

# Chapter 8

## Effects of Bioenergy Production on Carbon Sequestration in Forest Ecosystems

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**Abstract** This chapter explores the dynamics of carbon sequestration in forest ecosystems. The focus is on the physiological and ecological mechanisms that control the carbon uptake and emissions in boreal forests. Findings from long-term monitoring and process-based modeling are used to demonstrate the sink/source dynamics of carbon sequestration in naturally growing and developing forest ecosystems and how this deviates from that under regular management. Carbon retention in the ecosystem is addressed based on model simulations, which represent both natural and managed forests. The effects of biomass production on carbon sequestration are analyzed based on model simulations in order to identify how management may affect carbon residence in the boreal forest ecosystem.

**Keywords** Carbon cycle · Carbon sequestration · Boreal forest ecosystem · Carbon residence · Eddy covariance measurement · Energy biomass · Ecosystem model · Litter · Humus · Emissions · Carbon sink · Carbon source · Decomposition · Physiological process · Ecological process · Net carbon exchange

### 8.1 Global Carbon Cycle

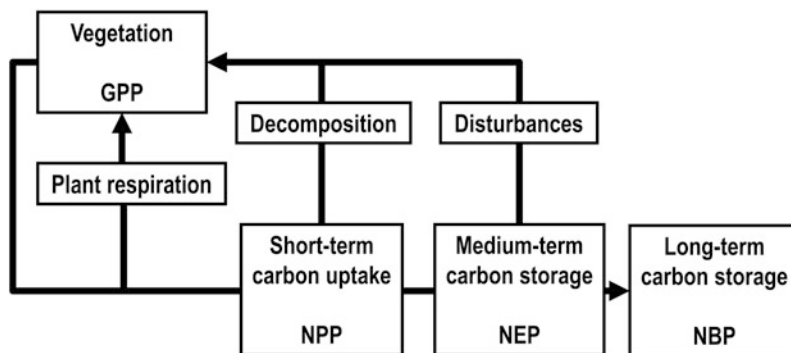
Managed forests provide biomass for energy production, but their potential to provide energy biomass is very much dependent on management. The harvest of forest biomass for energy alters the carbon sink/source dynamics of forest ecosystem. This links the carbon sequestration and the consequent carbon balance in the ecosystem

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**Fig. 8.1** Outlines of global carbon cycle as adapted from Grace (2005, p. 24). *Gross primary production (GPP)*: carbon fixed in photosynthesis; *Net primary production (NPP)*: gross primary production minus carbon lost in plant respiration ( $RA$ ) (autotrophic respiration),  $NPP = GPP - RA$ ; *Decomposition (RH)*: carbon lost in heterotrophic respiration; *Net ecosystem production (NEP)*: net primary production minus heterotrophic respiration ( $RH$ ):  $NEP = NPP - RH = GPP - (RA + RH)$ ; *Net biome production (NBP)*: net gain or loss of carbon in a given area at the biome level equal to the net ecosystem production minus carbon loss in disturbances such as fire or logging; *Biome*: major region of distinctive plant and animal groups well adapted to the physical environment in its distribution area, e.g. boreal forests

with the global carbon (C) cycle. As outlined in Fig. 8.1, carbon is fixed in photosynthesis of plants (gross primary production) and lost in respiration of plants (autotrophic respiration) and in decay of litter and humus (heterotrophic respiration). Furthermore, disturbances like fire and harvesting of biomass cycle carbon back to the atmosphere. Between uptake and loss, carbon is retained for shorter and longer periods in the ecosystem (carbon storage), but finally carbon will end up in the atmosphere. Short-term carbon storage refers to net primary production (gross primary production minus autotrophic respiration), whereas medium-term carbon storage indicates the carbon bound in plant biomass and other organisms (gross primary production minus autotrophic and heterotrophic respiration), and organic matter in soil. Long-term carbon storage describes carbon storage over areas of varying spatial scale (stand, landscape, national, and continental), including effects due to changes in land use and practices in land management.

## 8.2 Bioenergy to Mitigate Climate Change

Carbon in the established forests is bound in trees and other plants and in soil in the form of decaying litter and humus. The residence time of carbon in forests depends on the management and the prevailing environmental conditions which control the decay of litter and humus. Thus, the mitigation of climate change through sequestration of carbon in forest ecosystems depends on their management.

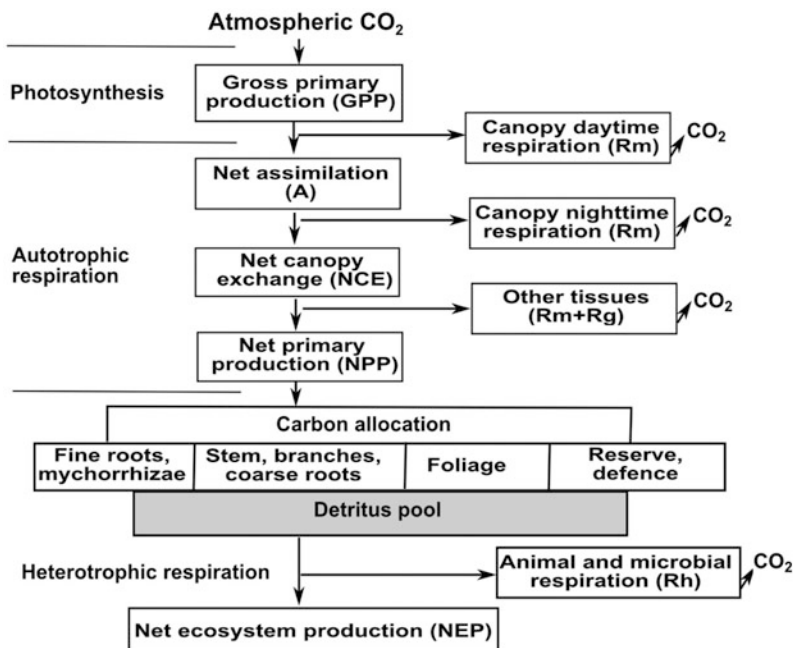
Mitigation of climate change refers to the anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases in order to reduce the intensity of radiative forcing, thus reducing the potential global warming due to the increasing concentration of greenhouse gases in the atmosphere (IPCC 2001, p. 990). In forestry, there are several ways to mitigate climate change by sequestering carbon dioxide ( $\text{CO}_2$ ) in forest ecosystems and reducing the emissions of  $\text{CO}_2$  to the atmosphere (IPCC 2007):

- (1) to reduce deforestation and degradation of forests;
- (2) to increase forested land area through afforestation/reforestation;
- (3) to increase the carbon density in existing forests;
- (4) to increase the use of biomass to replace fossil fuels in energy production; and
- (5) to increase the use of biomass-based products to increase carbon density outside existing forests.

Activities (1) and (2) aim to maintain and increase the sink capacity in terms of conserve forested land, whereas activity (3) refers mainly to increasing the carbon uptake rate through proper management. Activity (4) refers to the reduction of emissions of fossil carbon by substituting fossil fuels with biomass, thus cycling carbon in the atmosphere/biosphere system in order to slow the increase of atmospheric  $\text{CO}_2$  or even to reduce it. Activity (5) indicates the carbon sequestered in biomass-based products, thus cycling carbon through the biosphere/technosystem/atmosphere systems. The residence time of carbon in forest products varies from a few years in paper to several decades in solid wood products, like building materials. In biomass harvested for energy, the residence time is less than a year or even a matter of weeks.

### 8.3 Carbon Flow Through Forest Ecosystem in Physiological and Ecological Processes

Figure 8.2 shows the carbon flow through a forest ecosystem in physiological and ecological processes based on Waring and Running (2007). Gross primary production (*GPP*) is mainly controlled by the interception of radiation in tree canopies and the cycle of nutrients, in boreal conditions especially by the availability of nitrogen (Hyvönen et al. 2007). Uptake of  $\text{CO}_2$  is further limited by temperature, humidity, concentration of atmospheric  $\text{CO}_2$  and availability of soil water affecting stomatal conductance. Following Waring and Running (2007), the difference between the gross primary production and daytime respiration ( $R_m$ ) in canopy yields the net canopy assimilation (*A*), which is partly lost in nighttime respiration. Gross primary production minus the carbon losses in canopy respiration gives the diurnal net canopy exchange (*NCE*). In this context, net primary production (*NPP*) refers to the gross primary production minus carbon lost in autotrophic respiration. Half of the gross amount of carbon assimilated in photosynthesis (*GPP*) is cycled back to the atmosphere in autotrophic respiration (*RA*) originating from the synthesis and maintenance of living cells in various organs of trees (Hyvönen et al. 2007).

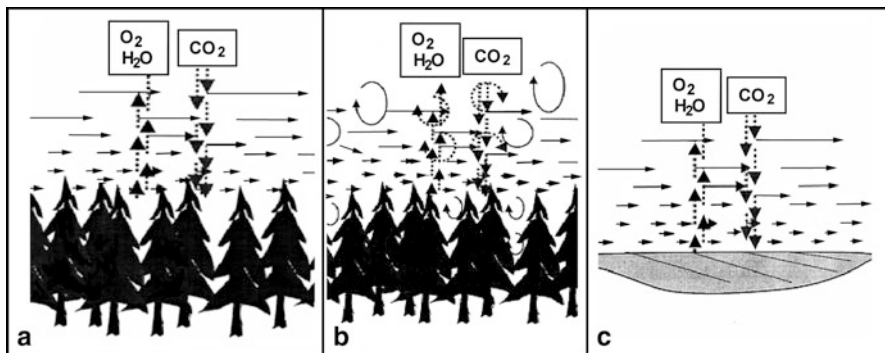


**Fig. 8.2** Schematic representations of the flow of carbon through a forest ecosystem as adapted from Waring and Running (2007)

Carbon in net primary production is allocated into various organs; i.e. fine roots and mycorrhizae, stems, branches and coarse roots, foliage, and chemicals for defence (Fig. 8.2). Turnover of foliage and fine roots are the major contributors to litter on a seasonal basis, but the biomass in all organs finally enters the detritus pool following the turnover of mass in different organs. Decomposition of litter and release of  $\text{CO}_2$  due to the activity of heterotrophic organisms are functions of substrate quality (e.g. the ratio between carbon (C) and nitrogen (N), C/N ratio) and the temperature and moisture conditions in soil profile (e.g. Chertov et al. 2001). In this context, the net ecosystem production (NEP) or net ecosystem exchange (NEE) indicates the difference between the carbon taken up in gross primary production and lost in autotrophic and heterotrophic respiration. Taking account of the loss of carbon in disturbances (e.g. forest fire, harvest of trees), one obtains the net biome production (NBP) linking the physiological uptake and loss of carbon with the losses in ecological processes. Their time steps are typically longer ( $>$  years and decades) than those for physiological processes ( $<$  few days). Table 8.1 summarizes the flow of carbon through the forest ecosystem in physiological terms.

**Table 8.1** Concepts used in analyzing the carbon flow through forest ecosystems

Concepts	Definition
Gross primary production, $GPP$ ( $g\ m^{-2}\ a^{-1}$ )	Gross carbon fixation rate into the forest ecosystems through trees and other green organisms
Autotrophic respiration, $RA$ ( $g\ m^{-2}\ a^{-1}$ )	Loss rate of carbon through autotrophic respiration rate, $RA = R_{day} + R_m + R_g$
Day, $R_{day}$	
Dark, $R_m$	
Growth, $R_g$	
Net primary production, $NPP$ ( $g\ m^{-2}\ a^{-1}$ )	Gross production rate minus autotrophic respiration rate, $NPP = GPP - RA$
Heterotrophic respiration, $RH$ ( $g\ m^{-2}\ a^{-1}$ )	Loss rate of carbon through respiration of secondary producers
Total respiration, $RT$ ( $g\ m^{-2}\ a^{-1}$ )	Sum of autotrophic and heterotrophic respiration rates, $RT = RA + RH$ over a year
Net ecosystem production ( $NEP$ ) or Net ecosystem exchange, $NEE$ ( $g\ m^{-2}\ a^{-1}$ )	Gross primary production minus total respiration or net primary production minus heterotrophic respiration, $NEE = GPP - RA - RH = NPP - RH$
Net biome production, $NBP$ ( $g\ m^{-2}\ a^{-1}$ )	Net biome production $NBP = NEE$ plus $CO_2$ lost in disturbances, e.g. harvest, fires etc.



