Effects of initial age structure of managed Norway spruce forest area on net climate impact of using forest biomass for energy

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Abstract

We investigated how the initial age structure of a managed, middle boreal (62° N), Norway spruce dominated (*Picea abies* L. Karst.) forest area affects the net climate impact of using forest biomass for energy. The model-based analysis used a gap-type forest ecosystem model linked to a life cycle assessment (LCA) tool. The net climate impact of energy biomass refers to the difference in annual net CO_2 exchange between the biosystem using forest biomass (logging residues from final felling) and the fossil (reference) system using coal. In the simulations over the 80-year period, the alternative initial age structures of the forest areas were: (i) skewed to the right (dominated by young stands), (ii) normally distributed (dominated by middle-aged stands), (iii) skewed to the left (dominated by mature stands), and (iv) evenly distributed (same share of different age classes). The effects of management on net climate impacts were studied using current recommendations as a baseline with a fixed rotation period of 80 years. In alternative management scenarios, the volume of the growing stock was maintained 20% higher over the rotation compared to the baseline, and/or nitrogen fertilization was used to enhance carbon sequestration. According to the results, the initial age structure of the forest area affected largely the net climate impact of using energy biomass over time. An initially right-skewed age structure produced the highest climate benefits over the 80-year simulation period, in contrast to the left-skewed age structure. Furthermore, management that enhanced carbon sequestration increased the potential of energy biomass to replace coal; reducing CO_2 emissions and enhancing climate change mitigation.

Keywords: bioenergy, climate impact, forest biomass, forest management, radiative forcing, substitution

Acknowledgements: This work was mainly funded by the METY project (A32172) under the European Regional Development Fund. Its finalization was also supported by the FORBIO project (14970), funded by the Strategic Research Council of Academy of Finland.

Introduction

An understanding of the dynamics of carbon flows in managed forests is needed to increase their capacity to remove and store carbon dioxide (CO_2) outside the atmosphere [1]. Management and harvest cycles over a rotation affect the carbon sequestration potential of the growing stock, as well as the potential for biomass harvest. The potential of biomass for replacing fossil-based materials (e.g. concrete and plastics) and fossil energy (e.g. coal and oil) is further affected by the harvest intensity of the biomass (e.g. saw log, pulp wood, energy biomass). All of these factors affect the possibilities for mitigating emissions through increasing carbon sequestration in ecosystems, and using forest biomass in place of fossil fuels. In this context, the timing of emissions has an impact on the climate benefits of biomass production and utilization when compared to the use of fossil counterparts, and consequently on efficient management measures for climate change mitigation [e.g. 1–6].

A forested area initially dominated by mature stands provides the maximum potential for timber, whereas areas with a normal age distribution of stands, or those dominated by young stands provide the highest carbon sequestration in the short term [7, 8]. Harvested biomass produces the highest climate benefits when it is used in replacing both fossil fuels and/or fossil-based materials, while maintaining sustainable carbon sequestration of forests [9–11]. In the case of energy biomass (e.g. logging residues), the initial level of carbon sequestration in a forested area critically affects the mitigation potential. This is because the amount of CO_2 released into the atmosphere during the combustion of energy biomass may be higher per energy unit than that emitted when using fossil fuels (e.g. coal), temporarily increasing the amount of carbon in the atmosphere [12, 13]. However, the temporary increase in CO_2 is offset by carbon sequestration after regrowth of the stand, in a time frame that is dependent on forest management practices and harvest intensity [11]. Therefore, the joint impacts of CO_2 release and carbon sequestration on total emission mitigation are highly sensitive to the initial conditions of the studied biosystem [14].

In general, the carbon uptake of a forest stand peaks earlier than the point when the maximum carbon stock (carbon in trees and soil) is achieved. Therefore, forest area initially dominated by young stands have been found to produce the lowest emissions for energy biomass utilization when rotation lengths of 60–80 years are used [7]. In turn, rotation lengths of 120 years in a forest area with initially normally distributed age structure have been found to produce the lowest emissions [7]. Intensive management of a single stand, including the use of nitrogen fertilizers, improved planting material, and high stocking density, also increases the climate benefits of using energy biomass compared to the use of fossil-based energy under alternative rotation periods, due to increased carbon sequestration [9, 15–20]. However, the potential of forest management to increase carbon sequestration within a certain time frame also depends on the age structure of a forest area. This further affects the temporal distribution of the future climate benefits and CO_2 emissions of energy biomass utilization.

In this context, the effects of the alternative initial age structures and management of a Norway spruce (*Picea abies* L. Karst.) forest area in the middle boreal zone (62^{o} N) on the net climate impact, and its timing when using forest biomass for energy, were quantified. A model-based analysis using a gap-type forest ecosystem model, linked to a life cycle assessment (LCA) tool was used. The net climate impact of energy biomass is defined as the annual difference in net CO_2 exchange between the biosystem using forest biomass (logging residues from final felling), and the fossil (reference) system using coal, over an 80-year period. The net climate impact of energy biomass was expressed in terms of carbon neutrality and relative radiative forcing. Four initial age structures of a forest area were used in initializing the simulations: (i) skewed to the right, (ii) normally distributed, (iii) skewed to the left, and (iv) evenly distributed. To determine the effects of management, current forest management recommendations (baseline management, without harvesting of logging residues) were used as a reference. In alternative management scenarios, stocking density (basal area of the stands) was maintained at a level 20% higher over the rotation than in the baseline, and/or nitrogen fertilization was used to enhance carbon sequestration and energy biomass production.

Materials and methods

Outlines for calculating net climate impacts between biosystems and fossil system

The net climate impact for energy biomass production and utilization was calculated by comparing the use of logging residues from final fellings (including the top part of the stem, branches, 70% of needles, stumps, and coarse roots) to the use of fossil coal. The calculation was carried out for model forest areas consisting of 80 single Norway spruce stands (each covering 1 hectare) and by using alternative initial age structures for these areas at the beginning of the 80-year simulation period (**Fig. 1**). The alternative initial stand age structures were used to quantify in which initial conditions, and within which time horizon energy, biomass production and its utilization for fossil coal substitution gave the highest net climate impact. The alternative initial age structures were created by using the even age class distribution, since each stand represented one age class in this case. The tree stand characteristics and amount of initial soil organic matter for the stands of the even age structure were created based on an 80-year simulation using current management recommendations (see also [21]). Current management practices were used to make the initial conditions of the forested areas comparable with the alternative management scenarios.

