FORESTRY OPPORTUNITIES IN THE UNITED STATES TO MITIGATE THE EFFECTS OF GLOBAL WARMING

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ABSTRACT. There are a variety of opportunities in the United States to expand the area of trees and forests, and to improve their growth, that could have significant impact upon the annual uptake of atmospheric CO_2. Work coordinated by the American Forestry Association has attempted to quantify those opportunities, and demonstrate what kinds of costs and benefits might result from an attempt to begin implementing them. The first section of the work, reported in this paper, has focused on the opportunities that are seldom thought of as regular forestry—planting trees on marginal crop and pasture lands, increasing windbreaks and shelterbelts, growing trees as a biomass energy source, and improving urban tree canopies and placements as an energy-conserving measure. The benefits from such work include the C sequestered in the biomass and soils involved, as well as the carbon emission reductions achieved through energy conservation. These opportunities could add up to a total C impact per year in the range of 141 to 382 x 10^6t—somewhere between 10 and 30% of the current net C emission from fossil fuel in the United States. Additional work is underway to quantify the opportunities inherent in improving the management of existing forestlands, through more traditional forestry. The results of that work will be available in late 1992.

Biomass and Global Warming

Although the ability to predict future climate change is controversial, the fact is that it will, if it occurs, be extremely disruptive. The concerns are significant enough to cause policymakers to look for opportunities to encourage mitigative measures. Forestry is one of those opportunity areas that can provide a degree of protection to help buffer too-rapid changes in climate.

Many of the possible investments in forests, in addition to helping offset atmospheric carbon buildup are, in fact, economically advantageous. Others, particularly those that build long-lived ecosystems, create new resource strength that represents a sound investment in the future. Some replace the need to burn fossil fuels, leaving those fuels available for another day. Some, like the shade trees around homes, make each day more pleasant while saving air-conditioning dollars that will never need to be spent, and reducing fossil-fuel burning in power plants.

Thus, there are several global warming preventative strategies based on forestry that, far from being economically burdensome, represent immediate and tangible

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benefits. This is not to suggest that forestry can "take care of" the threat of global warming. Forestry is just one aspect of an initial agenda. While taking action on that agenda, policymakers must continue to develop the research and information that will help everyone better understand the continuing threat, and the further action agenda that is warranted.

Atmospheric CO_2, the most important of the greenhouse gases, is inextricably tied to growing plants and thus is directly linked to the growth of the trees and forests of the world. The global CO_2 level has fluctuated in the range of 200 to 280 ppm over the past 160,000 years, according to studies of historic records contained in deep icecaps and ocean sediments. Since the beginning of the industrial revolution, however, atmospheric levels of CO_2 have shot up rapidly, from about 280 ppm in 1750 to 350 in 1989. With CO_2 levels continuing to increase at an estimated rate of 0.5% annually, a growing number of scientists are concerned with the potential for significant global warming within the coming century (Hansen et al., 1989, Schneider, 1989b, Trexler, 1991).

An overwhelming proportion—some 80% of the net annual CO_2 addition—comes from fossil-fuel burning, and the United States, with its highly energy-intensive economy, contributes about 22% of that total (Boden et al. 1990). Thus, the reduction of fossil-fuel burning, particularly where it can be done without loss of productive output (through higher efficiencies, for example) becomes a first-order goal in the attempt to reduce atmospheric CO_2 accumulation. Wood used in place of fossil fuel for energy represents a recently formed source of C and one that can readily be replaced by new growth in forests. This means that a recycling C source can replace a nonrecycling fossil source, and the net addition of C to the atmosphere over time can be reduced accordingly.

While paying attention to lessening atmospheric C uptake, it seems prudent to try to increase the rate at which C is taken up and stored in Earth's biophysical systems. The major "sinks" for C are oceans (estimated to contain some 43 x 10^{12}t), soils (estimated to hold 1.5 to 2 x 10^{12}t), and forests (estimated to hold .5 x 10^{12}t) (Trexler, 1991).

Trees and forests are tremendously important as one terrestrial sink of CO_2. About half the dry weight of wood is C, so as trees add mass to trunks, limbs, and roots, C is stored in relatively long-lived structures instead of being released to the atmosphere. Obviously, all plants do this same conversion, but grasses and crops that are eaten by herbivores and digested, or that die and decompose within a season, are not as effective in providing long-term storage as are the woody structures of trees and the wood products made from them.

Significant ways to increase terrestrial C storage include enlarging the area of trees and forests, and increasing the rate of tree growth on those that already exist. Each of these strategies has the advantage of being easier than affecting ocean storage, and each would have the effect of "locking up" additional C in the Earth's biosphere. Eventually, of course, an upper limit on living forest biomass is reached, and additional tree growth is largely offset by mortality, plant respiration, and use so that the net additions to the terrestrial C store become marginal.

There are, however, at least three ways to extend the contribution of trees in storing C and make the expansion or improvement of forest ecosystems even more valuable in addressing the global climate change issue:

(1) Forests can be harvested and converted into long-lived wood, paper, or other products. So long as these products are in use or storage, the C remains out of atmospheric circulation. In addition, where wood is used in place of concrete or steel, significant energy is saved in the production process and lower CO_2 emissions result, making wood an attractive environmental alternative (CORRIM 1976).

(2) Forest biomass can be converted to energy, either directly through burning or indirectly through biological and chemical conversion. If the resulting energy is used to replace fossil energy, the effect is to retain fossil C in storage, a net gain in mitigation efforts.

(3) Properly located and managed trees can reduce the demand for fossil energy through effects such as shading buildings to reduce air conditioning demand, breaking winter winds to lower space-heating needs, preventing soil erosion to lower the amount of fertilizer and fossil fuel that would be needed to produce necessary food and fiber from higher areas of degraded soils, manipulating snow drifts to reduce winter snow-plowing costs and automobile accidents, and sheltering livestock in both winter and summer to reduce stress and improve feed efficiency.

