Chapter 11
Time Dynamics and Radiative Forcing of Forest Bioenergy Systems

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Abstract In this chapter we explore the temporal dynamics of using forest bioenergy to mitigate climate change. We consider such issues as: growth dynamics of forests under different management regimes; the substitution effects of different bioenergy and biomaterial uses; temporary carbon storage in harvested biomass; the availability of different biomass fractions at different points of a wood product life cycle; and changes in carbon content of forest soils. We introduce the metric of radiative forcing, which quantifies the accumulating energy due to the global greenhouse effect, and we describe a method to estimate quantitatively and to compare the cumulative radiative forcing (CRF) of forest bioenergy systems and reference fossil energy systems. In three case studies, we describe the time dynamics and estimate the CRF profiles of various forest biomass systems.

11.1   Forest Sector in Mitigating Climate Change

The forest sector plays an increasing role in climate change mitigation in some countries, with the prospect of sustainably providing essential materials and services as part of a low-carbon economy. In contrast to fossil energy systems which deplete on a geologic time scale, forest bioenergy systems are cyclically renewable through ecological processes. The dynamic nature of forest systems is complex, and should be understood and incorporated into our modeling, policymaking, and management

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frameworks. There are multiple climatic aspects of biomass, such as fossil fuel substitution (Schlamadinger et al. 1997), material substitution (Gustavsson and Sathre 2011), and carbon stocks and flows within living biomass, wood products and soils (Eriksson et al. 2007).
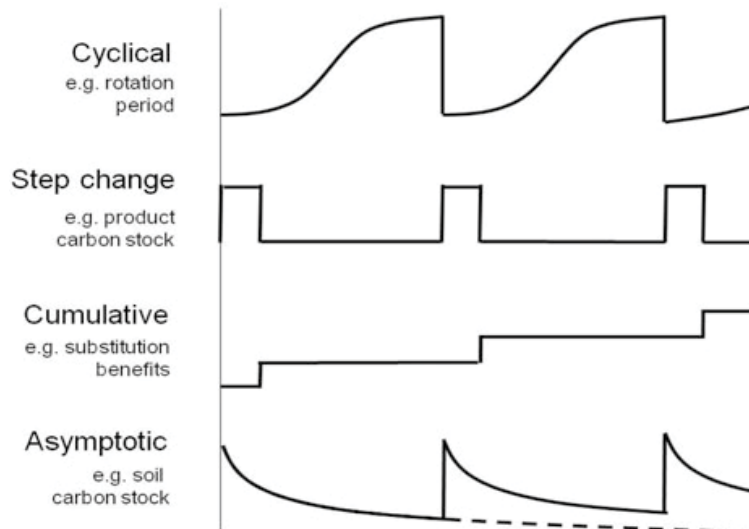
The carbon flows of forest biofuels from a life-cycle perspective include the phases of growth, processing, utilisation, and return. In the growth phase, carbon dioxide (CO_2) is removed from the atmosphere through photosynthesis, and held as carbon-based compounds in tree tissues. The chemical bonds of these reactions result in accumulated solar energy. In the processing phase, tree biomass is harvested, transported, and refined to give it desired characteristics. The energy sources used for these processes may be fossil fuels. Carbon is temporarily stored in biomass fibre, until the biofuel is finally combusted. Upon combustion, the accumulated energy is released and used, and the carbon is ultimately released back to the atmosphere. From a wider perspective, this energy service substitutes for other energy sources, likely fossil fuels.

There are several approaches to quantifying dynamic carbon flows over time. Flow-based approaches seek to quantify the carbon mass balance, where input minus output minus stock change is constant, over a given time horizon, e.g., annual or rotational. A common method of analysing mitigation options is the greenhouse gas (GHG) balance approach, where all GHG emissions that occur during a given time period are simply summed up regardless of when they occur. Cumulative net emissions are determined, beginning from zero emission in the baseline year. A system with lower cumulative emissions at the end of the time period is considered to have less climate impact than a system with higher emissions. Non-CO_2 GHG emissions (e.g., CH_4 and N_2O) are typically converted to "CO_2 equivalents" (CO_2e) based on the Global Warming Potential (GWP) of the gases, which express the relative climate impact of the gases compared to an equal mass of CO_2 over a fixed time horizon, typically 20, 100, or 500 years (IPCC 2007).

This approach does not fully describe the complexity of the system, however, because the sum is static and does not take into account the temporal patterns of the GHG emissions and the resulting dynamics of atmospheric radiative imbalance. The heterogeneity of stocks and flows over time reduces the effectiveness of static methods of analysing and comparing the mitigation effectiveness of forest systems. Within any finite time period, the accumulated radiative imbalance, and hence the climate impact, depends not only on how much GHG is emitted but also on when it is emitted. Cumulative radiative forcing (CRF), also called integrated radiative forcing or absolute global warming potential, is a metric that more accurately estimates the time-dependent climate impacts of dynamic systems, but is a more complex analytical procedure than GHG balance calculation and requires information on time profiles of emissions and removals (Fuglestvedt et al. 2003).

Several authors have proposed indicators based largely on CRF. For example, Kirkinen et al. (2008) introduced a "relative radiative forcing commitment" defined as the CRF caused by using a fuel divided by the combustion energy of the fuel. O'Hare et al. (2009) proposed a "physical fuel warming potential" defined as the CRF caused by using a fuel, relative to the CRF of using a reference fuel. Kendall et al. (2009) introduced a "time correction factor" to be applied to CO_2 emissions that occur at the beginning of a defined time horizon but are amortised over the entire horizon, such that the CRF is equivalent for both. Levasseur et al. (2010) proposed

Fig. 11.1 Illustrative examples of temporal patterns of carbon stocks and flows associated with forest bioenergy systems. Positive values show atmospheric net carbon reduction. Vertical axes are not to scale

the use of "dynamic characterisation factors" for the global warming impact category of life cycle assessment, based on the CRF of different GHGs over different time horizons. Cherubini et al. (2011) calculated a "GWP$_{bio}$" defined as the CRF resulting from a unit of bioenergy divided by the CRF resulting from an equivalent amount of fossil energy. The GWP$_{bio}$ notion was expanded by Pingoud et al. (2012) to include substitution effects of wood-based products. As currently applied, however, the GWP$_{bio}$ indicator gives simplified approximations of climate impacts, but does not incorporate comprehensive life-cycle emissions modeling of specific forest stands and landscapes. Bergman (2012) developed a metric called "time-zero equivalent", based on CRF, to consider the effect of timing of GHG emissions on the climate change impacts of building products.

Robust estimates of short- and long-term impacts resulting from GHG emissions are needed for various products, fuels, and management practices. For example, forest growth modeling under simulated environmental conditions may seek to identify changes in future growth patterns (Poudel et al. 2011). In this chapter we explore the temporal dynamics of using forest bioenergy to mitigate climate change. We focus on the metric of radiative forcing, which quantifies the accumulating energy due to the global greenhouse effect, and we describe a method to estimate quantitatively and compare the CRF of forest bioenergy systems and reference fossil energy systems. In three case studies, we describe and compare the time dynamics and estimate the time profiles of CRF of various biomass uses. Although the emphasis of this chapter is on forest biofuels, many issues are equally relevant to agricultural biofuels.

11.2   Time Dynamics of Forest Systems

Time dynamics of GHG stocks and flows associated with forestry and wood product use exhibit a variety of temporal patterns (Fig. 11.1). Cyclical patterns repeatedly accumulate and release carbon stocks, such as a forest rotation cycle. Step changes involve a discrete increase or decrease in carbon stock in a given pool, for example
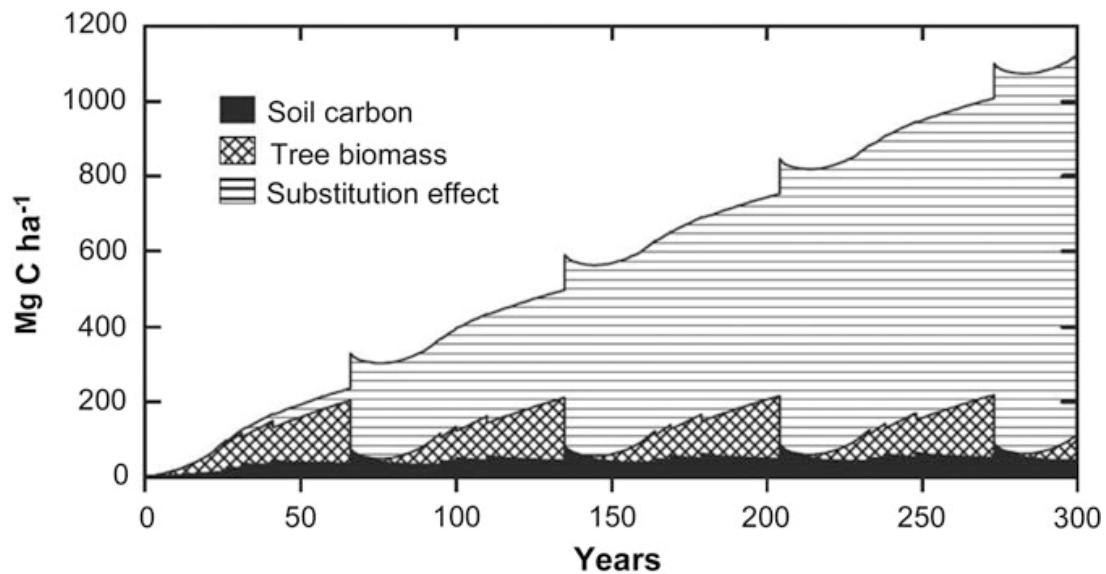
Fig. 11.2 Atmospheric net carbon reduction development over time of a managed forest stand (MgC ha^{-1}), including carbon stocks in tree biomass and forest soil, and cumulative substitution benefits. (Source: Eriksson et al. 2007)

