Carbon Sequestration and Substitution by Wood Energy[1]

Seqüestro e Substituição de Carbono por Sistemas Dendroenergéticos

Luiz Augusto Horta Nogueira[2] and Miguel Angel Trossero[3]

Abstract: Forestry for energy should play a significant role in reduction of atmospheric carbon increase, not only by carbon sequestration, but also and mainly by substitution effect, offsetting permanently fossil fuels gaseous emissions and contributing for regional development. In this paper the importance of wood fuel is reviewed from a worldwide perspective, comparing estimated wood consumption energy with other sources of energy and with timber production. The sustainability of wood energy systems is briefly introduced. Following both carbon sequestration and substitution effects of wood energy systems are discussed, as well as expected environmental impacts are presented for some forest productivity scenarios.

Key words: Woodfuels, carbon sequestration, carbon substitution.

Resumo: A silvicultura para fins energéticos pode cumprir um importante papel na redução do carbono atmosférico, não apenas mediante o seqüestro de carbono como também através do efeito de substituição, deslocando permanentemente combustíveis fósseis e suas emissões, além de contribuir para o desenvolvimento regional. O presente trabalho apresenta uma revisão da demanda dendroenergética em uma escala global, avaliando sua importância relativa diante das outras fontes energéticas e da demanda de madeira para usos não-energéticos. Comenta-se brevemente a sustentabilidade da dendroenergia e, em seguida, discutem-se os efeitos substituição e seqüestro de carbono associados à dendroenergia. Os impactos ambientais são estudados em cenários, considerando as distintas produtividades silviculturais.

Palavras-chave: Dendroenergia, seqüestro de carbono e substituição de carbono.

1 Introduction

The basic aim of this paper is to present and discuss the role of wood energy systems in reducing atmospheric carbon emissions and contributing to mitigate climate change. In fact, woodfuels are carriers of recently stored solar energy and might be considered as a sustainable energy source. Although woodfuels can be environmentally sound (and in many situations they are, indeed), they are neither conventional nor alternative sources of energy, but rather the very first source of primary energy used by mankind, with a large potential to be explored.

The first part of this paper discusses the current situation of wood energy systems,

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stressing the present contribution of forest energy to world energy demand and the relevance of forest removals for energy compared to whole forestry production. Some aspects of sustainability of wood energy systems are briefly commented, and in a third topic, basic concepts are reviewed concerning wood energy parameters, specific emission coefficients and forest carbon storage, leading to the following sections on woodfuels and their potential role in atmospheric carbon dioxide emission abatement and substitution.

Although the first version of this paper was prepared in 1998, when the first author was working as Visiting Scientist at FAO headquarters, the wood energy database currently available is not significantly different. Even considering the relevant improvement on wood energy data presentation and adjustment allowed by WEIS, Wood Energy Information System of FAO, already available in a Microsoft Access interactive version (FAO, 2003a), the lack of recent efforts in data gathering and processing in many countries and regions turn impossible bringing more recent wood fuels data, for a global perspective. However, it is important to mention that in many cases updated information is already available and could be used in more focused studies.

2 Wood energy Demand and Perspectives

Since the recent introduction of fossil fuels in modern economy, forest based-fuels have been partially displaced mainly by coal, oil and natural gas, but remain as an important component of energy supply, not only for developing countries. In Figure 1, wood energy is compared to other energy sources. For woodfuels consumption data, values were obtained from FAO's Forestry Department and using as main data source FAOSTAT, which figures are official country data. For comparability, data for fossil fuels demand was taken for same period, from United Nations Energy Statistics (UN, 1997).

For countries such as Finland, Sweden and Austria, forest energy provides up to 17% of their demand. In global terms, woodfuels represent about 7% of the world's total primary energy consumption, most of which (76%) is used in developing countries and the remaining (approx. 5400 PJ) in developed countries. This contribution rises to 14% if other biofuels are considered, thus reaching a magnitude similar to that of other conventional energy sources, such as coal, gas and electricity (IEA, 1997).