A serious consideration of forest biomass expansion as a global warming mitigation strategy requires that we consider:

** The amount of land biologically suited to expanded or accelerated forest production;

** The new technologies needed to create opportunities for expanded use of wood and other biomass in long-lived applications, or as a replacement for fossil energy sources;

** The market incentives needed to encourage private landowners to expand forests, and the amount of additional public incentive that might be required to meet forest goals in the event that market forces remain inadequate;

** The potential for using trees in ways that curb energy usage in transportation, agriculture, and everyday living;

** The effect of each of these elements on the net fluxes of C between Earth and its atmosphere; and,

** The likely effect of C flux changes in causing a significant global warming trend.

This paper addresses only a portion of that broad agenda, leaving to others the questions of new technology for improving the use of biomass in energy-generating facilities, the economic incentives needed to spur forest expansion, and the question of global climate change in response to atmospheric phenomena. Here we focus mainly on the land, water, and forest resources of the United States, trying to outline:

** The opportunity to expand the land area of the United States that is occupied by forests;
** The impact of those changes on C storage in biomass, and on annual production of usable biomass;
** The potential to utilize a higher percentage of forest biomass for energy, including the growing of biomass specifically as an energy crop; and,
** The C impact possible through expanded use of trees in energy-conserving ways.

The U.S. Land Base, its Use and Potential

The United States has about 916.6 x 10^6 surface ha of land that are currently used in four general categories (Table 1). These land uses are dynamic, with millions of hectares changing from one use to another each year. However, the overall totals don't move a great deal over time. For example, there have been about 160 x 10^6 ha of cropland in the United States since 1920 (Fedkiw, 1989). In that time, however, millions of ha of cropland have been developed for urban and other built-up uses. Those losses have been offset by conversion of pasture, range, and forest to crops.

Table 1. Major uses of land in the United States at selected years

	1950	1969	1987
		10^6 Ha	
Cropland	166	155	171
Pasture and Range	284	280	238
Forest	292	293	296
Other	179	188	211
Total Land Area	920	916	916

Source: Frey and Hexem, 1982; U.S. Department of Agriculture, 1989.

THE IMPACT OF LAND-USE CHANGE ON C DYNAMICS

Before evaluating the opportunity to shift land use through policy mechanisms and incentives, it is useful to review the impact that such changes may contribute to the nation's efforts to address greenhouse gas concentrations. As described above, trees and forests can increase the amount of C held in the terrestrial C sink when compared to other land uses such as cropland, pasture, or range.

In measuring the actual amount of C stored in forests, there is considerable data based on the measurements of trees made by foresters over the years. These measurements, and the resulting tree growth models that have been developed, focus almost exclusively upon the merchantable portion of the tree—the straight trunk portion (or bole) that can be converted into traditional wood products. It is possible, however, to utilize this vast array of scientific information about trees and forests for the purpose of estimating C reserves by making some reasonably straightforward conversions.

Converting merchantable timber volumes to tree biomass estimates can be done in two parts. For only the aboveground portion of the forest, it is estimated that tree biomass averages 1.67 times the computed amount of bolewood (Cost et al., 1990). This calculation would be appropriate if used to convert the estimated annual growth of merchantable timber into an estimate of the total-tree biomass that might become available for an operation such as whole-tree chipping to provide fuel for a biomass energy generator.

Trees also have significant below-ground root structures, and including them in the calculation leads to a conversion ratio that is about 1.91 for softwoods and 2.44 for hardwoods, or about 2.18 for all species (Birdsey, 1992). These factors provide an estimate of the total biomass, both above- and below-ground, for a given volume of merchantable timber.

This figure, calculated as cubic feet of biomass, must be converted to weight and to C content if we are to estimate the effect of forests upon the conversion of atmospheric C into C stored in trees. In converting the wood volume to weight, Birdsey has calculated an average of 490 kg of dry weight per m^3 of wood. The C content is estimated to be 50 percent of the dry weight. Thus, if the estimated annual growth of merchantable timber for a hectare of forest, in cubic meters of wood per year, is known, it can be multiplied by 534 [490 x 2.18/2] to get an estimate of the annual C storage in kg/ha/yr. If the tree species involved is known, Birdsey's work can be used to get a more precise estimate based on the differences between softwood and hardwood species.

For major timber types, Birdsey also calculated the biomass contained in the litter on the forest floor and the soil C, as they are related to the stage of forest growth from seedlings to maturity. Two of his resulting tables are shown graphically as Figure 1. The tables are shown together to illustrate two points: (1) the importance of soil C in the total reservoir; and, (2) the greater impact of soil C in the cooler, more northern forest.

Perhaps the least understood, and least appreciated, C that is stored by trees and forests as they grow is that which is stored within the soil profile itself. This below-ground storage occurs largely as the result of the continuous growth and death of small roots, but decayed leaf and other litter, as well as the large woody debris that falls to the forest floor, contributes significantly as well. Soil C provides the essential food base for the largely unseen, but widely diverse, populations of soil organisms that are so critical to the healthy functioning of ecosystems. Current research indicates that the soil organic C under forest cover is significantly greater than under either cropland or grassland (Birdsey, 1992).

Using this information, it is easy to calculate the potential impact of planting trees upon land that is physically and biologically suited for forest growth, but where forests do not now exist. Much of that land was in natural forest cover in the past but was cleared for a variety of human purposes, such as cropland or grazing. Since people continue to need crops and animals, no one would propose that all these lands be returned to forest for the sole benefit of helping mitigate the buildup of greenhouse gases. There are, however, many areas where the current use is unsustainable—where crops and grazing are ill suited, and where both environmental damage and, in many cases, unprofitable economic performance are realized. It is on those lands where society can look for opportunities that are immediately beneficial and should be pursued.

