UNIVERSITY OF FLORIDA ■ SCHOOL OF NATURAL RESOURCES AND ENVIRONMENT

Opportunities for Greenhouse Gas Reduction through Forestry and Agriculture in Florida

APRIL 2008

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Executive Summary

Key findings





Florida has the opportunity to help structure emerging carbon markets because it is uniquely endowed to participate through forestry and agriculture. The opportunities for forest management, afforestation, biofuels production, and soil carbon sequestration are greater in Florida than in most other regions of the U.S., giving Florida an advantage in carbon markets. Components reviewed in this study include biofuels, woody biomass for power generation, energy crops, agricultural biogas, managed pine forestry, soils management, and afforestation. All market values in this executive summary reflect an expected carbon market value of $20 per tonne CO_2eq, as herein defined, and do not reflect costs of creation and maintenance of mitigation projects.

- In the U.S., carbon markets could support greenhouse gas mitigation through forestry and agriculture throughout this century.

- In Florida, these components would be collectively valued at $340 million per year as carbon credits in the near term. The annual values of individual components would be
  — Biofuels, energy crops and biomass—$147.2 million
  — Biogas produced from livestock wastes—$19.2 million
  — Increased management intensity on pine plantations—$116.8 million
  — Conservation tillage on half of cropped lands—$34.4 million
  — Afforestation of 5% of Florida range and pasture lands—$22.8 million

- Additional annual income associated with traditional markets include:
  — Biogas as replacement for fossil natural gas—$62.7 million
  — Sale of crop and logging residues as fuel—$48 million
  — Reduced fuel costs from conservation tillage—$14 million

- The total value of these components including traditional market value would be $465 million.

Most environmental co-effects of managing lands for carbon offsets can be positive, resulting in enhanced ecosystem function. Key to proper management of lands for offsets is full accounting of the greenhouse gases emitted during a mitigation project, including those associated with land use change. If properly implemented, mitigation projects could provide an indirect means of economic valuation of additional ecosystem services such as watershed protection, biodiversity conservation, and maintenance of soil nutrients.

Overview of carbon market opportunities in forestry and agriculture in Florida

Climate change caused by human activities is one of society's greatest challenges. Increasingly, various public and private stakeholders are working toward reducing the production of greenhouse gases (GHGs). Toward that end, policies and management practices are being developed to optimize the capacity of natural and managed ecosystems to mitigate climate change. One important option within this framework is the management of forestry and agricultural activities to offset GHG production. The forestry and agriculture sectors have enormous potential to reduce and avoid the release of the three most important greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The global warming potential of each gas is expressed as carbon dioxide equivalents (CO_2eq), which is the warming potential of an equivalent amount of CO_2. This is typically measured in metric tons (tonnes).

Combined, the forestry and agriculture sectors in the United States have the capacity to sequester a vast amount of carbon. Over 90% of this sink occurs on forested lands, equivalent to 12 to 16% of U.S. GHG emissions. By contrast, the agricultural sector is a net emitter of GHGs, produces over 6% of U.S. annual emissions (primarily as CH_4 and N_2O). Together these sectors compensate for at least 6% of U.S. annual greenhouse gas emissions. Florida ranks sixth among the states in total GHG emissions. Florida's emissions are predicted to grow 88% by 2020, while those of the U.S. as a whole are predicted to grow 50% within that same time period relative to 1990. The forestry and agriculture sectors of Florida represent an important tool for offsetting and mitigating the state's projected increases in fossil emissions over future decades.

Mitigation scenarios for lands are based on carbon-market drivers and the traditional markets for forest and agricultural products. The U.S. EPA model known as the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG) shows that at $15 per tonne CO_2eq, it is reasonable for carbon markets to support GHG mitigation across the U.S. through forestry and agriculture throughout this century (Figure ES-1). As individual mitigation projects reach the peak amount of carbon they can sequester, land managers may move to alternative practices depending on the market value

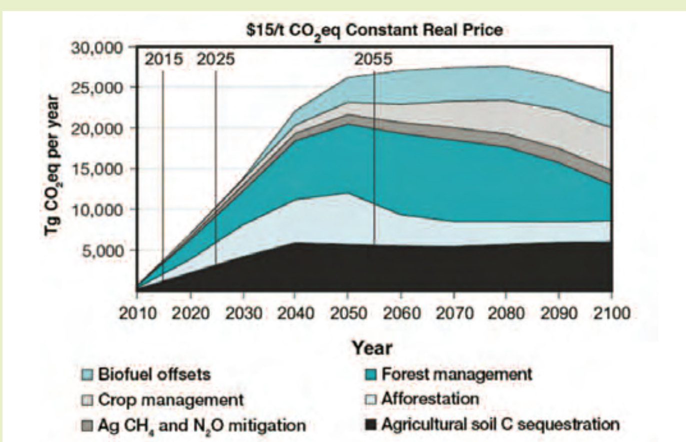


Figure ES-1. Cumulative GHG mitigation potential over time at a fixed price (Tg = 1 million tonnes). *(Reproduced from Figure 4-6, U.S. EPA 2005)*

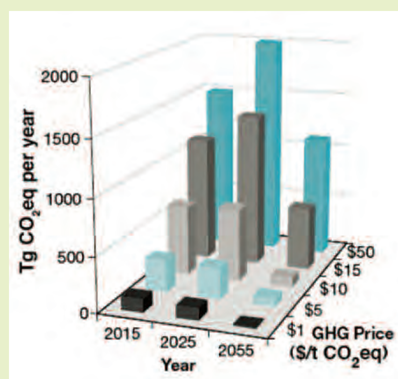


Figure ES-2. Average annual offset potential at three focus dates by GHG price (Tg = 1 million tonnes). *(Reproduced from Figure 8-1, U.S. EPA 2005)* of carbon credits. Constant price scenarios show a decreasing rate of mitigation per year after 2025 for the U.S. as a whole (Figure ES-2).