Woodfuels are also relevant for the forest sector. In 1995, the total production of wood for energy and non energy uses reached approx. 3 900 million CUM (cubic meter), out of which 2 300 million CUM have been used for woodfuels. This means that approx. 60% of the world's total wood removals from forests and non-forest lands have been used for energy purposes. While only 30% of the wood produced in developed countries is used for energy (33% in Europe and 29% in North America), in developing countries that amount accounts for 80%. In fact, Figure 2 shows that a high proportion of the total wood consumption is used for woodfuels in Africa, Asia and Latin America where woodfuels account for 89%, 81% and 66% of their respective total consumption. The share of woodfuels within the total wood consumption

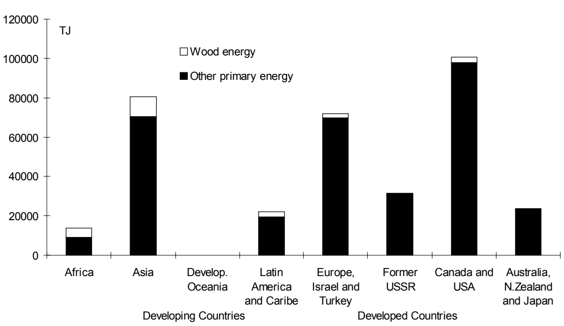


Figure 1 – Woodfuel in primary energy supply, 1995.
Figura 1 *– Posição do combustível de madeira entre as fontes de energia primária, 1995.*

ranges from a low 22% in Malaysia (which is in line with European countries) to 98% in countries such as Bangladesh, Cambodia, Nepal and Pakistan.

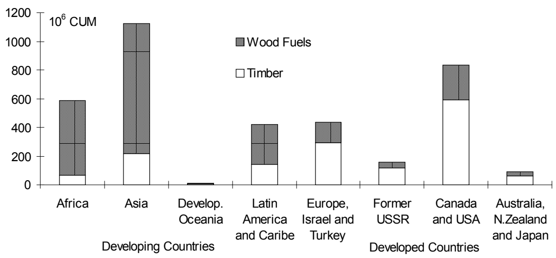


Figure 2 – Total wood products demand: woodfuels versus timber, 1995
Figura 2 *– Demanda total de produtos de madeira: combustíveis de madeira "versus" madeira para outros usos, 1995.*

Besides environmental factors, technological development of wood energy has been recently promoting the expansion of biomass as a clean energy source. In this sense, the use of woodfuels in industrial and power sectors is in many situations economically feasible and operationally reliable. For instance, electricity generation from recovered black liquors is high in many countries, where large pulp and paper industries have cogeneration plants fuelled with such woodfuel. Almost all their energy needs are met and sometimes surpluses are sold to the public grid (FAO, 1997a). Figure 3 shows the relative importance of different types of woodfuels, including all forest and tree direct and indirect energy, accounted as fuelwood, charcoal, residues from mechanical wood industries and black liquor from chemical pulping process.

It is interesting to observe that including the wood industries by-products used for energy supply in wood energy statistics, woodfuel demand per capita is increased both in developing and in developed countries. In fact, as it can be seen in Figure 4, there is a very wide range of woodfuel use in high-income countries, reaching, in some cases, high levels of specific consumption, with its obvious implication of non-residential use. The two highest per capita consumption of woodfuels observed in this figure refer to Finland and Sweden. This is strong evidence that woodfuels can no longer be considered as old-fashioned energy source, with its usual association to poverty and smoky households.

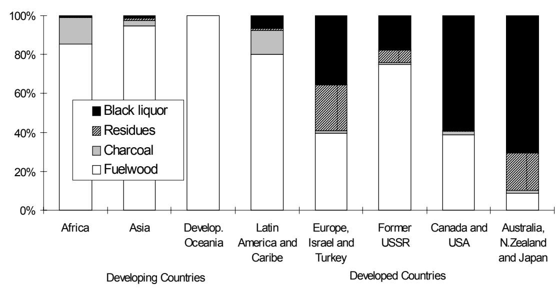


Figure 3 – Share of different woodfuel types (relative values), 1995.
Figura 3 *– Participação dos diversos tipos de combustíveis de madeira (valores relativos), 1995.*

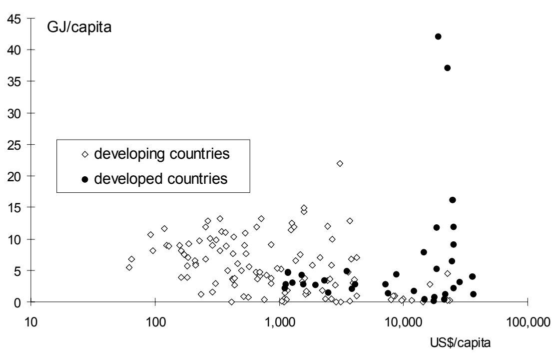


Figure 4 – Woodfuel demand versus GNP per capita, 1995.
Figura 4 *– Demanda por combustível de madeira "versus" GNP "per capita", 1995.*

3 Sustainability of Wood Energy Systems

In general, wood energy systems can be considered sustainable, basically because they are using a renewable biomass which, if not used, will rot and contribute to GHG emissions. Modern forestry practice, either for planted forest or sustainable exploitation of native forests, allows a proper natural resource management, with minimum soil damage and erosion (see, for example, FAO,1995a). The use of chemicals as fertilizers and products for weed and pest control can be significantly reduced. As a result, fuelwood is produced from the same area or forest for decades, without any significant environmental damage, in many cases.

