Chapter 9
Carbon Sequestration in Temperate Forests

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Abstract Temperate forests, located between 25 and 55° N and S of equator, are highly diverse in species, soils, and the ecosystems' carbon (C) pool. Their composition and characteristics change among regions. Principal forest types are broad-leaved deciduous, broad-leaved evergreen, coniferous, and mixed. Temperate forests are primarily located in North America, Central and Western Europe, north-eastern Asia, southern Chile, New Zealand and the Mediterranean. Principal soils of the temperate forests are Alfisols, Inceptisols, Mollisols, Spodosols, and Ultisols. These are generally fertile soils with high soil organic C (SOC) pool. Typical temperate forest soils contain about 100 Mg C ha^{-1} in the soil profile, and often more. Total ecosystem C pool in biomes and soils of temperate forest is equivalent to, and sometimes even more, than that of the tropical rainforest ecosystems. The projected change in climate may shift the temperate forest biome polewards, alter species composition, and change the ecosystem C pool. With favorable climate characterized by four distinct seasons and relatively fertile soils, the temperate forest biomes have a high C sink capacity. Thus, sustainable forest management, planting and rehabilitation can contribute to recarbonize the biome previously disturbed by deforestation, degradation and poor forest management, and create draw down in the atmospheric concentration of carbon dioxide (CO_2). Fast growing temperate trees can accumulate about 20 Mg of wood ha^{-1} year^{-1}. The strategy is also to preserve the old-growth forests, and establish new forests on degraded lands and agriculturally marginal soils through afforestation and reforestation. In addition to

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biomass, C can also be sequestered in soils. The rate of soil C sequestration is lower than that in the biomass, and depends on soil type, antecedent pool, species and other natural and marginal factors. While trading C credits can promote adoption of an appropriate forest land use and management to enhance C sequestration, how to account for changes in forest C pools (soil and biota) remains a contentious issue. Additional research is needed in understanding processes and practices to sequester C in soils and vegetation of temperate forests, and to develop methods of measurement, monitoring and verification of C pool and changes over short periods of 2–5 years.

Keywords Deciduous forests • Evergreen forests • Coniferous forests • Mixed forests • Alfisols • Mollisols • Inceptisols • Spodosols • Ultisols • Climate change • Hardwood forests • Marginal soils • Afforestation • Reforestation • Soil carbon sequestration • Trading carbon credit • Soil carbon pools • Hydrologic cycle • Net primary production • Mean residence time • Gross primary production • Fire • Steppe • Greenhouse gases • Missing carbon sink • CO_2 • Fertilization effects • Forestry-based off-sets

Abbreviations

R_a	autotrophic respiration
C	carbon
CO_2	carbon dioxide
FACE	Free Air Atmospheric Carbon Dioxide Enrichment
GCC	global carbon cycle
GHGs	greenhouse gases
HAC	high activity clays
LAC	low activity clays
MRT	mean residence time
NBP	net biome productivity
NEP	net ecosystem production
NPP	net primary production
SOC	soil organic C
SOM	soil organic matter content

9.1 Introduction

World forests play an important role in climate and the environment (Streck and Scholz 2006). Temperate forests cover a global area of about 767 Mha (Pan et al. 2011), and have an important role in the global carbon cycle (GCC), are characterized by relatively cool temperatures, high precipitation, and high humidity

Table 9.1 Characteristics of the temperate forests

Characteristics	Descriptions
1. Geography	Temperate forests extend from and occur in North America, 25–55°N, middle Europe, southwest Russia, Japan, eastern China, southern Chile, middle east coast of Paraguay, New Zealand and southern Australia. Total land area is about 767 Mha.
2. Climate	Temperature varies from −30°C to 30°C. The mean annual temperature is 5–10°C, and the mean annual precipitation is 50–150 cm. There are four distinct seasons. Decidious trees drop their leaves during the winter. The growing season is 140–200 days with 4–6 frost-free months.
3. Canopy	It comprises of five zones in intact mostly primary forests: (i) the tree stratum, (ii) the small tree and sampling zone, (iii) the shrub zone, (iv) the herb zone, and (v) the ground zone.
4. Types of vegetation	Temperature forests comprise of several categories: (i) moist conifer and evergreen with wet winter and dry summer, (ii) dry conifer: high altitude, low precipitation, (iii) temperate conifer: high precipitation, mild winter, (iv) broad leaved forests: mild frost-free winters and high precipitation, (v) Mediterranean: winter rainfall of ~1,000 mm year^{-1}.

