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Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit

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Abstract

This study compares the costs and quantity of carbon mitigation by afforestation and fossil fuel substitution based on simple mathematical models of carbon stocks and flows assuming the growth conditions of trees in the southern US. Significant carbon benefit can be obtained by substituting biomass derived from short-rotation woody crops (SRWC) for coal or gasoline as opposed to sequestering carbon in standing trees. When biomass substitutes fossil fuel, the use of a given piece of land is not limited to just the period until the forest matures, as in the case of afforestation. At present high costs of existing biomass-based technologies and unavailability of cost-effective technologies (e.g., biomass-integrated gasifier/steam-injected gas turbine (BIG/STIG)) limits carbon sequestration to afforestation/reforestation for which the costs have been found to be modest. If growth rates of trees in afforested/reforested lands could be increased to the levels that are comparable to SRWC, more carbon benefit could be realized for a short-term horizon from afforestation than using biomass to displace fossil fuels. Carbon sequestered through afforestation projects can be used to earn carbon credits to meet carbon reduction targets through Kyoto mechanisms. As biomass-based technologies such as BIG/STIG or conversion of biomass to ethanol become commercially viable in the future, growing SRWC for substituting fossil fuels may become a cost-effective strategy to combat climate change.

Keywords: Carbon sequestration; Carbon offset; Afforestation; Fossil fuel substitution; Bioenergy

1. Introduction

The growing evidence of climate change resulting from the continued increase of greenhouse gas concentrations in the atmosphere has made it a powerful political, social, and trade issue. In response to climate change threats, interest in increasing carbon stocks in trees, and the use of tree biomass for fossil fuel substitution to minimize the increase in the atmospheric carbon concentration, has been growing among scientists, policymakers, and governments. Carbon (C) stocks in organic matter are one of the world's major carbon pools and the destruction of forests for agricultural uses and absence of appropriate fire management regimes accounts for about 20–30% of anthropogenic CO_2 emissions [1]. Large-scale reforestation has been proposed by Breuer [2] to offset fossil fuel-based

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CO_2 emissions. According to Hall [3,4], 600 million hectares (ha) of tree plantations having an average yield of 12 dry metric tons (t)/ha/year could offset 50% of 1985 emissions by the year 2050 when the tree biomass is used for fossil fuel substitution. Hasenkamp [5] suggested that the global climate problem could be solved by planting a total of 500 million hectares of plantations, even without parallel efforts to minimize carbon emissions from fossil fuel combustion.

The Kyoto protocol, under Article 3, provides for Annex B parties including the US to take into account afforestation, reforestation and other forest activities in meeting CO_2 reduction targets [6]. Given that carbon emissions from deforestation are still around 2 billion tC/year (over three times the emissions from motor cars), it has been argued that conservation of forests by using good management practices along with afforestation/reforestation through tree planting can enhance the carbon sink provided by terrestrial ecosystems. Forestry projects to counteract climate change have figured in the US strategies to reduce increasing anthropogenic emissions of CO_2 [7]. Examples of policies and programs that have been developed in the US to create incentives for carbon sequestration include the America the Beautiful Program, the Forest Stewardship Program [8], the Reforest America Program [9], and the Global Climate Change Prevention Act [10].

IPCC [6] defines carbon sequestration as an increase in carbon stocks in any non-atmospheric reservoir. Carbon sequestration by trees from the atmosphere is a function of the land used, time for growing and technological progress. There are two ways trees can be used to reduce carbon emissions. One is direct carbon sequestration by reforestation and afforestation that yields a stock of carbon in standing trees. The other is the use of forest products as substitutes for fossil fuels or fossil fuel intensive goods such as steel and concrete. In both instances, carbon offset occurs by preventing the emissions from fossil fuels which would otherwise have been used.

Direct carbon sequestration by trees is only a temporary measure. As trees reach maturity, the sequestration rate declines because respiration begins to equal or exceed primary production. Direct carbon sequestration by trees has been proposed as an emergency stop-gap measure to stop or reverse the increase in atmospheric CO_2, while allowing time to develop and implement clean energy technologies. Since forests are susceptible to fires and natural disasters, the strategy of sequestering carbon in standing trees is fraught with the risk of carbon leakage. However, it is not fires or natural disasters per se that reduce the long-term carbon stocks in a given piece of land. It is the likelihood of human intervention that does not allow natural regeneration or reforestation of the affected areas. In contrast, the use of tree biomass for fossil fuel substitution can be a longer-term measure because harvesting and replanting in a given piece of land can be carried out in perpetuity. Additionally, the use of biomass for energy production helps rural economies to grow and enhances energy security.

There are several studies regarding the relative merits of these two strategies when the amount of land potentially available for growing trees is limited [7,11,12]. Marland and Schlamadinger [12] compared these two approaches and found that direct carbon sequestration is favored under low growth and low conversion efficiency, while fossil fuel substitution is favored under high growth and high conversion efficiency.

The available literature on carbon mitigation by forests has focused exclusively either on the costs or the magnitude of carbon benefits under different management scenarios. There has been no attempt to juxtapose cost issues with carbon benefit issues to arrive at the holistic picture of potential carbon mitigation strategies. Therefore, this study aims to compare and contrast the two approaches on the basis of costs (i.e. costs per ton of carbon sequestered/offset) and quantity of carbon sequestered/offset over a 100-year period, taking into account the growth conditions of forests in the south/southeast US.