The initial values for the alternative age structures were derived by multiplying the values for the tree stand characteristics and soil organic matter of the even age structure by the relative frequencies of the stands in the forest area shown in **Fig. 1.** The initial age structure of stands in the forest area used in the calculations were (i) right-skewed (most of the stands are young), (ii) normally distributed (most of the stands are middle-aged), (iii) left-skewed (most of the stands are mature), and (iv) even age class distribution (each stand represents one age class and one stand is harvested every year) (**Fig. 1**). The mean ages of the stands for right-skewed, normally distributed, and left-skewed structures were 10, 40, and 70 years, and the standard deviations of the stand ages were 40, 30, and 40 years, respectively.

In the comparison of the biosystem and fossil system, the (current) baseline management was used as a reference forest management for the fossil system (**Fig. 2**). Baseline management included only timber (sawlogs and pulpwood) harvest—logging residues were not harvested. In the biosystem, alternative management scenarios deviating from the baseline management were used to study the sensitivity of the climate change mitigation potential of energy biomass under the alternative initial age structures. The alternative management scenarios aimed to enhance the carbon sequestration and energy biomass production of the forests in the area. When energy biomass was used, it always replaced fossil coal in the calculations. The annual quantity of energy was assumed to be equal in both systems, so that the use of fossil energy followed the amount of energy in the harvestable energy biomass in the biosystem. When fossil energy (coal) was utilized, the logging residues were left on the site to decay, emitting carbon to the atmosphere. The energy content used for energy biomass was 8.1 GJ Mg^{-1} (40% moisture content of wood) [21, 22, 23], and the CO_2 mass emission factor used for the combustion of coal was 93.3 kg GJ^{-1} [24].

Calculation of net climate impact for the production and utilization of energy biomass

The net climate impact of the production and utilization of energy biomass (I_{NET}) in comparison to the use of coal was indicated by the differences in: (i) annual net CO_2 exchange, (ii) carbon neutrality, and (iii) radiative forcing. In each case, the differences were related to the CO_2 exchange (C_{net}) between the alternative initial stand age structures and management scenarios in the biosystem and the baseline (reference) scenario in the fossil system (**Eq. 1**):

$$I_{NET} = (a + (a - d) \times c) - (b) \quad (1)$$

In Equation 1, a is the C_{net} (g CO_2 m^{-2} yr^{-1}) (**Eq. 2**) of the biosystem under baseline management with the use of energy biomass, b is the C_{net} (g CO_2 m^{-2} yr^{-1}) of the fossil system under baseline (reference) management with the use of coal, c is the share of energy biomass from the total harvested biomass (between 0 and 1), and d is the net CO_2 exchange of alternative management scenarios (g CO_2 m^{-2} yr^{-1}). The enhanced carbon sequestration in the alternative management scenarios was partitioned by the share of the energy biomass from total harvested biomass over the rotation period. Partition was done to allow the biosystem to benefit only from the share that belongs to energy biomass.

The calculation of annual C_{net} (g CO_2 m^{-2} yr^{-1}) (**Eq. 2**) is based on the carbon uptake during growth (C_{seq}), carbon emissions from decaying soil organic matter (C_{decomp}), and the combustion of either energy biomass in the biosystem (C_{harv}) or coal in the fossil system (C_{coal}). The release of carbon during the combustion of energy biomass was assumed to take place immediately after harvesting.

$$C_{net} = C_{seq} + C_{decomp} + C_{harv} \vee C_{coal} \quad (2)$$

The carbon neutrality (CN) of energy biomass production and utilization was calculated by comparing the net CO_2 exchange (C_{net}) of using energy biomass to the CO_2 exchange of the utilization of coal (**Eq. 3**), in kg CO_2 MWh^{-1}.

$$CN = \frac{FOSSIL\ SYSTEM - BIOSYSTEM}{FOSSIL\ SYSTEM} \quad (3)$$

Radiative forcing (RF) refers to the change in the balance of incoming and outgoing energy in the Earth-atmosphere system. A negative RF cools the surface of the Earth, whereas a positive RF warms the surface. The net climate impact (I_{NET}) was converted into the instantaneous RF (Wm^{-2}) using **Eq. 4–6** [25].

$$\Delta RF = \alpha \ln\left(\frac{C}{C_0}\right) \quad (4)$$

$$\Delta C(t) = \int_0^t E(\tau) f(t-\tau) d\tau \quad (5)$$

$$f_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i e^{-t/\tau_i} \quad (6)$$

In **Eq. 4**, the parameter α has the value 5.35 Wm^{-2}, C_o is the reference concentration of CO_2 in the atmosphere, and C is the prevailing CO_2 concentration, both in ppm. In **Eq. 5**, ΔC(t) is the change in the CO_2 concentration (ppm), τ is time, t is the time period in question, and E is the change in CO_2 concentration in the atmosphere (expressed in kg relative to the total mass of atmosphere in kg). In **Eq. 6**, the function f is the lifetime function of CO_2, indicating the decay of a pulse of CO_2 with time, where a_0, a_1, a_2, and a_3 are parameters with the values 0.217, 0.259, 0.338, and 0.186. Similarly, the values of the parameters τ_1, τ_2, and τ_3 are 172.9, 18.5, and 1.2, respectively [26].

For the final analysis, cumulative radiative forcing (CRF) (an integral of instantaneous radiative forcing over time) was calculated over the 80-year simulation period for the areas with alternative initial stand age structures and management scenarios. The same scenarios of the atmospheric CO_2 concentrations were used in the forest growth simulations and the radiative forcing calculations.

Model simulations needed to calculate an annual net CO_2 exchange for the management scenarios

Outline of the forest ecosystem model

The outputs of ecosystem model simulations [27] were utilized to estimate the annual net CO_2 exchanges (C_{net}) in the systems by using a life cycle assessment (LCA) tool [28]. The forest ecosystem model SIMA [29, 27, 15, 16] was used to simulate the forest growth and development of the tree stands under the influences of temperature; the availability of light, soil water, and nitrogen; and the CO_2 concentration in the atmosphere. Trees may die randomly, but the probability of death increases with a decline in growth. In the simulations, organic matter in litter and dead trees ended up in the soil where it decayed, releasing CO_2 and nitrogen. In decomposition, carbon emissions originated from new litter, old litter, and humus on the site. The old soil organic matter (SOM) was 67 Mg ha^{-1} for the initial medium fertile stand (*Myrtillus* type) [26]. New litter and humus made up the SOM generated during the simulations. The dynamics of available nitrogen were determined by the amount of nitrogen released and immobilized in the decomposition of soil organic matter. Annual nitrogen deposition was set at 10.0 kg ha^{-1} [30]. The decomposition rate parameters for the litter and humus of Norway spruce are shown in [31]. In simulations, the current climate (temperature, precipitation) during the period 1971–2000 [32, 33] was used. The atmospheric CO_2 concentration was 372 ppm.