The opportunities for afforestation, reforestation, and soil sequestration are greater in Florida than in other regions of the U.S., giving Florida an advantage in carbon markets. Similarly, there is great potential for biofuels in Florida, especially through woody biomass for power generation. These characteristics give Florida the opportunity to help structure the emerging carbon market while benefiting from the experience of markets elsewhere. The environmental co-effects of mitigation through forestry and agriculture are largely positive. Properly managed mitigation projects offer great potential for maintenance and enhancement of ecosystem services such as watershed function and soil nutrient content. Carbon mitigation projects in Florida using forestry, agriculture, and possibly natural lands, could have a significant effect on land use and land prices.

Forests

Gross growth of Florida forests, before deducting for harvest and tree death, is about 9.5 million tonnes of carbon annually. Pine plantations cover 5 million acres of Florida, and switching from lower intensity management to higher intensity management could increase the biomass in these forests. The potential value of this increase on the carbon market is based on a market value of \$20 per tonne CO_2eq, assuming a shift of 1.85 million acres from low intensity to medium intensity management, and switching 2.9 million acres from medium intensity to high intensity management. This change in management intensity would be worth \$116.8 million (Table ES-1). In addition, afforestation of 5% of Florida range and pasture could result in an annual

Table ES-1. Additional sequestered carbon and potential revenue from shifts in management intensity on commercial pine plantations in Florida

Change in management intensity	Increase in carbon (million tonnes C)	Potential revenue from increase ($ in millions)
Low to medium	0.46	33.8
Medium to high	1.13	83.0
Total		**116.8**

increase in 1.14 million tonnes C, representing \$23 million. Replacing fossil fuels with woody biofuels would also be eligible for carbon market value.

It is likely that managing Florida forests for participation in carbon markets will result in significant positive environmental co-effects. Both long and short rotation stands can be managed simultaneously for carbon offsets, watershed protection, and soil nutrient capacity. Switching to higher intensity management should include plans for maintenance of soil nutrients and assessment of GHG emissions associated with management treatments. Innovative forestry practice involving biotechnologies and novel substitution of energy-intensive products with long-lived wood products could provide additional opportunities to maximize the role of forests as carbon offsets.

Biofuels

A promising opportunity for GHG reduction in the forestry and agriculture sectors is the production of energy crops, woody biomass, and various byproducts and waste materials for direct combustion or gasification to replace the coal, natural gas and oil currently used for heat and power generation. Although the combustion of biofuels directly releases CO_2, that CO_2 was itself taken up from the atmosphere as the plants grew, and thus does not constitute a net increase in atmospheric CO_2. Wood and woody waste materials together represent the largest segment of non-hydropower renewable energy, and the use of biomass for power production has nearly tripled in the past 15 years.

The likely delivered costs of woody biomass for electric power generation are competitive with coal and natural gas in Florida. A supply-curve analysis shows the range of prices at which quantities of woody biomass could be supplied to central plants (Figure ES-3). At a price of \$50 per tonne, Florida could produce about 5.5 million dry tonnes of biomass annually.

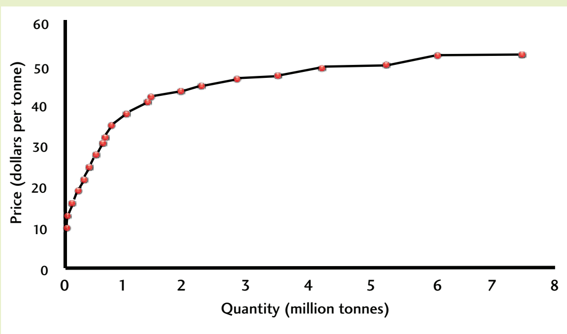


Figure ES-3. Supply curve for woody biomass in Florida.

Fuel ethanol produced from sugarcane in Florida is an unlikely source of biofuels because of current U.S. sugar policy. Corn, sorghum and citrus byproducts are produced in small quantities or have competing uses in Florida, and are limited near-term opportunities for ethanol production. Combined, these sources of ethanol could offset about 3.5% of Florida's demand for gasoline (2006 data) if produced at maximum potential.

The near-term carbon offset value of Florida biofuels is high (7.36 million tonnes, Table ES-2), representing a market value of \$147 million at \$20 per tonne CO_2eq. GHG emissions from biofuels production, such as those associated with harvesting, processing, transportation, and distribution, must be considered for the development of a successful long-term public policy. Moreover, a full lifecycle assessment of emissions associated with production must include emissions resulting from any land use change resulting from the expansion of acreage for biofuel crops. Similarly, it is important that the preservation of critical ecosystems and species be part of plans for development of biofuels.

Table ES-2. Potential fossil carbon displaced from biofuels, biomass, and energy crops in Florida

Resource	Share currently utilized	Share potentially utilized	Fossil fuel CO_2eq displaced (million tonnes)
Crop residues	5%	50%	1.762
Logging & thinning residues	5%	75%	1.465
Urban tree debris	10%	90%	1.793
Pulpwood	10%	30%	1.061
Energy crops	0%	50%	0.761
Ethanol from carbohydrates	1%	30%	0.516
Total			**7.360**

Livestock waste management

Managing livestock wastes can reduce methane and nitrous oxide emissions. In Florida, the main opportunities for reducing GHG emissions in the agricultural sector occur in concentrated dairy and poultry operations. Methane emissions from manure management of confined animal populations in Florida total 24,900 tonnes of methane per year. The estimated biogas production potential of anaerobic digesters for dairy and poultry manure in Florida is 222 million cubic meters of methane per year, which could be used for power generation or included in the natural gas distribution network. This avoids CO_2 emissions resulting from fossil fuel usage. If this methane were used to replace natural gas, approximately 0.436 million tonnes CO_2 per year of fossil CO_2 emissions would be avoided. The value of the carbon credits associated with biogas production is shown in Table ES-3.