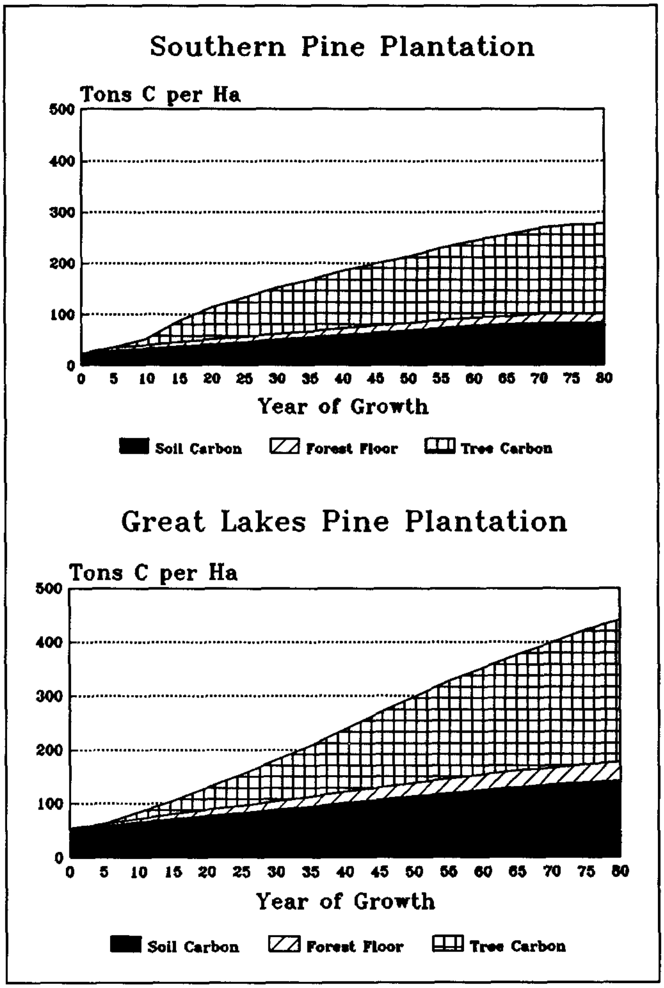

Figure 1. Carbon accumulations over time on pine plantations in two locations, following cropland.

Converting Marginal Crop and Pasture Lands to Forests

There are 47 x 10^6 ha of privately owned crop and pasture land that are marginal for crop and pasture use, using the criteria of the Department of Agriculture, and that are biologically capable of supporting tree growth (Parks, 1992). This land pool, three times as large as the target of the U.S. Conservation Reserve Program contained in the 1985 farm bill, presents a major opportunity for expanding the area of forest land in the United States.

These convertible lands are roughly divided between cropland and pasture in regard to their current use. They are also roughly equally divided between land where softwoods or hardwoods would appear to be most well adapted (Fig. 2).

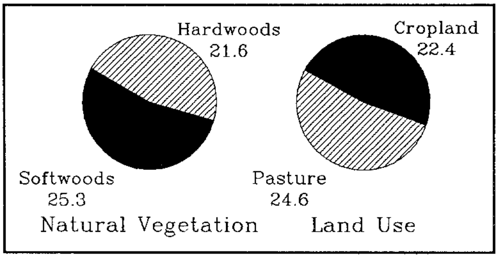

Figure 2. Marginal land suited for forest production, by timber type and current land use (10^6 ha).

On some of these lands, conversion to timber production under current economic situations would be profitable, as well as possible. Of the 25.3 x 10^6 ha adapted primarily to softwoods, Parks estimates that 9.5 x 10^6 ha would be economically more profitable in trees than in their current marginal crop or pasture use. On the 21.6 x 10^6 ha best suited to hardwoods, the lack of forest economic data prevents such analysis, but it is logical to assume that part of those lands would be economically competitive in forest, as well.

For the softwood regions where economic opportunities exist, annual net timber growth on the newly converted crop and pasture lands will average 7 m^3/ha/yr under well-managed plantations. Using the basic conversion factors developed for southern pines by Birdsey, that could mean C storage of 3–4.5 t/ha/yr during the growth cycle of these new forests. This is based on the assumption that about half of the converted land will be cut for pulpwood at age 25 and replanted, and that the rest will be thinned and grown to sawtimber size. Thus the C stored includes some in wood-in-use and in landfills.

In evaluating the opportunity for expanding forests, the 47 x 10^6 ha of marginal crop and pasture land is indicative of the highest amount of forest conversion that could reasonably be expected. Obviously, there are other crop and pasture lands that might be converted, particularly in the case of small areas of better land located in the midst of a surrounding conversion. However, such possibilities have been ignored. For a low estimate of the land that might be converted, the 9.5 x 10^6 ha with an economic advantage to be gained from planting softwoods has been used. While this leaves out land that could perhaps be economically converted to hardwoods, no attempt was made to estimate those areas because economic data were not available.

Lest the conversion of the economically feasible land sounds easy, it is instructive to remember that, while the Conservation Reserve Program was encouraging American farmers to convert 12.3 x 10^6 ha of marginal cropland to permanent cover between 1986 and 1989, only about 1.2 x 10^6 ha of that land was planted to trees (Esseks, et al., 1992). Farmers are reluctant to plant trees for a variety of reasons, including the fact that trees limit their flexibility in using the land in future years, and the evidence that the U.S. Department of Agriculture personnel advising them did not always explain the opportunities for tree planting and commercial harvest after the expiration of the 10-year Reserve contract. Thus, converting 9.5 x 10^6 ha over 10 yrs will not come easily, or without cost and program effort on the part of federal and state governments.

That caveat aside, however, it is estimated that the planting of trees on 9.5 x 10^6 ha of marginal crop and pasture land could in time result in an annual production of 42.5 x 10^6 m^3 of softwood timber per year. That would translate into 30 x 10^6 tons of total C storage per year (Table 2). C emissions from fossil fuels would be reduced by 10 x 10^6 tons. The total input of planting the economically convertible softwood lands would thus be 40 x 10^6 tons a year. The total C impact potential of planting trees on the entire 47 x 10^6 ha that are biologically suited for forests would be approximately 162 x 10^6 tons per year.