**Fig. 8.3** Schematic representation of the exchange of  $CO_2$  and  $H_2O$  in a forest ecosystem if air flow through canopy is laminar (a), and turbulent (b), and the exchange of  $CO_2$  and  $H_2O$  in the boundary layer of leaves (c)

## 8.4 Carbon Sequestration in Boreal Forest Ecosystem

### 8.4.1 Net $CO_2$ Exchange in Forest Ecosystem ( $NEE$ ) – Basic Mechanisms

The concept of eddy covariance (EC) with the proper technology is widely used to measure the net  $CO_2$  exchange of ecosystem ( $NEE$ ) in a forest ecosystem (e.g. Baldocchi 2003); i.e. the difference between carbon uptake through photosynthesis and carbon loss through autotrophic and heterotrophic respiration. Figure 8.3

shows air flow through the forest canopy of a high enough velocity to be classed as turbulent (middle of Figure) with eddies. The eddies carry  $\text{CO}_2$  and  $\text{H}_2\text{O}$  back and forth between atmosphere and canopy, whereas a slower air flow is classed as laminar (left) with no/few eddies and with only a small exchange of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  between canopy and atmosphere. In both cases, the exchange of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  occurs in the boundary layer of leaves/canopy through uptake of  $\text{CO}_2$  in photosynthesis and emission of  $\text{H}_2\text{O}$  in transpiration. In determining EC, the  $\text{CO}_2$  content in eddies and the three-dimensional wind velocity are measured and used to calculate the exchange rate between the atmosphere and the ecosystem.

In EC measurements, photosynthesis is regarded as a negative flux into the ecosystem from the atmosphere, while respiration is a positive flux out from the ecosystem to the atmosphere. During the daytime,  $NEE_{day}$ , [ $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ] equals  $GPP$  in the canopy minus the carbon lost in autotrophic respiration in leaves ( $R_l$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ), branches, sapwood and roots ( $R_{b,w}$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ) and in heterotrophic respiration in soil ( $R_s$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ). Furthermore, autotrophic respiration in leaves may be divided into photorespiration ( $R_{l,p}$ ) and respiration in darkness ( $R_{l,d}$ ) (Ge et al. 2011):

$$NEE_{day} = GPP - (R_l + R_{b,w} + R_s) = GPP - (R_{l,p} + R_{l,d} + R_{b,w} + R_s) \quad (8.1)$$

Net ecosystem exchange at night ( $NEE_{night}$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ) includes only autotrophic losses in darkness and in heterotrophic respiration:

$$NEE_{night} = R_{l,d} + R_{b,w} + R_s \quad (8.2)$$

On the daily basis, the net  $\text{CO}_2$  exchange between the forest ecosystem and the atmosphere is the sum of eddy fluxes ( $F_e$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ) from the canopy, monitored by the EC instrument, and the flux representing the storage of  $\text{CO}_2$  ( $F_s$ ,  $\text{g C m}^{-2}$  ground  $\text{day}^{-1}$ ) in the air layer below the canopy (Aubinet et al. 2000).

$$NEE = F_e + F_s \quad (8.3)$$

The flux from the canopy ( $F_e$ ) refers to the mean covariance between the vertical wind velocity ( $w'$ ) and the fluctuations in the  $\text{CO}_2$  density ( $c'$ ) including the correction of measured  $\text{CO}_2$  flux due to changes in air density (Aubinet 2000; Ge et al. 2011):

$$F_e = \left( \frac{\overline{pT_i}}{\overline{p_i T_a}} \right) \left[ \overline{w'c'_i} + \frac{m_a}{m_v} (\overline{c'}/\overline{\rho_a}) \overline{w'\rho'_{vi}} \right] \quad (8.4)$$

where  $p$  is pressure (Pa),  $T$  is temperature ( $^{\circ}\text{K}$ ),  $\rho_{vi}$  and  $\rho_a$  are the mean densities of water vapor and dry air respectively. Furthermore,  $m_a/m_v$  is the ratio between the molecular mass of dry air and that of water vapor. The bars over factors refer to the time averages and primes to the instantaneous fluctuations around the mean quantities (Aubinet et al. 2000). The carbon storage below the canopy ( $F_s$ ) is obtained by integrating the rate of temporal change in the  $\text{CO}_2$  concentration profile below the canopy:

$$F_s = \frac{v_a \Delta C_r}{m} \quad (8.5)$$

where  $v_a$  is the volume ( $m^3$ ) of the air column below the height of the EC instrumentation,  $\Delta c_r$  is the change in  $CO_2$  density per unit time at the canopy source height, and  $m$  is the molar volume of  $CO_2$  (Aubinet et al. 2000).

**Box 8.1 How to scale up from photosynthetic biochemistry per unit leaf area to canopy photosynthesis per unit ground area (Ge et al. 2011)**

To scale up from photosynthetic per unit leaf area to canopy photosynthesis per unit ground area ( $A_c$ ) is based on micro-meteorological models. For example, they may use an integrated sun/shade sub-model to consider the daily change in the fraction of sunlit ( $LAI_{sun}$ ) and shaded leaf index ( $LAI_{sh}$ ) in the canopy and the corresponding difference in photosynthetic rate and canopy stomatal conductance ( $g_{cs}$ ). Net radiation absorbed in the canopy ( $R_{nc}$ ) is divided into sunlit ( $R_{nc.sun}$ ) and shaded ( $R_{nc.sh}$ ) fractions of foliage; i.e. net canopy photosynthesis ( $A_c$ ) includes photosynthesis both in sunlit ( $A_{c.sun}$ ) and shaded ( $A_{c.sh}$ ) foliage (Kellomäki and Wang 1999, 2000):

$$\begin{aligned} A_c &= A_{c.sun} + A_{c.sh} \\ &= \int_0^{LAI} f(R_{nc.sun})f(T_c)f(c_a)f(N_L)f(LAI_{sun})f(g_{s.sun})dLAI \\ &\quad + \int_0^{LAI} f(R_{nc.sh})f(T_c)f(c_a)f(N_L)f(LAI_{sh})f(g_{s.sh})dLAI \end{aligned} \quad (8.6)$$

$$R_{nc} = R_{nc.sun} + R_{nc.sh} \quad (8.7)$$

$$g_{cs} = \frac{LAI_{sun}}{LAI} \int_0^{LAI} g_{s.sun} + \frac{LAI_{sh}}{LAI} \int_0^{LAI} g_{s.sh} \quad (8.8)$$

where the functions  $f(T_c)$ ,  $f(C_a)$ ,  $f(N_L)$ ,  $f(g_{s.sun})$  and  $f(g_{s.sh})$  refer to the effects of air temperature, atmospheric  $CO_2$ , foliage nitrogen content and stomatal conductance on the  $CO_2$  uptake rate. Stomatal conductance ( $g_s$ ) is controlled by radiation ( $R_{nc}$ ), vapor pressure deficit ( $D_a$ ), concentration of  $CO_2$  ( $C_a$ ), canopy temperature ( $T_c$ ), soil moisture ( $W_{soil}$ ) and soil temperature ( $T_s$ ):

$$g_s = g_{s,max} f(R_{nc})f(D_a)f(c_a)f(T_c)f(W_{soil})f(T_s) \quad (8.9)$$

where  $g_{s,max}$  is the maximum values of stomatal conductance. Respiration in foliage in darkness ( $R_{l,d}$ ) is controlled by canopy temperature and the nitrogen content in foliage. Heterotrophic respiration in the forest floor is the function of soil temperature ( $T_s$ ) and water content ( $\theta_s$ ) of soil:

$$R_{l,d} = R_{l,d(20)}f_1(T_c) \int_0^{LAI} f(N_L)f(LAI)dLAI \quad (8.10)$$

$$R_{b,w} = (M_b R_{b(20)} + M_w R_{w(20)})f_2(T_w) \quad (8.11)$$

$$R_s = R_{s(20)}(1 - e^{\theta_s c \theta}) f_2(T_s) \quad (8.12)$$

where  $R_{L,d(20)}$ ,  $R_{b(20)}$ ,  $R_{w(20)}$  and  $R_{s(20)}$  are the rates of autotrophic respiration in foliage, branches, sapwood and the rate of heterotrophic respiration in the forest floor at a temperature of 20 °C. Furthermore,  $T_w$  refers to the temperature in sapwood. The functions  $f(N_L)$ ,  $f_1(T_c)$  and  $f(LAI)$  represent the nitrogen content in foliage, temperature in canopy, and the fraction of foliage area. The factors  $M_b$  and  $M_w$  (kg m<sup>-2</sup> ground) are dry biomass of living branches and sapwood.

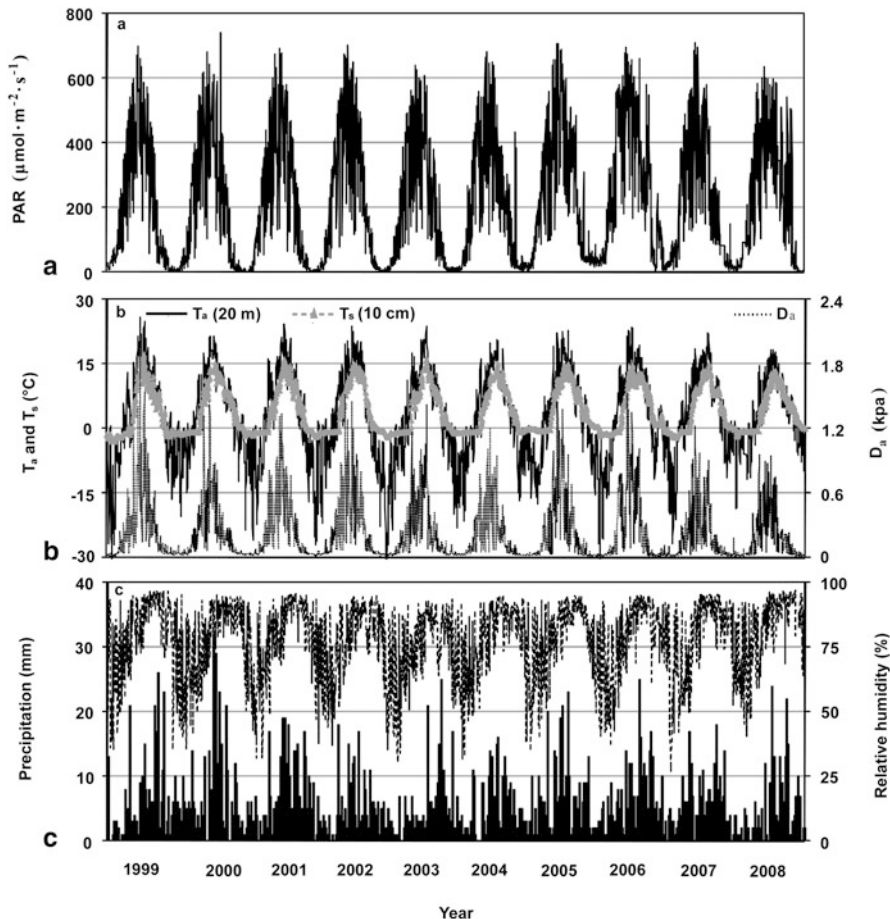
#### 8.4.2 Carbon Sequestration in Forest Ecosystems – a Case Based on Eddy Covariance Measurements

Ge et al. (2011) reported a time series of EC measurements over the period 1999–2008 in a boreal Scots pine forest located in eastern Finland (62°52'N, 30°49'E, 145 m a.s.l) on soil of low fertility (*Vaccinium* site type). The mean density of the forest was 1175 trees ha<sup>-1</sup>, with a mean height of 12 m (the mean of the dominant trees (upper 10 %) was 17.6 m) and a mean diameter of 11 cm. The soil at the site is a sandy loam with a water-holding capacity of 35 mm in the top 50 cm of soil. Climate at the site is characterized by cold winters with thick snow cover and short growing season (140–175 days). Mean annual precipitation in the area for the period 1961–2000 was around 700 mm, of which about 38 % was snow. The mean temperature is – 10.4 °C in January and 15.8 °C in July (Fig. 8.4) .