Alternative management and harvesting scenarios used in the simulations

The alternative management and harvesting scenarios used in the simulations are shown in **Table 1**. In the baseline management (BT), only timber was harvested and the current forest management recommendations were followed [34, 35]. The timing and frequency of thinning over a fixed rotation period of 80 years were determined based on the thresholds for basal area at given dominant heights. Energy biomass was harvested only in the final felling of the stands at the end of the 80-year rotation (BNR scenarios). Energy biomass included logging residues (top part of stem, branches, and 70% of needles) with stumps and coarse roots [34]. In alternative management scenarios, 20% higher basal area thresholds were applied for thinning to maintain higher stocking density (basal area of the stand) over a rotation compared to the baseline management (BNR20). In addition, nitrogen fertilization (150 kg ha^{-1} at fixed years of 50 and 65) was applied (BNRF and BNR20F). After final felling, the site was planted with 2500 Norway spruce seedlings per hectare and managed following the alternative management scenarios.

Results

Energy biomass production

The production of energy biomass was the highest for the initially left-skewed and the lowest for the initially right-skewed age structure at the beginning of the study period. The initially normally-distributed age structure reached energy biomass production similar to that of the initially evenly-distributed age structure 40 years from the start of the simulation in all the management scenarios. Mean cumulative energy biomass production (expressed in energy units) over the whole simulation period, and in all the initial age structures, was the highest when maintaining 20% higher stocking density than in the baseline, and using nitrogen fertilization in the forest area (2.55 MWh $ha^{-1}yr^{-1}$) (**Fig. 3**). When maintaining 20% higher stocking density, energy biomass production was 2.50 MWh yr^{-1} and when using nitrogen fertilization, it was 2.06 MWh $ha^{-1}yr^{-1}$ over the 80-year simulation period. Under the baseline scenario with energy biomass harvesting (BNR), the energy biomass production was at its lowest (2.02 MWh $ha^{-1}yr^{-1}$).

Net climate impact in terms of difference in annual net CO_2 exchanges (C_{net}) between the biosystem and fossil system

The net climate impact (I_{NET}) of the energy biomass production and utilization is shown in **Fig. 4** as a cumulative mean difference in net CO_2 exchange (C_{net}) between the biosystem and fossil system. Initially, the highest values of net climate impact were for left-skewed and the lowest ones for right-skewed age structure. The net climate impact was highest (lowest climate benefit) in the baseline management scenario (-600 kg CO_2 ha^{-1} yr^{-1}) and lowest (highest climate benefit) in all the initial age structures when maintaining 20% higher stocking density with nitrogen fertilization (-1200 kg CO_2 ha^{-1} yr^{-1}) over the simulation period.

Net climate impact in terms of carbon neutrality (CN) and avoided CO_2 emissions between the biosystem and fossil system

The cumulative mean CN values for the energy biomass were 0.87, 1.14, 1.14, and 1.39 over the whole simulation period in baseline (BNR), nitrogen fertilization (BNRF), 20% higher stocking density (BNR20), and nitrogen fertilization and 20% higher stocking density (BNR20F), respectively (**Fig. 5**). CN values were initially highest (highest climate benefits) for the right-skewed age structure and the lowest (lowest climate benefits) for the left-skewed age structure.

The use of energy biomass instead of coal avoided CO_2 emissions of 257–424 kg MWh^{-1} over the study period (**Table 2**). The highest reductions were found when maintaining 20% higher stocking density, using nitrogen fertilization, and in the baseline management. Maintaining 20% higher stocking density with nitrogen fertilization increased net carbon sequestration and energy biomass production the most (**Fig. 3 and 4**), but could not reach the highest amount of emissions avoided per produced MWh over the whole study period. The lowest avoided emissions per MWh were for the even age structure, followed by the normal, left-skewed, and right-skewed initial age structures (**Table 2**).

Net climate impact in terms of radiative forcing (RF) between the biosystem and fossil system

The net climate impacts (I_{NET}) of the utilization of energy biomass compared to the use of fossil coal under alternative initial age class structures and management scenarios are shown in **Fig. 6** in terms of radiative forcing. Generally, negative forcing (cooling climate impact) was found for the production and utilization of energy biomass as compared to coal, up to -5.8 nWm^{-2}. The lowest cooling impact was found for the initially left-skewed age structure. By using baseline management (BNR) for this structure, the climate benefits realized at the end of the simulation. In the initially left-skewed age structure, the use of nitrogen fertilization increased the net climate impact, and the radiative forcing was lower after 40 years from the start of the simulation period than when coal was used. With this same age structure, when maintaining 20% higher stocking density, with or without nitrogen fertilization, the net climate impact was lower after the first 10 years than when coal was used. Whereas with the other initial age structures, the climate benefits were gained after a few years from the start of the use of energy biomass.

Discussion

In this study, the effects of initial stand age structures and management of Norway spruce in a forest area in the middle boreal zone (62° N) on the net climate impact of energy biomass production and utilization was analyzed. Forest ecosystem model [27] simulations linked to a life cycle assessment (LCA) tool [28] were used. The net climate impact was calculated by comparing the CO_2 exchange of the use of logging residues harvested from final fellings to the use of fossil coal, and was further expressed in terms of carbon neutrality, average amount of avoided CO_2 emissions over the study period, and relative radiative forcing. The energy biomass produced in the forest area always replaced fossil coal in the calculations. To determine the effects of management, current forest management recommendations were used as a reference. In the biosystem, alternative management scenarios included 20% higher stocking density over the rotation and/or nitrogen fertilization to increase carbon sequestration and energy biomass production.

The net climate impact of energy biomass production and utilization over the simulation period was the lowest (highest cooling impact) if the stand age structure of the forest area was initially right-skewed, and the highest if it was left-skewed. This was due to differences in net carbon sequestration and timing of emissions from energy biomass utilization, in comparison with the fossil system under the alternative age structures. With the initially left-skewed age structure, and under baseline management, the carbon neutrality (CN = 1) was not obtained over the study period, but the use of energy biomass produced lower emissions than fossil coal (CN > 0). In this case, over the initial 19 years of the simulation, the emissions from energy biomass were lower than when using coal, which was in line with studies showing that logging residues from final felling have lower climate impacts than coal about 20 years after use e.g. [36–39, 11]. In this case, maintaining 20% higher stocking density and using nitrogen fertilization, a 60% increase in carbon neutrality of energy biomass could be obtained over the study period compared to the baseline management.