Table 2. Potential for mitigating U.S. carbon emissions through converting marginal crop and pasture lands to forests

Current Land Use	Potential	Annual Carbon Storage[1]	Fossil Energy Conser-vation	Total Impact
	10^6 Ha		*10^6tC/yr*	
Low Estimate of Poten-tial				
Cropland	2.4	3.6	0.9	4.5
Pasture	18.6	26.1	9.0	35.1
Totals	21.1	29.7	9.9	39.6
High Estimate of Poten-tial				
Cropland	49.9	62.1	16.2	78.3
Pasture	54.6	66.6	17.1	83.7
Totals	104.5	128.7	33.3	162.0

Woody Crop Production

The potential for increasing the production of woody crops on what is now cropland can be considered in two contexts: the production of short-rotation, intensive culture wood crops for energy usage and the increased production of food crops from trees. Neither is common today, but that is not to say that increased research, development of appropriate commercial markets and financial incentives, and continued concern for the need to alter land use for improved impact upon environmental factors, including global warming, might not result in significant changes within the coming decades.

Estimating the land base available for energy production is tricky, because the technology is more akin to commercial crop production than to forestry, requiring attention to such details as soil preparation, fertilization, weed control, and mechanical harvesting (Wright, et al., 1992). Thus, it is doubtful that this technology would be economically competitive on land that was marginal for crops or pastures. An exception may be land that is marginal by reason of erosion hazard due to slope, where cultivation of short-rotation woody crops may be feasible as long as slopes are not so steep (over 8%) as to interfere with mechanical harvesting and other operations. In general, however, it is estimated that the land most suitable for wood energy production is not the same land identified by Parks as being marginal for crop or pasture production, so there is little or no duplication when the opportunities for each are calculated separately.

Efficient wood energy production depends on the production of very rapid juvenile woody growth rates, usually in a rotation of 4–8 yrs. Species favored are those that show fast juvenile growth, good stress tolerance and disease resistance, and good coppice growth. These stands are harvested in the winter after leaf fall, and many of the preferred hardwood species then resprout (coppice) from the stump, making recultivation and replanting of the land unnecessary for several rotations. Current yields run 9–16 harvestable dry t/ha/yr in production research trials, although observed maximums range from 16–45, and goals of 16–30 dry t/ha/yr are thought to be reasonable by the year 2010 on moderate-to-good cropland. Costs currently run $37–56 per dry ton, where relatively good cropland can be rented for $100–150 per ha. Of that cost, half to two-thirds is in harvesting and handling—an area where additional research and development appears to offer significant benefits.

Land availability for energy production seems more a function of economic opportunity and technological development than of biological capacity. Of the 171 x 10^6 ha of U.S. cropland, about 124 x 10^6 have the combination of fertility, rainfall, and slope that would make them suitable for short-rotation woody crops. In addition, there are over 34 x 10^6 ha of pasture and forest land that are estimated to have good to moderate potential for conversion to cropland. Most of the suitable lands are in the North Central States (Fig. 3). Of these lands, about 91 x 10^6 ha have the capability to yield 5 or more t/ha of standing dry biomass per year under current technology.

Competition for cropland would not appear to be intense at this time, as national farm policy still encourages the conversion of crop and pasture land to permanent cover. A program such as the Conservation Reserve Program, aimed at encouraging farmers to switch to production of short-rotation woody crops, would need only modest financial incentives if farmers were assured that their "base crop" area would be protected in the event that future national farm policies were once again based upon their crop production history.

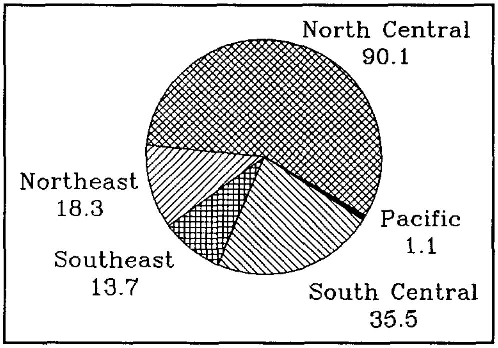

Figure 3. Land considered capable of supporting short-rotation woody crops without irrigation, by major land use regions (10^6 ha).

Wright, et. al. (1992) established a low estimate of potential land availability for wood energy production at 14 x 10^6 ha and a high estimate of 28 x 10^6. While the high estimate sounds ambitious, it must be noted that soybeans now occupy about 24 x 10^6 ha—up from next to nothing prior to World War II (New Farm and Forests Task Force, 1987). New technologies and economic market inducements can cause significant shifts in U.S. agriculture. While the conversion of 14–28 x 10^6 ha seems feasible, given the estimate in the recent Resources Conservation Act appraisal that the United States could meet crop needs until 2030 while idling as much as 52 x 10^6 ha of current cropland, it is also clear that such a massive conversion will not occur unless biomass markets that provide economic incentives for such a massive shift are developed (U.S. Department of Agriculture, 1989).

Another variable, of course, is the conversion efficiency with which dry biomass can be converted to energy. Again, this is an area where research and development can make significant changes. Currently, it is estimated that, with a net dry biomass yield of 11 t/ha/yr and present technology, using wood energy for producing electricity will result in a net C offset of 5 t/ha/yr. If that same biomass is used to produce ethanol, efficiencies are less than half at this time, and the result is estimated to be 1.80 t/ha/yr. Increasing net yields to 22 t/ha/yr and raising conversion efficiencies through research, could, it is proposed, raise those C offset estimates to 10 t/ha/yr for electrical production, and 6 t/ha/yr for ethanol.