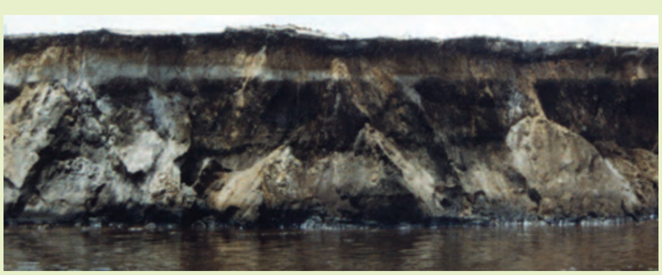
Table ES-3. Economic potential of livestock waste in Florida

Animal type	Annual value of carbon credits ($ in millions)	Annual value of biogas as fuel
Dairy cows	5.4	$16,779,312
Poultry layers	1.15	$4,473,353
Poultry broilers	12.64	$41,465,239
Total	**$19.18**	**$62,717,904**

Initially, some of this income might be used to help finance the further development of this practice. Opportunities for renewable biogas production are improving due to higher energy costs and a greater recognition of the environmental benefits associated with biogas production. Tipping fees taken from local organic waste delivered to on-farm biogas plants can further improve revenue prospects, and this added waste can increase biogas production. Wastes from ethanol and biodiesel production can also be used in biogas plants.

Soils

Florida has a unique landscape that can store great amounts of carbon with proper land management and hydrologic manipulations. On average, Florida soils have the highest organic carbon content of soils in the conterminous United States. Mitigating climate change through soil management is a long-term, complicated issue because soil formation has a long response time for carbon storage, and carbon stored in soil is a function of multiple interacting factors (below right). Florida has high precipitation, and carbon tends to be stored in the lower soil horizons through leaching (dark spodic horizons, below left).



Determinants of Soil Carbon

- Climate—hydrology and temperature
- Land cover
- Land use management
- Organisms
- Soil type
- Parent material/geology
- Topography
- Stressors—fires, tropical storms

In the near term, the most valuable strategy for increasing carbon sequestered in soils is through management of agricultural practices. Conservation tillage (low-till or no-till) improves the carbon and nutrient retention of soils. If 50% of agricultural lands in Florida were converted to no-till, 1.72 million tonnes CO_2eq per year would be sequestered, representing an annual economic value of $34.4 million at $20 per tonne CO_2eq. Soil nutrient and carbon content are also increased through optimized crop rotations and by fertilization with compost manure, sewage biosolids and other organic waste streams.

Over decades, manipulating the hydrology of an area and creation of wetlands offers a means of increasing the amount of carbon sequestered in subsoil. Note that wetlands naturally produce methane, which decreases the overall GHG mitigation potential of these soils. This report shows that the net long-term carbon sequestration value of creating a 1 cm layer of a Histosol (a wetland soil) through manipulating the hydrology of 1,525 km^2 of land would be $58 million at $20 per tonne CO_2eq after 90 years. A similar strategy might be to increase the area of sandy Spodosols by 1%, assuming a 1-meter profile. Although it is not known how long this would take, it would be worth $989 million total at $20 per tonne CO_2eq (because of the uncertain time horizon, this value is not included in the totals presented here).

Additional land management activities that can have net greenhouse benefits include increasing the area of meadow and forested wetlands and enlarging riparian buffers. Maintaining proper water levels also reduces the loss of stored carbon in wetlands. Other strategies include increasing the acreage of forest and wetlands, and matching land use to local water table conditions to minimize drainage in sandy or muck soils. Positive environmental co-effects of mitigation through soil management include improved soil nutrient content, greater soil biodiversity, and improved water retention.

Potential market value

The near-term potential of these components of forestry and agriculture to sequester carbon and avoid fossil fuel emissions is conservatively estimated at 16.98 million tonnes CO_2eq per year. While this is 7% of total Florida emissions (based on 2004 data), it more than offsets the projected annual increase of CO_2 emissions, which could be as high as 2% given high economic growth.

The activities shown in Table ES-4 below represent feasible changes in practice that could be implemented within the next 5 years. With carbon market prices at $20 per tonne CO_2eq, this portfolio would be valued at approximately $340 million annually (Figure ES-4 below). As learned from the European carbon market, it is reasonable to expect values to be $20 per tonne CO_2eq or higher once federally mandated caps are in place. Biofuels, biomass, and energy crops represent the largest immediate potential of the sectors considered in this report, and there is also significant potential in managing pine plantations and soils.

Table ES-4. Summary emissions offset potential from components of Florida forestry and agriculture

Activity	Near-term carbon offset potential (million tonnes CO_2eq yr^{-1})
Biofuels, biomass, and energy crops	7.36
Agricultural biogas	0.96
Conservation tillage on 50% of Florida agricultural lands	1.72
Shifts to medium and high intensity pine management	5.80
Afforestation of 5% of range and pastureland	1.14
Total	16.98
Market value @ $20 per tonne CO_2eq	$340 million

It is significant that the data in Figure ES-4 do not include the market value of the products of these components. For example, the market value of biogas as a replacement for fossil natural gas would amount to an additional $62.7 million annually (Table ES-3). Similarly, sale of crop and logging residues as fuel would be worth $49 million per year at $10 per dry ton. Additionally, reduced fuel costs from implementation of conservation tillage would save $14 million per year. Including these values with the numbers in Figure ES-4, the total annual value of these components of forestry and agriculture is about $465 million. (Note that these figures are estimates of potential market size, not net income, as they do not reflect any incremental production or transaction costs.)

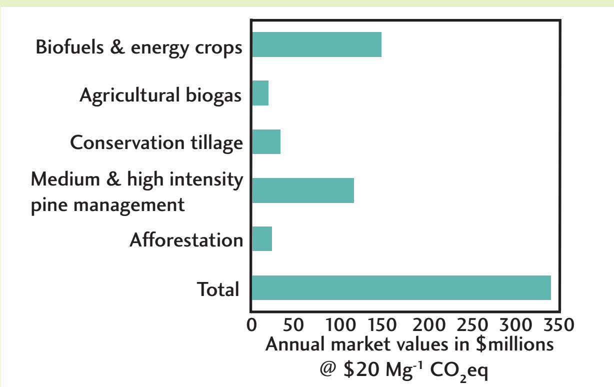


Figure ES-4. Annual carbon market value for the components of Table ES-4.