Over the whole study period, the largest quantity of emissions avoided (per produced MWh) was also found for the right-skewed initial age structure when maintaining a 20% higher stocking density. Maintaining a 20% higher stocking density and using fertilization increased both carbon sequestration and energy biomass production, but did not result in the highest amount of avoided emissions per energy unit when considered over the whole study period. This was especially the case for the even initial age structure in which the management measures (e.g. fertilization) taking place in the later stages of stand development mostly increased the energy biomass production rather than net carbon sequestration. However, the fastest occurrence of net climate impact was found for the initially right-skewed age structure in which management regimes could also increase carbon sequestration efficiently in the early stages of stand development. For the initially normal and left-skewed age structures, the intensified management regimes produced lower amounts of avoided emissions compared to the baseline management over the whole study period.

Based on our results for radiative forcing, the climate benefits of using energy biomass were realized later than indicated by carbon neutrality (CN). As the radiative forcing calculation takes into account the accumulation of carbon released into the atmosphere, any change in carbon concentration in the atmosphere at the beginning of the simulation period is emphasized. The cumulative radiative forcing under baseline management, for example, became negative after 75 years in the initially left-skewed forest area, and after 13 years in the initially right-skewed forest area (Figure 6). Use of the large amount of energy biomass from the initially left-skewed forest area caused a delay in recovery of emissions from using coal, but finally resulted in a cooling climate impact, compared to the fossil system (e.g. [12, 40–42]). However, under other initial age structures, radiative forcing became negative a few years after the start of the simulation. Therefore, the interpretation of the results from fully dynamic approaches and from the static ones (e.g. global warming potential, GWP) should be done with care when assessing net climate impacts of energy biomass from forest ecosystems.

Regardless of the initial age structure of the forest area, the use of higher stocking density and/or nitrogen fertilization could enhance the climate benefits of energy biomass. However, forest management also enhanced climate benefits most in the forested area with an initially right-skewed or even age-class structure. Previously, it has generally been observed that forest management could affect largely the climate benefits when using biomass for energy [9, 43]. Forest fertilization has been found to reduce carbon emissions and to increase the availability of primary energy in the integrated production of timber and energy biomass [44]. Decreases in carbon emissions have also been found when emissions for nitrogen fertilizers were included in the analysis [15]. However, the availability of nutrients after the harvesting of logging residues may decrease, affecting the long-term productivity of the forest ecosystem [45, 46]. The whole tree harvesting of energy biomass from thinnings has been found to reduce the volume growth of Norway spruce stands (6%) during the first 10 years after thinning [47]. However, in our case the logging residues were harvested only from final felling. On the other hand, the nitrogen fertilization may also decrease microbial activity and decrease decomposition of organic matter in the soil [48].

In this study, higher rates of carbon sequestration could also shorten the time during which the emissions from the comparator fossil system were recovered, regardless of initial age structure. Previously, the lowest emissions for energy biomass in the integrated production of energy biomass and timber have been found over rotation lengths of 60–80 years [7]. The cooling climate impact (negative radiative forcing) started under the baseline management 35 years earlier when nitrogen fertilization was used in the forest area with a left-skewed age structure. With this same initial age structure, using 20% higher stocking density and nitrogen fertilization, the cooling impact was evident after 10 years. In general, evaluation of the climate benefits of energy biomass based on radiative forcing has been stated to produce overestimates over short-term periods, compared to estimations expressed as global surface temperature change [38]. On the other hand, if the effects of climate change are included in the long-term analyses of the carbon sequestration of the forest ecosystems, the efficiency of energy biomass in replacing fossil coal may decrease due to an increase in CO_2 concentration in the reference climate scenario [21].

In conclusion, the results of this study show that the initial stand age structure of the forest area plays an important role in determining the potential of using energy biomass in climate change mitigation in boreal conditions over different time spans. The initial age structure affects the possibility of using forest management to increase carbon sequestration and energy biomass production, and consequently the potential of energy biomass in replacing fossil coal. The results of this study also show that forest management that increases carbon sequestration recovers the initially higher unit emissions of the energy biomass faster compared to those of fossil coal. Our analysis considered only the net climate impacts for using energy biomass. Therefore, future work should also consider the impacts of using wood products in fossil material substitution. Further analyses are still needed to define efficient management of alternative biomass-based production systems for climate change mitigation, as well as under a changing climate.

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Figure and table captions

Fig 1. Alternative initial stand age structures of the forest area producing energy biomass used in the study. Right-skewed = forest area occupied initially by mostly young stands. Normal = forest area occupied initially by mostly middle-aged stands. Left-skewed = forest area occupied initially by mostly mature stands. Even = forest area consisting of stands each representing one age class.

Fig 2. Schematic figure of system boundaries of the study.

Fig 3. Cumulative mean energy biomass (logging residues, stumps, and roots) production from forest areas with alternative initial stand age structures (see **Fig. 1**) and forest management scenarios over the 80-year study period expressed in energy units. a = baseline with energy biomass harvesting (BNR), b = nitrogen fertilization (BNRF), c = 20% higher stocking density (BNR20) and d = 20% higher stocking density and nitrogen fertilization (BNR20F).