the beginning and end of the life span of a wood product. Cumulative changes are flows that accumulate over time, such as fossil emissions avoided due to ongoing biomass substitution. Asymptotic changes are rapid at first and become slower over time, for example a decrease in soil carbon stock due to decay. Different forest management actions and wood product uses will result in different combinations of GHG emissions and removals over time. The climate effects of different biomass uses may entail material substitution (displacement factors for material use; Sathre and O'Connor 2010), fuel substitution (displacement factors for different fossil fuels; Gustavsson et al. 1995), and multiple or cascaded use (material use followed by energy recovery; Sathre and Gustavsson 2006).

Dynamic analysis of the climate implications of forest bioenergy systems may be conducted across various spatial scales, from the stand level to the landscape level. At the stand level, a unit ha of forest land may be followed throughout multiple rotation periods to generate understanding of the time-dependent changes in stocks and flows in biomass, wood products, litter and soil under various management and use scenarios. The overall climate significance of this stand-level forest management may be put in a larger context by landscape-level analysis incorporating many stands within a region or a country. Carbon dynamics differ substantially as the scale increases from the forest stand level to the landscape level. Within a managed forest stand a characteristic curve can be traced over time: carbon is bound in tree biomass during stand establishment and growth, then eventually accumulates at a decreasing rate, then is removed during harvesting, followed by establishment of the subsequent rotation. With each harvest, the benefits of biomass substitution benefits accumulate, and changes in soil carbon stock depend on relative rates of litter inputs and organic matter decay (Fig. 11.2).
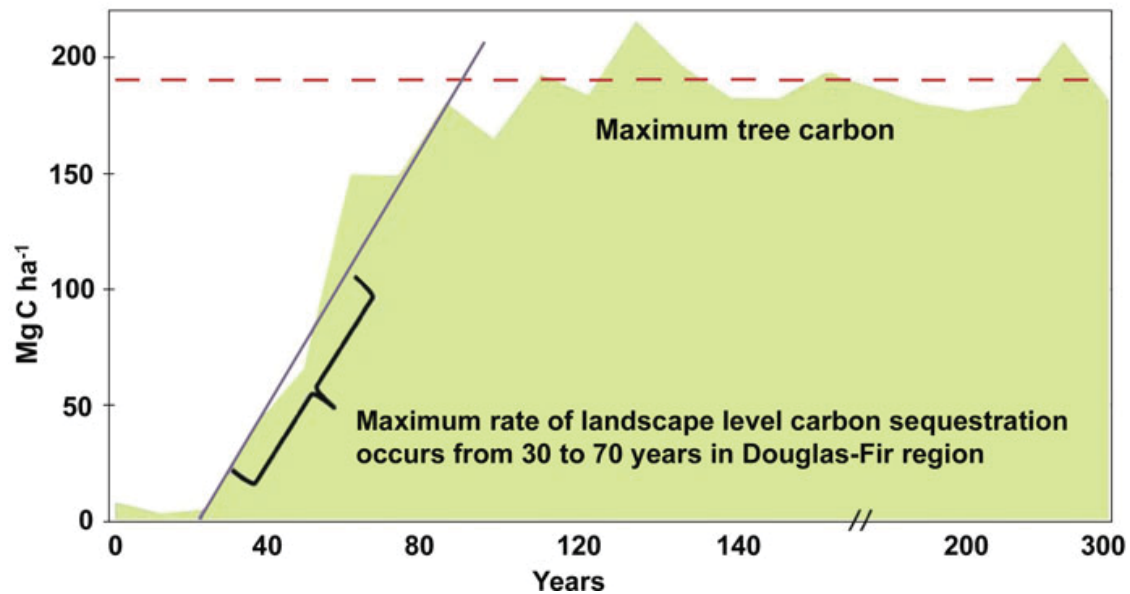
Fig. 11.3 Forest carbon accumulation in Washington State, USA (MgC ha^{-1}). Little net growth occurs beyond the age of 100 years. (Source: Lippke et al. 2011, based on data from US Forest Service Forest Inventory (Bolsinger et al. 1997))

At the landscape level in a managed forest, the total carbon balance at any time is the aggregate of the balances of a multitude of stands. The total carbon stock in living biomass at the landscape level tends to remain fairly stable over time in a healthy forest ecosystem, as the harvesting of some trees during a given time period is compensated by other trees growing during the same period. The maximum carbon stock at the landscape level is lower than the maximum at the stand level, because not all the individual stands will hold the maximum stock at the same time (Kurz et al. 1998). If forests are managed appropriately, the average carbon stock in forest biomass can increase over time, while simultaneously producing a flow of harvested biomass out of the forest that gives continually increasing carbon benefits due to fuel and material substitution (Pingoud et al. 2010).

Understanding of forest biomass growth dynamics is integral to robust system analysis. Managed forestry typically involves cyclical growth curves or rotation periods, with the magnitude and frequency of cycles depending in part on climate and management regimes. If a mature forest stand is not harvested, the growth rate decreases and the carbon stock levels off (Fig. 11.3). Eventually, non-harvested forest stands are subject to natural disturbance regimes such as fire or insect attacks that result in release of stored carbon (Kurz and Apps 1999), damning prospects for permanent carbon storage in living trees. In addition to dynamics of living tree biomass, corresponding patterns of carbon stock change can be identified in wood-based products, dead and decaying biomass, and forest soils.

The significance of temporary carbon storage in harvested biomass varies with the life span of the product. The short time (weeks or months) between harvest and typical use of biofuels is less significant than the longer lifespan (decades or centuries) of wood construction material used as bioenergy after building demolition. Long-term carbon storage occurs in long-lived harvested forest products, which may be used

as bioenergy at the end of their service lives. Atmospheric CO_2 concentration is affected by *changes* in the stock of carbon in forest products, not by the magnitude of the stock. The stock of forest products will stabilize if the rate of wood entering the products reservoir is equal to the rate of wood leaving the reservoir. Over time an increase in carbon stock in forest products could occur as a result of general economic implications such as economic growth, whereby more products of all kinds are produced and possessed, or through a societal transition from non-wood to wood-based products.

An integrated life cycle approach using cascaded biomaterial and bioenergy becomes more critical if biomass production rates become limited in relation to demands (Sathre and Gustavsson 2006). The limiting factor of the system can be the available biomass resource for energy or the land available for biomass production. This limit implies that use of biomass in one application will reduce the amount available for other applications. Different biomass uses may have different impacts, and the efficiency of replacing different fossil fuels in different sectors can vary. For example, using biomass in a large stationary plant such as a combined heat and power (CHP) plant to replace fossil-based electricity and heat is more climatically beneficial than substituting fossil transportation fuels with solid biofuels (Joelsson and Gustavsson 2010).

11.3 Radiative Forcing

11.3.1 What is Radiative Forcing?

Radiative forcing is a quantification of the *greenhouse effect*. This effect is caused by particular gases in the atmosphere with a peculiar property that allows short wavelength radiation (for example, visible light and ultraviolet radiation) to pass through, but restricts longer wavelength radiation (for example, infrared radiation) from passing. Solar radiation as sunlight passes through the atmosphere and is absorbed by the earth's surface. The solar radiation that is absorbed by the earth's surface warms up the surface and atmosphere. That heat will then radiate away from the earth, analogous to a fireplace radiating heat felt by those sitting near it. In the absence of GHGs that heat would radiate out into space, but the GHGs block part of the heat and trap it in the atmosphere. The naturally-occurring greenhouse effect is crucial, because it maintains the earth at a suitable temperature for current life. In the absence of GHGs in the atmosphere, the planet would be much colder.