Table 9.2 Examples of climate of some temperate forests (Adapted from Luyssaert et al. 2007; Keith et al. 2009)

Parameter	Humid evergreen	Humid deciduous	Semiarid evergreen	Overall mean
Mean winter temperature (°C)	4 ± 5	2 ± 9	0 ± 5	1.5
Mean summer	17 ± 4	20 ± 5	14 ± 3	18.9
Precipitation winter (mm)	449 ± 337	183 ± 164	356 ± 182	404 (minimum, annual)
Precipitation summer (mm)	194 ± 234	356 ± 259	81 ± 99	5,000 (maximum, annual)
Net radiation winter (W m^{-2})	147 ± 92	150 ± 100	152 ± 141	–
Net radiation summer (W m^{-2})	437 ± 104	425 ± 78	502 ± 95	–
Mean humidity winter (%)	84 ± 11	79 ± 11	85 ± 18	–
Mean humidity summer (%)	67 ± 12	77 ± 5	50 ± 6	-

(Table 9.1). These biomes have four distinct seasons with wide variation in temperatures and precipitation among seasons. The annual precipitation ranges from 50 to 200 cm, and comprises of both rain and snow. Temperate forests are characterized by warm or mild summers and cool or cold winters. The mean continental temperature may range from 30°C to −30°C, and the maritime from −10°C to 20°C. The mean annual rainfall in continental climate may range from 15 to 100 cm and in the maritime regions from 50 to 200 cm. Examples of some climates of temperate forests are shown in Table 9.2.

Geographically, temperate forests are located in North America, Central and Western Europe, north-eastern Asia, southern Chile, New Zealand and the Mediterranean. These biomes comprise a wide range of vegetation with a large variety of species. Important temperate deciduous tree genera include *Acer*, *Ailanthus*, *Albizzia*, *Betula*, *Carya*, *Castanopis*, *Fagus*, *Fraxinus*, *Juglans*, *Liriodendron*, *Magnolia*, *Nothofagus*, *Populus*, *Quercus*, *Tilia*, and *Zelkova*. Common temperate coniferous tree genera include *Abies*, *Picea*, *Pinus*, *Pseudotsuga*, *Thuja*, and *Tsuga*. The genera *Agathis*, *Dacrycarpus*, *Eucalyptus*, *Nothofagus*, *Podocarpus*, and *Quercus* are common to temperate broadleaf evergreen forests. Yet, the species diversity in temperate forests is much lower than that in tropical rainforests. Trees are good indicators of site-specific climate. For example, birch (*Betula spp.*) and juniper (*Juniperus spp.*) grow under cold climate, alder (*Alnus spp.*) and willow (*Salix spp.*) on poorly drained soils. Holly (*Ilex spp.*) grows in western Europe and north-eastern USA but along coastal regions because it does not survive under the extreme continental climate. Similarly, ivys (*Hedera spp.*) have specific climatic adaptation. Thus, the projected change in climate may alter the species composition, and also influence soil properties.

The canopy of intact temperate forest areas without signs of significant human transformation driven by intrinsic tree population processes is distinctly stratified into diverse zones. The top tree zone may consist of hardwood trees. The second tree zone includes smaller trees. The third canopy zone is made of shrubs, and the fourth zone comprises of herbs. The fifth zone may be comprised of lichens and mosses (Table 9.1).

The temperate forest biome has four distinct seasons. The summer season is characterized by long day light hour and warm temperatures (~30°C maximum). Most deciduous trees drop leaves during the fall. The winter temperature may be −30°C (the minimum). Thus, vegetation regrowth and the flowering season begins with spring. Trees, compared with grasses, exert a strong influence on the hydrological cycle, and to a large extent promote their own growth hydrologically and suppress fire. In contrast, grasses take hold and promote their own growth through fire (Mayer and Khalyani 2011). Increase in frequency and intensity of fire decreases the dominance of trees.

