirth, C. and Heimann, M. 2000. Managing forests after Kyoto. *Science*, **289**, 2058–2059.

Skog, K. E. and Nicholson, G. A. 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *For. Prod. J.* **48**, 75–83.

Sohngen, B. and Sedjo, R. 2000. Potential carbon flux from timber harvests and management in the context of a global timber market. *Climatic Change*, **44**, 151–172.

Sohngen, B. and Mendelsohn R. (2003) An optimal control model of forest carbon sequestration. *Am. J. Agric. Econ.* **85**, 448–457.

UN ECE/FAO. 2000. *Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand*. Report No. 17. United Nations, Geneva.

UN Framework. 2002. Convention on climate change. Report of the Conference of the Parties on its 7th session, held at Marrakesh from 29 October to 10 November, 2001. UNFCCC, Marrakesh.