Figure 8.5 shows the daily data points of EC measurements and the model values, which are calculated on the basis of meteorological measurements using the process-based model outlined in Box 8.1 (Ge et al. 2011). For most of the winter time, the daily values of NEE were slightly positive (carbon source) until the end of April, representing the time of release of winter dormancy and enhancing photosynthesis; i.e. the site became a carbon sink (negative values of EC measurements). In May, the carbon uptake increased rapidly, and from June to August the site was a carbon sink, where the carbon uptake substantially exceeded the carbon emissions. Thereafter, the carbon uptake declined through September and October until trees fell into winter dormancy and the site became a slight carbon source once again. The model simulated in an adequate way the annual course of daily values of carbon flux as measured by the EC method (Ge et al. 2011).

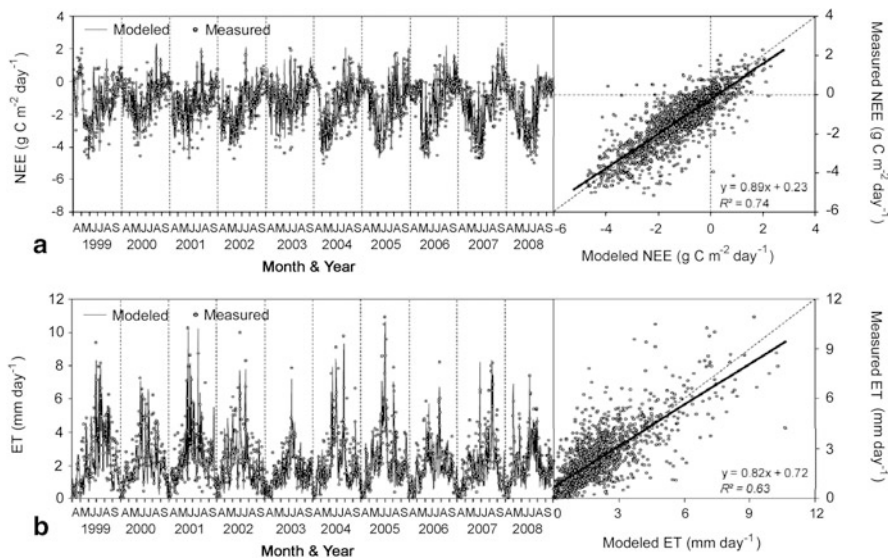
During the growing season (May–September), the amount of modeled NEE values varied from – 189 to – 263 g C m<sup>-2</sup>, and from – 195 to – 268 g C m<sup>-2</sup> for EC measurements (Table 8.2). Outside the growing season, the simulated values varied from 34 to 69 g C m<sup>-2</sup>, whereas the measured values fell in the range from 27 to 67 g C m<sup>-2</sup>. On an annual basis, for the period 1999–2008, the modeled values of NEE ranged





**Fig. 8.4** Meteorological and soil conditions 1999–2008 in the Huhus monitoring site (Ge et al. 2011). (a) the integrated daily photosynthetically active radiation (*PAR*) above the canopy, (b) the mean daily canopy temperature ( $T_c$ ) at a height of 20 m and soil temperature ( $T_s$ ) at a depth of 10 cm, (c) the mean vapor pressure deficit ( $D_a$ ) at a height 8 m and the daily precipitation and the mean relative humidity above the canopy. (Ge et al. 2011)

from  $-130$  to  $-203 \text{ g C m}^{-2}$  and the measured values from  $-161$  to  $-232 \text{ g C m}^{-2}$ . During the growing season, the daily values of *NEE* were dependent on air temperature ( $T_c$ ), photosynthetically active radiation (*PAR*) and vapor pressure deficit ( $D_a$ ). The trend of *NEE* variation roughly met the response of net photosynthesis of Scots pine to corresponding environmental variables under laboratory conditions (Kellomäki and Wang 1997a, b, 1998; Wang 1996; Wang et al. 1996).



**Fig. 8.5** Annual variation of daily ecosystem net carbon flux (*NEE*) in the boreal Scots pine stand in the Huhus monitoring site in 1999–2008. Points are measured fluxes and solid lines are modeled fluxes. (Ge et al. 2011)

**Table 8.2** Seasonal (growing season: May–September, outside growing season: October–April) and annual amount of net ecosystem CO<sub>2</sub> exchange (*NEE*, g C m<sup>-2</sup>) based on model computations and EC measurement. (Ge et al. 2011)

Year	Growing season		Outside growing season		Whole year	
	Modeled	Measured	Modeled	Measured	Modeled	Measured
1999	-205.7	-213.0	39.8	26.7	-165.8	-186.3
2000	-189.0	-195.0	59.2	34.0	-129.8	-161.0
2001	-239.8	-237.0	59.3	55.0	-180.5	-182.0
2002	-246.7	-250.4	43.9	36.7	-202.8	-213.7
2003	-255.3	-267.7	60.6	36.2	-194.7	-231.5
2004	-189.8	-206.8	34.3	48.6	-155.4	-158.1
2005	-255.4	-254.4	64.5	40.0	-190.9	-214.4
2006	-252.4	-240.9	65.9	50.2	-186.5	-190.7
2007	-223.9	-219.8	61.1	49.3	-162.8	-170.4
2008	-263.1	-257.0	68.8	67.2	-194.3	-189.8

## 8.5 Carbon Flow Through Forest Ecosystems in Ecological Processes

### 8.5.1 Dynamics of Carbon in Populations of Trees

In forestry, trees provide the basic unit for analyzing the sink/source dynamics of carbon. In physiological terms, trees represent the NPP production (i.e. gross production

**Table 8.3** Selected concepts used in growth and yield studies in assessing the dynamic of populations and communities of trees

Concept	Explanation
Gross growth, $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$	Total annual growth of trees
Total gross growth, $\text{m}^3 \text{ha}^{-1}$	Total accumulated growth over time
Mortality, $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$	Annual rate of tree death
Total mortality $\text{m}^3 \text{ha}^{-1}$	Accumulated rate of death over time
Net growth, $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$	Rate of difference between the gross growth and mortality
Total net growth, $\text{m}^3 \text{ha}^{-1}$	Accumulated net rate of growth over time
Stocking, $\text{m}^3 \text{ha}^{-1}$	Amount of stem wood at a given point of time

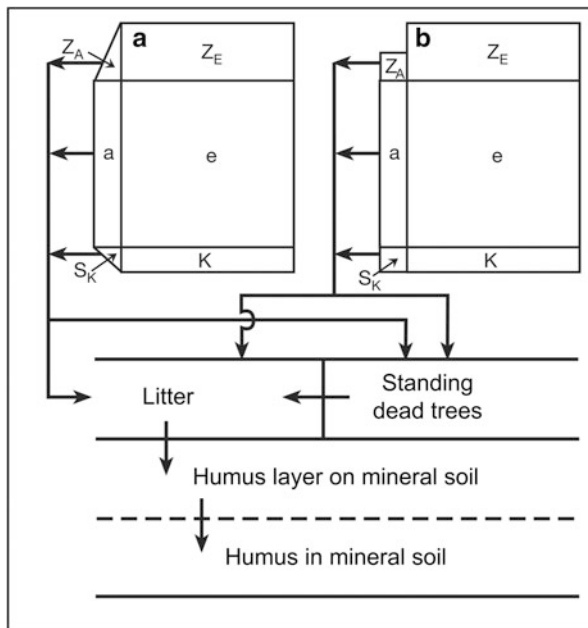
rate minus autotrophic respiration rate,  $\text{NPP} = \text{GPP} - \text{RA}$ ). In the forestry context, the dynamics of carbon in trees is related to the dynamics of population/community of trees defined by the birth (regeneration), growth and mortality of trees:

$$M(t) = n(t-1) \cdot m(t) + n(t-1) \cdot g(t) + h(t) \cdot s(t) - k(t) \cdot (m(t) + g(t)) \quad (8.13)$$

where  $M(t)$  is the mass (volume) of trees at the moment  $t$ ,  $n(t)$  is the number of trees,  $m(t)$  is the mean mass (volume) of trees,  $g(t)$  is the mean growth (volume, mass) of trees,  $h(t)$  the number of new trees (regeneration),  $s(t)$  the mean mass (volume) of new trees, and  $k(t)$  the dying trees at the moment  $t$ . Thus, the stocking at a given moment is the balance based on the mass in the previous moment plus the growth of trees and the mass of new (regenerated) trees minus the mass of dying trees and their growth at the current moment, as summarized in Table 8.3. In this case, the amount of trees is given in terms of  $\text{m}^3 \text{ha}^{-1}$  and the rate of change in terms of  $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$ , as widely used in forest inventories and forestry.

Based on Lönnroth (1929); Kilkki (1984) demonstrated the dynamics of a tree population by applying the graphic model in Fig. 8.6. The model includes further the litter and humus on the soil surface and humus deeper in the soil profile. In the model, growth is given in terms of net growth ( $Zn$ ) and gross growth ( $Zbr$ ), the latter indicating the increase of living mass in the tree population/community in a given period (in growth and yield studies, the living material also includes sound heartwood, even though it has no role as regards the metabolism of the tree). The gross growth includes the living mass and the mass dying during a given period, e.g. foliage, branches, bark and roots dying annually, and whole trees dying and falling down or continuing to stand for a while. The dying mass forms the removal, which may represent the natural removal and/or removal in cuttings. In both cases, the growth of dying trees during the given period contributes to the gross growth of population/communities of trees. The model includes also the ingrowth ( $K$ ) of trees occurring during a given period. The ingrowth refers to the mass of trees that exceed the threshold (e.g. height, diameter of seedlings born previously and/or during a given period) used to include/exclude trees in inventory.

In Fig. 8.6, the left-hand boxes represent the naturally (a) growing and developing population/community of trees and the right-hand boxes the same, with thinning (b).



**Fig. 8.6** Relations between growth, removal and stocking in natural developing (a) and managed (b) forests over a given period as presented by Kilkki (1984).  $e$  = Initial stocking surviving to the end of the period;  $a$  = Initial stocking removed naturally or in cuttings during the period;  $K$  = Growth surviving to the end of the period for the trees exceeding the measuring accuracy at the beginning of the period;  $S_K$  = Share of growth removed during the period for the trees exceeding the measuring accuracy at the beginning of the period;  $Z_E$  = Share of growth for the initial stocking surviving to the end of the period;  $Z_A$  = Growth of initial trees removed naturally during the period

In both cases, the initial stocking is divided into that surviving to the end of the period ( $e$ ) and into that dying ( $a$ ) naturally or in cuttings during a given period. The growth during the given period is divided into the growth of trees surviving throughout the period ( $Z_E$ ), the growth of trees removed naturally or in cuttings during the period ( $Z_A$ ) and the growth of ingrowth dying during the period ( $S_K$ ). Consequently:

- Stocking at the beginning of the period:  $B = e + a$
- Stocking at the end of the period:  $E = e + Z_E + K$
- Gross growth during the period:  $Z_{br} = Z_E + Z_A + K + S_K$
- Total removal during the period:  $A = a + Z_A + S_K$
- Net growth during the period:  $Z_N = E - B = Z_{br} - A = Z_E - a + K$

Kilkki (1984) demonstrated the performance of the model with a calculation where the initial stocking was  $200 \text{ m}^3 \text{ ha}^{-1}$  and the stocking at the end of period was  $225 \text{ m}^3 \text{ ha}^{-1}$ . At the middle of the 10-year period, the thinning removal was  $50 \text{ m}^3 \text{ ha}^{-1}$ . During this period, the gross growth of stemwood was:

$$\begin{aligned}
 Z_{br} &= Z_E + Z_A + K + S_K = E - e - K + A - a - S_K + K + S_K \\
 &= E - (a + e) + A = 225 \text{ m}^3 \text{ ha}^{-1} - 200 \text{ m}^3 \text{ ha}^{-1} + 50 \text{ m}^3 \text{ ha}^{-1} \\
 &= 75 \text{ m}^3 \text{ ha}^{-1}
 \end{aligned}$$