The range of total national C impacts from wood energy opportunities are shown in Table 3. The major C storage in wood energy plantations will take place in the root systems and soil C levels because the top growth will be harvested on a regular basis. Each year's root growth and leaf fall will, however, build soil C. On most soils, an increase in soil organic matter of between 0.5 and 1.5% is expected as a result of the conversion to tree crops. In addition, the reduction in soil erosion and the reduced rates of fertilizer and pesticide required could also add to the net beneficial effect.

Energy savings will depend on two factors: whether or not the biomass is utilized to produce ethanol or electricity, and how aggressively improved technology is pursued to improve conversion efficiencies. In Table 3, the "future" column assumes aggressive technology development. Several potentials emerge. A 14-million ha program using current technology to produce ethanol from biomass would have a 90 x 10^6tC/yr impact, representing the low estimate from the table. At the high end, planting 28 x 10^6 ha, using all the biomass for electricity production, and developing future technology could have an annual C impact of 287 x 10^6 tons.

Table 3. Potential for mitigating U.S. carbon emissions through growing short-rotation woody crops to replace fossil fuels in energy production.

	Technology	
Land Utilization	Current	Future
	10^6tC/yr	
Low Estimate (14 x 10^6 ha)		
Soil and Plant Carbon Storage	26	26
Energy Conservation—Ethanol	25	85
Total Opportunity	51	111
Soil and Plant Carbon Storage	26	26
Energy Conservation—Electricity	64	144
Total Opportunity	90	170
High Estimate (28 x 10^6 ha)		
Soil and Plant Carbon Storage	52	52
Energy Conservation—Ethanol	50	169
Total Opportunity	103	221
Soil and Vegetation Carbon Storage	52	52
Energy Conservation—Electricity	127	287
Total Opportunity	179	339

Another interesting idea is that of replacing annual crops such as corn and soybeans with specially managed woody crops domesticated and grown for the production of protein, carbohydrates, and oils (Rutter, 1989). Far more revolutionary than many of the other forestry-related options for affecting the emission of greenhouse gases, this proposal foresees research and development leading to a gradual change in the plant cover on significant areas of cropland, both in the United States and around the world.

In asking rhetorically why one would consider such a revolutionary approach, Rutter argues that a switch from annual crops to perennial woody plants captures the natural advantages that woody plants have in sequestering CO_2. Because their leaves develop early in the spring and have more layers of leaf surface, a more complex canopy, and a longer growing season than annual crop plants, woody perennials are able to capture far more sunlight and build far more cellulose per unit area. For example, in May and June, when daily solar energy levels are peaking in North America, woody perennials are fully functioning while corn is still trying to get "knee high by the Fourth of July." In addition, their deep rooting structures often enable woody plants to sustain photosynthesis during dry periods when annual crops struggle to maintain growth rates.

In citing research that calculates the harvestable biomass from a hybrid poplar plantation as representing roughly three times the amount of C content in a total corn crop, Rutter also points out that the C sequestered in the woody plants is more likely to be fixed in long-lived woody structures, including roots, than in the annual crop. In addition, some of the wood production might be used for energy, replacing fossil fuels.

While more revolutionary than other forestry strategies, the systems that Rutter proposes are fertile ground for research and development. In addition to posing enormous potential for increasing the annual uptake of CO_2 on cropland, they offer the potential for increasing the long-range storage of C, both through woody structures and through an increase in soil organic matter, which should be significant in comparison to annual cropping methods. There is also the vision of energy savings due to greatly reduced cultivation on a significant amount of cropland. The proposals are too preliminary at this time to be used as the basis for a realistic estimate of potential impact in the near future, but they are also too interesting to cast aside without further investigation.

Potential To Increase Energy-Saving Trees and Forests

Windbreaks and shelterbelts are associated mainly with the farm and ranch lands of the United States, and their effect upon the root causes of global warming lie in the biomass that they create (within both woody plants and soils and the energy savings their employment facilitates). Brandle, et al. (1992) have looked at this aspect of forestry closely, and drawn estimates leading to the following conclusions:

** The potential for new shelter belt plantings is enormous. It would take 2.25×10^6 km of field windbreaks, occupying 1.4×10^6 ha, to provide protection to the 27.3

x 10^6 ha of U.S. croplands that were found to be suffering from accelerated rates of wind erosion in 1982 (Trexler 1991). Total tree planting needs are 920 x 10^6.
** An estimated 14.3 x 10^6 ha of additional cropland would benefit from wind protection, needing over 782,000 km of trees that would occupy .5 x 10^6 ha. Total tree planting needs are about 320 x 10^6.
** There are over 1.6 x 10^6 unprotected farmsteads that could utilize 200,000 new farmstead windbreaks involving almost 121,000 ha of trees, adding up to over 55 x 10^6 trees to be planted.
** Facilities housing beef cattle on feed—and dairy cattle in regions where winter conditions would justify wind and/or snow protection—could require over 900 km of windbreaks covering 1,200–2,000 ha, just to protect 10 percent of the exposed livestock. Total tree planting needs are about 1–1.4 x 10^6 trees and shrubs.
** There are significant opportunities for wildlife habitat plantings, shelterbelts, and streamside plantings, but it is impossible to estimate their magnitude.
** The total 1–1.5 x 10^9 trees that could be planted in a complete windbreak and shelterbelt program could contain in the range of 90 x 10^6 tons of C in vegetation and soil by the time they reached 20–25 years of age.
** Indirect C savings are also realized from fuel and fertilizer reductions due to removing land from cultivation (both because the windbreaks take up land and because they raise yields on the remaining land enough to compensate for the land devoted to trees).

There are over 1 x 10^6 km of rural roads in the northern half of the United States that would benefit from the planting of a living snow fence. Living snow fences have only recently been tested in states such as Colorado, Wyoming, and Nebraska. It is estimated that there are only about 182 km in existence today.