Most of the forest biomass used for woodfuel in rural areas comes from dead trees, prunings and other woody residues collected from forests, woodlands and trees, as well as from trees planted in marginal and farming lands through agroforestry schemes (FAO, 1996). In many other areas, a substantial amount of woodfuel originates from the biomass produced by land clearing operations to transform forests and woodlands into agricultural farms, where the use of this biomass as woodfuel is better than simply using "slash and burn" practices. Moreover, a considerable amount of woodfuels are obtained as an industrial by-product, reducing the environmental impact and improving the overall energy efficiency of associated industrial process. In fact, rational wood energy expansion should be assumed as an effective practice towards the sustainable development, integrating nature and society as well as promoting employment, infrastructure and land protection (FAO, 1995b).

However, woodfuel consumption is so widespread in many places that it exceeds its sustainable production from available and accessible supply sources, leading to fuelwood and charcoal shortages and wood stocks depletion in many areas. Therefore, while, in general, woodfuel demand and, in particular, fuelwood utilization as a household cooking fuel does not seem to face supply constraints, it is worth to mention situations, such as in Haiti, the Andean highlands and Sahelian countries, where there is a clear and worrisome pressure on forest resources. Of course that type of fuelwood demand is clearly not sustainable and deserves prompt attention to be properly tackled.

The development of sound wood energy programmes should be considered for both situations: where there is good availability of woodfuels and where these resources are scarce. The existence of traditional fuelwood demand and the perspectives for development of modern wood energy systems imposes suitable strategy-building and well-based decisions, either in supply or demand, integrating local, national and regional forestry, energy, environmental and rural development policies. These programmes and their strategies demand a sound database, regarding the different aspects and issues of the wood energy systems. Unfortunately, due to the difficulties associated with wood energy data collection, caused mainly by the decentralized nature of wood energy systems and the lack of adequate national capabilities, data on wood energy are not regularly collected and monitored. Aiming to deal with such important aspect, the FAO's Forestry Department proposed a WEIS (Wood Energy Information System) and put forward a standardized set of woodfuel definitions, UWET (Unified Wood Energy Terminology) looking for improving the FAO statistical woodfuel database and co-operating with other important wood energy databases, such as UN-Energy Statistics, IEA, EUROSTAT, UN-ECE and OLADE (Trossero, 2004). Another very important tool created by FAO to deal with actual wood energy systems, specifically able to evaluate sustainability in this context is WISDOM, Wood Integrated Supply/Demand Overview Mapping, which uses a GIS based approach to make a

Table 1 - Specific theoretical emission coefficients
Quadro 1 *– Coeficientes teóricos de emissão específica*

Fuel	Specific theoretical emission ($t\ C\ TJ^{-1}$)	Reference
Woodfuels	24.7	FAO/WEIS
Solid fossil fuels	25.2	IPCC, 1996a
Liquid fossil fuels	18.5	IPCC, 1996a
Gaseous fossil fuels	15.0	IPCC, 1996a
Fossil fuels (average)	19.7	IPCC, 1996a

geographical representation of fuelwood production and consumption areas which can help, for instance for identifying "hot spots", where the estimated wood energy demand could not be attended by a sustainable way (FAO, 2003b).

4 Basic Parameters on Wood Energy Carbon Emissions and Storage

The main parameters to analyze the atmospheric carbon balance regarding wood energy and forestry are the carbon emission for each fuel type and carbon storage in forest, evaluated as annual increment and total stock, as well. Depending on both heating value and chemical composition, a specific theoretical carbon dioxide emission, can be calculated for each fuel type, as shown in Table 1 per tons of carbon emitted when an amount of such fuel is totally burned to supply 1 TJ of heat energy. In this table, the "average fossil fuel" assumes the global total fossil fuel demand and the associated carbon dioxide emission, according to 1995 figures (IPCC, 1996). For woodfuel values, a net heating value of 13.8 MJ kg^{-1}, 30% moisture (dry basis) and 48.8% carbon fraction in biomass dry matter have been assumed.