This report likely understates the potential for forestry and agriculture in Florida to participate in a low carbon economy. For example, pine forestry is only one component of industrial and managed forestlands in Florida. Management of other forest types and inclusion of long-term sequestration in new forest products, assuming that these products displace products produced with fossil fuels, would provide additional value. Similarly, production of cellulosic ethanol feedstocks presents an expanding economic opportunity for Florida's agricultural sector. Although the rate at which new soils can form is poorly quantified, creating soil horizons through hydrologic manipulation or other land management practices could sequester additional carbon and provide revenue in a low carbon economy. Finally, it should be noted that if the market price of carbon exceeds $20 per tonne CO_2eq, the economic opportunity for Florida's forestry and agriculture sectors becomes correspondingly greater.

Contents

Introduction to greenhouse gas mitigation through forestry and agriculture in Florida

Stephen Mulkey

Anthropogenic climate change is one of the most significant challenges facing humanity (IPCC 2007). Climate change over the next 100 years and beyond will affect virtually every aspect of living systems in Florida and the world. One result of this reality has been the development of policies and practices to reduce the production of greenhouse gases (GHGs) and increase the potential for natural and managed systems to mitigate climate change. Central among these concepts is the use of carbon markets to monetize GHG emissions. Management of forestry and agricultural activities for offsetting GHG production is regarded as an important option for climate mitigation through their participation in carbon markets (IEA 2007). Activities in these sectors can reduce and avoid the release into the atmosphere of the three most important GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Sequestration in carbon "sinks", the removal of CO_2 from the atmosphere through photosynthesis, is a primary focus of mitigation through forestry and agriculture. The following introduction provides a review of concepts that are fundament to the development of forestry and agriculture in a low carbon economy, with specific reference where possible to their application in Florida.

GHG flux through forestry and agriculture

Forestry and agriculture in the United States are a net carbon sink of about 830 Tg of CO_2eq.[1] Sequestration of carbon in this form is greater than CO_2 emissions from events such as forest harvest, land use change, or fire. U.S. GHG emissions and the relative contributions of forestry and agriculture are shown in Figure 1. Over 90% of the U.S. carbon sink occurs on forested lands, offsetting 12 to 16% of U.S. GHG emissions. In contrast, agriculture is a net emitter of GHGs, producing over 6% of U.S. annual emissions of CH_4 and N_2O. The net combined impact of forestry and agriculture in the U.S. is a sink that offset at least 6% of U.S. GHG emissions (U.S. EPA 2005, 2007). Worldwide, deforestation is second only to fossil fuel use as a source of emissions, and activities in the forestry and agricultural sectors (including deforestation) account for over 30% of worldwide greenhouse gas emissions. As discussed in this report, considerable opportunity exists to increase the sequestration capacity of Florida forests and agricultural soils, while reducing CH_4 and N_2O emissions from agricultural activities, and for biofuels to displace fossil fuels.

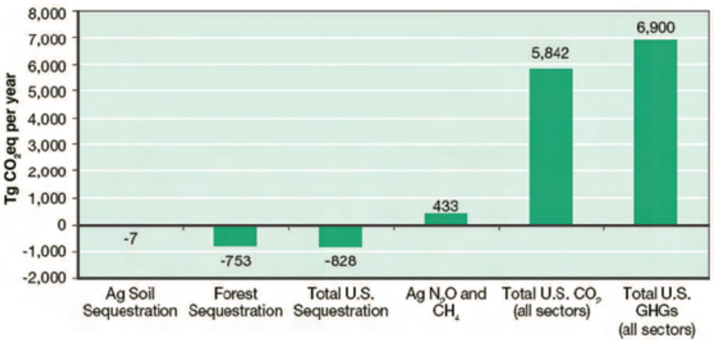


Figure 1. Forestry and agriculture net contribution to GHG emissions in the U.S., 2003. Total agriculture and forestry sequestration also includes urban trees, landfill yard trimmings and food scraps. Negative values represent a sink, positive values a source. *(Figure 1-1 from U.S. EPA 2005)*

Florida GHG emissions

Florida ranks sixth among the states in total GHG emissions, and is 30th among the world's top 75 emitters among states and nations (Center for Climate Strategies 2007). Florida produced 255.4 mmt (million metric tons, hereafter designated tonnes) of CO_2 in 2004. From 1990 to 2004, Florida CO_2 emissions increased 37%, second in absolute growth only to Texas (Environment Florida 2007). Most of this increase in CO_2 emissions came from increases in the transportation sector, specifically gasoline consumption, while most CO_2 emitted was produced by power plants. Because 12–7% of Florida's electrical power comes from petroleum, its use for transportation and power generation make petroleum the largest source of CO_2 by fuel type, followed by coal and natural gas (U.S. DOE/EIA 2006; Elliot et al. 2007). Given the present trajectory, Florida's GHG emissions will grow by 88 percent by 2020 relative to 1990, compared with 50% for the U.S. as a whole (Center for Climate Strategies 2007). A 1997 GHG inventory conducted by ICF Consulting (Washington, DC) showed that similar to the U.S. as a whole, the agricultural sector in Florida is a net emitter of GHGs while the forestry sector is a net sink, roughly balancing the emissions of agriculture in carbon equivalents. Overall, these fluxes are a small proportion of the total emissions from the energy sector in Florida and the U.S. Florida has over 95 active landfills, which are the largest source of CH_4 emissions in the state (Florida Department of Environmental Protection). Some landfills, such as ones in Orange County and Alachua County, use this methane for power generation in "green power" programs.

Overview of forestry and agricultural mitigation potential for Florida

Development of carbon markets in Florida through using forestry, agriculture, and possibly natural lands for mitigation could have profound implications for land use and land prices. Although the GHG sources and sinks in the forestry and agriculture sectors of Florida are minor portions of the total emissions profile, they represent an important tool for offsetting and mitigating the state's projected increases in fossil emissions over future decades. This argument is compelling only if fossil fuels are displaced through the use of biofuels and biomass, and sequestration of carbon is substantial and long term. With worldwide CO_2 emissions rising at a rate of 1.1% per year for 1990–1999 to greater than 3% per year for 2000–2004 (Raupach et al. 2007), management of forests and agricultural lands could provide a highly effective tool for stabilization of GHGs in the atmosphere. The opportunity for mitigation provided by forestry and agriculture varies regionally throughout the U.S., but there is especially great potential in the southeastern and south-central U.S. because of extensive forestlands and the opportunity to use biomass and biofuels as energy sources (EPA 2005). In 2003, forests covered 47%, and crop and pasture lands covered 24.5%, of Florida's 34.6 million land acres. By 2002, forested land in Florida had dropped by about one third from a high of 22.8 million acres in 1945, while the area occupied by urban lands increased by 3.4 million acres, or nearly seven-fold. In contrast, during the same period, crop and pasture lands increased by 22% (USDA/ERS 2006).