The potential benefits, however, are significant. Where road departments now erect temporary slatted snow fences, prices are reported to run as high as $115 per unit of snow storage per km per year, and the structures last an average of 7 years. Large permanent structures, such as one sees along the highways of Wyoming, for example, are cheaper, costing some $12 per unit of snow storage per km per year and having an average service life of 35 years. A 3-row living snow fence, however, drops unit costs for snow storage to about $2 per km per year, with a service life of 75 years. In addition, the trees provide wildlife habitat and increased biodiversity in a region where tree habitats are fairly limited.

Research in Wyoming has demonstrated that snow fence protection can result in a 70 percent reduction in accidents related to winter weather while reducing the cost of snow and ice removal by one-third (Brandle, et al., 1992). The resulting fuel savings add up to emissions reductions of about .5t C/km of snow fence per year.

Assuming that a typical living snow fence will require 2–3 rows of conifers spaced at 3 m, about 1–2 x 10^6 trees on 1,200–2,000 ha will be needed for each 1,600 km of living snow fence. A goal of protecting 1% of the rural roads would add up to 6.4–12.7 x 10^6 trees on 7,500–13,000 ha. Direct C sequestration would be on the order of 27,000 tons per year, and indirect C reductions could run 4,500–9,000 tons per year.

In Table 4, the "low" estimates indicate a "feasible goal" given current information and landowner interest. The "high" estimate shows what the Brandle team calculated as the highest potential opportunity. It is clear that not all these opportunities will be undertaken, but Table 4 shows what the range in opportunity seems to be.

Table 4. Potential for mitigating U.S. carbon emissions through planting trees for soil conservation, windbreaks, and snow control.

Type of Planting	Trees	Hectares	Annual Carbon Impact
Low Estimate of Potential	*(10^6)*	*(10^6)*	*(10^6 t)*
Field Windbreaks	920	1.4	1.4
Crop Protection	320	0.5	0.5
Farmstead Windbreaks	60	0.1	0.4
Other Plantings	30	0.0	0.1
Totals	1,330	2.0	2.4
High Estimate of Potential			
Field Windbreaks	920	1.4	1.4
Crop Protection	1,250	1.9	2.2
Farmstead Windbreaks	110	0.2	0.7
Other Plantings	650	0.9	2.3
Totals	2,930	4.5	6.7

Urban and Community Trees

In addition to sequestering C directly, properly placed urban trees can have a significant impact on atmospheric C buildup through energy conservation. Studies in Florida found that the daily electrical usage for air-conditioning could be reduced by as much as 50% by properly located trees and shrubs (Parker, 1981). Other research has demonstrated that three properly placed trees around homes and small business buildings can cut air-conditioning demand by as much as 50% (Akbari et al., 1988).

Models constructed for Sacramento, CA; Phoenix, AZ; and Lake Charles, LA, indicated that the effect of an additional three trees per house (raising canopy cover by about 30% per dwelling) would result in approximately 30% savings in annual cooling energy used (Huang et al., 1987). McPherson and Woodward (1990) found annual savings of 1,351 kwh for a 137 m^2 house in Tucson, AZ and 1,665 kwh for a similar house in Phoenix.

The impact of large-scale tree plantings in cities can also be very important in reducing the well-documented urban heat-island phenomenon. Researchers have demonstrated that tree planting could save as much as 34, 18, and 44% of residential cooling demand on a hot summer day in Sacramento, CA; Phoenix, AZ; and Los Angeles, CA, respectively (Akbari et al., 1988). If that heat-island impact, which often runs 3–5°C, can be eliminated, or an "oasis" effect created, the cost savings will be enormous.

On the other side of the energy conservation equation, properly placed trees can also reduce winter heating costs by 4–22% (DeWalle, 1978). Heisler (1990) estimates that a good windbreak which does not shade the house in winter will save about 15% of the energy used to heat the home. In residential neighborhoods, windbreaks—as such—are not common, but all the trees act as one huge windbreak. Where tree density is high (canopy cover 77%), Heisler measured wind reductions of 66% in winter and 75% in summer, as compared to open land.

With energy conservation as a major goal, tree planting programs should focus first upon those trees (including species selection and location) that provide direct energy benefits to buildings. The next priority for planting is trees that would provide maximum shade for parking lots, streets, and other dark-surfaced areas. The lowest priority is to plant those open areas where trees could "fill in" the open spaces that, while not directly shading or protecting buildings, would help reduce the urban heat-island effect by modifying albedo and wind patterns as part of the total urban forest.

There have been several attempts to estimate what the C impact of a major urban and community tree program would mean to the nation's efforts to mitigate C emissions. Akbari, et. al. (1988) have estimated that the total impact of planting 100 x 10^6 trees around homes and small businesses, coupled with an effort to reduce albedo through a program of converting dark-colored surfaces such as streets, parking lots, and buildings to light colors, could save about 15 x 10^6 tons of C emissions each year. Their calculations indicated that about half that effect would be due to the trees, for an annual national savings in the range of 5–9 x 10^6 tons of C per year.

Mark Trexler (1991) estimated that the total urban forestry planting opportunities could result in a reduction as high as 15 x 10^6 t/yr, a gain he labelled "modest." He then went on to discount the likelihood of achieving anywhere near that reduction, estimating that even an aggressive policy effort would likely yield a reduction of only 3–5 x 10^6 tC/yr.

Trexler's conclusions were based upon the air-conditioning savings associated with direct shading of small buildings. There are other areas of benefit, however, and they may be more significant than prior work has recognized. Additional trees throughout the urbanized area can reduce the heat-island effect for an entire city. To the extent that peak temperatures can be drawn down on a summer afternoon, everyone's air conditioning works more efficiently, as do most electrical motors and appliances. This citywide improvement in efficiency means a far broader range of savings than will result from directly shading small buildings.

Another area of benefits can come from wintertime savings for space heating that are associated with well-placed windbreaks, as well as with the total windbreak effect of the urban forest itself. Because space heating produces four times the C emissions of air conditioning, such savings could be enormous.