9.2 Soils of Temperate Forests

Principal soils of temperate forests are Alfisols, Inceptisols, Entisols, Mollisols, Spodosols, and Ultisols, (Table 9.3) (FAO-UNESCO 1974, 1988). These soils have a high inherent fertility (Martin et al. 2001; Gower et al. 2003), soil organic matter content (SOM), and favorable moisture and temperature regimes during the growing season. Temperate forest biomes have high net primary production (NPP). Thus, soils of temperate forests have the capacity to support a large amount of biomass production, and a large amount of C is stored in soils and the vegetation. The soil C density to 1-m depth (kg C m^{-2}) for temperate forests in the U.S. ranges from 8 to 9 in Alfisols, Ultisols and Entisols to >20 in Spodosols (Table 9.3), and correspond with the soil organic carbon (SOC) pool of ~80–90 Mg C ha^{-1} in Entisols/Alfisols, 150 Mg ha^{-1} in Inceptisols, 170 Mg ha^{-1} in Mollisols, and 250 Mg ha^{-1} in Spodosols (Table 9.3).

Table 9.3 Soils of temperate forests (Adapted from Brady and Weil 2002; Johnson and Kern 2003)

Order	Area in the temperate regions (10^6 ha)	Description	SOC density to 1-m in forest soils of the U.S. (kg m^{-2})
Alfisols	165	Soils with argillic, kandic or nitric horizon or a fragipan with clay skins, developed under a hardwood forest cover	9.2
Entisols	–	Soils of recent origin and less development	8.2
Inceptisols	–	Recent soils which exhibit mineral horizon development, and containing cambic, calcic mollic, umbric or histic epipedon	15.6
Mollisols	–	Soils with high organic matter content and containing mollic epipedon	17.2
Spodosols	252	Soils containing amorphous mixtures of organic matter and Al, with or without Fe, with and overlying eluvial horizon of grey to light color	24.1
Ultisols	330	Soils with an argillic or kandic horizon and fragipan commonly known as red clay soils	8.5
Total	767		

Soil description is from Brady and Weil (2002), SOC density from Johnson and Kern (2003), estimated of area under different soil orders are taken as the difference between the total area (Brady and Weil 2002) and subtracted for the area under tropics (van Wambeke 1992)

Table 9.4 Productivity of some temperate forest (Mg C ha^{-1} $year^{-1}$) and biomass (Mg C ha^{-1}) (Recalculated and adapted from Luyssaert et al. 2007)

Parameter	Humid evergreen	Humid deciduous	Semiarid evergreen
Gross primary production	17.6 ± 0.6	13.8 ± 0.6	12.3 ± 0.3
Net primary production	7.8 ± 0.6	7.4 ± 0.6	3.5 ± 0.3
Net ecosystem production	4.0 ± 0.4	3.1 ± 0.4	1.3 ± 0.5
Above ground biomass (AGB)	149.3 ± 135.6	108.8 ± 56.7	62.8 ± 55.5
Below ground biomass (BGB)	42.3 ± 46.7	25.7 ± 26.1	22.4 ± 17.3
Ratio BGB:AGB	0.28	0.24	0.36

Because of a high rate of biosequestration, temperate forests play an important role in the GCC. Ecosystem productivity has four distinct but related components (Table 9.4). The gross primary production (GPP) represents the total uptake of carbon dioxide (CO_2) by photosynthesis. However, some of the biome's photosynthesis is used in autotrophic respiration (R_a). The balance (GPP-R_a) is the NPP. Some of the NPP is lost in heterotrophic metabolism and microbial respiration. The remainder is called the net ecosystem production (NEP) and the C comprising of NEP has a longer mean residence time (MRT). A large fraction of NEP, however, is subject to losses through harvest, herbivory, fire and other perturbations. The final remaining fraction is called the net biome productivity (NBP). Some examples of these components of the temperate forest biomes given in Table 9.4 indicate that NPP and NEP of these biomes is equivalent to that of the tropical humid evergreen forest