The forestry and agricultural sectors in Florida have yet to be managed for GHG offsets and reduction, and thus they represent obvious targets for inclusion in a climate action plan for the state. The huge acreage in Florida devoted to forestry and agriculture could help stabilize emissions in the U.S. if GHG offsets are derived from transparent definitions and standards based on solid science. Florida's policy makers have just begun this conversation, and there are significant areas of science that must be developed for the state to adopt comprehensive standards for GHG mitigation. As detailed in the following essays, the most important task is for scientists to quantify the carbon currently sequestered in Florida forests and soils, which is a baseline necessary to develop management strategies to maximize carbon storage over time. For example, a recent paper by Binford et al. (2006) shows that many of the industrial forests of the Southeast have been harvested over decades while maintaining a high potential for landscape carbon sequestration. Satellite imaging is essential for scaling forest CO_2 exchange processes over time and space. Given an adequate supply from such forests and a favorable market, this implies that wood could be used as a replacement for coal at power plants (see sections by Hodges and Alavalapati). Similarly, Florida's agricultural resources are only now being assessed for their GHG reduction potential in biofuel production (section by Hodges) and livestock waste management (section by Wilkie). Although some of the basic data for understanding the potential for additional carbon sequestration in Florida's agricultural soils are lacking, it is clear that soils emissions could be decreased and sequestration increased by changing current agricultural practice (section by Grunwald).

Carbon credits derived from afforestation and tree planting are currently traded on carbon markets, and forests are touted as a major source of carbon offsets. It is arguable that Florida will have a significant advantage in carbon markets through reforestation and afforestation. For example, there is clear evidence that afforestation of marginal agricultural lands can provide significant ecosystem carbon sequestration (Morrris et al. 2007), and Florida has an abundance of lands with limited agricultural potential. An added complication that may favor Florida's role is that recent science has raised issues about the effect of afforestation on global radiant energy balance. It is possible that widespread afforestation may actually warm the atmosphere, despite the increased carbon sink provided by such forests. Because of the diminished albedo of snow cover in forested lands in the mid to high latitudes during the winter months, global climate models show that global replacement of current vegetation by trees would lead to mean global warming, while replacement of forests by grasslands would result in cooling (Gibbard et al. 2005). In contrast, models show that afforestation in warm latitudes would be clearly beneficial in mitigating global-scale warming (Bala et al. 2007). Because evapotranspiration removes heat efficiently from the surface under warm temperature at low latitudes, a cooling effect should dominate in the warm forests of Florida where there is little or no opportunity for snow cover. Accordingly, afforestation is an appropriate climate mitigation activity for Florida, but needs to be carefully evaluated through construction of landscape radiant energy budgets for more northern regions of the U.S. It is thus possible that carbon offsets from Florida forests will have a competitive advantage in carbon markets because they are more tightly linked to climate mitigation than are forests in more northern latitudes.

Overview of carbon markets

Existing emissions regulatory systems throughout the world rely primarily on some form of cap-and-trade mechanism, and the same will likely occur for markets being developed for carbon credits. Such a mechanism caps the total emissions permissible from regulated activities, and emitters can comply by (1) improving efficiency to reduce emissions, (2) purchasing allowances from other emitters who are below their regulated limit, and (3) by purchasing carbon offsets from enterprises that remove GHGs from the atmosphere. Forestry and agriculture are by far the most important sectors for creation of biological offsets, but in theory natural landscapes could also play a role if we choose to include them in carbon markets. While trading schemes have been developed based on the potential of managed lands, they frequently omit significant components of reversal and leakage (discussed below) and lack independent verification. This lack of total accountability has called into question the effectiveness of the biological offsets and makes clear the need for comprehensive assessments of GHG flux over time and space.

Mitigation scenarios are based on carbon-market drivers as well as the traditional markets for forest and agricultural products. The current state of the art is represented by the model employed by the U.S. EPA known as the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG; U.S. EPA 2005). This is a partial equilibrium economic model of U.S. forest and agricultural sectors, with land use competition and linkages to international trade. Another example that is perhaps more applicable to regions such as Florida is the Integrated Assessment Model developed by McCarl and colleagues (e.g., McCarl and Schneider 2001). This model portrays farmers choices across regions among a set of crop and livestock management options including tillage, fertilization, irrigation, manure treatment, and feeding alternatives. At the heart of this exercise is the market price of carbon equivalents, which is used to model future impacts of mitigation. An example of the outcome of the EPA modeling effort is shown in Figure 2.

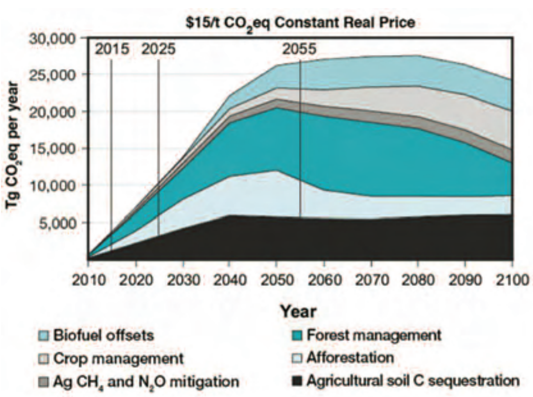


Figure 2. Cumulative GHG mitigation potential over time as an example of output from FASOMGHG. *Reproduced from Figure 4-6, U.S. EPA 2005.*

While it is likely that carbon markets could support GHG mitigation through forestry and agriculture throughout this century, FASOMGHG shows that the mitigation potential per year is sensitive to the market price of CO_2eq and carbon saturation of the systems in question. Figure 3 shows that higher values result in greater mitigation, but individ-