For the actual conditions, the effective carbon emission from a given fuel and the impact produced when fuel substitution occurs is affected by the combustion efficiency (fraction of fuel effectively oxidized) and heat efficiency (ratio between useful and total heat produced). Regarding these aspects, it is interesting to note that combustion equipment used for biomass and fossil fuels can be very different. For a typical solid woodfuel, stokers and grates are usually adopted while burners are used for liquid and gaseous fossil fuels. In both cases, combustion and heat efficiency vary greatly, however, under typical conditions, the figures presented in Table 2 can be assumed. The following equation relates these parameters to carbon emission.

Table 2 – Typical values of combustion and thermal efficiency
Quadro 2 *– Valores típicos de eficiência de combustão e eficiência térmica*

Fuel	Combustion efficiency	Thermal efficiency
Fossil	0.98	0.85
Biomass	0.95	0.80

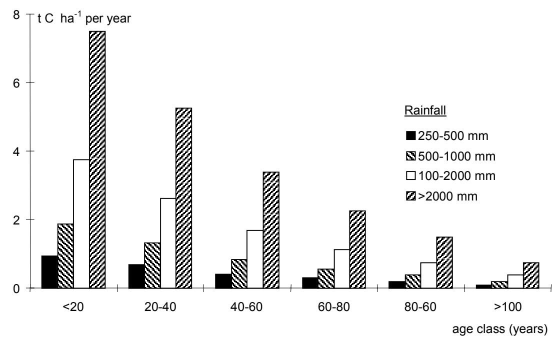
$$\frac{\text{Effective carbon emission}}{\text{Useful heat produced}} = \text{Specific theoretical emission}_{(\text{Table1})}\left(\frac{\text{Combustion efficiency}}{\text{Thermal efficiency}}\right)_{(\text{Table 2})}$$

From the expression and values presented above are can conclude that, for each useful terajoule produced either by a woodfuel or an average fossil fuel about 27.8 and 22.7 ton of carbon, is emitted, respectively. Thus, it is important to bear in mind that when a woodfuel is burned to substitute an amount of useful heat from fossil fuel, there is an emission decrease equal to the fossil fuel carbon emission. However, when comparing carbon emissions, it should 1.22 joules of woodfuels should be burned to substitute the amount of carbon dioxide not emitted when 1 joule of an average fossil fuel is not used.

To assess the amount of carbon that flows into and is effectively stored in a tree or a forest is a not simple task theoretically, taking into account a generic photosynthesis process under optimal conditions of temperature, water availability and solar radiation, it would be possible to fix about over 500 tons of carbon ha^{-1}, annually. This value decreases to a more reasonable 60 to 86 tons carbon ha^{-1}, when respectively calculated based on the estimates of annual overall productivity of two main metabolic photosynthesis paths: Calvin Cycle (used for C-3 plants) and Hatch-Slack Cycle (used for C-4 plants) (Smil, 1983). Moreover, in actual conditions autotrophic and heterotrophic losses should be included reducing even more these last figures.

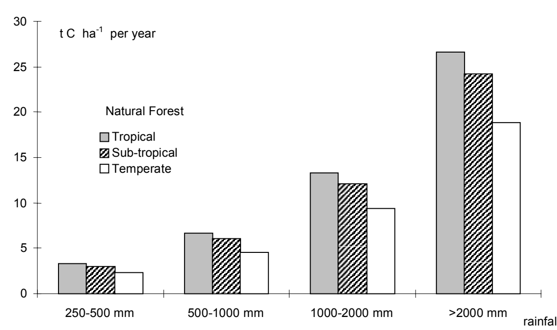
It is clear that real ecosystems present many variables affecting net productivity, such as species, diseases, soil fertility, seasonality, but mainly plant age climate and rainfall. Figure 5 shows the "average above ground carbon" annually stored in tropical natural tree formations, fully stocked, as a function of age class and rainfall (calculated from Whittaker and Marks, 1975). To assess root mass, these authors recommend multiplying by 1.33 for trees growing on deep soil, 1.29 for medium soil trees and 1.25 for shallow soil trees. Again using data from that reference, it was possible to estimate the effect of climate and rainfall on the total annual carbon fixed in natural forests (including roots, for a medium soil), under average conditions, as presented in Figure 6.

As in the case of natural forests, in man-made forests, the values for plant productivity and associate rate of atmospheric carbon capture vary extensively, depending mainly on species, climate and water availability.



Adapted from: Whittaker & Marks (1975).