2. Carbon sequestration mechanism

Fig. 1 shows the pools and fluxes of carbon in an even-aged, single species plantation that is periodically harvested and replanted. Trees take atmospheric CO_2 during photosynthesis and fix it in woody (branches, stems, and woody roots) and non-woody (foliage and fine roots) parts. Woody and non-woody parts have different growth dynamics and decay characteristics [13]. At the end of each rotation, a portion

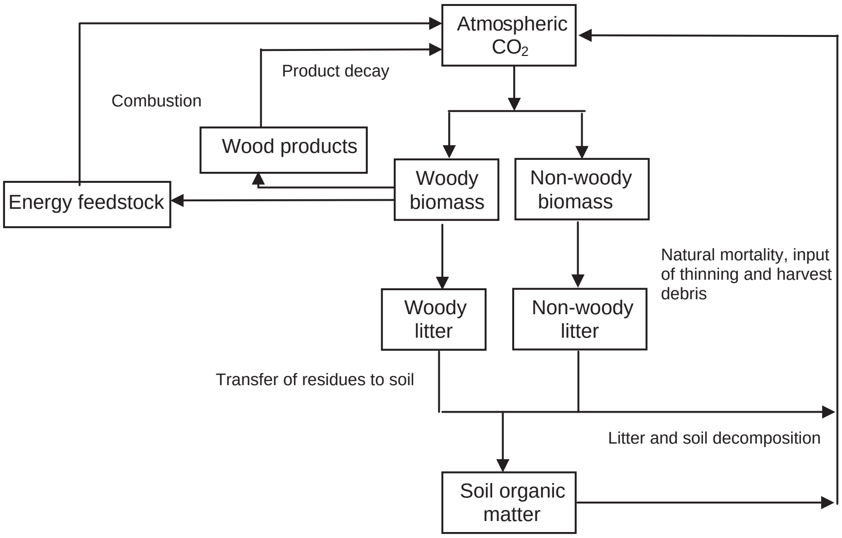

Fig. 1. Carbon mitigation by trees, which are regularly harvested and planted (*Source*: Dewar and Cannell [13]).

of biomass is transferred to wood products, or energy feedstocks. The energy feedstocks release carbon back to the atmosphere upon combustion. The wood products eventually decay to release the carbon either by aerobic or anaerobic decomposition.

The forest floor receives dead woody and non-woody litter continuously as tree components die because of natural mortality throughout each rotation and also at each thinning and harvest. A portion of litter is decomposed by microorganisms into CO_2 and the remaining litter is transferred to soil organic matter. In the soil, organic matter undergoes further decomposition into CO_2, which eventually returns to the atmosphere. The amount of carbon sequestered in soil and litter is variable and highly uncertain. The GORCAM model indicates that the carbon content in soil increases when former agricultural land is converted to forest [14]. However, a recent study suggests that afforestation of former arable land does not lead to increased carbon stock in soil in a short-term scenario of 30 years [15]. In the forest system, although carbon is sequestered in the upper 5 cm of the mineral soil, it is offset by carbon release from the lower soil layers (5–15 and 15–25 cm).

The amount of carbon that can be sequestered by trees depends on the biomass accumulation rate, and rotation length. For long rotation forests, the present forest management can provide harvestable yields of about 4–8 dry metric tons (or 2–4 tC)/ha/year in temperate and 10–12 metric tons (5–6 tC)/ha/year in tropical areas [11]. For short-rotation woody crops (SRWC), yields as harvestable woody biomass in the range of 9–16 metric tons (4.5–8 tC)/ha/year are common in production research trials (Table 1). The maximum observable experimental yield was found to be about 43 metric tons (21.5 tC)/ha/year in a temperate region [16]. The yields of SRWC largely depend on genotype, cultural practices and site quality [17]. Among SRWC, silver maple, sweetgum, American sycamore, black locust, poplars, and eucalyptus

Table 1
Current, future expected, and maximum observed yields for short-rotation woody crops in the US

Region	Yields (dry) metric ton/ha/year		
	Current	Goal	Maximum observed
Northeast	9.0	15.7	15.7
South/southeast	9.0	17.9	15.7
Midwest/lake	11.2	20.2	15.7
Northwest	15.7	29.1	43.3
Subtropics	15.7	29.1	27.6

Source: Wright et al. [16].

have been identified as potential SRWC species. Hybrid poplar and eucalyptus have shown the greatest potential for very high growth rates in the US. In order to obtain high yields, SRWC must be maintained under the same conditions as any other agricultural crop. Fertilization is needed almost every year for SRWC species to maintain rapid growth and preserve the fertility of the land. SRWC must be planted on agricultural cropland (Cropland classes IV or better) to obtain high yields at reasonable costs. It has been found that growth of SRWC species was poor in a site prepared by clearing forests. It suggests that the conversion of forested land to SRWC is not desirable from economic and carbon mitigation perspectives [17]. Harvesting and handling losses also decrease the net yields of SRWC and affect prices of biomass. It is generally assumed that harvest losses are about 5–10% of aboveground biomass at the time of harvesting and storage losses are about 10–15% [16].

3. Methods

To evaluate the carbon mitigation potential of afforestation and fossil fuel substitution, simple models based on aboveground tree growth rate, carbon uptake in soil and litter, harvest and storage losses, and energy conversion efficiency are used. Equations provided by Hall et al. [11] are modified to estimate the costs of carbon offset for fossil fuel substitution. The amount and cost of carbon sequestered or offset are compared for afforestation and energy substitution scenarios.

Direct carbon sequestration: This refers to afforestation projects in which trees are planted, protected, and allowed to grow, thereby sequestering carbon in permanent stands. The direct sequestration scenario assumes that trees are planted and grown in one hectare of agriculture land. The typical yield for south/southeast forests in the US is used in the model.

Fossil fuel substitution: This refers to planting and harvesting of SRWC on a regular basis and using harvested products to substitute for coal and gasoline. It is assumed that hybrid poplar are planted on 1 ha of agriculture land, harvested, and replanted regularly every 10 years. The full harvest is used for coal and gasoline displacement. Since productivity declines over multiple rotations, it is assumed that fertilizers are applied to maintain productivity. A constant growth rate of 5.5 tC/ha/year is considered until the time of harvest. Under fossil fuel substitution three scenarios are considered:

1. Substitution of biomass-fired steam-electric power (BS) for coal-fired steam-electric power (BS-CS substitution),
2. Substitution of biomass-integrated gasifier (BIG)/steam-injected gas turbine (STIG) power for coal-fired steam-electric power (BIG/STIG-CS substitution),
3. Substitution of ethanol (EthOH) derived from biomass for gasoline (B/EthOH–gasoline substitution).