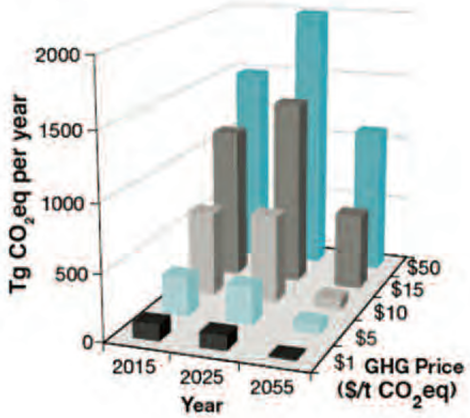


Figure 3. Average annual offset potential at three focus dates by GHG price. *(Reproduced from Figure 8-1, U.S. EPA 2005)*

ual projects become saturated at about 2025. Beyond 2025, landowners may shift from mitigation to alternative practice, and thus constant price scenarios eventually show a declining rate of mitigation. While incentives for offsets are weak in the U.S. voluntary market, mandatory caps in Europe rapidly drove the price to $30–40 per tonne CO_2eq, but eventually relaxed to the present value of about $15–20.

Although a carbon market based on voluntary caps exists in the U.S. through the Chicago Climate Exchange, forestry and agriculture in Florida have yet to participate in any meaningful way. It is clear that mandatory federal caps will be necessary for such markets to have a significant role in national GHG management. Within this context, Florida has considerable latitude to develop its own market through mitigation projects capitalizing on regional and local biological resources, possibly including a role for natural and semi-natural lands. Regional markets, such as the one in the European Union and the Regional Greenhouse Gas Initiative (RGGI) including 10 northeastern U.S. states, have demonstrated that regional policy can establish an effective cap and trade system. It seems likely that appropriate policy could foster the creation of an effective carbon market for Florida, possibly including other states in the Southeast. As demonstrated by RGGI, a federally mandated carbon cap need not conflict with regional policies and markets, which may serve instead as a platform for the implementation of future additional emissions trading programs.

Using managed and natural ecosystems for GHG mitigation requires an understanding of the dynamics of their GHG flux. Quantification of the time-specific carbon budget of these biological systems is an essential first step, but it does not account for all GHGs associated with a mitigation project or the changes in the carbon budget over time. For example, under a given practice, soils can become saturated with carbon over time, and thus GHG management must account for this likelihood. Similarly, the GHG advantage provided by biofuels must account for fossil fuels used in the production and distribution of energy crops. Understanding these dynamics is a complex economic and ecological analysis that requires quantification of markets, incentives, and mitigation targets over a specified time frame. Two concepts help define the caveats associated with mitigation projects—reversal and leakage.

Reversal Reversal refers to the loss of sequestered carbon if it is re-released into the atmosphere at some future date. Typically, most biological systems capable of sequestering carbon will exhibit a slowdown of carbon capture until an equilibrium point is reached such that there is little or no additional net sequestration of carbon. Some fast-growing forests in the temperate zone will approach maximum net sequestration at about 80–100 years following afforestation (Willey and Chameides 2007). A disturbance such as a forest fire or clear-cutting with associated burning can cause reversal for forestlands. Fires, reduced hydroperiods, and intensive cropping of soils are an ongoing significant source of reversal for the Everglades, one of the largest pools of sequestered carbon in the U.S. Soils may exhibit reversal when placed under intensive tillage as opposed to conservation tillage or no-till practice. Table 1 below shows the qualitative risk of reversal of GHG benefits for various aspects of forestry and agriculture. Not included in the consideration of reversal is

Table 1. Qualitative consideration of potential and risk of reversal for activities in the forestry and agricultural sectors
(Adapted from Table 6-6 U.S. EPA 2005)

Activity	Potential	Risk of reversal
Afforestation	High in most places within U.S.	Moderate if timber or land prices change or natural disturbances (fire, pests)
Forest management	Carbon budget analysis necessary to demonstrate the value of alternative practice	Moderate if timber or land prices change, or natural disturbance (fire, pests)
Protection (avoided deforestation)	High if current rates of deforestation are high	Low if legal protection is enforced. High if susceptible to wildfire, has uncertain legal status, or major commodity price change, etc.
Agricultural soil carbon sequestration	High if alternative tillage is adopted and maintained	Moderate to high: potential seasonal tillage change (e.g., weed control); or change in crops or tillage practices in response to commodity prices or programs
Agricultural CH_4 and N_2O mitigation	Moderate to high, assuming emissions per unit production data are known. Requires known changes in management practice	Low or none. No carbon storage subject to re-release involved.
Biofuels offsets	High based on recent market trends in fuels.	Low or none. Primary benefit does not involve carbon storage subject to re-release, although response to market prices could affect soil carbon.

the fate of carbon embodied in long-lived products after the time of harvest. Given that stabilization of the climate system is an intergenerational enterprise, embodied carbon must ultimately be quantified in the analysis of the potential for mitigation. Note also that mitigation through biofuels and agricultural CH_4 and N_2O are permanent emissions reductions to the extent that they do not involve carbon storage and are not subject to reversal. This assessment is generally valid only if biofuels are used to permanently displace fossil fuels, and croplands for growth of fuel crops are managed to reduce loss of carbon from the soil.

Leakage Leakage refers to goods and services derived from processes that have released GHGs and are imported from, or created outside, the boundaries of a mitigation project. Thus, the GHG mitigation benefits of a project can be diminished by leakage. Leakage is calculated as a proportion of the direct GHG reductions achieved by the targeted activity diminished by indirect GHG emissions from the non-targeted activity. This value needs to be assessed over a timeline appropriate to these activities and the market drivers (U.S. EPA 2005). Leakage also includes fossil fuel emissions associated with production of biofuels. For example, ethanol produced from corn transported long distances by conventional trucks or trains to coal-fired refineries can actually result in more net GHG emissions than petroleum (Farrell 2006). Similarly, afforestation without accounting for GHGs emitted by associated activities can decrease the GHG mitigation potential by more than 20 percent (U.S. EPA 2005). Leakage can result also when market forces affect a mitigation project. For example, afforestation of the South-Central U.S., could cause significant land use change in the southeastern U.S. (e.g., a shift to more acreage in agriculture), resulting in additional GHG emissions from this region. The most important point from analysis of leakage is that all internal and external activities associated with a mitigation project must be included in the GHG mitigation analysis. In order to minimize these unintended consequences, policies and incentives for mitigation must be comprehensive. Development of such comprehensive plans requires a thorough knowledge of market interdependencies and drivers as well as the carbon budgets of the managed biological systems.