There are about 300,000 ha of new land developed each year, and over half of it comes from crop, pasture, or vacant land uses (U.S. Department of Agriculture, Soil Conservation Service, 1990 unpubl.). Planting trees on that land as part of environmentally sensitive development could result in almost as large a net forest gain as converting marginal farmland to trees, and the potential annual energy savings realized by 2010, if new areas are all planted properly from now on, are significant.

In attempting to factor in all aspects of the urban forest and its effect upon C emissions, we constructed a model that starts with what is known or can be reasonably assumed about the extent of the urban forest, its component land-use portions, and the annual C emissions thought to occur from each land use component. We estimate the current tree canopy and tree population, based on the research data available, and propose a potential goal for a 10-year program aimed at increasing the canopy cover by 10% on residential lands, and 5–20% on other urban lands (Sampson, et al., 1992).

It is then possible to calculate what the attainment of that goal might do in terms of C results in the entire urban forest, not just around small buildings. These estimates are broken down into the additional biomass stored by trees and soils and the C savings due to energy conservation as a direct result of improved shading, evapotranspiration, and reduction of the urban heat island, along with an estimate of wintertime heat savings (Table 5).

The "low estimate" consists of only the annual impact that might be attributable to a good urban forest and tree planting program on the newly developed lands. If urban development continues for 20 yrs at the rate of 300,000 ha/yr, as it did between 1982 and 1987, such a program would require an annual tree planting of almost 17 x 10^6 trees to properly plant the new developments as they occur. For the low estimate, it was assumed that the existing lands would receive only enough attention to maintain current conditions (this would represent a significant urban tree planting program in itself, and a major increase in today's activity in many communities). While this would be better than letting the urban forest continue to decline, it would not result in any significant new energy savings or C sequestration in those areas.

Table 5. Potential for mitigating U.S. carbon emissions through improving urban and community trees and forests.

	Carbon Storage	Energy Conservation	Annual Carbon Impact
		(10^6 tC/yr)	
Low Estimate of Potential	2	7	9
High Estimate of Potential	5	29	34

The "high estimate" calculates the impact that would arise from both planting trees on the newly urbanized lands as they are converted and achieving the goal of increasing canopy cover in existing urban areas by an average of around 10%. About 85% of the total benefits, in terms of C impact, would be realized as a result of energy conservation.

The high estimate represents a huge tree-planting goal. It would require an annual program planting about 42 x 10^6 trees to in-fill the existing urban forest over a 10-yr effort. In addition, if we assume an average 50-yr lifespan for urban trees (which will require a significant improvement in the tree care program of many communities), about 30 x 10^6 trees per year will be needed to provide replacement plants for those that die or are removed. In total, the annual tree planting demand for urban forests appears to be in the range of 89 x 10^6 trees.

The costs of such a planting program are fairly high because urban trees must be specimens of better size and quality than the standard forest planting demands. Site preparation and special protection add significantly to the cost. In total, planting 89 x 10^6 urban trees a year could cost from \$9–20 x 10^9 annually. But much of that cost need not be borne by government. Individual citizens, developers, and businesses can plant and care for the vast majority of these urban trees, if local programs provide the proper education and inducements. Those programs, while not cost free, will consume only a fraction of the total investment, public and private, that the urban forest represents.

The benefits of an improved urban forest are equally large. The C impact, for example, of the high estimate opportunity looks to be about 27 x 10^6 tons of C mitigation per year, either sequestered in the plants and soils, or in reduced emissions due to energy savings. With about 80% of that benefit tied directly to savings in energy usage, the cost savings to consumers alone may be adequate to encourage the adoption of significantly higher levels of planting and care in the urban forest.

Bringing Many Options Together

Row (pers. comm.) evaluated the potential for U.S. military bases to improve their forest management programs as part of a national strategy for mitigating global warming. His results are of interest because military bases are often self-contained communities in their own right, and may provide insight into opportunities elsewhere. Row found that, in general, the forest lands of America's military reservations are managed about as well as can be expected under the conditions imposed by their primary purpose—military training grounds and security. Forests are hard to manage when they are used as training sites, and impossible after they are littered with unexploded ordnance. Even where forest management is not dangerous for work crews and equipment, damage from fires and shell fragments often limits the wood's commercial application. In general, base foresters can do little more than they are already doing (Row, in review).

Where intensive management of the manageable forest land (and occasional salvage from the forests impacted by military training) becomes most feasible is when it is incorporated in a basewide scheme of energy conservation and self-sufficiency. A military base is a well-defined community, with residential areas, office and production areas, land dedicated for transportation, recreation, training and security, and open land that is available for resource management. As such, it is an interesting study area, providing both research and management opportunities that could become models for other communities.

When a base develops an integrated plan for energy conservation and self-sufficiency, that plan normally includes a biomass burner that can utilize nonrecyclable solid waste, landscape trimmings, forest thinnings, nonmerchantable wood, and salvage from military-damaged trees. Once such a plan is operating, timber thinnings, for example, become a positive producer of biomass for energy rather than a nuisance product that must be burned or allowed to rot. Timber stand improvement costs can be partially offset by effective utilization of the thinned wood, and more-intensive management begins to look much more attractive. The burner also offers a way to reduce landfilling of scrap lumber and other solid wastes, as well as lawn and shrub trimmings. It makes wood energy production as part of base operations a feasible option.

The lesson from this look at military installations may be less about the military than it is about the need to consider modest-scale community approaches if there is to be much hope of significantly broadening the use of biomass as an energy resource. Biomass is a high-weight and low-value resource that does not remain economical if it must be moved far from its source to its end use. Burning forest wastes for heat and electricity has long been common at sawmills and paper plants, where such waste abounds, and even has reached commercial application at a few locations around the country where a combination of a large facility needing low-cost energy could be linked to a nearby source of forest products. The Central State Hospital, in Milledgeville, GA, for example, saved $\$1 \times 10^6$ in fuel costs during the first year of operating two wood-fired boilers with wood chips generated from the waste products from nearby state forest lands (Jarrett, 1989). But not very many of those situations exist as yet. If a concerted attempt is to be made to increase the opportunities for biomass to substitute for fossil-fuel energy, research and development in both institutional arrangements and engineering technologies must proceed apace on production and management techniques.