Table 9.5 Biomass (Mg C ha^{-1}) carbon in some temperate forests (Adapted and recalculated from Keith et al. 2009)

Parameter	Cool moist	Cool dry	Cool montane
Above ground biomass (live)	377 ± 182	176 ± 102	147
Root & dead biomass	265 ± 162	102 ± 77	–
Total living & dead biomass	642 ± 294	278 ± 173	153

Mean annual temperature = 1.5°C <min, 18.9°C maximum
Mean annual precipitation = 404 mm min, 5,000 mm, maximum
Gross ecosystem production (Mg C ha^{-1} $year^{-1}$) = 2.51 min, 4.75 maximum

(Luyssaert et al. 2007; Huston and Wolverton 2009). Keith et al. (2009) observed that the world's highest known total biomass C density (living and detritus) of 1,867 Mg C ha^{-1} may occur in Australian temperate moist forest (*Eucalyptus regans* F. Muell.). Furthermore, temperate moist forests contain diverse forest types characterized by a wide range of mature C pools. Some temperate moist forests have higher biomass C density than those of boreal and tropical forests (Keith et al. 2009). However, the data on biomass C in the below-ground or root allocation is limited, and is generally obtained through modeling (Rasse et al. 2001). Temperate forests with particularly high biomass density (Table 9.5) are dominated by *Tsuga spp*., *Picea spp*., *Pseudostuga spp*. and *Abies spp*. especially in the Pacific Northwest of USA and Canada (Keith et al. 2009). These forests contain the above-ground biomass of 224–587 Mg C ha^{-1} and total biomass of 568–694 Mg C ha^{-1} (Keith et al. 2009). The highest total biomass density has been measured at 600–982 Mg C ha^{-1} for the *Agathis spp*. in New Zealand, and 326–571 Mg C ha^{-1} (for *Nothofagus, Fitzroye, Philgerodendron* and *Laureliopsis spp*.) in Chile. High C density in the biomass plays an important role in the GCC (Houghton et al. 2009). Thus, deforestation and conversion to agricultural land use can drastically reduce the temperate forest ecosystem C pool. Total ecosystems C pool, that in soils and vegetation combined, is high in temperate forests (Table 9.5). In general, in contrast with the tropical rainforests, temperate forests may have relatively more C in soils than in the biomass/vegetation. Somewhat higher C proportion in soils may be due to a slower decomposition rate in soils of temperate than those of the tropics.

In intact temperate forests where vegetation dynamic is driven by intrinsic tree population processes, the density of SOC is extremely heterogeneous (Lorenz and Lal 2010). The heterogeneity is related to climate, soil type, vegetation, and drainage. Soils of the temperate forests have often a high C density, and total C pool (Eswaran and van den Berg 1993; Batjes 2010, 2011). With due consideration to concerns about the true and false interpretation (Powlson et al. 2011) and over optimism (Schlesigner 2000), soils of the temperate forest ecosystems have a high SOC pool and C sink capacity. Even to 30 cm depth, SOC pool under natural vegetation cover can be as much as 35–140 Mg C ha^{-1} under warm moist climates and 50–128 Mg C ha^{-1} under cool moist regions. Naturally, the SOC pool varies widely among soils. The SOC pool is large in soils containing high activity clays (HAC) compared to that in rocky and sandy soils, and those containing low activity clays (LAC). Further, SOC pool and its vertical distribution indicate high magnitude in soils of cool compared to warm climates (Table 9.6, Jenny 1941; Jobbágy and

Table 9.6 Organic carbon pool in soils of temperate forests to 30-cm depth (Adapted from Batjes 2010, 2011)

Soil	SOC pool in temperate forest (0–30 cm, Mg C ha^{-1})			
	Warm moist	Warm dry	Cool moist	Cool dry
High activity clay (HAC)	64 ± 33	24 ± 16	81 ± 40	43 ± 24
Low activity clay (LAC)	55 ± 29	19 ± 10	76 ± 48	–
Sandy soils	36 ± 26	10 ± 5	51 ± 39	13 ± 7
Spodic soils	143 ± 65	–	128 ± 61	–
Volcanic soils	138 ± 56	84 ± 88	126 ± 52	–
Wetland soils	135 ± 101	75 ± 45	128 ± 55	–

Jackson 2000). It is important to understand the mechanisms of stabilization of SOC pool, which differ among soils in relation to vegetation, climate, physiography and other factors (von Lützow et al. 2006; Schmidt et al. 2011).