3.1. Models

3.1.1. Model for aboveground tree growth

For aboveground harvestable tree biomass, a growth model proposed by Marland and Marland [7] is used. The growth pattern is such that C accumulation is linear until half of the maximum yield is achieved and slows gradually to reach the maximum yield asymptotically. The maximum aboveground yield and growth rate are assumed to be 160 [12] and 2 tC/ha/year, respectively, which are the appropriate values for a good site in the southeastern US.

The standing aboveground carbon (C_{t+1}) at any time (t) is a function of the original aboveground carbon (C_t), a growth rate (G), and an assumed limiting value for total standing stock which can be supported on the site ($C_{\max}$).

$$C_{t+1} = C_t + G \quad \text{when } C_t \leqslant C_{\max}/2, \tag{1}$$

$$C_{t+1} = C_t + (G/C_{\max}/2)(C_{\max} - C_t) \quad \text{when } C_t > C_{\max}/2. \tag{2}$$

The above model applies to the case where carbon is sequestered directly in standing trees. Although each species has a unique growth and yield pattern, the growth model described above represents the average growth pattern for most tree species on good sites in the southeastern US. This static growth model is fairly simple and deterministic. It does not take into account effects due to variation in moisture, temperature, nutrient availability, and climate change impacts over time. Despite such limitations, the model is still useful for comparing direct carbon sequestration with carbon offset obtained from energy substitution.

3.1.2. *Carbon sequestration models for litter and soil*

To calculate carbon sequestered in litter and soil when agricultural lands are used for tree plantations, parameters given by Schlamadinger and Marland [14] are used. Roots and litter are grouped as one pool (i.e. litter). For short-rotation forestry, soil carbon uptake is 10 tC/ha over 40 years, and the litter carbon uptake is 8 tC/ha over 10 years. For afforestation, soil carbon uptake is 20 tC/ha over 80 years, and the litter carbon uptake is 15 tC/ha over 30 years. The rate of accumulation of carbon in soil and litter is assumed to be linear until the maximum value is reached beyond which it remains constant. This carbon accumulates in soil and litter for a finite period until equilibrium is reached, and further carbon sequestration is balanced by the decay of wood products and soils.

The amount of carbon stock in litter including slash and soil is highly variable and site specific. There are conflicting findings regarding the carbon sequestration in soil. The models used by Liski et al. [18] indicate that soil carbon increases when rotation length decreases. Similarly, the GORCAM model developed by Schlamadinger and Marland [14] considers soil carbon increases for the conversion of agricultural land to forests. However, no such increases have been observed by Vesterdal et al. [15]. The carbon content in soil and litter is difficult to include in an accounting system. The present study employs the soil and litter C-uptake rates as suggested for the GORCAM model because any errors in assumptions will be present in both afforestation and fossil fuel substitution scenarios and therefore would not compromise the results of comparisons.

3.1.3. *Models for fossil fuel substitutions*

(a) *BS-CS substitution*: On an average, the C to energy ratio for coal is about 24.56 kg C/GJ, after considering the carbon released in mining and transportation of coal; whereas for wood it is 25.32 kg C/GJ. This suggests that wood burning would discharge 1.027 more C per unit of electricity than coal, if both were converted to electricity with the same thermal efficiency. However, typical values for efficiency of conversion to electricity are about 33% for coal and about 25% for wood [7]. This implies that 1 kg of C in wood is able to displace 0.73 kg of C in coal. Since fossil fuel is used in establishing, managing, and harvesting plantations, it contributes to emissions of CO_2 equivalent to 6% of the C embodied in harvested wood. Additionally, 15–20% biomass is lost during harvest and haulage. This paper considers a total loss of 20% biomass for these activities.

The carbon offset can be described by the model

$$C_{\text{net}} = 0.73[(C_{10} - C_{10} \times 0.20] + C_{\text{soil}} + C_{\text{litter}}, \quad (3)$$

where C_{10} is carbon sequestered in aboveground biomass at the end of a 10-year period. A linear growth is assumed such that C_{10} is equal to 10 times growth rate (5.5 tC/ha/year). C_{soil} is carbon sequestered in soil and C_{litter} is carbon sequestered in litter.

(b) *BIG/STIG-CS substitution*: Larson and Williams [19] and Larson and Svenningsson [20] have suggested that STIG coupled with BIG can be used to generate electricity in place of coal-fired power plants. Efficiency of 35.6% has been documented for BIG/STIG technology. Larson and Svenningsson [20] concluded that the biomass should have at least as high efficiency as coal if the gasifier system is designed for biomass, because of the ease with which biomass can gasify as compared to coal. Net carbon offset when BIG/STIG power is substituted for coal-fired steam-electric power is given by the equation

$$C_{\text{net}} = 1.05(C_{10} - C_{10} \times 0.20) + C_{\text{soil}} + C_{\text{litter}}. \quad (4)$$

(c) *B/EthOH–gasoline substitution*: Researchers have shown that a dry metric ton (or 0.5 tC) of wood can produce about 450 l of ethanol with a conversion process efficiency of 53.5% [21]. The ethanol is derived from the cellulose and hemicellulose present in the wood by a fermentation process. The conversion process requires energy, which is obtained by burning lignin and unfermented carbohydrates. At a 53.5% wood to ethanol conversion efficiency, a surplus of about 148 kWh of electricity is produced per dry metric ton of wood processed to ethanol. In general, a liter of ethanol can substitute for 0.8 l of gasoline [22]. Some energy is also required for refinement and transportation of crude oil (about 12% of the energy value of crude oil). The carbon content of gasoline is 20.76 kg/GJ (0.723 kg C/l) if energy costs are included. Hence the gross carbon offset by using ethanol in place of gasoline is

$$450\text{ l ethanol/dry metric ton} \times 0.8\text{ l gasoline/l ethanol}$$
$$\times 0.723\text{ kg C/l gasoline}$$
$$= 260.3\text{ kg C/dry metric ton}$$
$$\times (520.6\text{ kg C/tC in wood}).$$