Over the long term, the earth and atmosphere system remains in radiative balance, where the amount of incoming solar radiation absorbed by the system is balanced by the release of the same amount of outgoing longwave radiation (Fig. 11.4). However, as human society has increased the amount of GHGs in the atmosphere in recent decades and centuries, we have created a *radiative imbalance* in which there is less outgoing radiation than incoming radiation. That imbalance is called "radiative forcing". Thus radiative forcing is a measure of rate of flow of excess energy entering the earth system. It describes the state of energy imbalance, where radiative energy
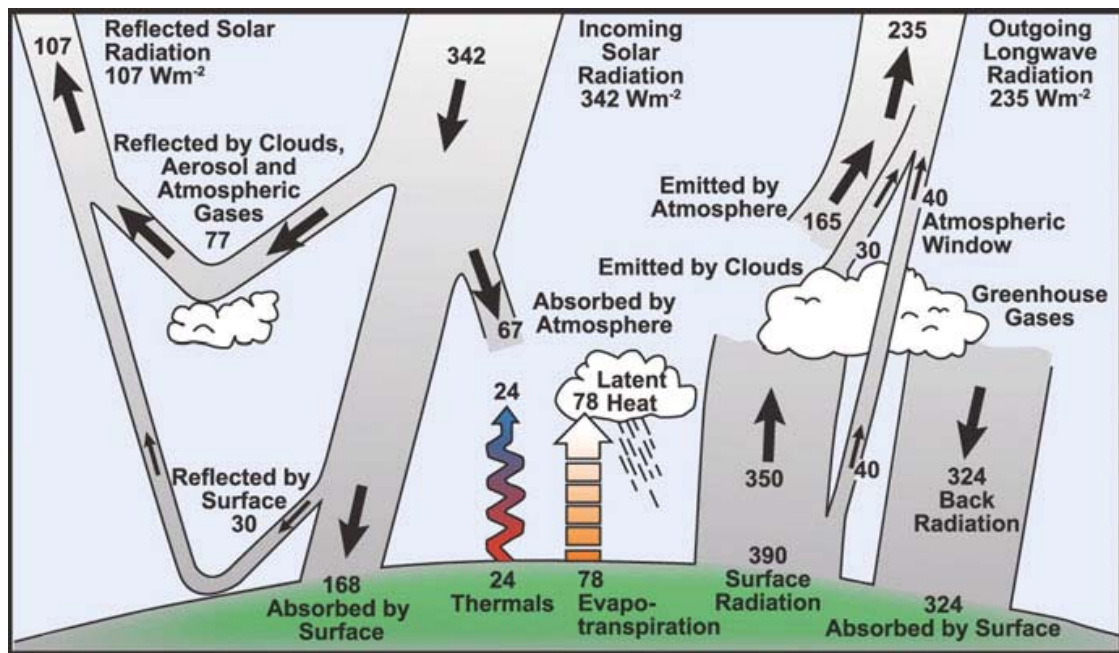
Fig. 11.4 Estimated annual and global mean energy balance of the Earth. (Source: IPCC 2007)

inputs minus outputs yield a positive accumulation of energy in the earth system, leading to climate impacts we experience. When summed over time, the accumulated energy can be termed "cumulative radiative forcing" (CRF), a measure of total excess energy trapped in the earth system, and a suitable indicator of climate change impacts. Hence, positive CRF implies global warming and negative CRF implies cooling.

When a carbon-containing fuel is burned, CO_2 is formed and is released into the environment. Other GHGs may also be emitted at various life-cycle phases, for example methane (CH_4) and nitrous oxide (N_2O). These GHGs mix uniformly throughout the atmosphere and begin to trap heat through the process of radiative forcing. GHGs vary in their radiative efficiency, which determines their ability to accumulate heat. Per unit of mass, N_2O traps the most heat of these three gases, followed by CH_4 and then CO_2.

GHGs are slowly removed from the atmosphere through natural processes, thus over an infinite time horizon a unit of GHG will cause about the same amount of radiative forcing regardless of when it is emitted. However, many policy objectives cover a finite time horizon, for example, reducing climate change impacts during the next 20 or 100 years. Thus the effectiveness of a mitigation activity to fulfil such policy objectives may depend not only on how much GHG is emitted, but also on when it is emitted.

Factors other than atmospheric concentrations of GHGs can alter the Earth's energy balance as well, including aerosols from volcanoes and air pollution and the amount of solar radiation delivered by the sun to the earth. Another potentially important factor in the energy balance is albedo, which is a measure of surface reflectivity. Changes in land surface albedo, e.g., between forested and harvested land, can significantly change the balance of solar radiation and hence radiative forcing, particularly in boreal forest regions (Marland et al. 2003).

11.3.2   Estimating Radiative Forcing

To estimate the radiative forcing implications of various forest management and bioenergy deployment pathways, we integrate three analytical elements: temporally-explicit life cycle system modeling to determine GHG emission profiles; atmospheric decay modeling to determine residence of GHGs in atmosphere; and time-dependent estimates of radiative forcing due to atmospheric concentration changes of the GHGs. Zetterberg (1993) described this method of estimation of radiative forcing, and the parameters have since been updated by the IPCC (1997, 2001, 2007).

To compare bioenergy and fossil energy systems, a detailed life cycle assessment of the elements of both systems is needed. The elements and system boundaries must be described and defined clearly (Schlamadinger et al. 1997). Both the bioenergy chain and the reference fossil chain must be accurately accounted from the natural resources to the delivered energy services. Along the whole chain all processes like transport, conversion, and distribution have to be considered and all GHG emissions must be accounted to compare the full systems rather than the individual components thereof. Comparing bioenergy and fossil energy systems involves both biological and technical features. Clear definition of the reference system and the forest bioenergy system requires delineation of system boundaries in terms of activities, time, and space. Temporal and spatial scales are interlinked through biomass growth rates, and stand-level analysis gives a different perspective than landscape-level analysis. The land that is used in the bioenergy system should be considered also in the fossil reference system. Definition of systems should be done to produce a comparable functional unit of goods and services (Gustavsson and Sathre 2011). Clear definition of the initial boundary conditions, or starting point of the analysis, is needed as it affects later results, though a long-term analysis will identify persistent trends.

Once emitted, a GHG will continue to cause radiative forcing and trap heat in the earth system as long as it remains in the atmosphere. GHGs are removed from the atmosphere by natural processes, at time rates that vary with the GHG. Net emissions of CO_2, N_2O and CH_4 that occur during a year are typically treated as pulse emissions. The atmospheric decay of such pulse emissions can be estimated using Eqs. 11.1, 11.2 and 11.3 (IPCC 1997, 2001, 2007):
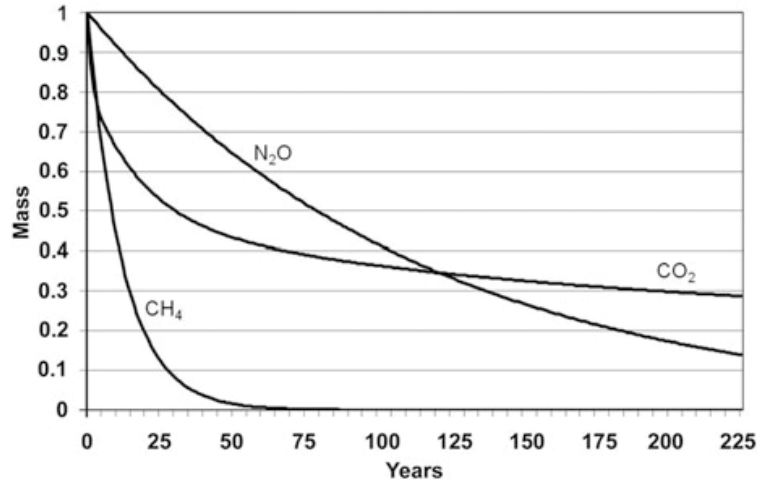
$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.259e^{\frac{-t}{172.9}} + 0.338e^{\frac{-t}{18.51}} + 0.186e^{\frac{-t}{1.186}} \right] \quad (11.1)$$

$$(N_2O)_t = (N_2O) \times \left[e^{\frac{-t}{114}} \right] \quad (11.2)$$

$$(CH_4)_t = (CH_4)_0 \times \left[e^{\frac{-t}{12}} \right] \quad (11.3)$$

where t is the number of years since the pulse emission, $(GHG)_0$ is the mass of GHG emitted at Year 0, and $(GHG)_t$ is the mass of GHG remaining in the atmosphere at year t, where GHG represents CO_2, N_2O and CH_4, respectively. The estimated decay over time of unit mass emissions of CO_2, N_2O and CH_4 is shown in Fig. 11.5.