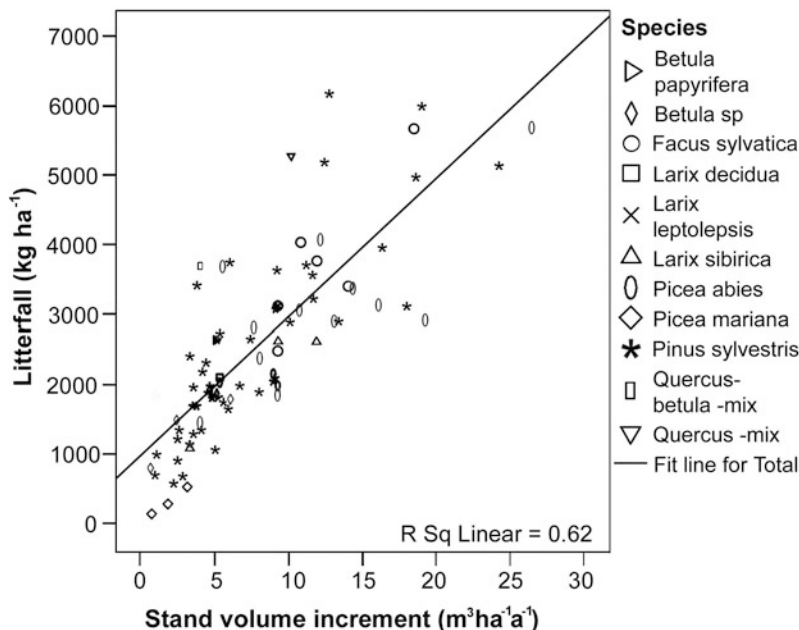
Consequently, the mean annual gross growth was  $7.5 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ . The difference between the initial stocking and the stocking at the end of the period would give a growth of  $25 \text{ m}^3 \text{ ha}^{-1}$  over the whole period, which clearly underestimates the gross growth. Regarding naturally growing and developing forests, the growth of natural removal may contribute substantially to the gross growth over a given period as is the case for cutting removal in managed forest. The omission of growth of removed trees may seriously bias the estimates on the potentials of forests to remove atmospheric carbon into the forest ecosystem.

### 8.5.2 Dynamics of Litter Fall

Litter fall links the autotrophic production with the heterotrophic production, with driving the nutrient cycle for the reuse of nutrients in the physiology and growth of trees. Litter fall refers to the dying of tissues and organs of trees and of whole trees occurring annually, with the transfer of dead material into the detritus pool. In general, the litter is divided into the foliage, branch, and stem and root (coarse and fine roots) litter in regard to their origin. In coniferous forests, the litter fall represents mainly the mass of organs over several years except the fine root litter (e.g. Helmisaari et al. 2009). In deciduous forests, a large part of litter represents the current-year foliage and fine roots. In both cases, the woody mass (e.g. branches) of the ageing mass cohort will reduce gradually and fall away. Dead material in the form of dead branches may remain attached to the stem until braches are decayed enough to be broken by wind and snow loads. In stem, the dead heartwood is transferred to the heterotrophic system after the death of the whole tree. The litter provided by dead trees presents the carbon accumulated over tens of decades or even centuries as in stems, thus representing an important storage of carbon in the forest ecosystem.

In boreal and temperate conditions, litter fall is related to growth following the allometric relationship between the growth and mass between different tree organs, as found by Matala et al. (2008). They analyzed the data available in the literature by relating litter fall (total above-ground litter,  $\text{kg ha}^{-1} \text{ a}^{-1}$ ) with the volume growth of trees in the stand level ( $\text{m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ ). Regardless of tree species, the litter fall was closely correlated with the growth of stem wood (Fig. 8.7). They also found a strong linear correlation between litter fall and basal area, stand volume and latitude. On the other hand, the litter fall was not correlated with the age and density of stand, contrary to what is often claimed in the literature. Litter fall seems to be closely related to the functioning and structure of trees in boreal and temperate conditions.

For further applications, Matala et al. (2008) calculated the relationship between the volume growth and litter fall as presented in Fig. 8.8. This was done in order to make it easier to integrate the litter fall with growth and yield applicable in supporting



**Fig. 8.7** Litter fall in relation to stand volume increment based on the literature representing boreal and temperate zones. (Matala et al. 2008)

the decision-making in forestry. Using linear regression, a non-intercept model was formulated:

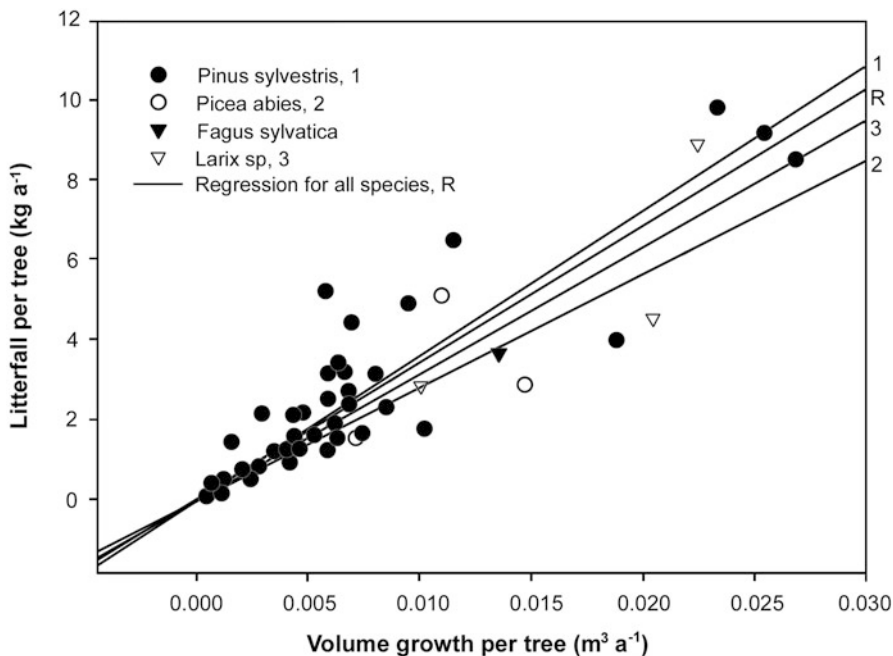
$$LF(t) = a \times \Delta V(t) \tag{8.14}$$

where  $LF(t)$  is litter fall from a tree ( $\text{kg a}^{-1}$ ),  $\Delta V(t)$  is volume growth of a tree ( $\text{m}^3 \text{a}^{-1}$ ) and  $a$  ( $\text{kg m}^{-3}$ ) is the species-specific parameter. The values of the regression coefficient varied from species to species; i.e. the values were 362 for Scots pine, 284 for Norway spruce and 317 for *Larix* species. Matala et al. (2008) applied the model across Finland using the data of the Finnish National Forest Inventory with the result showing that the mean litter fall on forest land varied from  $340 \text{ kg ha}^{-1} \text{ a}^{-1}$  in northernmost Finland to  $2300 \text{ kg ha}^{-1} \text{ a}^{-1}$  in southern Finland following an increasing pattern of forest growth from north to south.

## 8.6 Dynamics of Carbon in Soil

### 8.6.1 Outlines

Decay of organic matter in soil refers to the processes whereby litter (dead organic matter on soil with recognizable origin such as organs of the tree structure) and



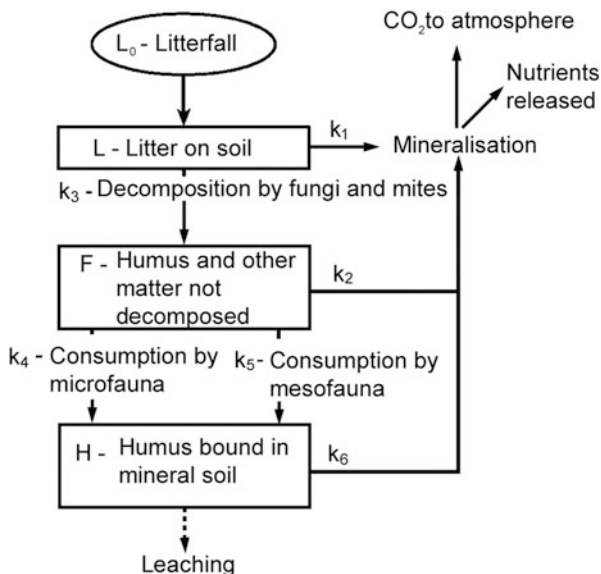
**Fig. 8.8** Litter fall calculated per tree as related to volume growth of a tree. The species-specific regression lines in Eq. 8.7 are referred to by numbers and the line *R* represents the linear regression for all species combined in the analysis. (Matala et al. 2008)

humus (dead organic matter on soil without recognizable origin) decompose into  $\text{CO}_2$ , water, and nutrients (e.g. Pastor and Post 1986). Decay includes leaching, weathering, and biological decomposition of organic matter. Leaching and weathering are mainly physical and chemical processes, where several organic and inorganic substances are released and they increase the nutrient content in soil organic matter. Biological decay represents mainly fungal and bacterial activity (Fig. 8.9), but several invertebrates also graze on the soil organic matter. During the final phases of decay, the nutrients bound in organic matter will be released, and the litter converted into humus colloids. These decay slowly with a life-span of hundreds or thousands of years (Chertov et al. 2001).

### 8.6.2 Decay of Litter

In the following, the classic paper by Olson (1963) has been used to outline the carbon dynamics in soil. Let  $X$  denote the accumulated amount of the soil organic matter per area unit at the moment  $t$ . Following Olson (1963), the change of  $X$  for a discrete time interval ( $\Delta t$ ) is:

**Fig. 8.9** Schematic representations of how litter is converted into humus with release of nutrient and emission of CO<sub>2</sub> to the atmosphere in the soil system under several decomposing processes driven by soil flora and fauna. (Chertov et al. 2001)



$$\frac{\Delta x}{\Delta t} = \text{Increase of matter} - \text{Decrease of matter} \tag{8.15}$$

If *L* indicates the constant (continuous) flow of litter on the soil, the change of soil organic is:

$$\frac{dx}{dt} = L - kX \tag{8.16}$$

where *k* is the instantaneous rate of decay or the fractional loss rate of weight. Let *X<sub>ss</sub>* refer to the amount of accumulated matter at the steady state, where the flow and weight loss of litter balance each other. Consequently, *X<sub>ss</sub>* = *L*/*k*, which gives the amount of matter at the steady state as a function of constant litter flow and decay rate.

Regarding the decay of a single litter cohort (*L* = 0, no constant flow of matter on soil) with the initial weight *X*, the constant rate of weight loss is (Olson 1963):

$$\frac{dX}{dt} = -k \times X \tag{8.17}$$

where *k* is the instantaneous rate of weight loss. Consequently, the constant fractional weight loss of the residual mass is:

$$\frac{dX}{dt} = -kdt \tag{8.18}$$

Let *X<sub>o</sub>* refer to the original weight of the litter cohort. The remaining fraction (0–1) of original weight (*X<sub>o</sub>*, *t* = 0) at the time *t* is (Olson 1963):

$$\frac{X}{X_o} = e^{-k \times t} \tag{8.19}$$



where  $X$  refers to the weight of litter cohort at the time  $t$  and  $k$  is the constant loss rate of weight (or decay rate). Consequently, the fraction of the original total mass ( $k'$ ) at the time  $t$  is:

$$k' = 1 - \frac{X}{X_o} = 1 - e^{-k \times t} \quad (8.20)$$

The relationship between the instantaneous weight loss ( $k$ ) and the fraction of original total mass ( $k'$ ) is:

$$k = \ln \left( \frac{X}{X_o} \right) = \ln(1 - k') \quad (8.21)$$

### 8.6.3 Accumulation of Organic Matter on Soil Under Litter Fall

The fractional increase of litter mass on soil relative to the steady state mass under the constant flow of litter ( $L$ ) is (Olson 1963):

$$\frac{dX}{(X_{ss} - X)} = \frac{dX}{L/k - X} = -k dt \quad (8.22)$$

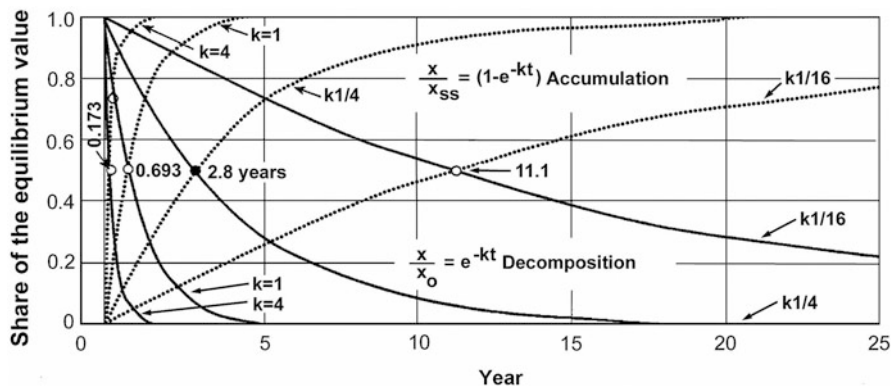
and the accumulated mass ( $X$ ) on soil at the time  $t$  is (Olson 1963):

$$X = (L/k) \times (1 - e^{-k \times t}) \quad (8.23)$$

Figure 8.10 shows the weight loss of a single litter cohort as a function of the decay rate and the steady state level of mass on soil for varying decay rate  $k$  assuming constant litter fall. For example, at the decay rate 0.25 the weight is halved in 2.8 years, whereas at the rate 0.0625 it takes 11.1 years for the weight to be halved. On the other hand, the same time is needed for the accumulation of matter to the value that is a half of that at the steady state; i.e. the half time is obtained from  $X/X_o = 0.5 = e^{-k \times t} = -\ln(0.5)/k = 0.693/k$  based on Eq. 8.10.