Figure 5 – Influence of rainfall and age class on average above ground carbon annually stored in tropical natural tree formations.
Figura 5 *– Influência da precipitação e da classe de idade no armazenamento médio anual de carbono acima do solo, em formações florestais naturais tropicais*



Primary data: Whittaker& Marks (1975).

Figure 6 – Influence of rainfall and climate on average total carbon annually stored in natural forests.
Figura 6 *– Influência da precipitação e do clima no armazenamento médio anual de carbono total em florestas naturais.*

Table 3 data were based on typical mean annual increment (MAI) values for some tree species, under good forestry practice with the values shown being considered representative for short rotation forests aiming at fuelwood production. An apparent density of 470 kg per stere, a moisture content of 30% (wet basis) and an additional of 15% of stem volume to include branches and 29% for roots were assumed to calculate the total amount of carbon annually stored. It is interesting to observe that the results in the last column seem to be conservative, when compared to those shown in Figure 6.

Table 4 shows values of total amount of carbon stored under different crops, shared in the plant above ground, plant roots and the organic carbon in soil (Openshaw, 1998). It is worth to note the high participation of this last component, referring to the soil carbon content. According to the same paper, the annual carbon accumulated in native forests is about 5 t C ha^{-1} per year.

In order to evaluate atmospheric carbon sequestration and substitution effects of forestry and wood energy use, Table 5 was prepared considering figures and results previously presented about this topic. Values considered typical for annual rate of carbon accumulation in short rotation forests and the total carbon storage in mature forests were selected. Two productivity scenarios were assumed for short rotation forests, from different contexts in terms of mean annual increment and rotation period: high productivity (13.5 t dry matter/ha/year and 5 years) and low productivity (8.1 t dry matter/ha/year and 10 years). It is important to observe that, since carbon sequestration by forests should be done predominantly under high productivity conditions, the soil to be used for planting trees is assumed as a soil already rich in organic matter thus, being assumed as net effect in terms of carbon storage only the tree (135 t C ha^{-1}), without including any eventual variation in soil biomass.

Table 3 - Productivity indicators in forests planted for energy
Quadro 3 *– Indicadores de produtividade em florestas plantadas para energia*

Specie	Mean annual increment (stem volume)		Total carbon annually stored
	(stere ha^{-1} per year)	(dry t ha^{-1} per year)	(t C ha^{-1})
Salix	16-24	5.3 - 7.9	3.9 - 5.9
Pinus	15-35	4.9 - 11.5	3.7 - 8.5
Eucaliptus	20-40	6.6 - 13.2	4.9 - 9.8

Table 4 – Carbon storage under different crops (Openshaw, 1998)
Quadro 4 *– Armazenamento de carbono por várias culturas (Openshaw, 1998)*

Drop	Carbon storage			
	Plant above ground	Plant below ground	Soil	Total
	(t C ha^{-1})			
Primary forest	90	45	200	335
Secondary forest	70	35	150	255
Grassland	18	9	150	177
Arable agriculture	7	3	115	125

Obs.: Annual rainfall 1,500 mm; soil type: nitrosols, carbon storage in soil includes organic carbon down to one meter in depth.

Table 5 – Atmospheric carbon annual removal and storage in forests
Quadro 5 – *Valores típicos de remoção e armazenamento anual de carbono atmosférico em florestas*

Scenario	Rotation	MAI	Atmospheric carbon effect	
			Annual removal	Storage
	(year)	(t ha^{-1} per year)	(t C/ ha^{-1} per year)	(t C ha^{-1})
Short rotation forest, high standard	5	13.5	10	-
Short rotation forest, low standard	10	8.1	6	-
Mature tropical forest	-	-	-	135

5 Woodfuel and Fossil Fuel CO_2 Emissions

The progressive accumulation of greenhouse gases, especially those derived from the massive use of fossil fuels, leads to climate change and the deterioration of global environment conditions; paradoxically, however, it also brings new opportunities for the development of forest energy as a major mechanism for carbon sequestration and carbon substitution, as explicitly mentioned in the Kyoto protocol (FCCC, 1997a). In order to evaluate the present role of woodfuels, in this section their absolute and comparative carbon emissions are presented in this section. In the next section, will be presented the forest role (passive and active) to curb the atmospheric carbon, are presented.

Using data and figures presented at previous sections of this paper, it was possible to calculate the global and regional values of the substituted and actual carbon emissions related to wood energy in 1995, as presented in Table 6 and Figures 7 and 8. Considering the evolution of national energy matrix and the level of demand during last years, these values could change, although the relative importance of wood energy seems to remain the same.