Fig. 11.5 Estimated atmospheric decay of unit emissions of CO_2, N_2O and CH_4

The time profiles of atmospheric mass of each GHG can then be converted to time profiles of atmospheric concentration, based on the molecular mass of each GHG, the molecular mass of air estimated at 28.95 g mol^{-1}, and the total mass of the atmosphere estimated at 5.148×10^{21} g (Trenberth and Smith 2005). Marginal changes in instantaneous radiative forcing due to the GHG concentration changes can then be estimated using Eqs. 11.4, 11.5 and 11.6 (IPCC 1997, 2001, 2007):

$$F_{CO_2} = \frac{3.7}{\ln(2)} \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\} \tag{11.4}$$

$$F_{N_2O} = 0.12 \times \left(\sqrt{\Delta N_2O + N_2O_{ref}} - \sqrt{N_2O_{ref}}\right) - f(M, N) \tag{11.5}$$

$$F_{CH_4} = 0.036 \times \left(\sqrt{\Delta CH_4 + CH_{4ref}} - \sqrt{CH_{4ref}}\right) - f(M, N) \tag{11.6}$$

where F_{GHG} is instantaneous radiative forcing in W m^{-2} for each GHG, ΔGHG is the change in atmospheric concentration of the GHGs CO_2, N_2O and CH_4, respectively (in units of ppmv for CO_2, and ppbv for N_2O and CH_4), $CO_{2ref} = 383$ ppmv, $N_2O_{ref} = 319$ ppbv, $CH_{4ref} = 1774$ ppbv, and $f(M, N)$ is a function to compensate for the spectral absorption overlap between N_2O and CH_4 (IPCC 1997, 2001, 2007).

CRF occurring each year in units of W s m^{-2} (or J m^{-2}) can then be estimated, by integrating the instantaneous radiative forcing occurring through each year. This operation converts the energy flow per unit of time of the radiative imbalance caused by GHGs into units of energy accumulated in the earth system per m^2 per year. Values of radiative forcing are annual and global averages, at the outer surface of the troposphere, estimated here based on earth radius of 6371 km and height of tropopause of 12 km.

The case studies in this chapter are expressed as CRF per unit of forest land (W s m^{-2} ha^{-1}) and CRF per unit of biomass dry-matter (W s m^{-2} Mg^{-1}). Firstly, radiative forcing is estimated in units of Watts of radiative imbalance per square meter of surface area of the troposphere (W m^{-2}). Secondly, this is integrated over time to become Watts × seconds (or Joules of accumulated energy) per square meter (W s m^{-2}). Thirdly, this is normalized to a unit hectare of forest land or a unit ton

of dry biomass, to determine the climate mitigation efficiency of forest management on the basis of land area or biomass production.

This type of analysis involves relatively simple models of complex natural processes, thus is subject to uncertainty. The calculations of radiative forcing assume relatively minor marginal changes in atmospheric GHG concentrations, such that radiative efficiencies and atmospheric decay patterns of the gases remain constant. However, significant increases in the atmospheric concentration of CO_2 can be expected during the coming decades and centuries. Increased atmospheric CO_2 concentration will decrease the marginal radiative efficiency of CO_2, but will also decrease the marginal atmospheric decay rate of CO_2. These will have opposite and therefore offsetting effects on radiative forcing, thus we expect this uncertainty to be minor (Caldeira and Kasting 1993). More sophisticated modeling could account for expected future trajectories of GHG concentrations and its effects.

Furthermore, the estimation of CRF by integrating instantaneous radiative forcing over time ignores the feedback effect that the accumulated energy will have on future outgoing radiation. Radiative forcing is a measure of the radiative imbalance given that atmospheric temperatures remain unchanged. In fact, positive radiative forcing will increase the heat energy accumulated in the earth system, leading to more outgoing longwave radiation and an eventual restoration of radiative balance. Since instantaneous radiative forcing does not account for this feedback effect, the described approach may therefore slightly overestimate the amount of accumulated heat caused by a unit of radiative forcing.

11.4 Case Studies

Here we illustrate the effects of the issues discussed above, by quantifying the GHG flows and radiative forcing over time for several illustrative forest biomass system scenarios.

11.4.1 Case Study: Using Forest Residues to Substitute Fossil Fuels

The time dynamics of carbon flows can be significant to the climate impacts of forest residues used for energy. Residues that are removed from the forest and burned release CO_2 into the atmosphere immediately, whilst residues left to decompose naturally in the forest slowly release CO_2 over a time scale of years and decades. If residues are used for energy to replace fossil fuel, the biogenic carbon is emitted immediately, and some fossil emissions also occur from fossil fuels used to recover and transport the biomass. If residues are left in the forest and not used as fuel, a corresponding amount of fossil fuel will be used instead resulting in immediate fossil emissions, followed by gradual emission of biogenic carbon from the decaying residues.

Sathre and Gustavsson (2011) conducted system modelling to estimate the CRF that results from recovering, transporting, and burning forest residues, compared with the forcing that would have occurred if the residues were left in the forest

and fossil fuels used instead. Harvest slash and stumps were differentiated as to their recovery difficulty and natural decay rate. CRF was significantly reduced when forest residues were used instead of fossil fuels. Fig. 11.6 shows the reduction in CRF over a 240-year period when slash and stumps are used to replace fossil coal or fossil gas at year 0. The assumed baseline for decay of residues if not removed from the forest follows either natural decay patterns, or is instantly oxidized to determine the significance of this common default assumption. The CRF reduction is greater if the biomass left in the forest is instantly oxidized than if it decays naturally. Natural decay occurs slowly over many years, thus the biogenic carbon is temporarily stored out of the atmosphere, delaying CO_2 emissions and reducing CRF. The natural decay curves are different for slash and stumps because of their different decay rates. Stumps decay slower than slash, thus if the biomass is not used as biofuel the carbon in stumps will remain stored out of the atmosphere for a longer time than the carbon stored in slash. The instant oxidation curves are almost identical for slash and stumps because their stored carbon is assumed to be fully released during the year of harvest.

The type of fossil fuel replaced influenced the result, with coal replacement giving the greatest CRF reduction. Replacing oil and gas also gave long-term CRF reduction, although CRF was slightly positive during the first 10–25 years when these fuels were replaced (Fig. 11.7). Globally, about 27 % of primary energy is supplied by coal, 34 % by oil, and 21 % by gas (IEA 2012). Coal emits more CO_2 per unit of energy than other fossil fuels, thus substitution of coal should be prioritized if possible. Greater climate benefits occurs when logging residues are transported longer distances and used to replace coal than when residues are transported shorter distances and used to replace oil or gas (Gustavsson et al. 2011). Biomass productivity also affected CRF reduction, with more productive forests giving greater CRF reduction per hectare. The decay rate for biomass left in the forest was found to be less significant. Fossil energy inputs for biomass recovery and transport had very little impact on the estimated CRF.

11.4.2 Case Study: Forest Fertilization and Biomass Substitution

More complex systems can also be modelled to estimate overall climate impacts and benefits of forest management and forest product use. Intensive forest management is time dependent, such that actions (e.g., forest fertilization) early in a rotation period result in management-related emissions, followed later by increased biomass growth and substitution potential. Harvested forest biomass is rarely used exclusively for bioenergy, and climate implications of other biomass uses should be considered. Important temporal issues include the duration of carbon storage in forest products, the fate of post-use forest products and the availability of residues at different times.