### 8.6.4 Factors Affecting Decay Rate

The decay rate of soil organic matter is a function of the site fertility (edaphic and climatic factors) and the quality of the litter (nitrogen and lignin contents). Furthermore, organisms using organic matter in soil as an energy source affect the decay rate. For example, the dominance of micro-flora implies low decay rate, as is typical for boreal conditions, whereas in temperate conditions bacteria have the dominant role in the faster decay rate (Chertov et al. 2001). On the other hand, the decay rate will be increased under higher temperatures and larger supply of water



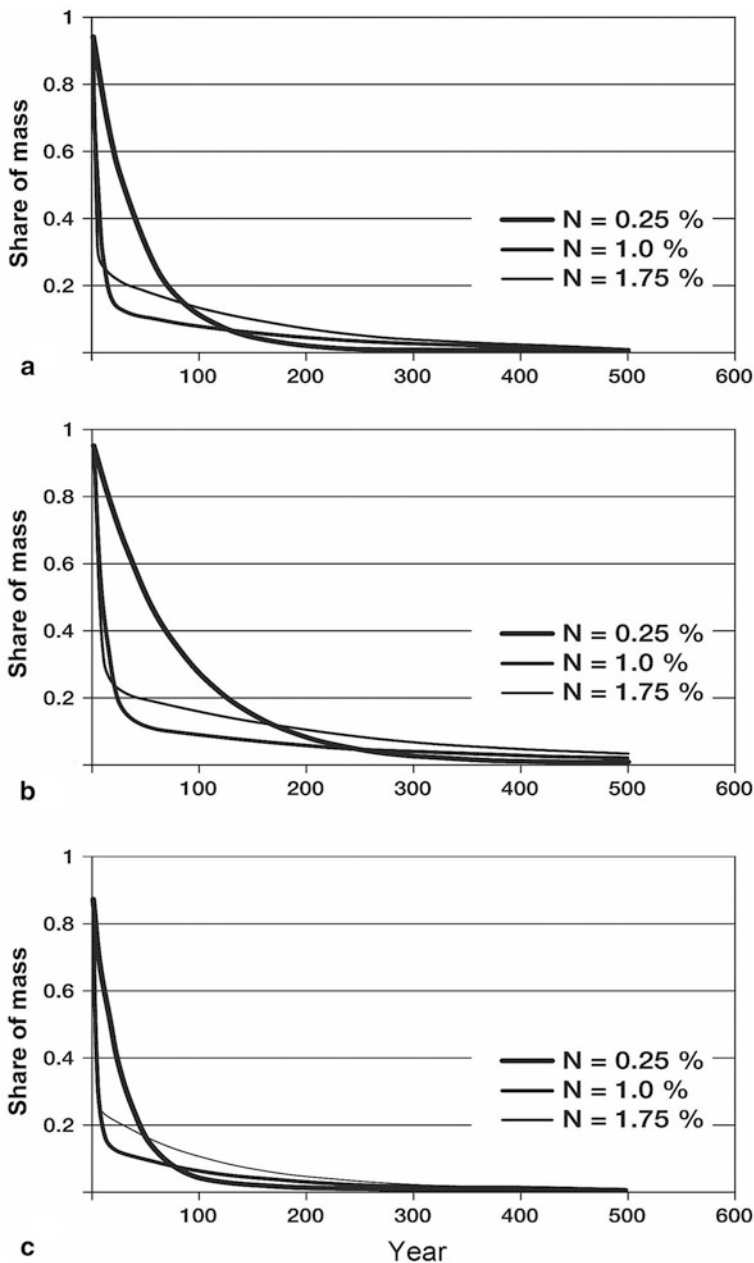
**Fig. 8.10** Remaining amount of the original mass of a litter cohort (*solid line*) and the accumulation of the organic matter on soil assuming continuous litter fall (*dotted line*) as a function of decay rate ( $k$ ) and time ( $t$ ) in years (Olson 1963). The accumulation of organic matter will be enhanced rapidly if the decay rate decreases. For example, the mass of the litter cohort will decrease by half in 2.8 years if  $k = 0.25$  but in 11.1 years if  $k = 0.0625$ . The same time is needed to achieve the steady state (balance between the litter fall and the decay of litter). The maximum amount of organic matter to be accumulated over time when  $k = 0.25$  is smaller than that when  $k = 0.0625$ , if the same amount of litter fall is assumed

and nutrients. Especially, the decay of litter with a higher amount of nitrogen in relation to lignin will be faster compared with litter with a low nitrogen/lignin ratio, as demonstrated in Fig. 8.11. The simulated values based on the model of Chertov et al. (2001) show that under given temperature conditions, the decay of litter is much enhanced by greater nitrogen content.

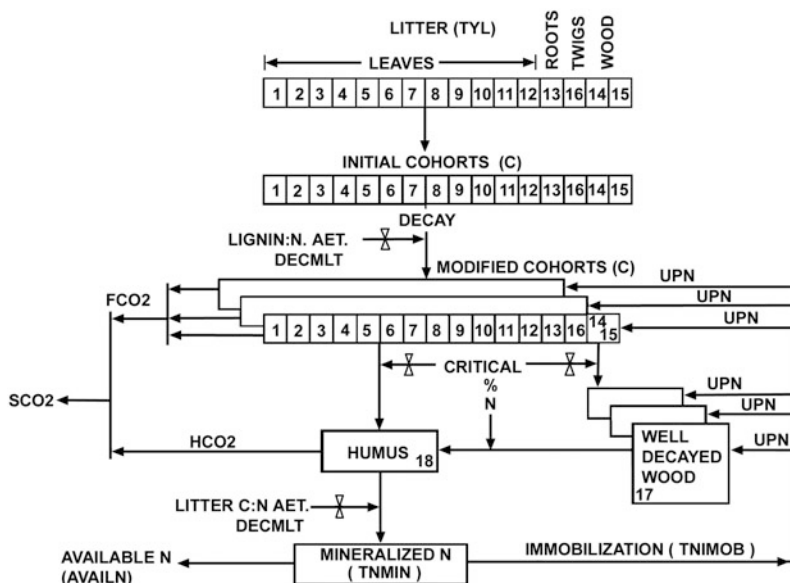
## 8.7 Carbon Sink/Source Dynamics and Carbon Sequestration in Forest Ecosystems

### 8.7.1 Outlines of Carbon Sink/Source Dynamics

A forest ecosystem is a carbon sink if trees (and other plants) absorb more carbon than they release in autotrophic and heterotrophic respiration; and a carbon source if the carbon absorption is less than is released in autotrophic and heterotrophic respiration. In this context, the sink rate refers to the carbon uptake rate and the source rate refers to the carbon emission rate; the relation between these two is the carbon balance. The carbon balance may be indicated by the balance of carbon fixation and emission rates at a given moment or over a given period. Sink and source rates (carbon dynamics, carbon sink/source dynamics) vary over time depending on the factors driving the carbon fixation rate in photosynthesis and the carbon emission rate in autotrophic and heterotrophic respiration. In the following, a process-based model (Sima, e.g.



**Fig. 8.11** Weight of litter cohort as a fraction of the original cohort as a function of time in years, nitrogen content of litter and climate. (a) Under the current climate (boreal conditions in Finland (62° N)); (b) Under a climate with temperature 4°C less than the current climate, (c) Under a climate with temperature 4°C higher than the current climate. (Simulated results based on the FinnFor model (Kellomäki and Väisänen 1997) using the decay model of Chertov et al. 2001)

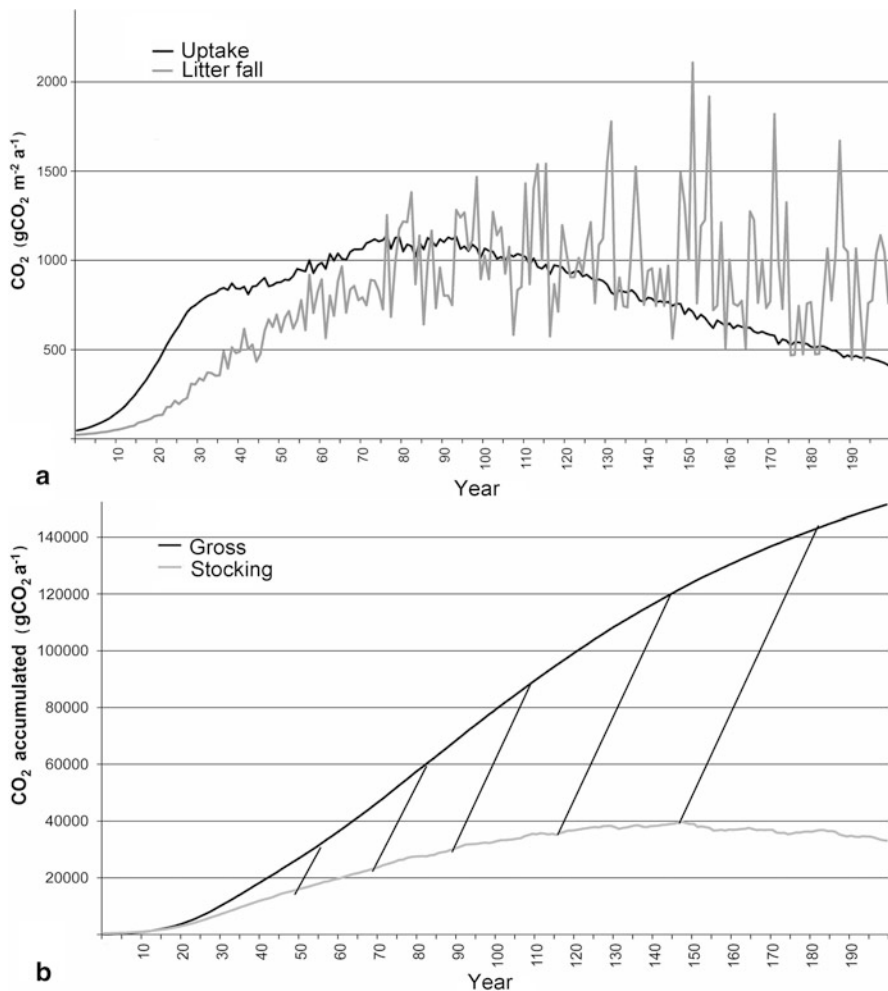


**Fig. 8.12** Outlines of the model for the decay of soil organic matter in the Sima model (Pastor and Post 1986; Kellomäki et al. 1992) used to analyze the carbon dynamics in a forested ecosystem

Kellomäki et al. 1992, 2008; Alam et al. 2012) was used to analyze the carbon dynamics in a forested ecosystem over time and changes in carbon dynamics due to the production of timber and biomass. Some main details of the decomposition model are given in Box 8.2.