It is worth to remember that substituted carbon emissions refer to the amount of carbon that is not released to atmosphere by fossil fuel combustion when a woodfuel is used. Thus, if the current woodfuel demand should be displaced by fossil fuels, the global carbon emission would increase in about 7%.

6 Carbon Sequestration by Passive Forestry

The first approach aiming to reduce atmospheric carbon concentration by forestry is to assume trees as permanent carbon sinks. In fact, many institutions and governments have been proposing to establish new forests to absorb carbon dioxide. The Kyoto Protocol explicitly mentions reforestation and afforestation as mechanisms for carbon dioxide atmospheric control (FCCC, 1997a). Regarding that approach, it is very important to stress two aspects: (a) the forests created to store carbon should be permanently preserved and maintained, without any use, at least until finding another way to control atmospheric carbon increase, (b) that kind of forests should be constantly planted, while fossil fuels are in use. Therefore, carbon sequestration by forestry is actually a partial solution, able just to mitigate greenhouse gases increase and allowing to postpone a permanent and effective solution.

In order to evaluate briefly the meaning of forestry as such kind of passive and static carbon store, as well as to verify the

Table 6 – Substituted and actual carbon emissions associated to woodfuels
***Quadro 6** – Emissões de carbono substituídas e reais associadas a dendroenergia*

Region	Carbon emissions from fossil fuels (theoretical)	*Substituted* carbon emissions by using woodfuels	*Actual* carbon emissions from woodfuels
	(Gt)		
Developing countries	**2.085**	**0.375**	**0.459**
Africa	0.173	0.110	0.135
Asia	1.603	0.203	0.248
Oceania	0.003	0.001	0.002
Latin America and Caribe	0.306	0.059	0.073
Developed countries	**3.96**	**0.104**	**0.128**
Europe	1.127	0.032	0.039
Former USSR	0.767	0.010	0.012
North America	1.677	0.055	0.068
Oceania + Japan	0.389	0.007	0.009
World	**6.045**	**0.479**	**0.586**

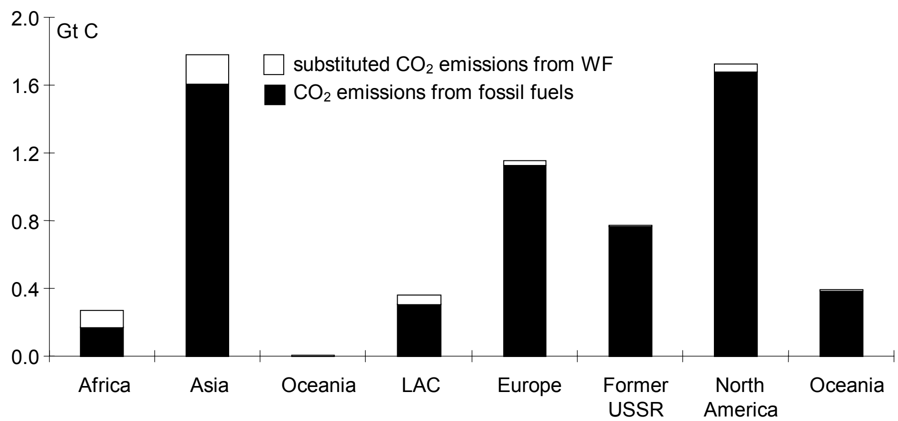


Figure 7 – Atmospheric carbon emission: woodfuels impact.
***Figura 7** – Emissão de carbono atmosférico: impacto de combustíveis de madeira.*

requirement of annual reforestation area to compensate fossil carbon emissions additional to the 1990 values, in Table 7 is presented estimates of area to be forested or reforest aiming to accomplish the Kyoto Protocol assuming that forestry would be the only mechanism adopted for climate change control. In this table is also presented values of total carbon emissions of selected Annex I countries in 1990 and the carbon reduction commitment (FPCC, 1997). It was used a total carbon accumulation of 135 t ha^{-1}. This group of 15 countries is responsible for more than 44% of world carbon emission associated to fossil fuels use and 71% of Annex I countries carbon emissions. For the last rows, values for all Annex I countries and global emissions are also presented.