Over the life cycle of a wood product, biomass residues will become available at different times. Thinning residues may be generated during the growth phase of the forest. Later, forest residues are created when the forest stand is harvested, processing residues are available when the roundwood is transformed into wood products, and construction site residues are left when a building is assembled using wood-based
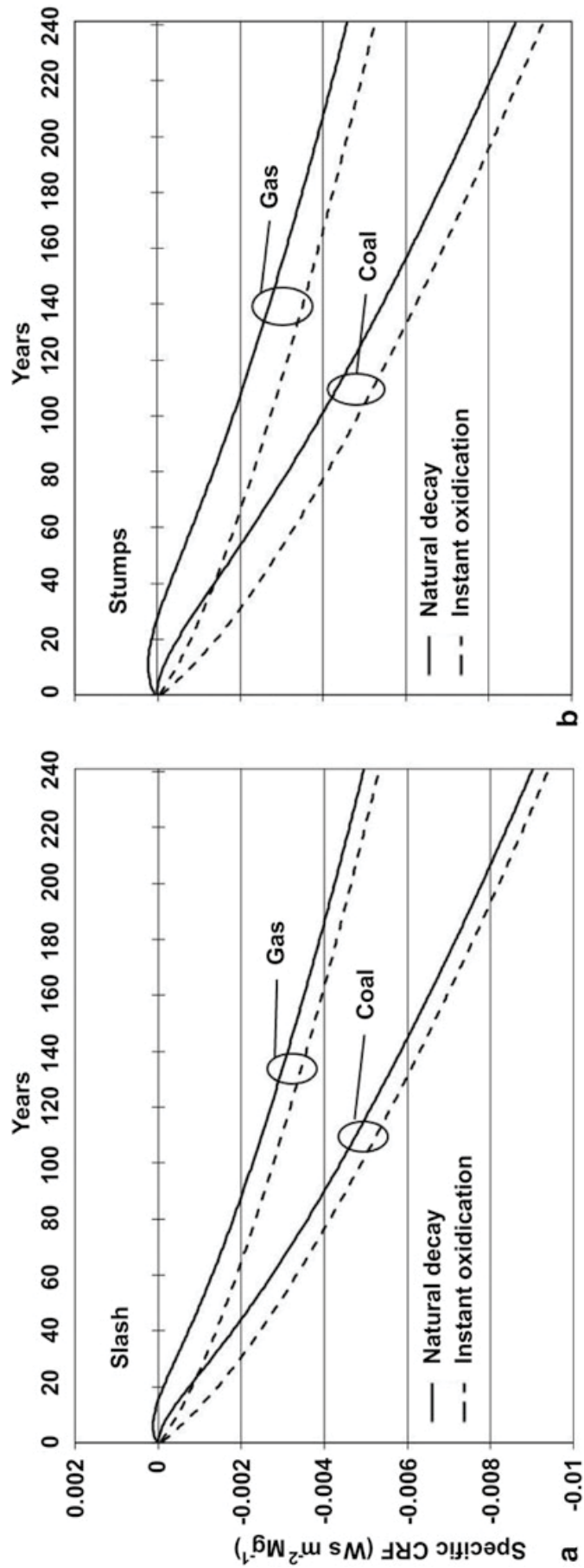
Fig. 11.6 Specific CRF (W s m^{-2} Mg^{-1} dry matter) when slash (**a**), and stumps (**b**) replace fossil coal or gas, assuming baseline of either natural decay or Instant oxidication (Source: Sathre and Gustavsson 2011)
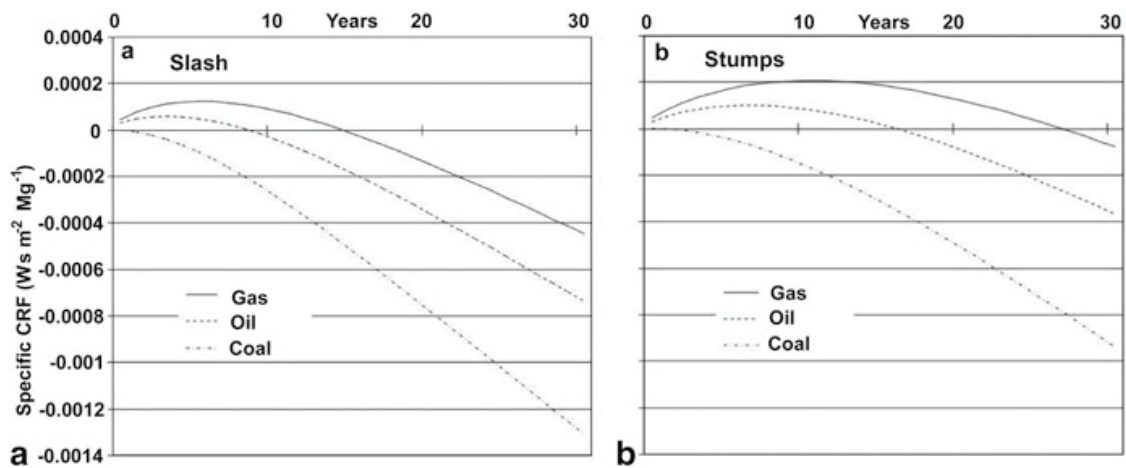
Fig. 11.7 First 30 years of specific CRF (W s m^{-2} Mg^{-1} dry matter) when slash (**a**), and stumps (**b**) replace coal, oil or gas, assuming baseline of natural decay. (Source: Sathre and Gustavsson 2011)
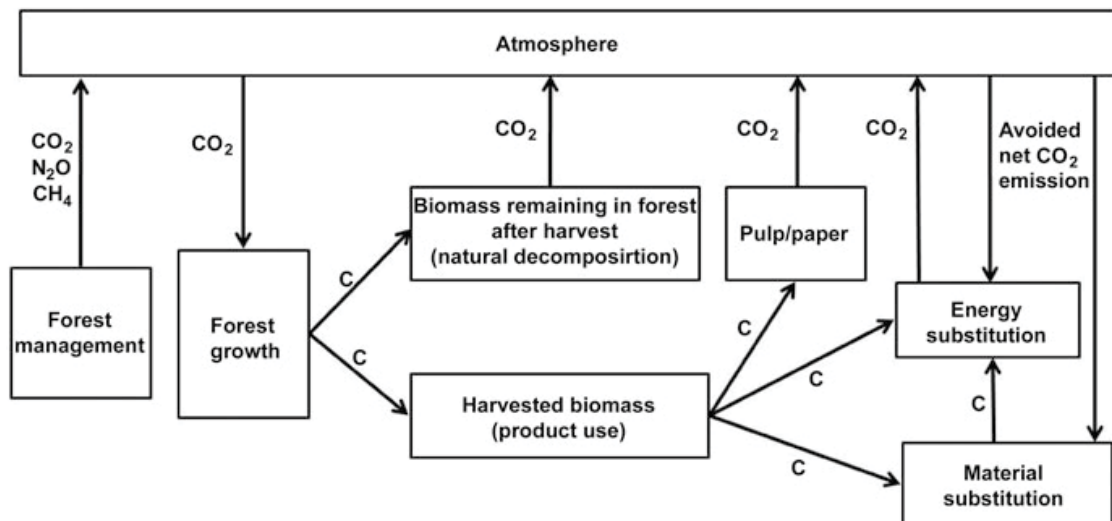

Fig. 11.8 Schematic diagram of GHG flows and stocks tracked on an annual basis. (Source: Sathre and Gustavsson 2012)

materials. Later still, post-use residues are produced at the end of a wood product life cycle. The use of these residues to replace fossil fuel results in reduced fossil carbon emissions at different times in the life cycle of the material.