9.3 Impact of Fire on Ecosystem Carbon Pool

Temperate forests are generally not fire-dependent ecosystems, and are less subject to fire than boreal and dry tropical forests, and the grass (steppe) ecosystems. Nonetheless, fire can affect both vegetation structure and C pools at spatial scales ranging from tree to stand to landscape scale. The magnitude of C lost from a temperate forest by fire depends on a range of factors such as the climate, vegetation, fire regimes and the post disturbance weather. Trees killed by fire may have a long turn overtime of 580 ± 180 years because of the charred biomass created by fire (Keith et al. 2009).

Fire can also impact the soil C pool. Bormann et al. (2008) assessed the impact of natural fires on the soil C pool in southwestern Oregon, USA. Bormann and colleagues observed the fire-related changes in SOC pool were extremely high and estimated at 23 Mg C ha^{-1} for organic and mineral soil layers, of which 60% were lost from the mineral horizon. The severe damage, especially to the soil quality, indicate not only the emission of greenhouse gases (GHGs) by fire but also the reduction of future forest productivity and decline in C sequestration in forest biomass and the soil. Savanna and the forest ecosystems can co-exist depending on the intensity and frequency of fire. The specific pattern of fire-caused discontinuities in the biome type also depends on the tree species, climate, soils, and the fire (Staver et al. 2011).

9.4 Factors Affecting Carbon Sequestration in Forest Ecosystems

There is a strong evidence of the high NEP of temperate forests, as high as those of the boreal and moist tropical forests. Barford et al. (2001) reported the net ecosystem exchange (NEE) of the Harvard Forest (42.5°N, 72.2° W) by the eddy-covariance techniques at 2.0 ± 0.4 Mg C ha^{-1} $year^{-1}$, with inter-annual variation exceeding 50%. Factors affecting NBP and NEE are climate growing season length, cloudiness, soil type, vegetation, perturbation (fire), any legacy of prior disturbance, and stand management. Principal factors affecting C uptake in soils under temperate forests are primarily those related to litter decomposition (Prescott 2010). Over and above the strong effects of temperature and moisture regimes, liter type, and relative preservation of recalcitrant compounds are other imported variables. In addition to total solum depth, the depth distribution (stratification) is also an important factor. Total annual soil respiration is strongly related to mean annual soil temperature, respective proportion of the type of ecosystems and biome (Bahn et al. 2010). The temperature-dependence, increase in respiration by increase in mean annual temperature by 10°C (Q_{10}), is especially high for non-water limiting ecosystems. The Q_{10} value was 2.2 for *Fagus sylvatica* L. forest (MAP of 1,100 mm, 41°52′ N, 13°38′ E), 3.4 for *Picea abies* (L.) H. Karst and *Pinus cembra* L. forests (MAP of 1,010 mm, 46°35′ N, 22°26′ E), 1.9 for *Pinus sylvestris* L. and *Quercus robur* L. forests (MAP of 750 mm, 51°18′ N and 4°31′ E), 4.0 for *F. sylvatica* L. forest (MAP of 600 mm, 56°00′ N, 12°20′ E), and 3.8 for mixed hardwood Harvard Forest (MAP of 1,089 mm, 42°32′ N, 72°11′ W), and 3.4 for mixed evergreen forest (MAP of 1,005 mm, 45°12′ N, 68°44′ W) (Bahn et al. 2010).

The rate of forest respiration decreases substantially in response to N deposition (Janssens et al. 2010). There are numerous factors which affect the rate of litter decomposition (Prescott 2010), and the knowledge of these factors can be used to enhance the MRT and total C pool in forest ecosystems. For example, there is a strong effect of drying and wetting on respiration and decomposition (Borken et al. 2003; Schmitt and Glaser 2011), and of the compounds of low molecular weight (van Hees et al. 2005).