Adding Up the Total Potential

Estimates of the C impact that could be achieved through land conversion and increased use of trees and forests for energy production and conservation are shown in Table 6. Obviously, this estimate must be couched in broad terms to portray the uncertainties at this point in the study of these questions. Science is a long ways from fully exploring all the many opportunities that exist on both public and private lands.

What can be concluded from these calculations, and the studies so far undertaken, is that there are major opportunities through the expansion of trees and forests in the United States to make a significant impact on net C emissions. Those opportunities provide no panacea, nor do they negate the need to consider many other forms of action, including aggressive energy conservation, alternate fuel, and other programs. They are, however, clearly a part of the total approach to the greenhouse gas challenge.

A solid economic case can be constructed for the "low opportunity" levels outlined in Table 6. In regard to conversion of marginal crop and pasture land, for example, it appears that trees can be planted for an average cost of around \$150–200 per ha. On a southern pine plantation, over a 40-yr life, that would be a cost of about \$1–1.50/t/C sequestered. If, as the National Academy of Sciences has estimated, an opportunity is "low cost" when it can sequester CO_2 for a cost of between \$1 and \$9 per ton, these costs are low (1991). Since these are the lands identified by Parks as being economically more profitable in trees than in their current usage, there should be no question of whether or not the subsequent land management costs can be recovered. Economic feasibility is less certain for the high opportunity levels shown in Table 6, and many of them would not be feasible without some sort of subsidy to reflect their value as C sequestration practices.

With the total net C emission from fossil fuels for the United States in the range of 1.3 x 10^9 t/yr (Boden et al. 1990), the forestry opportunities described and quantified in here, if implemented, could offset somewhere between 10 and 30% of that total annual emission level. The major difference between the low and high estimates appears to be the proportion of the impact that is directly related to energy conservation, as opposed to C storage in trees and soils. As more and more of the available opportunities are addressed, a higher percentage of those opportunities is directly connected to the production of biomass energy or the use of trees in energy conservation programs.

It should also be kept in mind that the estimates shown in Table 6 are based on current technology. As illustrated by the data in Table 3, improvements in technology could greatly increase the potential for mitigating C emissions through forestry programs. In addition, these estimates exclude the opportunities to affect C emissions by different management of the nation's timberlands.

Regardless of which estimate is used to portray the forestry opportunities to offset C emissions, several significant factors need to be taken into account. The forestry opportunities described could have many positive impacts on the environment and economy in addition to the effects upon C. Tree planting on marginal crop and pasture lands can reduce soil erosion, prevent water pollution, and improve wildlife habitat. Additional trees in urban areas, as well as shelterbelts and their many uses, means more moderate summer and winter temperatures, less energy used to heat and cool homes and other buildings, and less fuel, fertilizer, and livestock feed needed in production agriculture. There are significant esthetic and positive social impacts as well.

In addition, it should be noted that these opportunities would add to an already-growing forest resource in the United States. In 1987, the USDA Forest Service estimated that net softwood growth (after all mortality and harvests) was 42 m^3 x 10^6 and net hardwood growth was 129 m^3 x 10^6 (AFA, 1989). Converted to net C additions, this adds up to a net increase of about .125 Gt C per year, just in tree biomass on the nation's commercial timberlands. This does not include estimates of surface litter or soil carbon, nor does it estimate the net growth in parks, wilderness areas, non-commercial forests or urban areas. Forests in the U.S. are growing today, and these opportunities would enhance and increase that growth.

Economically, planting trees and more intensively managing the forests that result mean jobs and more wood products to hold down costs to consumers. Where new forms of products emerge, new processing and other facilities may also provide additional economic stimulus. Improving the conservation usage of trees means less money spent on energy, fuel, fertilizer, and feed, and more profit in agriculture.

But, there are cautions with the use of these findings, as well. The data upon which the estimates have been developed are highly variable in quality, as are scientists' understanding of the relationships between tree and forest growth and biomass impact. These are new questions, and a great deal of scientific effort is needed to improve the reliability of these, or any similar, estimates. Much of what is needed can be gleaned from data and research of the past, but there is also the need for a considerable amount of new empirical research.

Increasing the use of biomass as a replacement for fossil fuels can lower net C emissions, but it is not without pollution problems of its own. In addition to the necessity for using new technologies that reduce smoke and particulate release into the atmosphere, scientists must also be wary of the potential for other pollutants, such

Table 6. Opportunities to mitigate U.S. carbon emissions through land conversion, and fossil energy conservation using trees and fore sts

	Carbon Storage	Fossil Energy Conser-vation	Total Im-pact
		10^6 t/C/yr	
Low Estimate			
Converting marginal crop and pasture land to forests	30[1]	10	40
Growing short-rotation, high-intensity wood energy crops	26	64[2]	90
Windbreaks, shelterbelts, and other conservation trees	2	1	3
Urban and community tree planting and forest improvement	2	7	9
Total low opportunity	59	82	141
High Estimate			
Converting marginal crop and pastureland to forests	129	33	162
Growing short-rotation, high-inten-sity wood energy crops	52	127[2]	179
Windbreaks, shelterbelts, and other conservation trees	3	4	6
Urban and community tree planting and forest improvement	5	29	34
Total high opportunity	189	193	382

[1] Includes storage in forests (vegetation and soils) and in products.

[2] The carbon conserved from using woody crops for the production of electricity with current technology.

as heavy metals that may be concentrated in biomass grown in polluted regions or on polluted soils.

The total potential is large, however, and there are many economic and environmental benefits to be gained by pursuing these opportunities, in addition to their impact on the global C cycle. Perhaps continued attention to this subject will result in the kind of public attention and public policy support that can pave the way for these opportunities to be realized.

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