Sathre and Gustavsson (2012) conducted a broad system analysis of the time-dependent climate implications of various forest management regimes and forest product uses. They tracked the annual GHG flows and stocks for each system (Fig. 11.8), including the fossil CO_2 emissions from forest operations, the CO_2, N_2O and CH_4 from production and application of fertilizer, N_2O emission from fertilized soil, CO_2 from fossil fuels used for biomass harvest and transport, avoided CO_2 emissions from using the biomass to substitute for materials and fuels, and carbon stock changes in living trees, forest products, and in soil and decaying biomass. The annual net emissions of CO_2, N_2O and CH_4 were calculated for each system based on life-cycle modeling, as well as the resulting annual changes in instantaneous
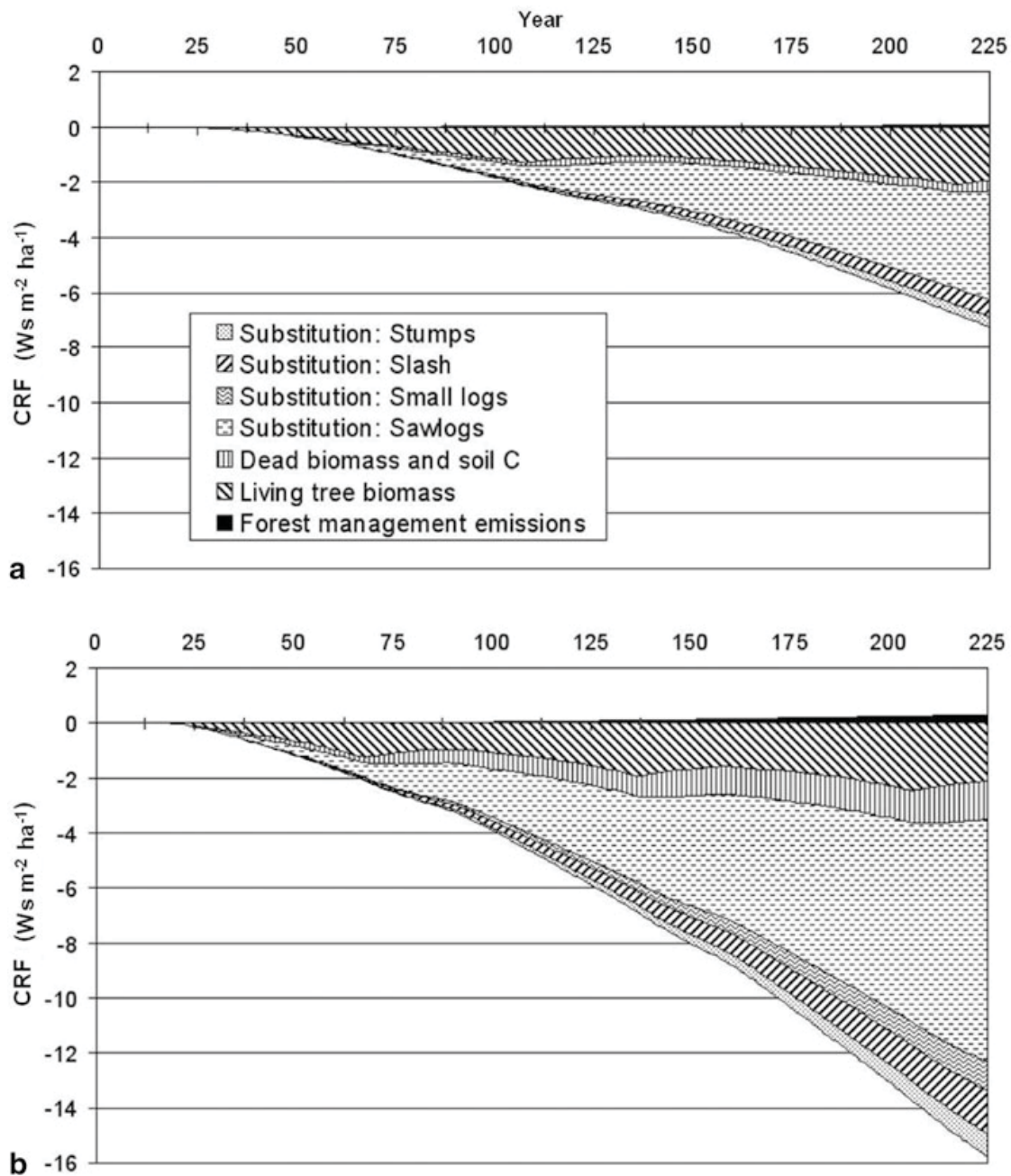
Fig. 11.9 CRF (W s m^{-2} ha^{-1}) of conventional (**a**), and fertilized (**b**) stands, broken down by biomass types and forest management actions. Energy substitution effects are based on replacing coal. Reference unmanaged land use is not considered. The potential impact on CRF due to the use of less forestland in the reference fossil scenario is assumed to be zero

radiative forcing and CRF over a long-term time horizon. As indicators of the efficiency of climate change mitigation of each scenario, Sathre and Gustavsson (2012) estimated the CRF reduction per hectare of forest and the CRF reduction per ton of dry matter of biomass.

The modelled forest management regimes include conventional production forestry in northern Sweden with a rotation period of 109 years, and more intensive fertilized management with a rotation period of 69 years. The CRF of the conventional and fertilized stands is shown in Fig. 11.9. The CRF is broken down into

contributions from different biomass types and forest management, with coal as the reference fossil fuel. During the first 15 years the CRF is the same in both managed stands. It begins slightly positive in sign due to fossil emissions from stand establishment, and by Year 10 becomes negative due to carbon uptake in growing trees. The radiative forcing of the fertilized stand increases during Year 16 due to GHG emissions from fertilizer production and application. By Year 18, however, the CO_2 removal due to the increased biomass growth of the fertilized stand compensates for these emissions, and the cumulative radiative forcing of the fertilized stand becomes less than that of the conventional stand. By the end of the 225-year study period, the avoided CRF of the fertilized stand is over twice that of the conventional stand.

Increasing biomass production through forest fertilization combined with substitution of non-wood products and fuels can significantly reduce CRF. The emissions from intensified forest management, including manufacture and application of fertilizer, resulted in very little radiative forcing in comparison with the negative radiative forcing from using the increased forest growth for biomass substitution. The biggest single factor causing reduction in radiative forcing was using sawlogs to produce wood material to replace energy-intensive construction materials such as concrete and steel. Another very significant factor was replacing fossil fuels with wood residues from forest thinning, harvest, wood processing, and post-use wood products. The fossil fuel that was replaced by the biofuels affected the reductions in GHG emission and radiative forcing, with carbon-intensive coal being most beneficial to replace. The climate benefits of fertilization were proportional to the increased rate of biomass production, in terms of shortened rotation lengths and increased harvest volumes.

Here we extend the analysis of Sathre and Gustavsson (2012) to include scenarios of unmanaged forest land in the reference fossil system. If a forest is not managed, at least three effects on carbon balance can be distinguished: (1) The forest biomass would continue growing until the stand is mature. At this point a dynamic balance would be reached, where natural mortality equals growth and average carbon stock remains near-constant. In the long-term, the living forest biomass may be reduced due to natural disturbances (wind, insects, etc.) and reach a new equilibrium lower than that of a managed forest at the time of harvest. (2) The soil carbon stock would vary somewhat depending on the amount of biomass litter from natural disturbance events. (3) No forest products would be produced and other, more carbon-intensive, materials and fuels would be used instead. The substitution effect of forest product use is cumulative; i.e., carbon emission is avoided during each rotation period due to the substitution of fossil fuel and material by the harvested biomass. Thus, not harvesting the forest would cumulatively increase the carbon emission over what would otherwise be possible if the forest stand were harvested and used on a regular rotation period.

The carbon stock in living biomass is here assumed to reach a level of 20 % greater than the harvest level of the conventionally managed stand. Due to uncertainties regarding the long-term development of the living carbon stocks in an unmanaged stand, we consider two scenarios: (a) the carbon stock remains constant at the 20 % greater level, and (b) the carbon stock reaches the 20 % greater level, and then is slowly reduced by natural disturbances to be 20 % less than the harvest level of the
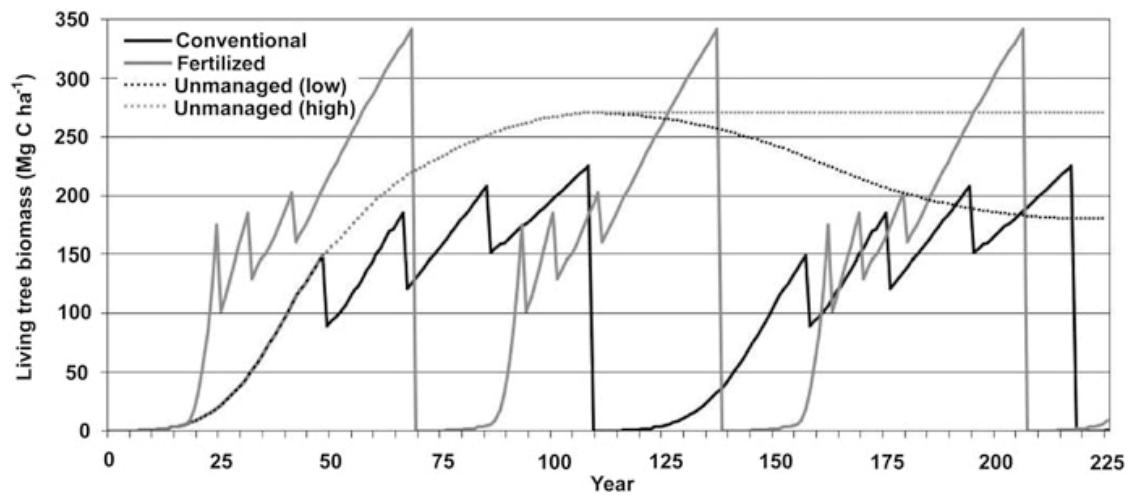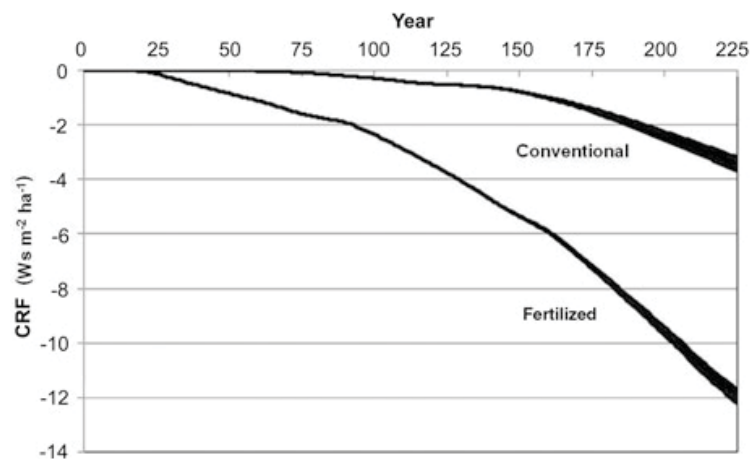
Fig. 11.10 Carbon stock in living tree biomass (MgC ha^{-1}) over time in forest stands with four different management regimes: (1) conventional management with 109 year rotation period, (2) fertilized management with 69 year rotation period, and unmanaged and unharvested with carbon stock stabilising at (3) 20 % above or (4) 20 % below conventional harvest level. For all management regimes, Year 0 begins with a cleared stand

Fig. 11.11 Net CRF (W s m^{-2} ha^{-1}) of forest use, calculated as CRF of conventional and fertilized stands minus CRF of unmanaged stands with high and low levels of equilibrium carbon stock. Energy substitution effects are based on replacing coal

conventionally managed stand. Fig. 11.10 shows carbon in living tree biomass in the conventional and fertilized forest stands, and in unmanaged stands with assumed high and low levels of equilibrium carbon stock.