As in the case of coal displacement, it is assumed that about 20% of C embodied in the harvestable biomass is lost due to fossil fuel use in the establishment, management, and harvesting of plantations, and the loss of biomass during harvest and haul. So carbon offset for ethanol substitution can be written as

$$C_{\text{eth}} = (C_{10} - C_{10} \times 0.20) \times 0.521. \quad (5)$$

While producing ethanol, about 296 kWh of electricity is co-produced from every 2 metric tons wood (1 tC) processed. Hence, some additional carbon offset is obtained since the coal required producing that much of electricity remains unused. The carbon content of coal is 24.12 kg/GJ and 1 kWh of electricity is equal to 3.6×10^{-6} J. Based on a coal conversion efficiency of 33%, 1 kWh of electricity is equivalent to the amount of energy derived from burning 0.26 kg of C in coal. Therefore, 296 kWh of electricity prevents 76.96 kg of C in coal from being burned. Carbon offset as a result of electricity production is therefore

$$C_{\text{elec.}} = (C_{10} - C_{10} \times 0.20) \times 76.96 \times 10^{-3}. \quad (6)$$

The model for net carbon offset when SRWCs are used for gasoline displacement is

$$C_{\text{net}} = C_{\text{eth}} + C_{\text{elec.}} + C_{\text{soil}} + C_{\text{litter}}. \quad (7)$$

3.2. Costs of carbon mitigation

The cost of sequestering carbon for afforestation or reforestation varies from \$0 to \$150/tC in the US. The production, harvesting, transport, storage, and drying of biomass, as well as energy production costs are included in the cost of fossil fuel substitution. The net costs of carbon offset when biomass is used as substitutes for coal and gasoline are calculated by modifying the equations of Hall et al. [11].

$$\text{Net cost for BS-CS(\$/tC)}$$
$$= (-61.44 + 63.33 \times P_{\text{b}} \times \varphi) \quad (\varphi = 0.95), \quad (8)$$

$$\text{Net cost for BIG/STIG-CS(\$/tC)}$$
$$= (-124.88 + 40.89 \times P_{\text{b}} \times \varphi)) \quad (\varphi = 0.96), \quad (9)$$

$$\text{Net cost for B/EthOH–gasoline(\$/tC)}$$
$$= (-214.1 + 72.1 \times P_{\text{b}} \times \varphi)) \quad (\varphi = 0.94), \quad (10)$$

where, P_{b} is the price of biomass in \$/GJ.

These equations imply that if the cost of producing energy from biomass is lower than from fossil fuels, carbon offset costs become negative. To estimate the costs of carbon offset, Hall et al. [11] did not take into account the amount of carbon sequestered in soil and litter when biomass derived from SRWC is used to substitute fossil fuels. To account for the relative contributions of carbon sequestered in soil and litter, cost equations have been modified by incorporating a factor (φ) in this paper. When carbon sequestered in soil and litter for 100 years is averaged over each rotation period, carbon sequestered in the litter and soil pool represents about 5.6% (BS-CS substitution), 6.8 % (B/EthOH–gasoline substitution), and 3.8% (BIG/STIG-CS substitution) of the carbon offset. The price of biomass is derived from the farmgate price, transport, storage, and drying costs. The farmgate price of biomass varies approximately between \$32/dry metric ton and \$78/dry metric ton [23]. The farmgate price of \$45/metric ton [23], which is a typical value for the Delta region and southeast US, is considered. The farmgate price includes the costs of harvesting, chipping, and baling.

These cost figures (Table 2) assume relatively good land and the best available SRWC techniques are used, and chips are used as the raw feedstock. For ethanol production, drying is not required as a result the price of biomass will be lower.

4. Results and discussions

4.1. Quantity of C sequestration/offset

Figs. 2–5 show the cumulative increase in C-stocks in the various pools over 100 years for carbon sequestration and fossil fuel substitution scenarios. In the case of carbon sequestration in a permanent stand, the C accumulation rate in aboveground biomass is linear initially but declines due to a saturation effect.

Table 2
Delivered cost of wood chips ($/dry metric ton)

Farmgate price[a]	45 (typical price)	32 (lowest price)
Transport[b]	10	10
Storage[c]	7	7
Drying[d]	11	11
Total	73 ($3.77/GJ[e])	60 ($3.09/GJ)

[a] *Source*: Graham and Walsh [23].

[b] Average transportation cost for 25 miles.

[c] Hall et al. [11].

[d] Hall et al. [11]. Since the real price of electricity (adjusted for inflation) has decreased slightly during 1990–2000 and the nominal price has remained constant during the same period, the drying cost provided by Hall et al. is still applicable.

[e] Poplar has a heating value of 19.38 GJ/ton.

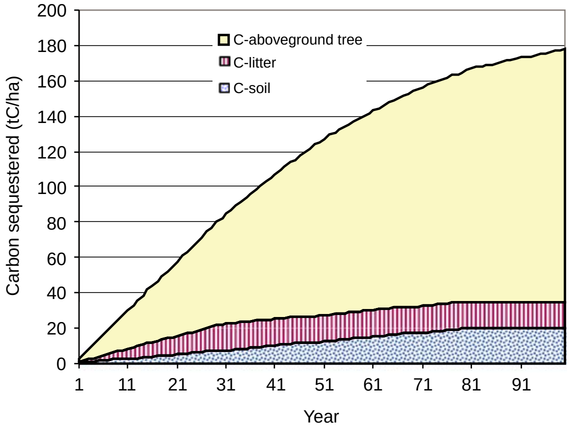

Fig. 2. Cumulative carbon sequestrated for afforestation.

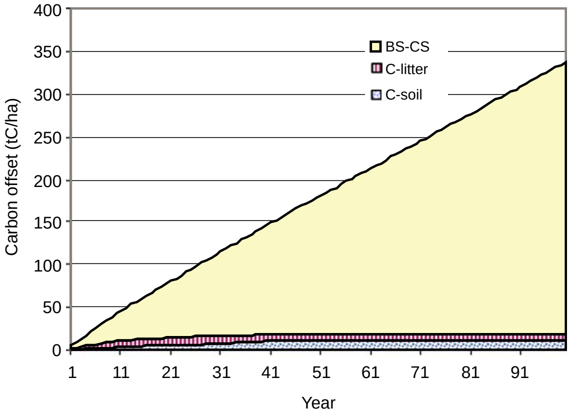

Fig. 3. Cumulative carbon offset for BS-CS substitution.