**Box 8.2 Outlines of the model for the decay of soil organic matter in the Sima model (Kellomäki et al. 1992) used to analyze the carbon dynamics in forested ecosystem**

The outlines of the decomposition model used in the Sima ecosystem model based on Pastor and Post (1986) (see also Meentemeyer 1978; Meentemeyer and Berg 1986) are presented in Fig. 8.12. Decay determines the weight loss and CO<sub>2</sub> emission from decaying litter and humus. Litter is divided into foliage, twig, root and woody litter. Decay is initiated by calculating the ash-free weight of the cohort. Weight loss (%) is a function of the current ratio between lignin (L) and nitrogen (N) contents (L/N) and evaporation (AET). Whenever the nitrogen content in decaying litter in a cohort exceeds the critical value, the organic matter and nitrogen in the cohort is transferred to the organic matter and nitrogen in humus, whose decay is dependent on AET and the C/N ratio in humus. The weight loss of litter and humus is converted to CO<sub>2</sub>, which is emitted into the atmosphere.



**Fig. 8.13** Panel a: Uptake and loss of CO<sub>2</sub> in a forest ecosystem, and Panel b: accumulated total growth and storage of CO<sub>2</sub> in stem wood. The simulations concern a site of medium fertility (*Myrillus* site type) in central Finland (62° N, 29° E) over 200-year period. The initial stand density was 1800 seedlings ha<sup>-1</sup>. Simulations based on the Sima model. (Kellomäki et al. 1992)

### 8.7.2 CO<sub>2</sub> Emission From Litter on Soil

Figure 8.13 shows how the litter fall is related to the growth over time if both factors are given in terms of g CO<sub>2</sub> m<sup>-2</sup> a<sup>-1</sup>. Typically, the carbon uptake and litter fall are closely related to each other in young forests. In this case, the carbon uptake culminated 40–50 years after initiating the simulation. In this phase, the main part of litter represents foliage and branches and suppressed trees of small dimensions.

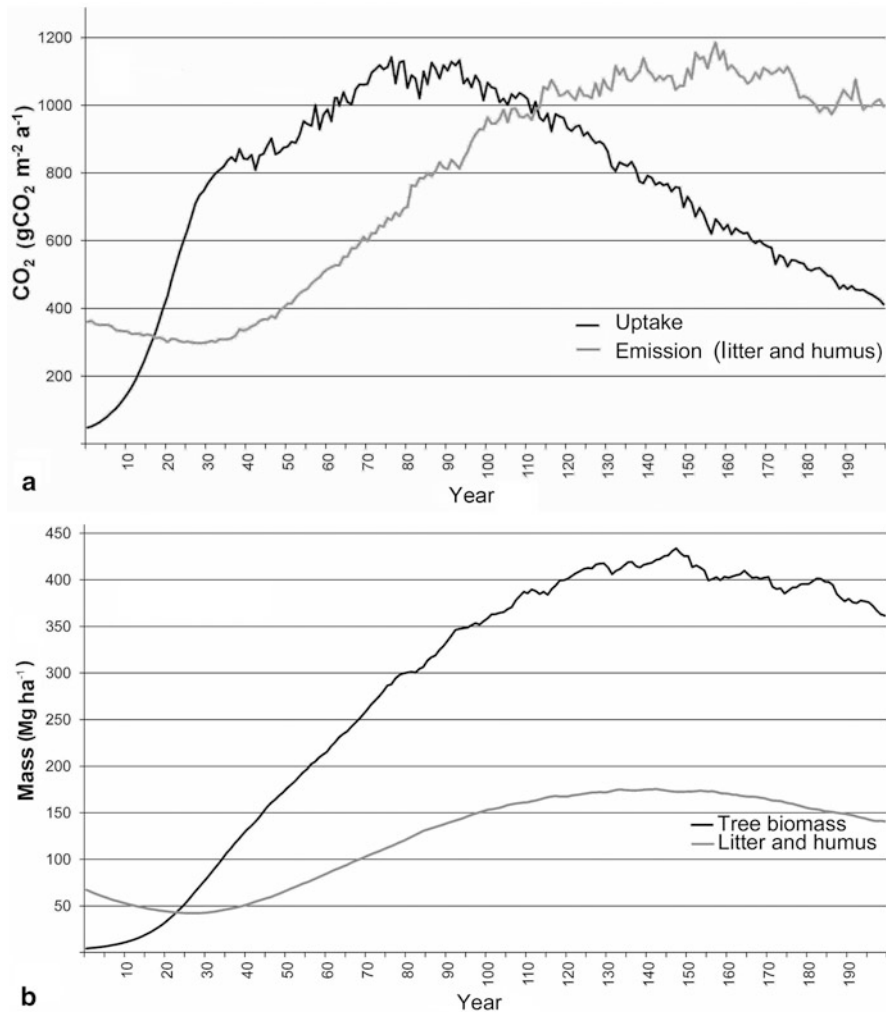
Thereafter, larger trees, too, were dying due to reducing space and the maturing of trees as indicated by the large variability in annual litter fall. This implies that the large part of gross growth is lost in litter and transferred into the soil for decomposition. Therefore, the stocking (the biomass in living trees) in naturally developed mature tree stands represents only a small part of total growth during the simulation period. For example, in the boreal conditions in Finland, the mortality of trees with stemwood litter represents 20–40 % of the total stemwood growth over a 100-year period, depending on tree species, site fertility and location. In general, the mortality takes place earlier in birch stands than in Scots pine and Norway spruce stands, earlier on fertile than on poor sites, and earlier in southern than in northern Finland, thus following the growth rate and life span of different tree species in given conditions.

### ***8.7.3 Relation Between CO<sub>2</sub> Uptake and Emission from Ecosystem***

Figure 8.14 shows the CO<sub>2</sub> uptake in growth and the CO<sub>2</sub> emission in decomposition of litter and humus. In the very early phase of the simulation, representing young seedlings, the emission exceeds the uptake because growth is still small but there is much litter and humus in the site, originating from the previous tree stand that was harvested before establishing the new tree stand. In fast growing young stand (age 20–60 years), the CO<sub>2</sub> uptake substantially exceeds the emission, which exceeds the uptake once again in more mature phases in the growth and development of the tree stand. In general, this seems to occur when the annual growth of trees falls below the mean annual growth (Kilpeläinen et al. 2011). However, CO<sub>2</sub> continues to accumulate in the trees and to stabilize at the level determined by the stocking of living trees, but fluctuating in relation to the mortality of trees and recovery of canopy. This phase also implies the culmination of mass of CO<sub>2</sub> in trees and soil and slow reduction thereafter due to declining growth and litter fall in a tree stand.

### ***8.7.4 Total CO<sub>2</sub> Emission from Ecosystem***

In managed forests, the current growth and development of trees is susceptible to the management history, which affects the current properties of the sites and thus the current carbon dynamics. In this respect, the carbon in soil may be divided into old carbon and new carbon, both of which contribute to the current CO<sub>2</sub> emission. Old CO<sub>2</sub> refers to the CO<sub>2</sub> bound in litter and humus in the time before establishing a new tree stand after a terminal cut, if standwise management is applied in forestry. New CO<sub>2</sub> refers to the CO<sub>2</sub> bound in litter and later in humus representing the time after establishment of a new tree stand. Figure 8.15 shows that the role of old CO<sub>2</sub> in the total emissions is very dominant in seedling stands, but its role will be reduced rapidly and later much exceeded by that of new CO<sub>2</sub> in the total emissions. Finally, the storage of new CO<sub>2</sub> will almost completely replace the storage of old CO<sub>2</sub> in soil.

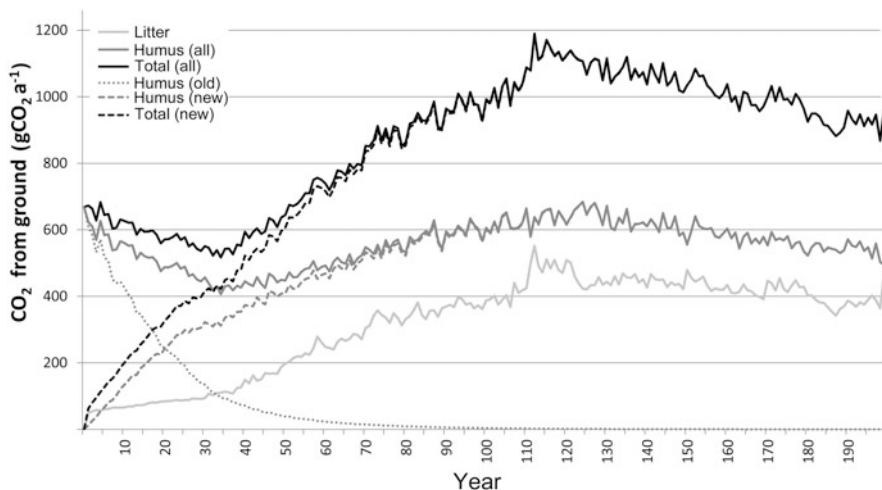


**Fig. 8.14** Panel a: Annual CO<sub>2</sub> uptake in trees and CO<sub>2</sub> emission from soil (litter and humus), and Panel b: Stocking of trees and soil organic matter (litter and humus) over a 200-year period. The simulations concern a site of medium fertility (*Myrtillus* site type) in central Finland (62° N, 29° E) applying a 200-year rotation. The initial stand density was 1800 seedlings ha<sup>-1</sup>. Simulations based on the Sima model. (Kellomäki et al. 1992)

## 8.8 Carbon Dynamics and Sequestration in Managed Forest Ecosystems

### 8.8.1 Carbon Flow Through Managed Forest Ecosystems

In general, carbon sequestration refers to storage of carbon that would otherwise be released into the atmosphere. Carbon sequestration may be based on natural or



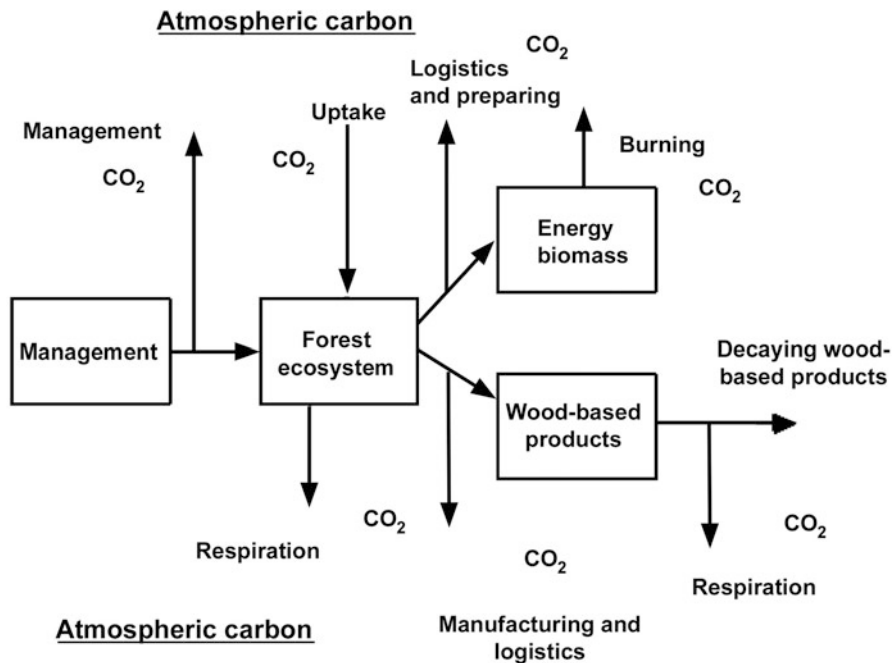
**Fig. 8.15** Relationship between the total soil carbon and CO<sub>2</sub> emission, and storage of old and new carbon in soil profile and the emission from them over time. The simulations concern a site of medium fertility (*Myrtillus* site type) in central Finland (62° N, 29° E) applying a 200-year rotation. The initial stand density was 1800 seedlings ha<sup>-1</sup>. Simulations based on the Sima model. (Kellomäki et al. 1992)

artificial processes by which CO<sub>2</sub> is absorbed and kept out of the atmosphere, where CO<sub>2</sub> contributes to the greenhouse effect and causes global warming by trapping heat in the lower atmosphere. In forestry, carbon sequestration implies management methods to enhance the CO<sub>2</sub> absorption and to prolong the residence time of CO<sub>2</sub> in the forest ecosystem.