The net climate benefits of forest management are quantified in Fig. 11.11, which shows the difference in CRF between the managed stands and the reference unmanaged stands. The shaded areas represent the difference in CRF between the low and high scenarios of the unmanaged stand. The CRF reduction of the unmanaged stands is due entirely to accumulated carbon stocks in living biomass and soils, with no ongoing substitution benefits from harvested biomass. The fertilized stand produces earlier climate benefits, and by the end of the 225-year study period it results in over three times greater reduction in CRF than the conventional stand.

The substitution benefits of forest product use are cumulative while the carbon sink in the forest biomass and soil is limited. Therefore, non-management and non-use of forest biomass becomes less attractive as the time horizon increases. Over the long term, an active and sustainable management of forests, including their use as
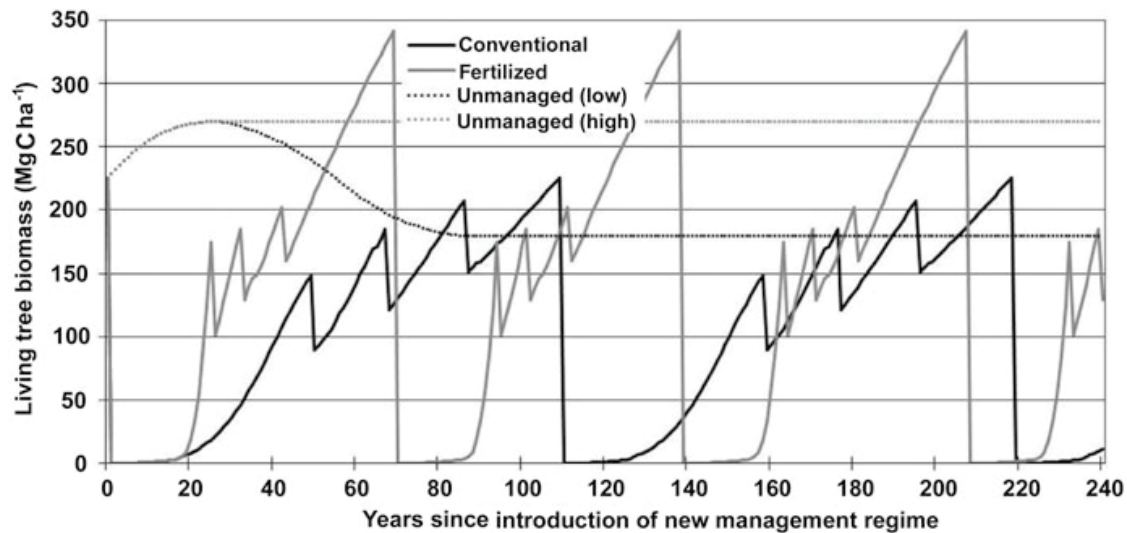
Fig. 11.12 Carbon stock in living tree biomass (MgC ha^{-1}) over time in forest stands with four management regimes (see Figure 11.10 for description). For all management regimes, Year 0 begins with a mature conventionally-managed stand

a source for forest products and biofuels, allows the greatest potential for reducing net carbon emission.

11.4.3 Case Study: Carbon Dynamics at a Landscape Level

A managed forest landscape typically consists of a number of even-aged forest stands, each representing a different age class. At the landscape level, the total carbon balance at any time is the aggregate of the balances of the stands, each of which is at a different stage of its rotation. Final felling occurs by definition only once for each rotation period of a single stand. Because each stand has a different age, only a fraction of the full area is harvested at a time, giving relative stability to productivity and carbon stock at the landscape level.

Here we present a case study of carbon accounting at the stand level and landscape level. The analysis begins with a landscape in northern Sweden composed of 109 separate forest stands of the same area. The stands have been managed conventionally with a 109-year rotation period, and the age structure of the stands is a uniform distribution of stand ages from 1 to 109 years; i.e., one stand becomes mature and is harvested each year. The mature stands contain a carbon stock in living tree biomass of 225 tC ha^{-1}. In this analysis, as each of the 109 stands becomes mature, one of four different management regimes is implemented on the stand: (1) clear-cut harvest followed by continuation of conventional management with 109 year rotation period; (2) clear-cut harvest followed by fertilized management with 69 year rotation period; (3) the stand is left unharvested and unmanaged with carbon stock stabilising at 20 % above or (4) 20 % below conventional harvest level. Stand-level carbon stock trajectories for each of these four regimes are shown in Fig. 11.12. The net effects
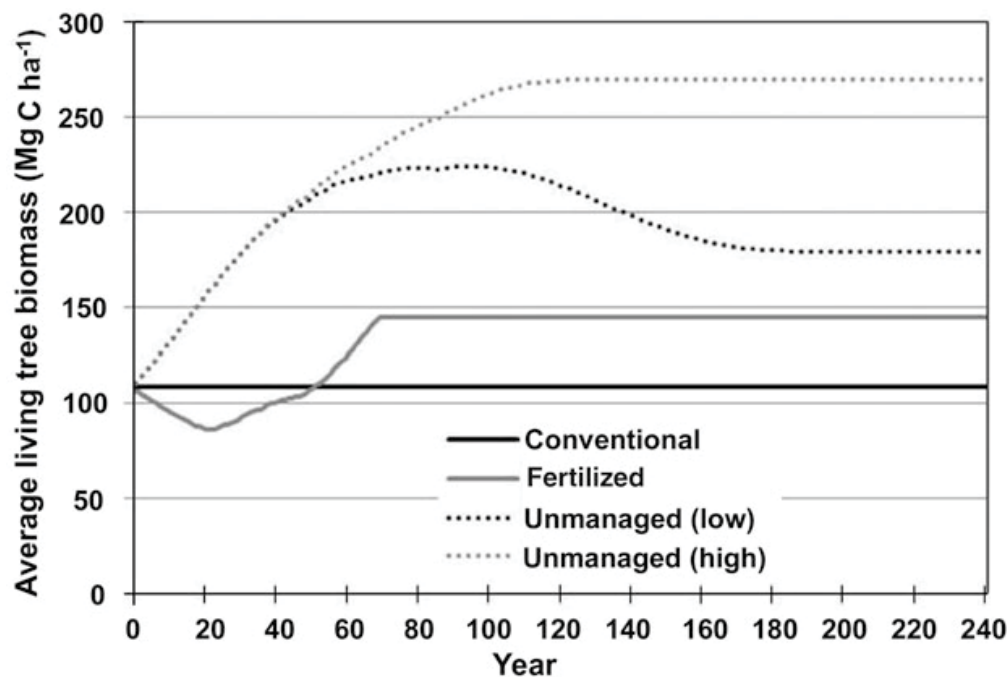
Fig. 11.13 Average landscape level carbon stock (MgC ha^{-1}) in living tree biomass of 109 forest stands under four different management regimes. During each of years 0 through 108, one of the 109 stands reaches maturity under conventional management and then continues under the four different management regimes (except transition to fertilized regime, which occurs from year 0 to 68; see text)

of forest management are calculated as the direct effects of a managed stand minus the reference effects that would have occurred if the stand had not been managed.

The carbon stock in living biomass over time on the landscape level including all 109 stands is shown in Fig. 11.13. If conventional management is continued, the landscape level carbon stock remains constant over time, because the same fraction of the forest land is harvested each year so the age structure remains constant. If fertilized management is adopted, to allow compatibility of the 69-year rotation period across the 109 stands and ensure an even distribution of stand ages on the landscape, we assume that 1.58 stands are harvested each year. This implies that during the transition from conventional management to fertilized management, some existing conventionally-managed stands are harvested before they are fully mature. This results in an initial temporary reduction in landscape level carbon stock, followed by an increase to a stable carbon stock at a higher level than the conventional management. If the forest is not harvested and left unmanaged, the reference landscape level carbon stock increases as each of the stands reaches mature or over-mature conditions. Depending on the equilibrium carbon stock in unmanaged stands, the reference landscape level carbon stock either remains at a high equilibrium or slowly decreases to a lower equilibrium level.