Concepts for creating, measuring and verifying Florida GHG offsets

Florida has the rare opportunity to help structure the emerging carbon market at the beginning of the low-carbon economy in the U.S., while benefiting from the experience of markets elsewhere. Critical to the creation of offsets is the process of quantification, validation, and determination of ownership. The following describes this process in overview, as detailed in a recently published manual from the Nicholas Institute for Environmental Policy Solutions (Willey and Chameides 2007). The necessity of validating offsets suggests that in addition to providing a meaningful carbon cap, a proper role of government is to provide oversight and certification of those businesses and industries that will service the carbon-offset market. Florida policy makers and state agencies could work with stakeholders and commercial entities to develop guidelines that insure the continued integrity of Florida's ecosystems and biodiversity, while defining the role of the state's landscape biological resources in the carbon market.

Creating offsets Offsets are created in a series of steps that would be fundamentally the same for Florida as elsewhere. Project managers must first define the land-management practices they will use to create offsets, and then establish the spatial and temporal boundaries of the project. Estimating the boundaries of a project allows developers to scope the costs and benefits to reasonably determine whether the net offsets will justify probable costs. In order for an offset to be valid and marketable it must be additional. That is, any reductions in GHG emissions or increases in stores of carbon would not have occurred without the project. Determining *additionality* is a complicated and critical effort in determining a project's net GHG benefit. This is accomplished by estimating the difference between GHG emissions from lands and facilities during a project and a designated baseline. The baseline consists of comparison lands similar to and near project lands or, in some cases, a small fraction of project lands or facilities where project activities are not implemented. As discussed in the section on forestry (Alavalapati), baselines could also be calculated with respect to avoided carbon emissions that would ensue if the land were used for a purpose other than mitigation, such as residential and commercial development. This opens the possibility of including Florida's natural and semi-natural lands in carbon trading.

Measuring offsets Developers need a monitoring and quantification plan before beginning a project to ensure a project's offsets are verifiable and satisfactory to buyers and regulators. The most important part of this plan lays out the methods used to monitor changes in GHG emissions or carbon stocks resulting from the project's land-management practices. Therefore, proficient monitoring services are crucial in determining a project's net greenhouse benefits. Monitoring services should accurately sample the project's GHG impacts at appropriate locations and frequency, and within an appropriate timeframe. The techniques used to measure net changes in emissions and sinks will depend specifically on the type of land-management project and accurate quantification of a baseline. Such accuracy may be problematic for projects in Florida where certain basic ecological data are lacking. For example, we presently have only crude estimates of sequestered soil carbon for many locations in Florida. Measurements are then used by quantifiers to calculate carbon offsets claimed by project developers, taking either the total stock of carbon stored on project lands (carbon sequestration) or total GHG emissions from project lands (emissions reduction), baseline measurements and leakage into account. Quantifiers must also account for uncertainty because as uncertainty rises, regulators of a capped system will generally accept a smaller proportion of offsets as real. Developers can optimize their profits by balancing acceptable levels of uncertainty and operating costs. For Florida, periodic reversals through wildfires are one source of uncertainty, but required prescribed burns could be included as a form of leakage.

Verifying offsets When a qualified, independent party verifies a project's offsets and those offsets are registered, all stakeholders receive assurance that the offsets represent real atmospheric benefits. After quantifying the offsets generated from a project, developers must make public a written report addressing key aspects of the project such as responsible parties, land-management activities, and quantities of offsets the project generated. This report ensures transparency and makes verification possible. Verifiers act as auditors of the offset process, and offsets must be independently verified before a developer can market them. Verifiers refer to documented plans to confirm that the methods, data, and calculations used to quantify net GHG benefits are reliable. To avoid conflicts of interest, verifiers should not be involved in the project in any other capacity. Project developers typically divide a project into accounting periods during which they quantify and market offsets. Accounting practices need to be specified to establish a single point where GHG benefits are counted in order to avoid double counting. Registering offsets with an appropriate agency assigns the owner a unique identifier and all subsequent transfers are amended within the registration, making the ownership of offsets unequivocal. Historical records ensure integrity and allow for audits by third parties or a regulating agency.

Aggregating offsets Buyers usually prefer to purchase aggregates of offsets instead of contracting with many landowners and project developers. This provides a role for retailers and brokers, who can aggregate offsets from numerous landowners, ensure that the offsets are reliably measured and verified, and provide blocks of offsets to the market. For example, the Florida Forestry Association is presently developing guidelines to act as an aggregator for Florida forest owners. Retailers and brokers do not own offsets, but buyers may prefer to work with them as an entity because they are in a better position to make up any shortfalls in the offsets they agree to provide buyers with. There may also be a role for insurance companies to underwrite risky projects and provide compensation to the insured if a project does not produce the anticipated offsets. Because offsets are property, participants need a contract before the project begins that clearly articulates the nature of the project and allocates costs, risks, liabilities, and profits. For example, a contract may specify delivery of a fixed number of tons, or require (or prohibit) specified activities and transfer all resulting tons to the buyer. These contracts can involve a perpetual commitment to keep carbon stored, or they may run for a fixed period. A buyer can secure a perpetual obligation by obtaining a property interest from the seller, for example in the form of an easement.