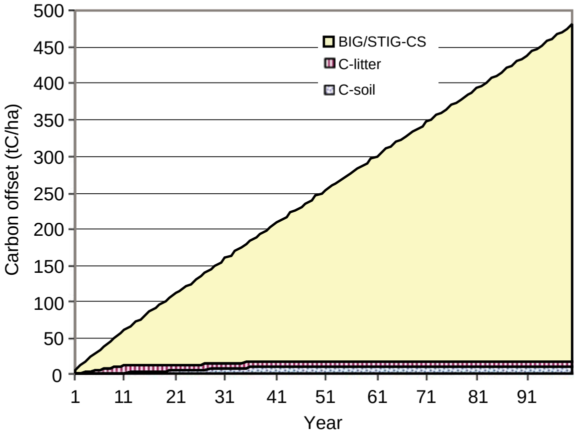

Fig. 4. Cumulative carbon offset for BIG/STIG-CS substitution.

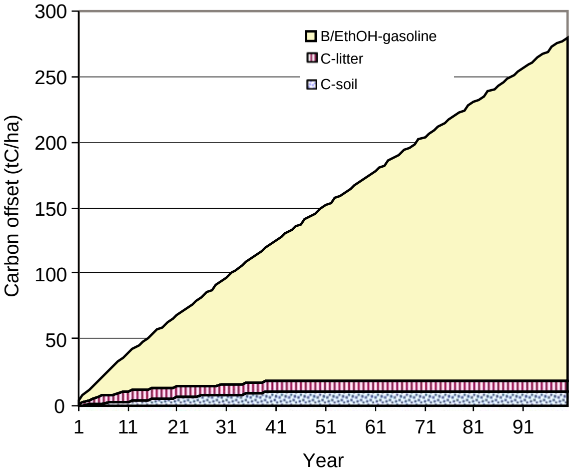

Fig. 5. Cumulative carbon offset for B/EthOH–gasoline substitution.

The growth rate declines when half of the maximum yield (160 tC/ha) is reached. In fossil fuel substitution, the amount of carbon offset increases linearly with time since biomass is continually harvested and replanted and used to generate energy.

Carbon sequestration in soil and litter through afforestation is higher than for fossil fuel substitution. One possible explanation is that disturbances due to repeated site preparation and harvesting at regular intervals enhances decomposition of soil and litter resulting in low carbon content when SRWC are used. Carbon sequestered in soil and litter over 100 years represents about 20% of carbon sequestered in aboveground biomass in the case of direct C sequestration.

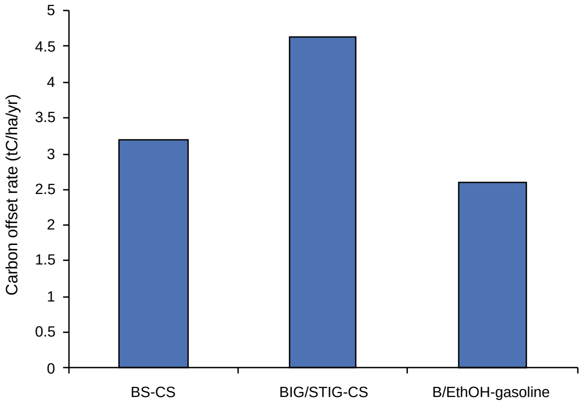

Fig. 6. Carbon offset rates (excluding C sequestrated in soil and litter) for fossil fuel substitution.

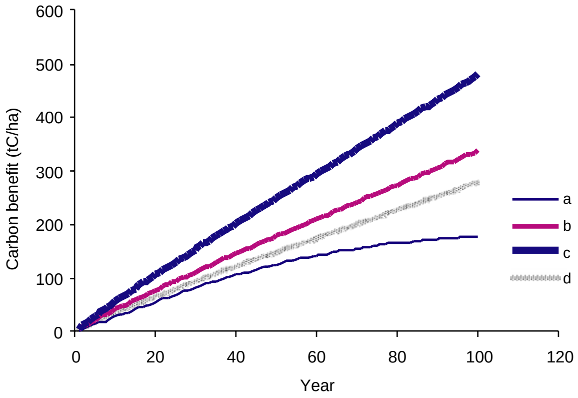

Fig. 7. Total carbon benefit (sequestration/offset) for different scenarios: (a) afforestation; (b) BS-CS substitution; (c) BIG/STIG-CS substitution; and (d) B/EthOH–gasoline substitution.

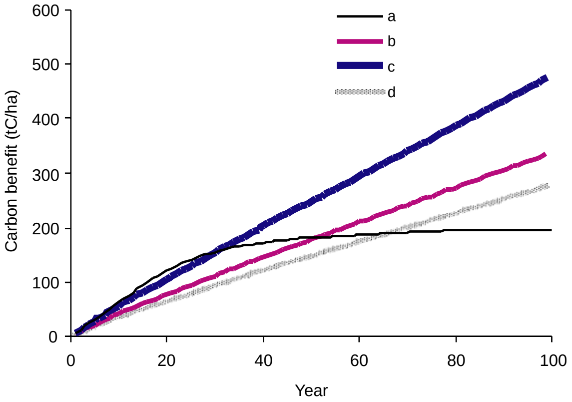

Fig. 8. Change in total C sequestration pattern for afforestation when its initial growth rate becomes equal to that of SRWC: (a) afforestation; (b) BS-CS substitution; (c) BIG/STIG-CS substitution; and (d) B/EthOH–gasoline substitution.

In contrast, carbon sequestration in soil and litter pool is less than 7% of carbon offset for fossil fuel substitution scenarios. Of all scenarios considered here, the carbon offset rate is the lowest for substitution of ethanol derived from biomass for gasoline (2.7 tC/ha/year), and is the highest when BIG/STIG is substituted for coal-fired electric power (4.6 tC/ha/year) (Fig. 6). The higher carbon offset rate of BIG/STIG-CS substitution as compared to BS-CS substitution is attributed to higher efficiency of BIG/STIG technology (35.6% vs. 25% for biomass-fired steam-electric power). Since carbon sequestered in SRWC is converted to equivalent carbon offset resulting from energy substitution, carbon sequestered in aboveground trees does not appear in Figs. 3–5 in contrast to previous studies [12,14].