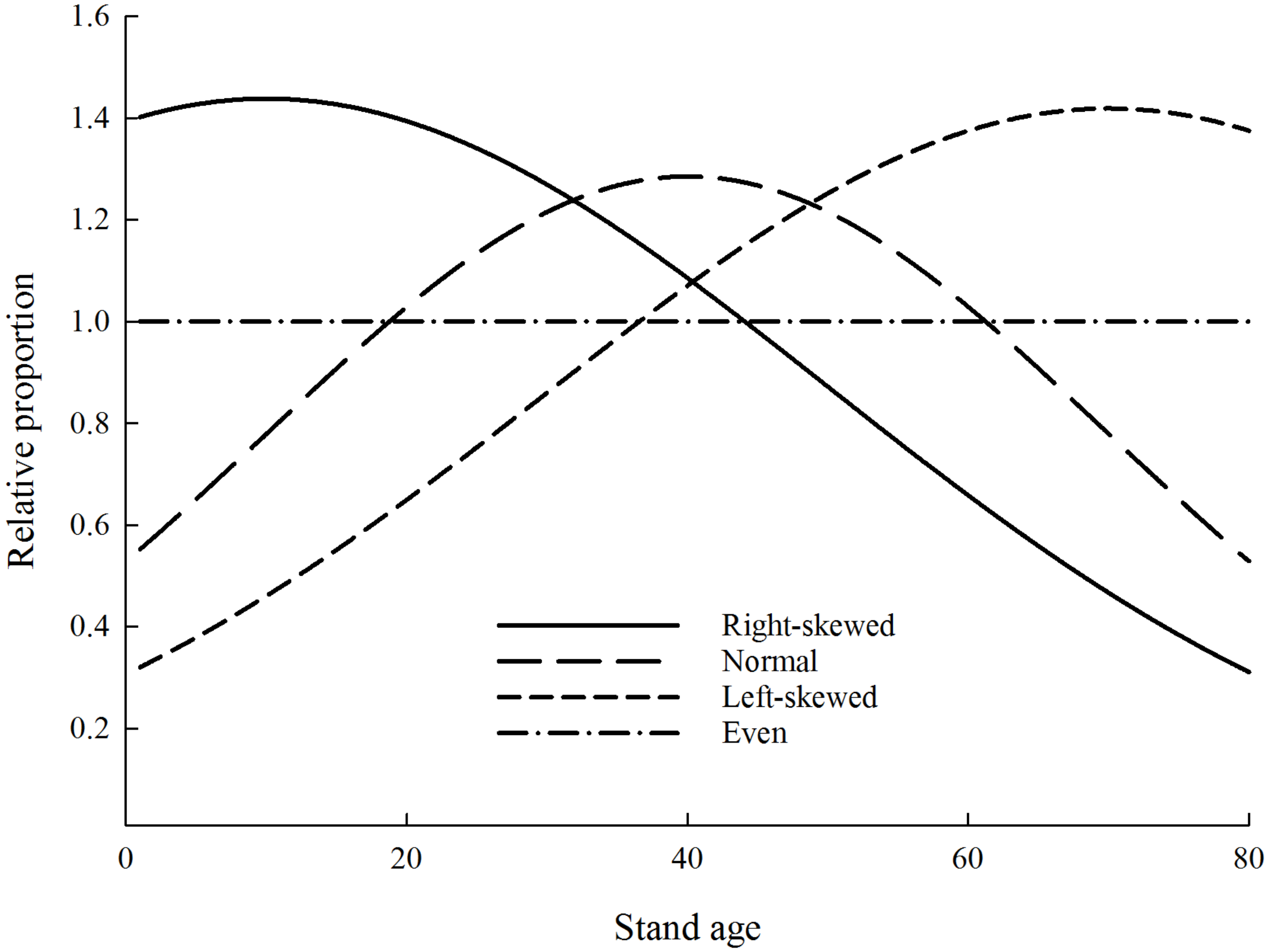
Fig 4. Net climate impact of energy biomass production and utilization (I_{NET}) (i.e. cumulative mean difference in C_{net} between biosystem and fossil system) from forest areas with alternative initial stand age structures (see **Fig. 1**) and forest management scenarios over the 80-year study period. a = baseline with energy biomass harvesting (BNR), b = nitrogen fertilization (BNRF), c = 20% higher stocking density (BNR20) and d = 20% higher stocking density and nitrogen fertilization (BNR20F).

Fig 5. Cumulative mean carbon neutrality of energy biomass production and utilization (CN) for forest areas with alternative initial age structures (see **Fig. 1**) and forest management scenarios over the 80-year study period. a = baseline with energy biomass harvesting (BNR), b = nitrogen fertilization (BNRF), c = 20% higher stocking density (BNR20) and d = 20% higher stocking density and nitrogen fertilization (BNR20F). Right-skewed = forest area occupied initially by mostly young stands. Normal = forest area occupied initially by mostly middle-aged stands. Left-skewed = forest area occupied initially by mostly mature stands. Even = forest area consisting of stands each representing one age class.

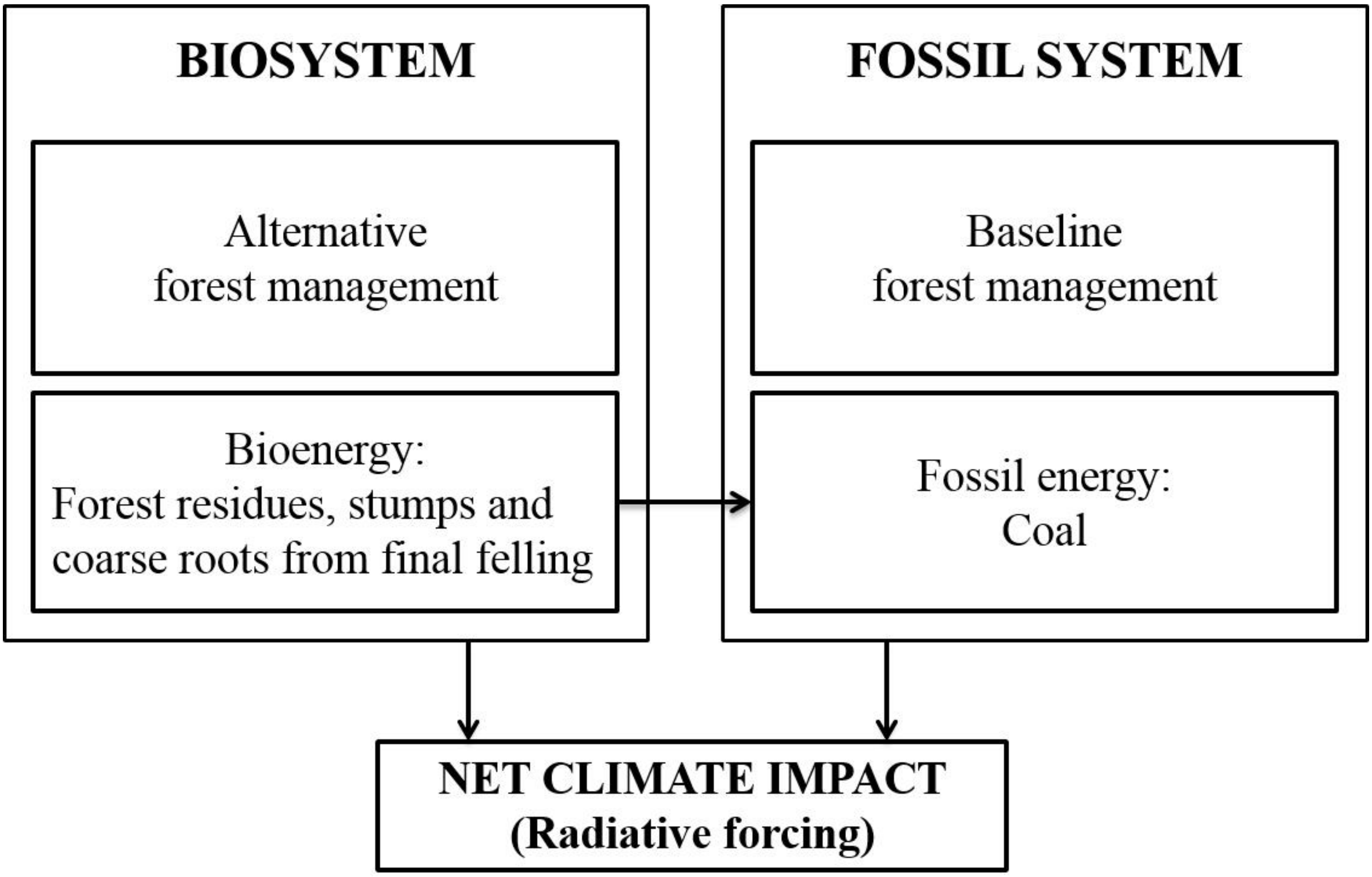
Fig 6. Cumulative relative radiative forcing (CRF) of energy biomass production and utilization under alternative initial age structures (See **Fig. 1**) and forest management scenarios over the 80-year study period. a = Right-skewed, b = Normal, c = Left-skewed and d = Even. BNR = baseline with energy biomass harvesting, BNRF = nitrogen fertilization, BNR20 = 20% higher stocking density and BNR20F = 20% higher stocking density and nitrogen fertilization.