The flow of carbon through the forest production cycle includes the carbon emitted in management/logistics needed in producing timber and biomass, and the uptake and emission of carbon in ecosystem processes controlled by management operations. Furthermore, the track of carbon is often extended to include also manufacturing and use of biomass in the energy industry and/or forest industry. The track of carbon can further include the carbon in abandoned wood-based products and the emission from decaying wood-based products, as demonstrated in Fig. 8.16. In the forest-based production system, the emissions of carbon from the ecosystem processes and from different phases of management, harvesting, logistics, manufacturing and use are balanced by the uptake of carbon in tree growth controlled by the management procedures. Such a life cycle assessment (LCA) in tracking carbon in the context of ecosystem/technosystem interaction with forestry applications is discussed in detail in Chap. 10 of this volume.

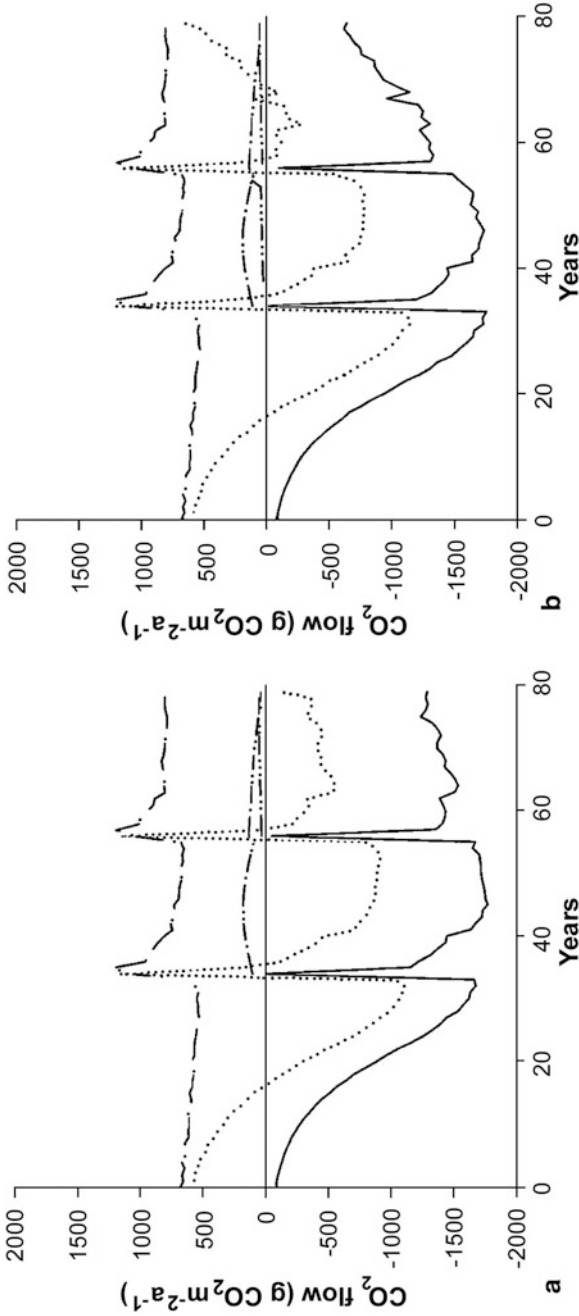
Figure 8.17 shows an example of how the carbon source/sink dynamics performs over time in a managed Norway spruce ecosystem on a fertile site in southern Finland, as adapted from Kilpeläinen et al. (2011). The carbon uptake follows the life span of trees; i.e. in young stand the uptake increases to the culmination of growth, and reduces thereafter following the maturation of trees. The uptake was maximized in the





**Fig. 8.16** Outline of the forest-based production system, which includes the emissions of carbon from the ecosystem processes and from different phases of management, harvesting, logistics, manufacturing and use. They are balanced by the uptake carbon in tree growth, which is controlled by the management procedures

middle of the rotation, the value being about  $1770 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . Towards the end of the rotation, the  $CO_2$  uptake decreased gradually due to the reducing growth and just before the final felling the uptake was about  $1280 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . On the other hand, the  $CO_2$  uptake was reduced temporarily in thinning due to the sudden reduction of stocking, but it recovered in a few years along with enhancing growth of the remaining trees. At the same time, the  $CO_2$  emission increased due to the sudden increase of litter in the form of harvesting residues (needles, branches, roots), which increased substantially the decaying matter. Over the rotation, the average  $CO_2$  emission due to the decay of litter and humus was about  $730 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . The  $CO_2$  emissions due to management were fixed for the planting practices ( $15 \text{ g CO}_2 \text{ m}^{-2}$ ), whereas they varied for harvesting operations from  $78 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$  for the first thinning to  $239 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$  for the final felling. Regarding the uptake and emissions of  $CO_2$  over the rotation, the average net  $CO_2$  exchange was  $-319 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . Thus, the forest-based production system was a sink of  $CO_2$ , but the sink values varied substantially through the rotation; i.e. during the first 20 years the ecosystem was a source and thereafter a sink with the highest value of  $-1100 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$  just before the first thinning. Thereafter, the sink values reduced towards the end of the rotation, and just before the value was  $-140 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ .



**Fig. 8.17** Dynamics of carbon in a forest ecosystem in southern Finland (62° N, 29° E) managed for timber (a) under the current climate, (b) under the climate change when applying the 80-year rotation in both cases (Kilpeläinen et al. 2011). The site was of medium fertility (*Myrtillus* site type) with soil organic matter (litter and humus) of 67 Mg ha<sup>-1</sup> in initializing the simulations. The initial density of Norway spruce (*Picea abies*) stand was 2500 seedlings ha<sup>-1</sup>. In thinning, the rules used in the practical management were used. *Solid line*: carbon uptake in growth; *Dashed line*: carbon emission from decay of soil organic matter; *Dotted line*: net ecosystem exchange (NEE)

Kilpeläinen et al. (2011) found a similar pattern to hold in the simulation, where the climate was assumed to warm by 3.4 °C over the growing season (April to September), precipitation to increase by 10% in the growing season and the atmospheric CO<sub>2</sub> to double from 390 ppm to 840 ppm during the rotation. The main difference in the carbon dynamics between these two climate scenarios was that the climate change enhanced the uptake in early phases of the rotation but reduced later in the rotation faster than under the current climate. This was due to enhanced maturation of trees with shorter life span under the climate change conditions. Again, the CO<sub>2</sub> uptake was the highest at the time of the first thinning, with a value of  $-1710 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . Thereafter, the CO<sub>2</sub> uptake decreased gradually towards the end of the rotation, and it was  $-1230 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$  just before the final felling. Over the rotation, the average uptake was  $-1040 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ , and the average CO<sub>2</sub> loss was  $790 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ . Consequently, the average net CO<sub>2</sub> exchange was  $-160 \text{ g CO}_2 \text{ m}^{-2} \text{ a}^{-1}$ , which was slightly larger than that under the current climate.

### 8.8.2 Retention of Carbon in Managed Forest Ecosystems

Carbon sequestered in the managed ecosystem may remain in the ecosystem over years or even decades depending on the growth rate of trees, management (enhancement of tree growth, soil management), harvesting (frequency, intensity) and the decomposition rate of litter and organic matter in the ecosystem. The duration of carbon retention in the ecosystem is referred to as the residence time ( $\tau$ ) in the ecosystem (Eq. 8.24), whereas the turnover rate is the inverse value of residence time. The residence time is obtained by dividing the storage of carbon (storage, e.g. kg CO<sub>2</sub> ha<sup>-1</sup>) in the ecosystem by the emission rate ( $q$ , e.g. kg CO<sub>2</sub> ha<sup>-1</sup> a<sup>-1</sup>):

$$\tau = \frac{\text{Capacity of a system to hold carbon}}{\text{Rate of carbon flow through a system}} = \frac{\text{Storage}}{q} \quad (8.24)$$

In calculating the residence time, the system is assumed to represent steady state conditions. The residence time begins at the moment when carbon enters the system and ends at the moment when carbon leaves the system. Under this assumption, typical values of carbon residence in forest ecosystem are listed in Table 8.4 assuming the steady state of the ecosystem.

Under management, the forest is unbalanced representing varying amounts of carbon in the ecosystem depending on uptake rate and flow rate in relation to the phase of ecosystem development. The uptake and flow rates are related to the management and harvesting operations affecting the carbon storage, uptake and emission of carbon. Regarding new carbon, the residence time varies over time:

$$\tau(t) = \frac{\sum S(n,t)}{\sum q(n,t)} = n \times \frac{\sum S(n,t)}{\sum q(n,t)} \quad (8.25)$$

**Table 8.4** Residence time and turnover of carbon in a forest ecosystem (Raich and Schlesinger 1992). Residence time and turnover rates are estimated by assuming that 30 % of soil respiration represents root respiration

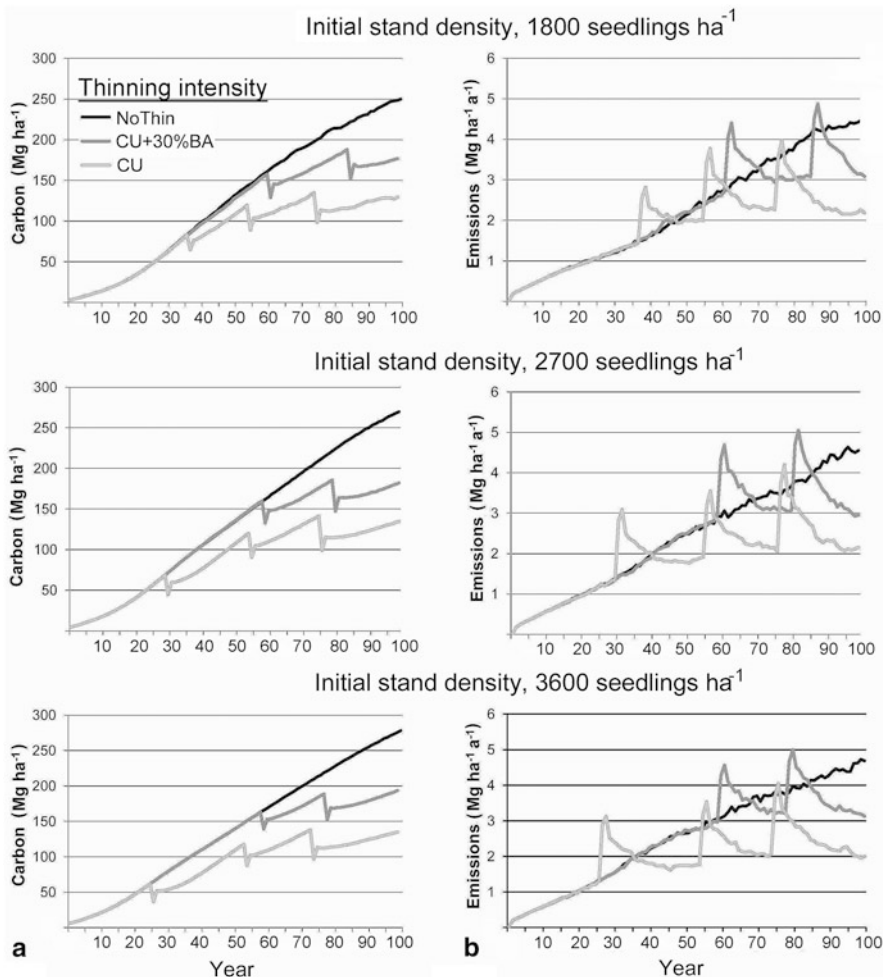
Forest ecosystem	Soil carbon, C kg m <sup>-2</sup>	Soil respiration, g C m <sup>-2</sup> a <sup>-1</sup>	Residence time, a	Turnover rate, a <sup>-1</sup>
Boreal forests	20.6	322	91	0.011
Temperate forests	13.4	662	29	0.034
Tropical lowland forests	28.7	1092	38	0.026

where  $S(n, t)$  refers to the mass in the cohort  $n$  (living, litter, humus) in the year  $t$  since the initiation of the cohort ( $t = 0$ ) and  $q(n, t)$  refers to the mean emission rate of CO<sub>2</sub> from the cohort  $S(n, t)$ .