Fig. 7 compares the total carbon benefit over time for four different scenarios. The C benefit (C sequestration/offset) at any time is the highest for the scenario involving displacement of coal by BIG/STIG. This is attributed to the high C sequestration rate for BIG/STIG-CS substitution, which in turn, results from high-energy conversion efficiencies. The magnitude of carbon benefit in the afforestation scenario is the lowest at any time compared to the fossil fuel substitution scenarios. A total of 177 tC/ha is sequestered for afforestation as opposed to offset of 480 tC/ha for BIG/STIG-CS substitution in 100 years.

Table 3
Carbon sequestration costs for afforestation/reforestation in the US

References	Methods	Quantity of carbon sequestered per year (million tC/year)	Marginal costs ($/tC)
Moulton and Richards [24][a]			
United States	Bottom-up	626.1	< 34 (25)
Delta States		60.7	(20)
Dudec and Leblanc (1990)[a]			(35)
Nordhus (1991)[a]	Bottom-up	39.9	(58)
Rubin et al. (1992)[a]		66.2	(21)
Richards, Moulton, and Birdsey (1993)[a]	Bottom-up		
United States		377.5	< 37
Delta States cropland		26.3	< 20 (16)
Adams et al. [30][a]	Sectoral optimization	635.2	< 25
Parks and Hardie (1995)[a]	Bottom-up	20	< 22 (19)
Plantinga (1995)[a]	Econometric	1.4	5–12
Callaway and McCarl (1996)[a]		254.1	< 21
Alig et al. (1997)[b,c]	Sectoral Optimization		24–141
Richards (1997)[b]	Bottom-up		10–150
Stavins (1998)[a]	Econometric		
United States		470.1	< 123 (64)
Delta States cropland		6.4	< 60 (7)
Adams et al. [27]	Sectoral Optimization	16–73	5–21
Plantinga et al.[d] [28]			
Maine	Econometric		79–100
Wisconsin			62–79
South Carolina			37–46
Huang and Kronard [29]			($0.74–$27)

Note: Figures in parentheses represent average costs.
[a] *Source*: Stavins [26]. Short tons (2000 lbs) are converted into metric tons.
[b] *Source*: Richards and Stokes [31].
[c] Reproduced from Shongen and Alig [25].
[d] At the highest carbon sequestration levels. Short tons (2000 lbs) are converted into metric tons.

Only when the growth rate in afforestation (direct carbon sequestration) is as high as that of SRWC (i.e. 5.5 tC/ha/year), can the carbon benefit for afforestation be initially higher than for any other scenario (Fig. 8). Under this high growth scenario, the total carbon benefit for BIG/STIG-CS substitution scenario exceeds that of afforestation after 30 years due to decreasing sequestration rate as a result of saturation effect (Fig. 8). The BS-CS and B/EthOH–gasoline substitutions overtake the afforestation scenario after 51 and 65 years in terms of total carbon benefit. Afforestation is favored over fossil fuel substitution scenarios, for a shorter time frame, only if its initial growth rate is comparable to that of SRWC. For a longer time frame, it is desirable to grow SRWC and use harvested biomass as a source of energy.

4.2. Costs of carbon mitigation

The review of the available literature on carbon sequestration in forests reveals discrepancies in the costs of sequestering carbon in forests (Table 3). The discrepancies in reported costs are attributed to differences in methodology (bottom up, sectoral optimization, or econometric models) and variations in scope (geographical area) of these studies. In addition, inconsistencies have been introduced as a result of the choice of factors, like the cost of initial treatment and the rate at which afforestation or reforestation plans are implemented; the continuing maintenance costs; the discount rate used; the administrative costs; the treatment of harvest and the use of forestry products; the consideration of different components of the forest ecosystem; and the secondary environmental effects associated with increased carbon sequestration. Earlier studies focused on the land value and planting costs to estimate the direct costs and the opportunity costs associated with changing land use. For example, Moulton and Richards [24] employed land rental payments from the Conservation Reserve Program and forests establishment costs to estimate carbon sequestration costs. Studies in recent years have used cross-sectional data and econometric models to take into account the effect of land quality on land opportunity costs [25]. An econometric study by Stavins [26] showed that the marginal costs of carbon sequestration increase linearly up to 7 million tons (short) beyond which they increase more rapidly. This implies that progressively higher marginal costs are associated with increasing carbon sequestration. Although we have assumed that no harvesting occurs in the direct sequestration scenario, some of the studies, for example, Adams et al. [27] and Stavins [26] considered periodic harvesting and sale of timber. An econometric model developed by Plantinga et al. [28] based on land use found that the lowest carbon sequestration costs are likely to occur in northern regions, especially Wisconsin. A recent study by Huang and Kronrad [29] showed that the average costs of sequestering an additional tC on already intensively managed lands by changing management regimes and unstocked land vary from $4.18 to $181.27 and $0.74 to $27.32, respectively. Since carbon stored in soil and litter was not accounted for, the study may have overestimated the average costs of carbon sequestration.

A summary of costs of C mitigation from different management scenarios is provided in Table 4. Although fossil fuel substitution possesses high C offset potential, an entirely different picture emerges if the costs of C mitigation ($/tC) are taken into account. The costs of C offset for BS-CS substitution being $165.4/tC ($124.5/tC for the lowest farmgate price [23]) lie above most of the average and the marginal costs of C sequestration for afforestation projects reported so far (Table 3). It has been argued that for biomass-fired electric power to be competitive with other energy sources in the US market, the delivered cost of biomass must be less than $37/dry metric ton (1.91/GJ) [32] which translates to an yield of about 16–22 metric ton (dry)/ha/year [16]. Such yields are quite high considering the best average yield obtained for hybrid poplar is 15.0 metric ton (dry)/ha/year.