Of course many other activities should be carried in addition to forestry aiming to mitigate climate change, like energy conservation as well as introduction of other renewable shown sources of energy. So, the values shown at Table 7 represent the maximum required to fulfill the Kyoto Protocol. In fact, IPCC proposes that 12-15% of the carbon emissions from fossil fuel could be offset by new forests (IPCC, 1996), corresponding to approximately 216,000 ha planted every year and requiring about US$ 216 million to be implanted, under a typical cost of US$ 1000 ha^{-1}. Anyway, such area estimated to be annually reforested and permanently immobilized to reduce atmospheric carbon dioxide resulting from fossil fuel burning is important and might be compared with some figures from the study State of the World's Forests (FAO, 1997b), as presented in Table 8. For instance, such afforestation/reforestation effort to mitigate climate change is similar to reducing deforestation in about 1.6% or forest fires in about 10%.

7 Carbon Sequestration and Substitution by Wood Energy Systems

Looking for a more active role for forestry towards a sustainable development and mitigation of climate change, it is interesting to consider forests not only for carbon sequestration, but also for carbon substitution,

Table 7 – Area to be annually reforested to fill Kyoto Protocol commitment (at 135 t C ha^{-1})
Quadro 7 *– Área a ser reflorestada anualmente para cumprir o compromisso com o Protocolo de Quioto (em 135 t C ha^{-1})*

Country	Current carbon emissions from fossil fuels	Kyoto Protocol reduction commitment	Area to be reforested to sequester global fossil carbon emission
	(Mt C per year)	(%)	(1000 ha per year)
Austria	16.1	8	9.6
Belgium	30.9	8	18.3
Canada	124.8	6	55.4
Denmark	14.2	8	8.4
Finland	14.7	8	8.7
France	100.0	8	59.2
Germany	276.1	8	163.6
Greece	22.4	8	13.3
Italy	117.0	8	69.3
Japan	320.0	6	142.2
Netherlands	45.7	8	27.1
Spain	71.1	8	42.1
Sweden	16.7	8	9.9
U. K. and Northern Ireland	159.3	8	94.4
United States of America	1351.9	7	701.0
Annex I Countries total	3,744		1442.5
World total	6,045		2875.4

* calculated considering the global emission reduction agreed by the Kyoto Protocol.

Table 8 – Relative value of area to be annually reforested to offset 15% of expected reduction in carbon emission of Annex I countries
Quadro 8 – *Valor relativo da área a ser reflorestada anualmente, para compensar 15% da redução esperada de emissões de carbono dos países do Anexo I*

Indicator (SOFO FAO, 1997)	Absolute value average in the period 1990-1995	Area required to offset 15% of global fossil fuels carbon emission as % of indicator
	(Mha per year)	(%)
Deforestation in developing countries	13.73	1.6
Forest fires in developing countries	~ 2	10.8
Reforestation in developing countries *	2.73	7.9
Global reforestation *	3.93	5.5

* Average 1980-1995, excluded Russian Federation.

which means to use wood products and particularly woodfuels to displace forever fossil fuels and fossil fuel based materials. There are several sound and mature technologies, able to supply heat and/or electricity in large capacity, using fuelwood or other wood-derived fuels.

To explore the emission impacts caused by fossil fuel substitutions and calculate the sequestration effect associated to keep a forest in permanent growth, it was assumed the scenarios shown in Table 4 for short-rotation forest. The sequestration effect was calculated for the biomass above and below ground. To include the organic matter incorporated to soil (roots and leaves), it was adopted a simple logarithmic model for biomass accumulation below ground, adjusted for a value of 33% of fuelwood produced as organic matter remaining in the soil after the first harvest. According to this model, after 60 years there is below ground 35.0 and 23.6 tons of dry matter ha^{-1}, respectively for high and low standard forests, which could be considered in line with values presented in Table 4. The sequestration effect of biomass above ground was calculated using a 10 years moving average model. Just for comparison, to indicate the growing of a permanent forest, it was adopted again a simple logarithmic model, adjusted to indicate a total biomass amount of 260 t as dry matter, after 90 years.

As typical results from this model, Figure 8 is shows presented the amount of dry biomass available per hectare for a permanent forest and a forest managed to produce fuelwood, considering a low productivity scenario along 60 years. Figure 9 shows the sequestration effect and accumulated substitution effect, for the high productivity scenario studied, along a period of 90 years. Table 9 the main indicators for carbon sequestration and substitution by woodfuels use are summarized for both studied scenarios.

These results indicate the substantial advantage in managing forests to produce fossil fuel substitutes in comparison to use trees as a simple carbon store. Besides the influence of forest productivity and the assumed parameters, of course that such advantage depends basically on the period of time considered in the comparison, because it is essentially a comparison of a stock (135 t C ha^{-1} in permanent forest) versus the sum of the integrated flow of woodfuels (4.0 to 6.6 t C ha^{-1} per year) plus the carbon sequestered above and below ground.