Figure 8.18 shows, that the accumulation of new carbon in the ecosystem is a function of the initial stand density. On the other hand, thinning reduces the carbon accumulation; i.e. at the end of a 100-year rotation the amount of carbon at the initial stand density of 1800 seedlings ha<sup>-1</sup> with basic or current thinning (130 Mg ha<sup>-1</sup>) was clearly less than that under no thinning (150 Mg ha<sup>-1</sup>). At the same time, the carbon emissions exceeded temporarily the emissions under thinning, but in the long term they stabilized lower than those under no thinning due to reducing carbon emission from decaying harvest residue. If the stocking in the stand under thinning is higher than under current thinning (basal area before and after thinning remain higher than that under current thinning), the stabilized carbon emission converged with that under no thinning.

By applying Eq. 8.24 one obtains the dynamics of residence time for the new carbon presented in Fig. 8.19 for Norway spruce. In young stands, not yet thinned or later left unthinned, carbon has a short residence time compared with that later due to the large share of foliage litter with a high rate of decay in relation to stem wood, whose amount was still small. On the other hand, the residence time in young stands increased along with the increasing initial stand density due to higher amount of stem wood. Over time, the share of foliage litter reduces and the share of woody litter increases, with a consequent increase of the carbon residence time. After the culmination of stem wood growth, the residence time stabilizes towards to the end of the rotation in the range 50–60 years under no thinning in such a way that the stabilization was earlier at the initial density of 1800 seedlings ha<sup>-1</sup> with thinning than under other management regimes. Under thinning the residence time varied from 20 years just after thinning intervention up to 60 years just before the thinning intervention, the lowest values representing the first thinning in stands of high density.

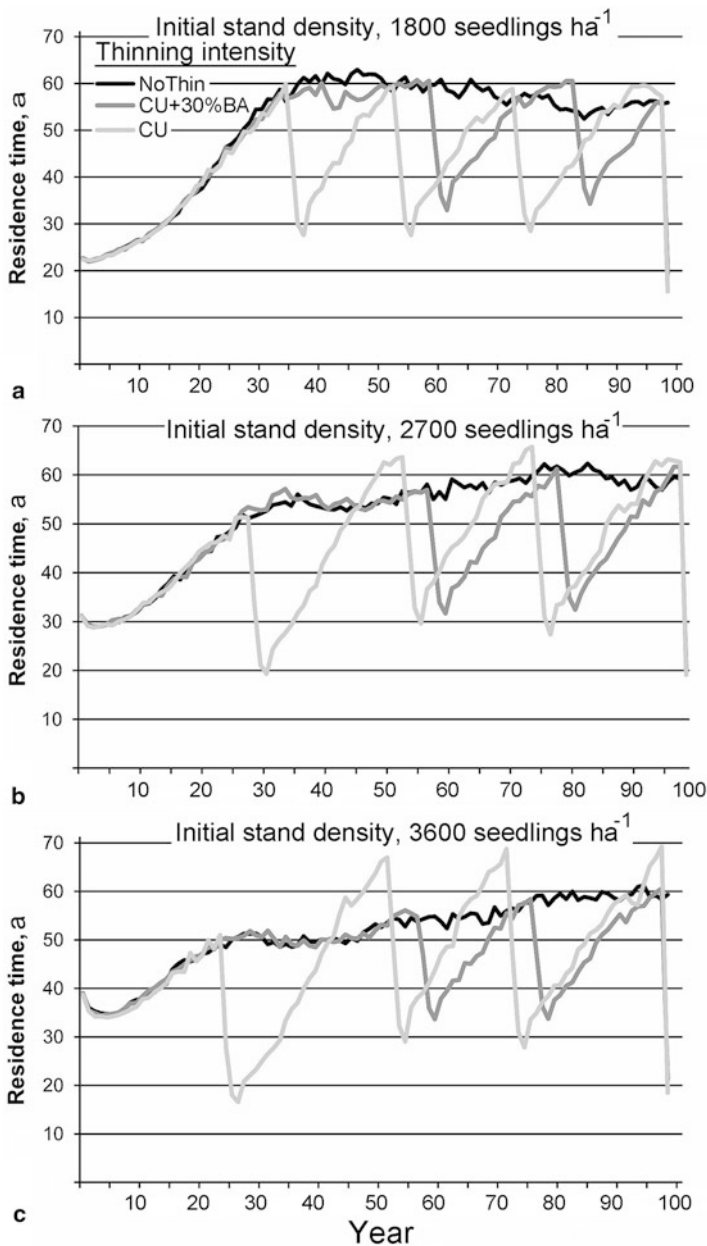
Over the whole rotation, the mean residence time was about 50 years under no management regardless of the initial stand density (Table 8.5). Thinning reduced the mean residence time up to 15 % compared with that under no thinning, the most under current thinning. This implies that management based on the frequency and intensity of thinning and rotation time has a clear effect on the residence and turnover of carbon in the forest ecosystem.



**Fig. 8.18** Stocking (trees and soil) of new carbon (a) in the Norway spruce stand and the carbon emissions (b) from new carbon as a function of the initial stand density and varying thinning intensity. The simulations concern a site of medium fertility (*Myrtillus* site type) in central Finland (62° N, 29° E) applying a 100-year rotation. The current thinning (CU) follows that used in the practical management and no thinning (*NoThin*) refers that thinning has not been done during the rotation. Higher stocking in thinned stand (CU + 30%BA) indicates that the basal area (BA) before and after thinning remains 30 % higher than that under current thinning. Simulations based on the Sima model. (Kellomäki et al. 1992)

### 8.8.3 Effect of Harvesting of Energy Biomass on Carbon Residence in Forest Ecosystems

In conventional forestry the focus is on timber production, where the residues (foliage, branches, small-dimensioned top part of stems, stumps) are left to decay in



**Fig. 8.19** Time series for the carbon residence time in the Norway spruce stand and the carbon emissions from new carbon as a function of the initial stand density and varying thinning intensity. The simulations concern a site of medium fertility (*Myrtillus* site type) in central Finland (62° N, 29° E) applying a 100-year rotation. The current thinning (*CU*) follows that used in the practical management and no thinning (*NoThin*) refers that thinning has not been done during the rotation. Higher stocking in thinned stand (*CU + 30%BA*) indicates that the basal area (*BA*) before and after thinning remains 30% higher than that under current thinning. Simulations based on the Sima model. (Kellomäki et al. 1992)

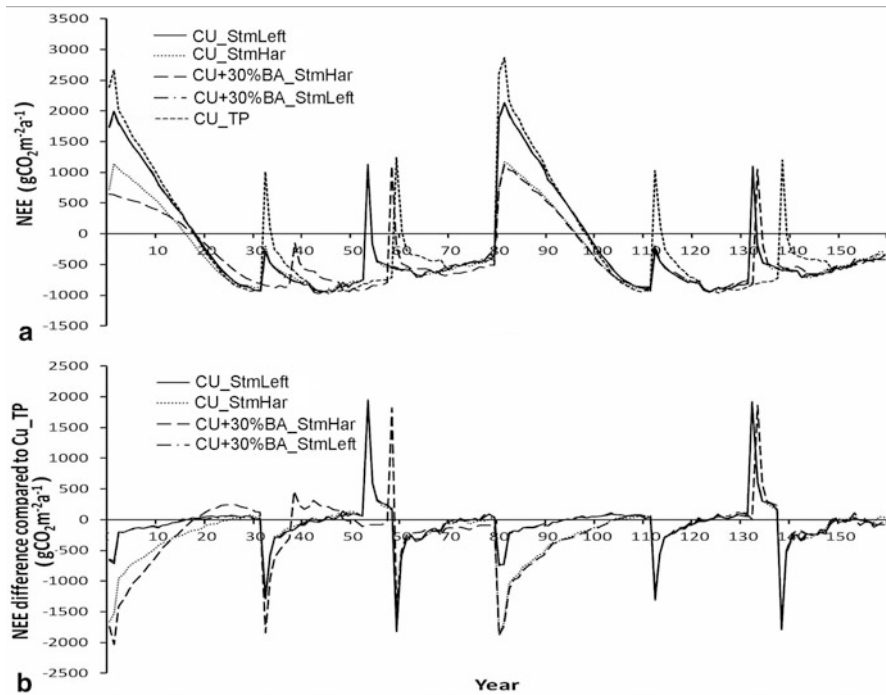
**Table 8.5** Mean amount of carbon and mean carbon residence time in the ecosystem as a function of management regime. In parentheses, the percentage of mean carbon and mean residence time under a no-thinning regime

Management regime	Mean amount of carbon over rotation, Mg ha <sup>-1</sup>	Mean residence time of carbon over rotation, a
<i>Initial density 1800 seedlings per ha</i>		
No thinning	127 –	51 –
Current thinning	83 (65)	45 (88)
Current thinning + 30 %	107 (84)	49 (96)
<i>Initial density 2700 seedlings per ha</i>		
No thinning	135 –	52 –
Current thinning	86 (64)	45 (87)
Current thinning + 30 %	113 (84)	47 (90)
<i>Initial density 3600 seedlings per ha</i>		
No thinning	139 –	51 –
Current thinning	85 (61)	45 (88)
Current thinning + 30 %	118 (85)	47 (92)

the forest. Thus, such residues have an important role in storing carbon in managed forests. This benefit is partly lost if the residues are used in energy production. The impact of stump extraction may be especially important, because the wood biomass in stumps is 20–40 % of the total tree biomass depending on the species and maturity of trees. This is demonstrated in Fig. 8.20, which shows the net ecosystem exchange in Norway spruce stand under varying management, including regimes with and without stump extraction. Stump extraction along with the delayed harvest reduced the CO<sub>2</sub> emission, and thus increased the CO<sub>2</sub> uptake in relation to emission compared with the current thinning practices, where stumps remain in the forest. The same pattern was repeated over both production cycles.

## 8.9 Conclusions

Managed forests provide biomass for energy production even when they are managed only for timber. The potential for energy biomass may be substantially increased by a management regime that combines the production of timber and energy biomass. However, the carbon sink/source dynamics in managed forests varies substantially over the whole production cycle following the amount of growth, litter fall and emission due to the decay of organic matter in the soil. The harvest of forest biomass for energy alters the carbon sink/source dynamics and the consequent carbon balance in the ecosystem, e.g. thinning and consequent harvest decreases the amount of growth and litter on the soil. The mitigation capacity of forests is thus affected by the ecosystem dynamics, management and harvest, including carbon emissions from management, harvesting and logistic operations. Therefore, it is important that the effects of management on carbon stocks are carefully considered when assessing of net atmospheric impacts of bioenergy production on carbon sequestration in managed



**Fig. 8.20** Net ecosystem exchange of carbon (*above*) and in Norway spruce (*Picea abies*) ecosystem under varying management regimes, and the difference in net ecosystem exchange between the current management for timber only and the management for energy biomass including and excluding stump harvest (*below*). Calculations are done with the CO<sub>2</sub> Emission Calculation Tool for the life cycle assessment (LCA) developed by Kilpeläinen et al. (2011). The simulations concern a site of medium fertility (*Myrtillus* site type) in central Finland (62° N, 29° E) when applying two 80-year rotations one after another. The initial density of stand was 2500 seedlings ha<sup>-1</sup>. In thinning, the rules used in practical management were applied. *CU\_StmLeft*: bioenergy harvesting, current basal area (BA) thinning thresholds, stumps left on site; *CU\_StmHar*: bioenergy harvesting, current basal area thinning thresholds, stumps harvested; *CU + 30%BA\_StmHar*: bioenergy harvesting, 30% increased thinning basal area thinning thresholds, stumps harvested; *CU + 30%BA\_StmLeft*: bioenergy harvesting, 30% increased thinning basal area thinning thresholds, stumps left on site, *CU\_TP*: traditional timber harvesting, no bioenergy harvested

forest ecosystems. Full understanding of these underlying processes helps to identify the potential of forest ecosystems to produce biomass for energy, along with other products and services (e.g. pulp wood and timber), and simultaneously to mitigate climate change.

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