Annual net CO_2 emissions on the landscape scale are shown in Fig. 11.14, calculated as emissions of conventional and fertilized stands minus emissions of reference unmanaged stands with high and low levels of equilibrium carbon stock. Emissions of CH_4 and N_2O due to fertilization are minor and are not shown. The net emissions

Fig. 11.14 Average annual landscape level net CO_2 emissions ($MgCO_2$ ha^{-1}) of the 109 managed forest stands, calculated as emissions of conventional and fertilized stands minus emissions of reference unmanaged stands with high and low levels of equilibrium carbon stock
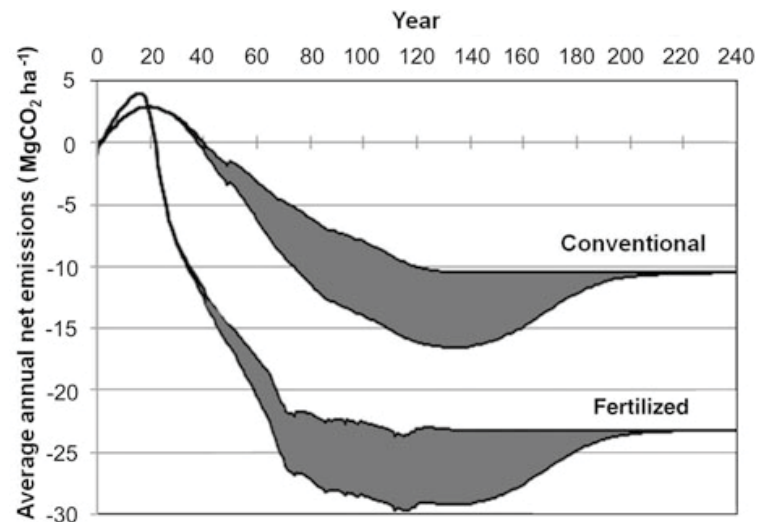
Fig. 11.15 Cumulative landscape level net CO_2 emissions ($MgCO_2$ ha^{-1}) of 109 managed forest stands, calculated as emissions of conventional and fertilized stands minus emissions of reference unmanaged stands with high and low levels of equilibrium carbon stock
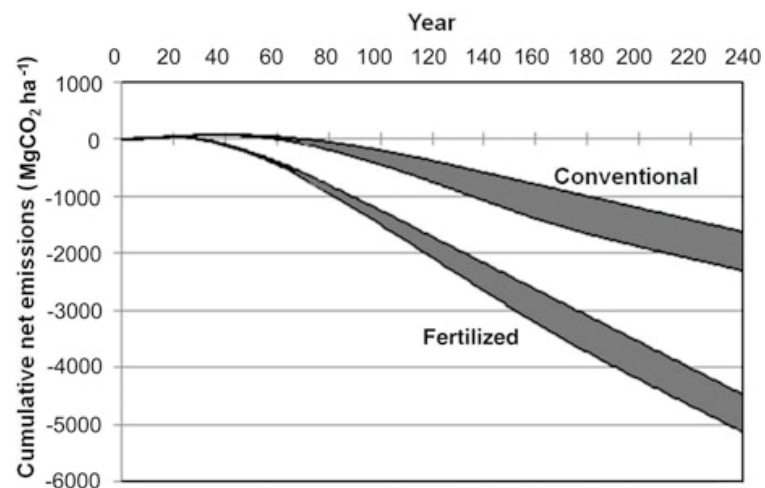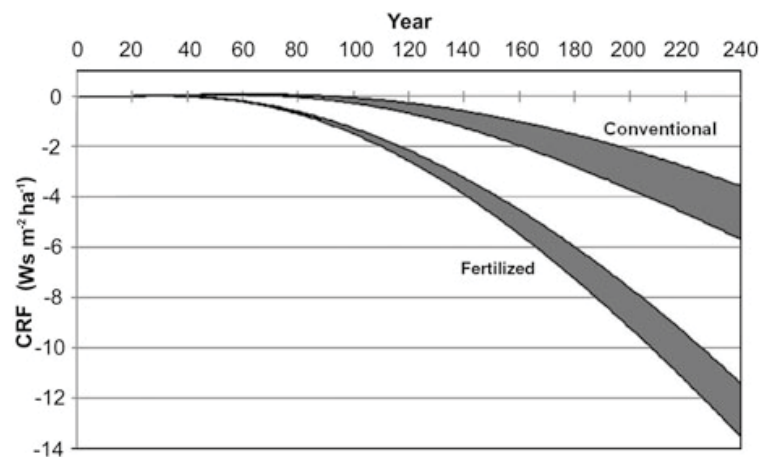
include changes in biomass carbon stock, changes in soil carbon stock, changes in wood product carbon stock, emissions from forest management activities, and avoided emissions due to substitution of non-wood material and fuel, estimated using the methodology of Sathre and Gustavsson (2012). The managed regimes result in negative emissions, mainly due to avoided emissions resulting from substitution of carbon-intensive non-wood fuels and materials. The fertilized regime has more avoided emissions than the conventional regime, because the biomass production is greater which allows more substitution of non-wood products. The unmanaged regime ultimately results in zero net emissions, as the forest ecosystem reaches dynamic equilibrium and no forest products are produced and substituted for non-wood products. If the unmanaged forest stabilises at a lower carbon stock, there is a period of net positive CO_2 emissions from dying biomass before reaching long term equilibrium at zero net emissions.

Cumulative net CO_2 emissions on the landscape scale are shown in Fig. 11.15. The unmanaged stands eventually stabilise and make no further contributions to the carbon balance. The managed stands, on the other hand, continue to accumulate

Fig. 11.16 CRF (W s m^{-2} ha^{-1}) over time of 109 managed forest stands, calculated as CRF of conventional and fertilized stands minus CRF of reference unmanaged stands with high and low levels of equilibrium carbon stock

avoided CO_2 emissions due to the use of harvested biomass to substitute for carbon-intensive non-wood fuels and materials. By the end of the 240-year study period, the avoided emissions from the fertilized stand are about double those of the conventional stand, due to the higher biomass production rates of the fertilized regime.

The net landscape level CRF over time is shown in Fig. 11.16, calculated as CRF of conventional and fertilized stands minus CRF of reference unmanaged stands. The fertilized regime results in significantly less climate impacts than the conventional regime, with a net CRF of about -11 to -13 W s m^{-2} ha^{-1} after 240 years, depending on the equilibrium carbon stock of the unmanaged reference case. The conventional regime results in about half as much the avoided net CRF as the fertilized regime, with about -4 to -6 W s m^{-2} ha^{-1} after 240 years. The difference between the CRF of the unmanaged regimes shown in Fig. 11.16 and that shown in Fig. 11.11 is due to the different starting conditions of the scenarios (compare Figs. 11.10 and 11.12). One scenario begins with a mature forest, and the other begins with a recently harvested stand. The carbon emission differences between the unmanaged (low) and unmanaged (high) scenarios have a greater impact on net CRF in Fig. 11.16 compared with Fig. 11.11 because emissions occurring earlier in time cause more radiative forcing because they reside in the atmosphere for a longer proportion of the study time horizon. This shows the importance of methodological choices in defining temporal system boundaries, which may be more significant for radiative forcing analysis than for carbon balance analysis.

11.5   Conclusions

In this chapter we have discussed the temporal dynamics of forest bioenergy systems, and have described the development and application of models to estimate the CRF associated with various forest management and forest product use options. This type of analysis provides insight into the potential trade-offs between short-term carbon sequestration benefits and long-term substitution benefits. It may be used to determine optimal strategies for managing forests and using forest products so as to minimise CRF and climate change impacts. Implementing these strategies will require the

integration of progressive practices of forest management, fertilization, soil science, forest products industries, energy systems, construction, and waste management.

Future steps are to further develop, improve, and use modeling tools to estimate the climate and energy implications of forest systems over varying spatial and temporal scales. The interactions of the following three important factors linked to forestry should be better understood: (1) Forest management intensity, e.g., conventional, fertilized and unmanaged regimes; (2) Geographic aggregation of analysis, i.e., stand level versus landscape level dynamics; and (3) Initial boundary conditions, e.g., a mature or harvested forest stand, or a range of age classes across a landscape. The patterns of these complex systems are difficult to compare quantitatively using conventional, static carbon balance approaches. Rigorous analysis of temporal dynamics may reveal subjective valuations of time preferences, e.g., the favor given to current population and desires. Radiative forcing analysis may be used to further our understanding of the appropriate roles for forests in the future, and appropriate management strategies for forests as part of a transition to a low-carbon society.

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