9.5 Temperate Forests and the Missing/Unidentified Carbon Sink

The term "missing C" proposed by Broecker et al. (1979), refers to "the amount of C released to the atmosphere from combustion of fossil fuel that is unaccounted for by the increase of C in the atmosphere and the ocean" (Houghton 1993). The awareness about the problem of balancing the C budget dates back to early 1970s (Woodwell and Pecan 1973; Study of the Critical Environmental Problems 1970; Studies of the Man's Impact on Climate 1971). The magnitude of missing C sink was initially reported to be as much as 1–2 Pg C $year^{-1}$ (Houghton 1993; Tans et al. 1990). However, there also exist temporal trends in the magnitude of land and ocean C sinks, and the magnitude of missing sink is determined by the difference or the default value. For example, Sarmiento et al. (2010) estimated the net land C sink of 0.27 Pg C $year^{-1}$ between 1960 and 1988, increase to 0.88–1.55 Pg C $year^{-1}$ between 1989, and between 2003 and 2007. The land-based C sink in the northern hemisphere was estimated at 1.7 Pg C $year^{-1}$ over the period 2000–2004 (Ciais et al. 2010).

However, the concept of "missing C" sink is questionable if not completely invalid in view of the fact that several sources and sinks are unaccounted for (Table 25.2 in Chap. 25).

Possible sites of the missing C sink have also been debated. Pacala et al. (2001) reported for 1980–1989 the magnitude of missing C sink in conterminous U.S. between 0.30 and 0.58 Pg C $year^{-1}$. Similar claims have been made for Siberia and the Amazon forest, and by the C transported into the oceans (Stallard 1998), and that contained in char in the fire-prone ecosystems. The uncertainties also depend on the methodological approach to reconstruct the GCC (House et al. 2003): ground-based inventories *vs.* model calculations. A major issue which needs to be addressed is that can the land-based sinks (presumably in the northern forest biome) be reconciled from the known data? (Ciais et al. 2010). Using forestry inventory data, Pan et al. (2011) estimated a total global forest sink of 2.4 ± 0.4 Pg C $year^{-1}$ for 1990–2007. Of this, C sink (Pg C $year^{-1}$) for the temperate forest zone was estimated at 0.67 ± 0.08 for 1990s, 0.78 ± 0.09 for 2000–2007, and 0.72 ± 0.08 for 1990–2007. Pan and colleagues estimated that temperate forests contributed 0.7 ± 0.1 and 0.8 ± 0.1 Pg C $year^{-1}$ (27% and 34%) to the global C sinks in established forests for 1990s and 2000–2007. The reasons for increase in C sink capacity of the temperate forests may be: (i) increasing forest density, (ii) reduced biomass removal with harvest, (iii) increase in the forest area, (iv) CO_2 fertilization effect, and (v) N deposition. For example, growing density was responsible for substantially increasing sequestered C in European and North American forests during 1990–2010 despite smaller changes in forest area (Rautiainen et al. 2011).

9.6 Climate Change and Carbon Storage in Temperate Forests

The projected climate change can strongly affect the ecosystem C pool of temperate forests. There are numerous factors that can determine the magnitude of the ecosystem C pool (Fig. 9.1). The growing season may be extended in the temperate zone (Menzel and Fabian 1999). In the Canadian prairies, for example, the growing season may increase by 10 days for every 1°C increase in temperature. In addition, the area under temperate forests may increase through encroachment into the boreal forests. Beniston and Tol (1998) observed that 0.8°C warming over Europe during the twentieth century has shifted the climatic isotherms by an average of 120 km. Such shifts have also been observed for alpine plants (Grabherr et al. 1994). However, if global warming happens at a faster rate (>0.1°C per decade) then trees can disperse to new ecoregions with more suitable climate, the composition of forest may change with poor survival of migrating species. In the mid latitude, pole ward shift of biomes is expected to be 200–300 km for every °C of warming (UNEP 1992).

Increase in atmospheric CO_2 concentration may also enhance NBP and NEP due to the CO_2 fertilization effect. The global increase in NPP attributed to the CO_2 fertilization effect was estimated at 0.5–2.0 Pg C $year^{-1}$ (Davidson and Hirsch 2001).