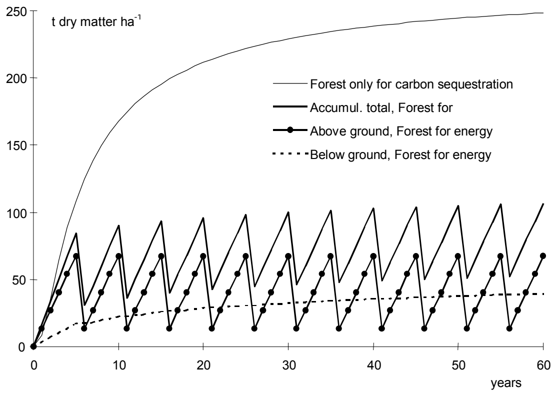


Figure 8 – Biomass in forests for carbon sequestration and carbon sequestration/ substitution for mean annual increment of 13.5 ton ha^{-1} and 5 years production cycle.
Figura 8 *– Biomassa em florestas para seqüestro de carbono e seqüestro/substituição de carbono para incremento médio anual de 13,5 t ha^{-1} por ano e ciclo de produção de 5 anos.*

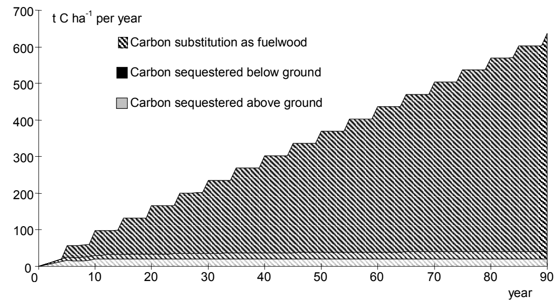


Figure 9 – Accumulated net carbon substitution and carbon sequestration for a fuelwood producing forest with mean annual increment of 12 ton ha^{-1} and 5 years production cycle.
Figura 9 *– Acúmulo líquido de substituição e seqüestro de carbono para florestas produtoras de combustível com incremento médio anual de 12 t ha^{1} e ciclo de produção de 5 anos.*

Table 9 – Forest productivity impact on carbon sequestration and substitution, 60 years period
Quadro 9 *– Impacto da produtividade florestal no seqüestro e na substituição de carbono, em um período de 60 anos*

Scenario	Low standard forest	High standard forest
Mean Annual Increment (ton ha^{-1} per year)	8.1	13.5
Production cycle (year)	10	5
Main results (ton ha^{-1})		
Sequestered carbon below ground	18.7	19.3
Sequestered carbon above ground	21.8	19.8
Sequestered carbon total	40.5	39.1
Substituted carbon	238.1	396.9
Sequestered plus substituted	278.6	436.0

8 Final Comments

For a reference coal fuelled thermoelectric power plant, operating in typical conditions (30% global efficiency and 80% capacity factor), with 1 MW of installed capacity, annually about 2,803 ton of carbon to the atmosphere is emitted. Such amount of carbon requires, under the concept of forestry for static carbon sequestration, with 135 tons of carbon fixed per hectare, the plantation of 15.7 ha of forest every year. So, for total economic life of such plantation (assumed as 30 years), it is required to forest about 481 ha, just to offset the emissions along that period.

However, if the active forestry and sustainable wood energy production for power generation, is considered by exploiting an area of approx. 508 ha, under a MAI (mean annual increment) of 12 t ha^{-1} per year, it is possible to supply permanently 6,094 t of fuelwood required for the same 1 MW power plant and besides to fix carbon enough to offset the emissions of an additional 0.28 MW power plant using coal. In other words, the sequestration plus substitution combined effects when producing 1 MW of power from woodfuels is equivalent to abate emissions from a 1.28 MW coal power plant.

Thus, the overall substitution plus sequestration effects of woodfuel use in power generation results, even for relatively short term exploitation periods, an area requirement quite similar to sequestration effect alone. This issue is very sensitive to power plant efficiency and operational conditions, deserving a more detailed discussion beyond the aim of the present paper.

The Kyoto Protocol to the United Nations Framework Convention on Climate Change and recent derived agreements could effectively play a catalytic role in the further development of woodfuels as an environmentally friendly and cost-effective source of energy. Either by carbon sequestration and substitution mechanisms, the rational wood energy systems can mitigate the atmospheric carbon increase and improve socio-economic prospects for those living in rural and forest areas. Thus, it is important to consider forests not only as a static store of carbon, but also as an actual and dynamic source for development.

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