Table 4
Comparison of costs of C sequestration/offset for afforestation and fossil fuel substitution

Strategies	Costs ($/tC)
Direct sequestration by forestation/reforestation	0.7–150
BS-CS substitution	165.4 (124.5)
BIG/STIG-CS substitution	23.1 (−3.6)
B/EthOH–gasoline substitution	2.8 (−42.7)

Note: Figures in parentheses represent the costs of carbon offset when the lowest biomass farmgate price as possible in the northeast US is assumed.

The typical costs of carbon offset from BIG/STIG-CS substitution and B/EthOH–gasoline substitution are $23.1 and $2.8/tC, respectively, which are comparable to the average and marginal costs for afforestation as reported in Table 3. The costs of carbon offset for fossil fuel substitution can become low or even negative as the price of delivered biomass falls. Any price of biomass below $3.2/GJ for BIG/STIG substitution and B/EthOH–gasoline substitution, and $1.0/GJ for BS-CS substitution makes the costs of carbon offset negative, i.e. carbon offset can generate profits. Considering the lowest farmgate price of $32/t as possible in the northeast US, the cost of B/EthOH–gasoline substitution becomes −$42.7/tC (Table 4). The negative cost indicates that cost of ethanol production from biomass in terms of gasoline equivalent will be lower than the cost of gasoline production. Moreover, if alternative markets for the lignin co-product can be explored (instead of using it for electricity generation in the wood–ethanol conversion process) the economics of ethanol production may improve [33].

To find out whether the costs of direct carbon sequestration in forests are significantly lower than the of costs of C offset from fossil fuel substitution, the upper marginal costs provided in Table 3 are used in the statistical analysis. Where marginal costs are not reported, average costs are used. Since the data do not follow normal distribution, the 1-Sample Wilcoxon test is used. The results of this test show that carbon mitigation cost of afforestation is significantly lower than that of BS-CS substitution even when the lowest farmgate price is considered (p value: 0). However, carbon mitigation cost of afforestation is significantly higher than that of BIG/STIG-CS substitution (p value: 0.005) considering typical farmgate biomass price and upper marginal carbon sequestration costs. Likewise, cost of carbon mitigation by afforestation is significantly greater than that of B/EthOH substitution (p value: 0) considering typical farmgate biomass price and upper marginal carbon sequestration costs.

There are, however, some caveats. The cost figures taken from different studies have not been converted to the dollars of the same year due to the absence of base year information in some of these studies (e.g., [29,30]). Neither the gas turbine technologies (e.g., BIG/STIG) nor the alcohol technologies described here are commercially available, as yet. Hence, the cost estimates may not reflect true market values. However, Hall et al. [11] argue that the cost estimates for fossil fuel substitutions are reasonable, since there should be no foreseeable hurdles in commercializing these technologies. Some of the studies for afforestation/reforestation involve the harvest and sale of timber after 40–50 years as opposed to sequestering carbon in permanent stands, which may deflate the costs. Since the technologies that can be immediately applied are either afforestation or biomass-fired steam-electric power, the obvious choice for carbon sequestration should be afforestation/reforestation with regard to cost of carbon mitigation. The costs data provided in Table 4 indicate that the long-term cost goal of \$11.03/tC set by the US Department of Energy (DOE) is achievable for planting trees (e.g., loblolly pine) in unstocked lands.

The cost of C sequestration by afforestation/reforestation is also modest relative to recovering and sequestering carbon from fossil fuel power plants. According to Hendriks et al. [34], the cost of recovering carbon from the flue gases of coal-fired power plants with a chemical absorption process, and sequestering it in abandoned natural gas wells has been estimated at \$120/tC (equivalent to \$151/tC in 2002). If a carbon tax is applied on all fossil fuels consumed, it is possible to generate revenues to cover the costs of carbon sequestration by forests. For example, Hall et al. [11] argued that the cost (\$19.5 billion/year) of planting trees in 139 million hectares of economically marginal and environmentally sensitive croplands, pasturelands, and understocked forestlands in the US could be paid for by a carbon tax of \$15/tC on all fossil fuels consumed. Also, implementing carbon taxes in future will raise the price of energy generated from fossil fuel plants thereby rendering SRWC-derived energy competitive in the markets. The existence of carbon taxes or high C mitigation costs may propel utility companies relying on fossil fuels to find cheaper alternatives to sequester carbon [29]. Under this scenario, utility companies may pay farmers to sequester carbon in trees considering the low sequestration costs for afforestation. This payment alone may not induce farmers to plant trees unless the revenues generated from tree plantations equal or exceed those derived from existing farm practices.

It may be noted that although this study aims to compare and contrast costs and carbon benefits of using trees for carbon sequestration vs. fossil fuel substitution, these two approaches are not mutually exclusive. For example, a synergy between bioenergy and carbon sequestration can be developed by adopting an integrated forest system in which the stand is thinned and thinnings are used for bioenergy. Similarly SRWC grown in formerly cultivated or degraded land increases carbon density above ground while allowing biomass to be used for energy production [35].

4.3. Bioenergy policy and incentives in the US

Despite several advantages of using SWRC-derived biomass for energy production and carbon mitigation, the progress on the technology front leading to commercialization has been slow. It has been attributed to the lack of adequate policies, incentives, investments in research and development (R& D), and institutions for creating the environment conducive to bio-energy promotion in the US. Even in R& D, research activities on bioenergy have been shifted from SRWC to agricultural crops (corn, soybean) and residues. Although limited policies and incentives exist in the US, they are not deemed sufficient by scientists, energy experts, and policymakers for bioenergy development and promotion. The 1978 Public Utility Regulatory Policies Act (PURPA) in the US has been responsible for expanding biomass-based power generation from about 250 MW in 1980 to about 9000 MW in 1990

[11]. The section 1202 of the Energy Policy Act of 1992 seeks to further commercialize renewable energy (including biomass) by providing financial assistance. It has been argued that much of the biodiesel growth is a result of the Energy Policy Act of 1992, which mandates that state and federal agencies promote alternative fuels through acquisition credits.