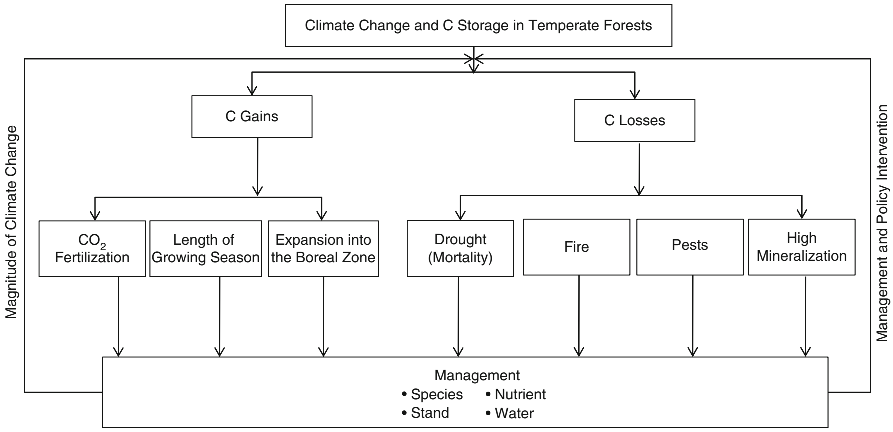

Fig. 9.1 Climate-induced changes in the C sink capacity of temperate forests

For example, the Free Air Atmospheric Carbon Dioxide Enrichment (FACE) experiments conducted in the southern U.S. showed that in comparison with the control photosynthesizing 0.3 kg $C\,m^{-2}$ $year^{-1}$, treatments receiving a higher CO_2 concentration sequestered additional 0.2 kg $C\,m^{-2}$ $year^{-1}$ (Davidson and Hirsch 2001). Furthermore, the MRT of the C sequestered ranged from 20 to 200 years in wood and soil, respectively. However, the CO_2 fertilization effect may be strongly limited by drought stress and/or nutrient deficiency. There is also a strong influence of the forest age on the CO_2 fertilization effect (Teneva and Gonzalez-Meler 2008). Specifically, the net response of photosynthesis, forest growth and C sequestration in the temperate forest biomes depends on the effects of elevated CO_2 during the entire cycle of forest stand development (Lorenz and Lal 2010). Further, some studies indicate that mature temperate trees may acclimate to the projected higher atmospheric CO_2 concentrations (Körner 2006). In summary, NPP in forest FACE experiments is increased by elevated CO_2, but the response can diminish over time (Norby and Zak 2011). Carbon accumulation is driven by the distribution of C among plant and soil components with differing turnover rates and by interactions between the C and N cycles. Plant community structure in forests may change, but elevated CO_2 has only minor effects on microbial community structure (Norby and Zak 2011).

The projected climate change can also exacerbate losses of C from forest ecosystems. The rate of mineralization/decomposition and erosion may increase with increase in temperature. There may be more frequent fires, and the incidence of pests and pathogens may increase (Fig. 9.1). The microbial activities in temperate forest soils are also affected by elevated CO_2 (Zheng et al. 2010).

The losses of C from the temperate forest biome affect the positive feedback between the climate change and the GCC. It is argued that global warming will reduce the efficiency of the C cycle to store anthropogenic CO_2 in the land and ocean sinks, and will exacerbate the positive feedback in the climate-GCC system. The magnitude of the feedback, however, may depend on: (i) climate-sensitivity of CO_2, (ii) the GCC-sensitivity of CO_2 and (iii) GCC sensitivity to climate change (Friedlingstein et al. 2003).