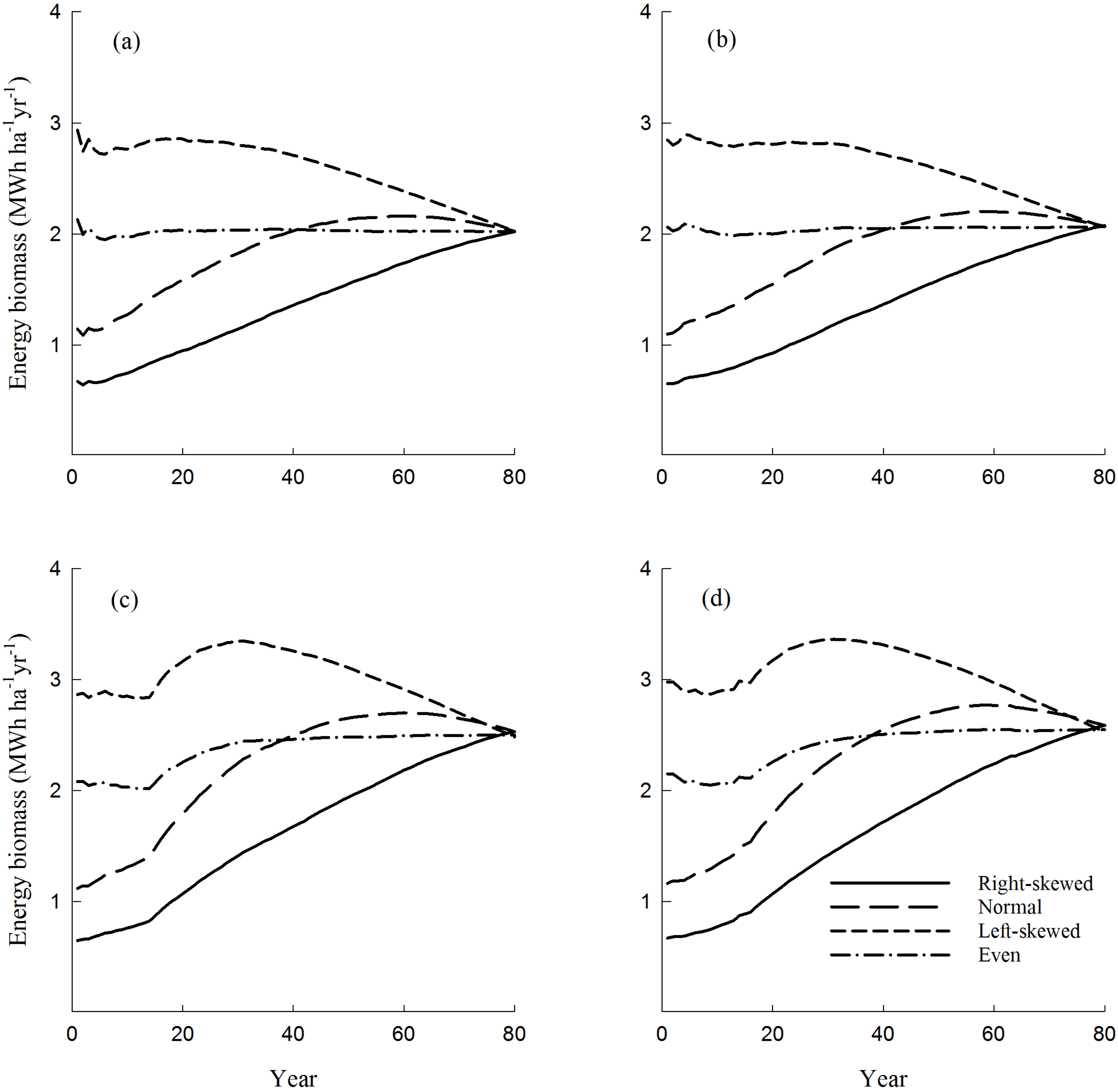
Table 1. Management and harvesting scenarios used in the study. BT = baseline (reference) management without energy biomass harvesting, BNR = baseline management with energy biomass harvesting, BNR20 = 20% higher stocking density compared to the baseline management, BNRF = nitrogen fertilization, and BNR20F = 20% higher stocking density compared to the baseline management and nitrogen fertilization.

Table 2. Avoided CO_2 emissions of energy biomass production and utilization (kg CO_2 $MWh^{-1}yr^{-1}$) under alternative forest management scenarios and initial age structures over the 80-year study period. BNR = baseline management with energy biomass harvesting, BNR20 = 20% higher stocking density compared to the baseline management, BNRF = nitrogen fertilization; and BNR20F = 20% higher stocking density compared to the baseline management and nitrogen fertilization.