The Alternative Motor Fuels Act (1988) has provided some impetus to promote biofuels. Clean Air Act amendments (1990) are expected to increase the demand for biofuels. The proposed Energy Policy Act of 2002, which is expected to shape the future national energy policy, has some provisions for bioenergy development and promotion. Section 818 of the proposed Act specifies that motor gasoline must contain a certain amount of renewable fuel (e.g., ethanol) beginning from 2003. Similarly, Section 1222 authorizes funding for the biopower and biofuels programs of the DOE for the fiscal year 2003–2006 [36]. Under the proposed Act, a significant growth in electricity production from a variety of renewable energy sources may be encouraged through Renewable Energy Portfolio Standard (REPS). At present there are a few federal incentives for the use and development of biomass-based energy such as renewable energy production incentives, income tax credits and exemption, and production tax credits (Table 5).

5. Conclusions

Several researchers have pointed out the relative carbon benefit of using land to grow SRWC as opposed to afforestation with the intent of sequestering C in standing trees. Marland and Schlamadinger [12] showed that under high growth rates and high displacement factors, it is more advantageous to use biomass for fossil fuel substitution rather than sequestering carbon in permanent stands through afforestation. In line with the above findings, this study also shows that significant carbon benefit can be obtained by substituting coal or gasoline by biomass. This is due to high growth rates of SRWC, and also because the use of a given piece of land is not limited to just the period until the forest matures, as in the case of direct carbon sequestration.

However, when costs and availability of technologies are taken into account, sequestering carbon in standing forests is cheaper than the carbon offset from BS-CS substitution, which is the only commercially available technology today. The high cost is due to the high price of biomass and low combustion efficiency of biomass-based steam-electric power plants. The added costs of harvesting, processing, transport, drying, and storage makes the price of biomass three times higher than the cost of growing trees. There are, however, highly efficient and cost-effective technologies that may be commercially available in the future, e.g., BIG/STIG and ethanol from biomass. When these technologies are commercially available, the costs of carbon offset will decrease and can generate profits. When this happens, far greater resources can be committed to fossil fuel substitution at any given time than to direct carbon sequestration because of the built-in economic incentives of growing SRWC as a source of bioenergy.

This study is based on the assumption that the growth rate of SRWC is 5.5 tC/ha/year. There is a potential for increasing the growth rate through plant biotechnology research. It is believed that the growth rates of 8–14.5 tC/ha/year are attainable [17]. Under such circumstances, the costs of carbon mitigation by substituting biomass for coal or gasoline would be considerably lower. The economic attractiveness of SRWC as an energy feedstock may increase if carbon taxes are imposed and fossil fuel prices increase.

The study by Dixon et al. [37] indicated that big differences in costs of carbon sequestration in forests exist across countries. If the Kyoto protocol comes into full force as a functional international agreement, an appropriate approach for Annex B countries with high carbon sequestration costs would be to carry out afforestation or reforestation projects in other Annex B countries with low carbon sequestration costs and use the carbon reductions as credits against its own commitments as envisioned by joint implementation (Article 6 of the Kyoto protocol). Alternatively, emission credits earned by one Annex B country from carbon sequestration can be traded with another Annex B country. There is no direct reference in the Kyoto protocol whether or not carbon sequestration can be used as part of the clean development mechanism (CDM) described in Article 12. If it is possible under CDM to use carbon sequestration resulting from forest projects in non-Annex B countries as credits against its own commitments, it provides another window of oppor-

Table 5
List of incentives available for biomass energy in the US

Type of incentives	Eligibility	Incentives	Remarks
Renewable energy production incentive (REPI)	States, political subdivisions, nonprofit electrical cooperatives	Incentive of 1.5 cents per kWh adjusted annually for inflation	Applicable to energy production from biomass resources, from solar, wind, or geothermal sources
Income tax credit (IRA code Section 45)	Blenders, alcohol producers	The blender's credit, the producer's credit and the small ethanol producer credit	Expires in 2007
Excise tax exemptions for alcohol fuels (IRA Code Sections 4041, 4048, and 4091)	Blended fuel users	Partial exemptions for fuel blends containing alcohol (e.g., exemption of 5.4 cents for a blend of 90% gasoline and 10% ethanol)	Expires in 2007
Production tax credit (IRA Code Section 45)	Producers of electricity from "closed-loop biomass", wind or poultry litter	Credit of 1.5 cents per kWh adjusted annually for inflation and changes in the economic competitiveness of qualifying resources	Closed-loop biomass does not include forest biomass, mill waste or urban wood waste To qualify, a closed-loop biomass facility must be placed in service after December 31, 1992, and before January 1, 2002

tunity for Annex B countries to implement afforestation/reforestation projects in non-Annex B countries with considerably lower carbon sequestration costs. However, it is to be noted that joint implementation, CDM, and emission permits trading have supplementary requirements, i.e. Annex B countries should be limited in the use of these mechanisms to help achieve their emissions reduction targets.

Although it is the least cost option among the scenarios considered in this study, direct carbon sequestration in forests has been criticized on the grounds of permanence, saturation, and verifiability [38]. The question of permanence is particularly applicable to non-Annex B countries with no emission reduction commitment under Kyoto protocol. The issues such as how long the carbon will be sequestered in forest stands, how long the carbon accumulation occurs at the increased rate, and whether it is possible to accurately account for the amount of carbon sequestered are central to the debate of direct sequestration. To overcome the problem posed by the issue of permanence, two accounting systems, i.e. ton years and renting credits have been discussed elsewhere [39–42]. Ton-year accountings systems help equate credits earned over the limited time frame to permanent sequestration by the use of the equivalency factor. When it is possible to rent emissions credits, they may be assigned to the renter when carbon is sequestered with the liability for sequestered carbon going to the host. When the rental contract expires, the renter would incur an emission debit and the host would be released from further liability. The problem of multiple credits that may occur with ton-year accounting when carbon is sequestered in trees and later harvested can be avoided with a rental accounting system [42]. However, in the absence of internationally agreed values and market structure, the renting credits is still an abstract idea.

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