9.7 Potential of Temperate Forests to Recarbonization of the Biosphere

Most temperate forests are not at maximum C storage because of natural disturbances and harvesting (Dixon et al. 1994). Thus, temperate forests potentially store more C after forest management changes. The increase in the forest C pool by enhancing sequestration is a novel intention of forest management but the knowledge about forest production and forest growth is still incomplete (Andersson et al. 2000). A quantitative understanding of how forest management simultaneously enhances wood production and C sequestration is lacking for most forest types (Gough et al. 2008). In particular, the potential for conserving C through changes in management of temperate forests has not been estimated (Ciccarese et al. 2005). Thus, it is unclear how the forest C sink can be managed to mitigate atmospheric increases in CO_2 (Canadell and Raupach 2008). Also, management strategies to increase forest C storage in one area may have unintended negative or positive consequences on C storage elsewhere (Magnani et al. 2009). Further, biophysical effects of forest management on the amount and forms of energy transfer to the atmosphere may also occur (Anderson et al. 2011).

Heath et al. (2003) estimated the potential of C sequestration in soils under forest ecosystems in the U.S. However, the data on potential C sink capacity in soils and biomass of the temperate forests is not known at regional, national or global scale. The high C pool in soils and the biomass, as indicated by the data in Tables 9.4 and 9.7, can be increased even more through management and policy interventions. The importance of compensation to land managers through payments for ecosystem services cannot be over-emphasized. Despite the large potential, little research information exists on the processes and practices, for soil/site/climate specific situations, with regards to the rates of C sequestration in soils and biota through land use conversion and management. Scientific understanding is especially scanty with regard to the rates of SOC sequestration and decomposition in changing climates.

Whereas payments to land managers/foresters can provide the much needed incentives, forest C markets are not in place. How to account for changes in forest C (soils and vegetation) has been contentious (Carnell 2010). There are numerous concerns about forestry-based off-sets especially with regards to the credibility related to "additional", "verifiable" and "permanent" off-sets (Gorte and Ramseur 2010). There is also an issue of "double-counting" the off-sets, implying that sellers may try to sell the same off-sets to multiple buyers (Gorte and Ramseur 2010).

Table 9.7 Carbon pool in temperature forest of the U.S. (Recalculated from Birdsey and Lewis 2003)

	Carbon density (Mg ha^{-1})					
State	Trees	Soil	Forest floor	Understory	Total	Soil:tree ratio
I. Northeast	59.3	127.6	20.2	1.2	208.3	1.6
II. North central	47.3	123.9	20.5	1.0	196.1	1.7
III. Great plains	39.8	90.4	20.8	0.8	151.8	1.5
IV. Southwest	85.2	97.6	42.4	1.7	226.9	0.75

Substantial uncertainties also exist about the technical skills to accurately quantify, monitor and verify the amount of C sequestered by soil and biomass components of the temperate forest ecosystems (Gorte and Johnson 2010). Incorporation of forest C off-sets in any emission reduction program necessitates a firm/credible basis for measuring C pools and fluxes over a short period.

9.8 Conclusions

The atmospheric C pool may increase from about 390 ppm in 2010 to 700–1,000 ppm by 2100. The attendant future climate change may adversely affect human wellbeing. Thus, there is a need to identify natural sinks which can decarbonize the atmosphere. Temperate forests, covering a total land area of about 767 Mha, between mid latitude and ~55° N and S of equator, have favorable climate, fertile soils, and diverse species. A large proportion of temperate forests are managed to produce timber and other wood products. Others have been converted to agroecosystems. Thus, there is a potential to enhance the ecosystem C pool through conversion to a restorative land use for optimizing C capture and storage in temperate forests.

Realization of the potential C sink capacity, through land use and management, can be advanced by payments to land managers/foresters for ecosystem services such as C credits as off-sets towards anthropogenic emissions. However, there are numerous scientific uncertainties which must be addressed. Important among these are: (i) credible information on C pool in biomass and soil, and on the management-induced changes in these pools over short periods of 2–4 years, (ii) process and practices which affect C pools in soils and biota, such as CO_2 fertilization effect, interaction with water and nutrients, and the effects of global warming, (iii) the role of wild fires on emissions and changes in soil C and other properties which affect succession, (iv) leakage related to changes in land use and soil/stand management practices, and (v) the feedback to climate change.

Despite the uncertainties, C sequestrated in temperate forest has a larger sink capacity and longer MRT than that sequestered under croplands and other biomes. Thus, scientific programs and policy interventions must be in place to realize the potential C sink capacity of the temperate forest biome.

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