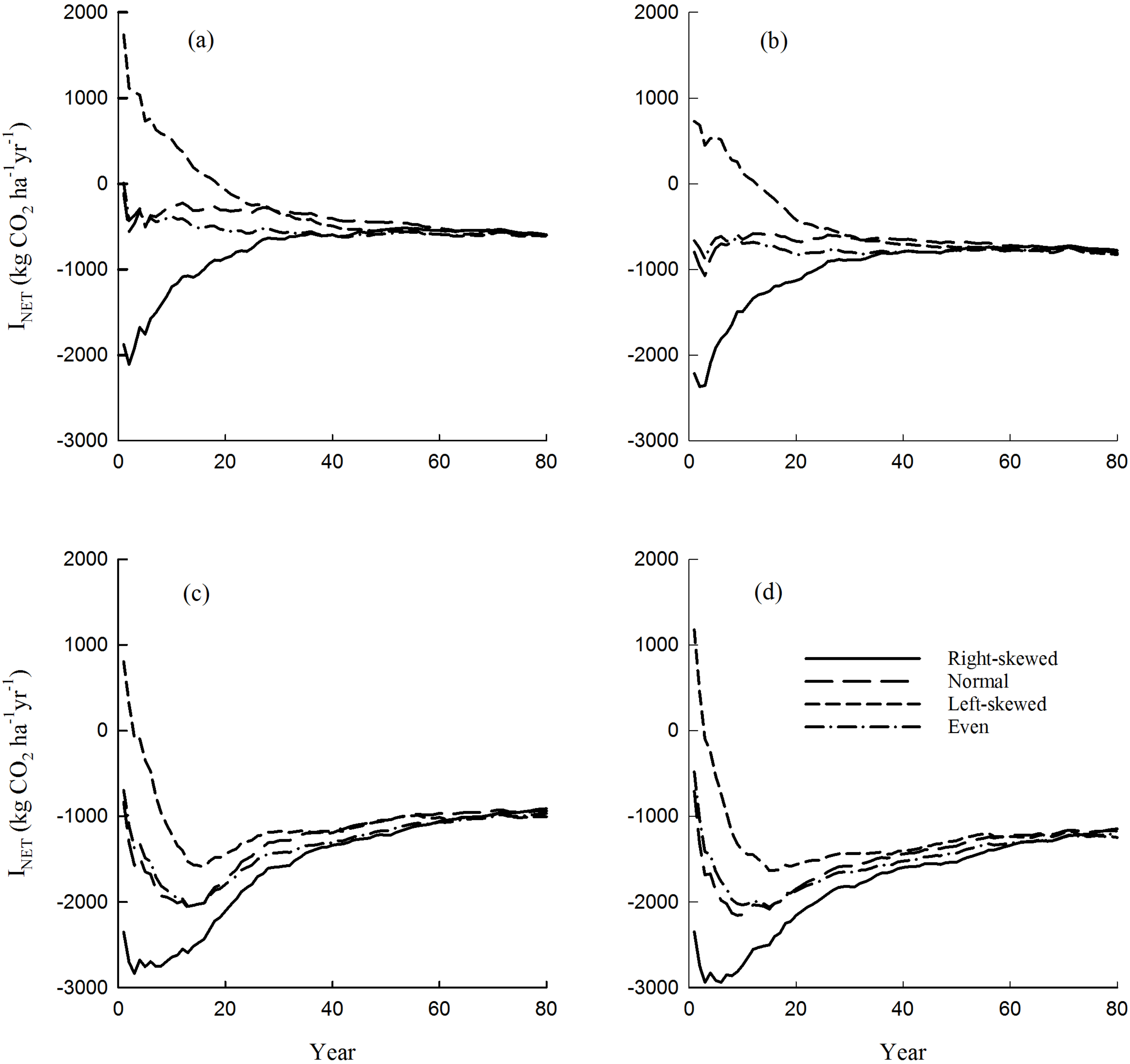


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Relative proportion
0
20
40
60
80
Stand age
Right-skewed
Normal
Left-skewed
Even

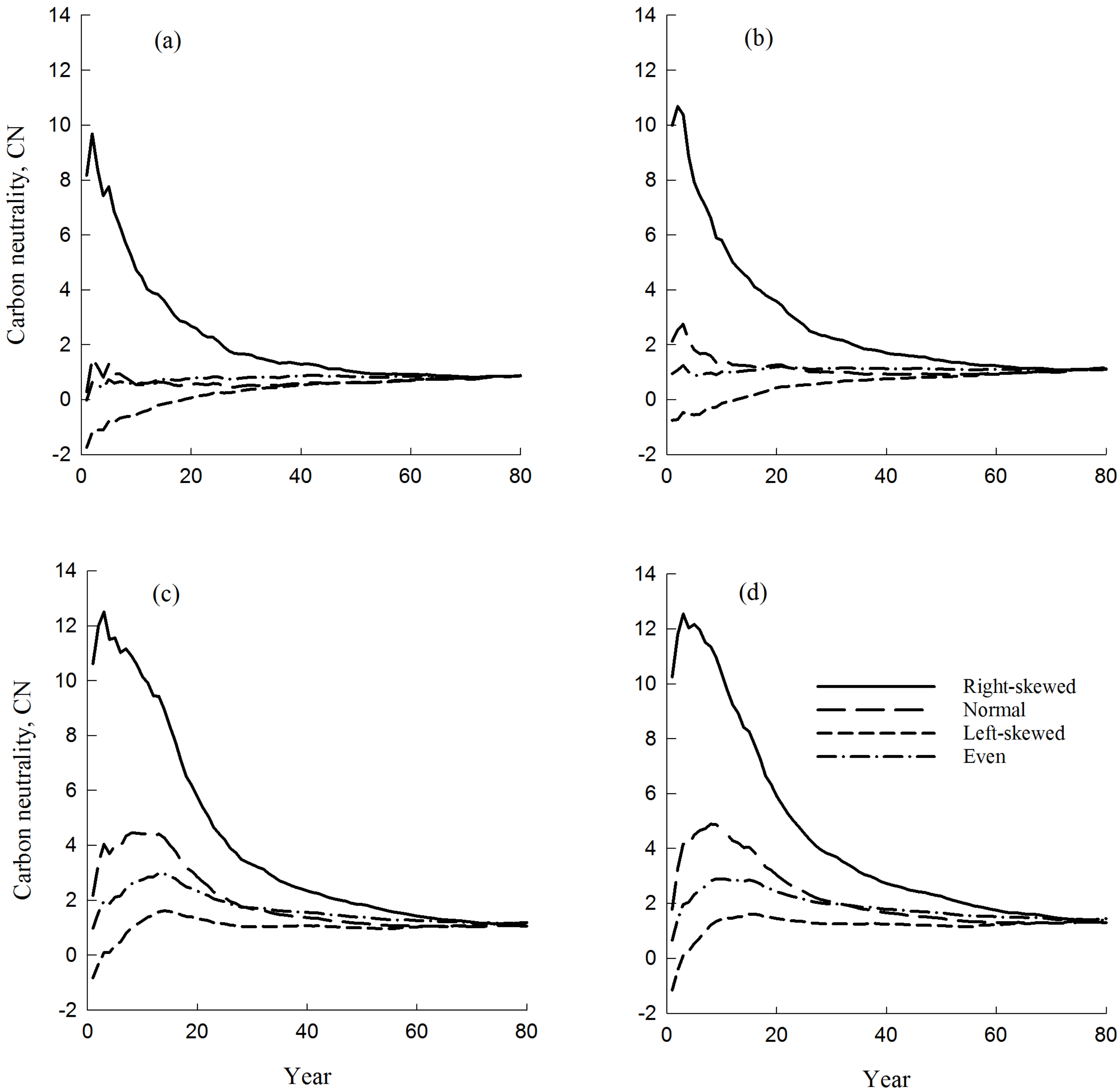

BIOSYSTEM
Alternative forest management
Bioenergy: Forest residues, stumps and coarse roots from final felling
FOSSIL SYSTEM
Baseline forest management
Fossil energy: Coal
NET CLIMATE IMPACT (Radiative forcing)



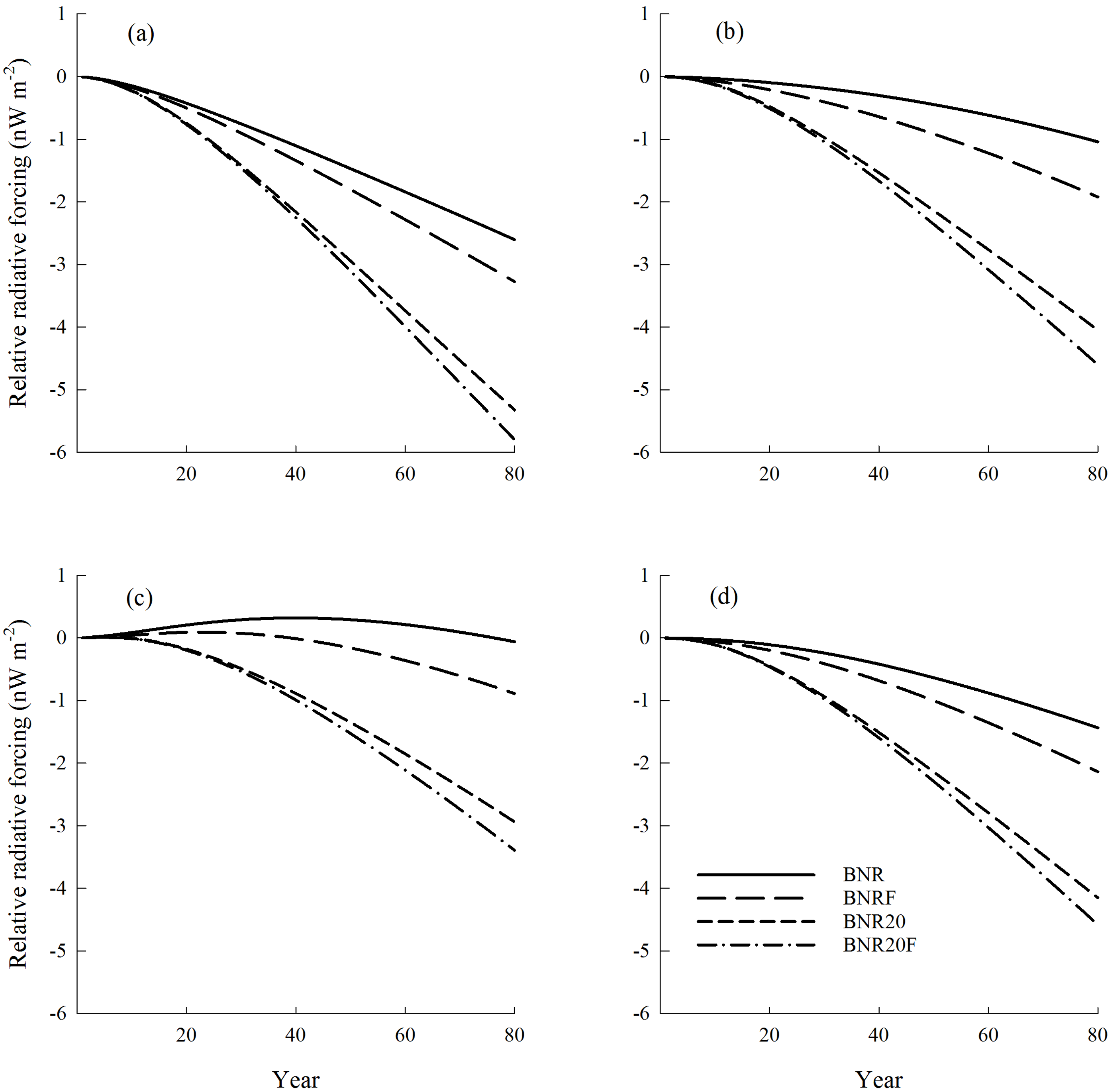
(a)
(b)
(c)
(d)
Energy biomass (MWh ha^{-1}yr^{-1})
Year
Right-skewed
Normal
Left-skewed
Even



(a)
(b)
(c)
(d)
I_{NET} (kg CO_2 ha^{-1}yr^{-1})
I_{NET} (kg CO_2 ha^{-1}yr^{-1})
2000
1000
0
-1000
-2000
-3000
0
20
40
60
80
Year
Year
Right-skewed
Normal
Left-skewed
Even



(a)
(b)
(c)
(d)
Carbon neutrality, CN
Year
14
12
10
8
6
4
2
0
-2
0
20
40
60
80
Right-skewed
Normal
Left-skewed
Even



(a)
(b)
(c)
(d)
Relative radiative forcing (nW m-2)
Year
BNR
BNRF
BNR20
BNR20F

Table 1. Management and harvesting scenarios used in the study. BT = baseline (reference) management without energy biomass harvesting, BNR = baseline management with energy biomass harvesting, BNR20 = 20% higher stocking density compared to the baseline management, BNRF = nitrogen fertilization, and BNR20F = 20% higher stocking density compared to the baseline management and nitrogen fertilization.

Management scenario	Change in basal area thresholds, %	Fertilization, 2 x 150 kg N ha^{-1}	Harvesting of energy biomass
BT(baseline)	-	-	-
BNR	-	-	Yes
BNR20	+ 20 %	-	Yes
BNRF	-	F	Yes
BNR20F	+ 20 %	F	Yes

Table 2. Avoided CO_2 emissions of energy biomass production and utilization (kg CO_2 $MWh^{-1}yr^{-1}$) under alternative forest management scenarios and initial age structures over the 80-year study period. BNR = baseline management with energy biomass harvesting, BNR20 = 20% higher stocking density compared to the baseline management, BNRF = nitrogen fertilization; and BNR20F = 20% higher stocking density compared to the baseline management and nitrogen fertilization.

Management scenario	Avoided CO_2 emissions, kg CO_2 $MWh^{-1}yr^{-1}$			
	Initial age structure			
	Right-skewed	Normal	Left-skewed	Even
BNR	-413	-328	-410	-303
BNR20	-423	-311	-360	-283
BNRF	-424	-302	-329	-265
BNR20F	-388	-284	-343	-257