Environmental co-effects of land management for offsets

There are significant concerns among environmental groups about using forestry and agriculture for the creation of offsets and participation in carbon markets. While much of this concern focuses on the rigorous accounting and verification necessary for offsets to be valid, there is also worry about negative environmental co-effects of managing the landscape for GHG offsets. Mitigation efforts using biological systems can have large non-GHG environmental co-effects with perceived positive or negative value. Even at a low GHG price, changes in land use and production can induce positive changes in tillage practice and promote carbon sequestration, while reducing erosion and nutrient runoff (U.S. EPA 2005). Control of weeds without tillage, however, may result in the negative co-effect of increased herbicide use and associated toxic runoff. Alternatively, large-scale conversion of agricultural lands to forest may have positive effects on water and air quality. One negative effect of producing energy crops is the creation of extensive monoculture tracts devoted to non-native species such as Elephant grass (*Pennisetum purpuretum* L.) or Spanish cane (*Arundo donax* L.). Similarly, ethanol production can require enormous quantities of freshwater, placing a strain on regionally scarce water resources. The co-effects of GHG mitigation on biodiversity may be both positive and negative, depending on location and mitigation activity. For example, industrial forests typically have lower biodiversity than natural or semi-natural forests, but higher diversity than crop and urban lands. These high-density forests tend to be more prone to reversal through wildfire than natural forests. Similarly, forests managed for bioenergy for co-firing power plants should be monitored for long-term maintenance of soil fertility because removal of stumps and logging debris for use as fuel may diminish the recycling of essential nutrients. The Forest Stewardship Council is presently developing protocols for the sustainable harvest of biofuels from forests.

It is arguable that most of the environmental co-effects of managing lands for offsets are clearly positive, resulting in enhanced ecosystem function. Indeed, relative to other regions of the U.S., it is arguable that Florida's unique climate and topography make it more likely that afforestation and management of soils for carbon sequestration will result in improved watershed function and increased soil nutrient holding capacity. Table 2 shows some of the possible positive and negative environmental co-effects and mitigation potential as determined through the use of U.S. EPA models. Central to managing lands appropriately will be proper oversight and regulation of mitigation projects to ensure that negative environmental co-effects are minimized. An inventory of Florida's critical lands and

Table 2. Environmental co-effects of GHG mitigation activites *(Adapted from Table 8-1 U.S. EPA 2005)*

Activity	GHG Mitigation Potential	Key Environmental Co-effects
Afforestation	High	Increases forest cover; improves water quality; biodiversity effects either positive or negative depending on characteristics of new forests and ecosystem displace by new forest.
Forest management	Moderate	Enhances forest biological stock; longer rotations can provide critical habitat.
Agricultural soil carbon sequestration through	Moderate to low	Reduced erosion and nutrient runoff. Small increase in pestcide use
Fossil fuel mitigation from biofuel crop production	Moderate to low depending on intensity	Negligible effects within agricultural sector
Agricultural CH_4 and N_2O mitigation	Low	Air quality improvements from some activities (e.g., manure management)
Biofuel offsets	Very high	Biodiversity effects depend on previous land use and intensity of harvest

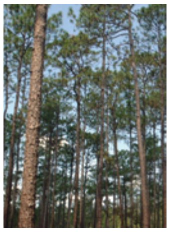
waters is currently underway under the auspices of the Century Commission for a Sustainable Florida. Such an inventory can be a critical decision support tool to ensure that new mitigation projects are designed in a manner consistent with the maintenance of biodiversity and ecosystem services (Mulkey 2007).

The profound implication of incorporating biological systems into carbon markets is that this represents a major step toward reconciling the planet's living carbon economy with its monetary economy. If carbon markets are truly comprehensive and implement honest accounting including reversals and leakages, they can begin to provide a common denominator for economic valuation of ecosystems and many of their associated services. With water in critically short supply, certain regions of Florida could benefit from watershed based mitigation projects. To the extent that the practice of GHG mitigation results in enhancement of these ecosystem services, carbon markets can facilitate the development of sustainable resource and land use. As these markets are implemented, nature's goods and services will increasingly cease to be treated as externalities in the human economic system. Because Florida has yet to begin the carbon accounting of its biological systems, the opportunity exists to take the first bold steps toward creation of a powerful new economic means of promoting sustainable practice across a broad array of human activities. Clearly, the details of how mitigation projects are managed are critical to their success in maintenance and possible enhancement of ecosystem services.

Focus of this report

Because Florida has only recently begun the conversation about mechanisms of GHG mitigation, the following reviews represent a first-pass assessment of opportunities. The quantification of carbon market potential in these essays is speculative, but based on the best available data. Janaki Alavalapati reviews forestry as a dominant land use in Florida, showing major cumulative carbon emissions avoided with appropriate forest management and uses of forest products. Florida forests sequester about 9.5 million tonnes of carbon annually, and this value can be substantially increased over coming decades. Croplands and other resources converted to biofuels (reviewed by Alan Hodges) provide an impor-

tant opportunity for GHG mitigation through offsets, and the resulting fuels can meet a significant part of Florida's growing demand for energy. Wood products are a promising replacement for coal and natural gas in Florida power plants. Ann C. Wilkie reviews the opportunities for livestock waste management and distributed power production by small generators from methane derived from these wastes, showing the potential carbon market and fuel value of Florida biogas. Central to facilitating this form of energy conversion is the clear need for a favorable fee structure associated with connection of distributed power to the grid. Finally, Sabine Grunwald shows that on average, Florida soils have the highest organic carbon content of soils in the conterminous United States, while they are highly heterogeneous in their carbon content and sequestration potential. Land management practices that can increase soil carbon are discussed. Throughout the body of this report, we use a carbon market value for these offsets of \$4 Mg^{-1} CO_2eq, which is typical of the U.S. voluntary market. In the summary, we project the value of these components based on a likely value of \$20 Mg^{-1} CO_2eq, which reflects a mandated cap-and-trade market. We hope that these essays will provide a starting point for construction of scenarios and quantitative modeling of GHG mitigation for the state.



Role of forests in reducing greenhouse gases

Janaki Alavalapati

It is widely recognized that forests play an important role in the global carbon cycle by sequestering carbon dioxide and storing it in the form of biomass (U.S. EPA 2005)[2]. A recent study found that a broad range of possible forest-based carbon sequestration opportunities are available at various magnitudes and associated costs (Stavins and Richards 2005). In forests, the amount of sequestered carbon is largely influenced by three factors:

(1) carbon stored in standing biomass; (2) carbon stored below ground; and (3) carbon stored in forest products (Johnsen et al. 2001). These factors are in turn influenced largely by management intensity, soil characteristics, and longevity of forest products. For example, the growth rates of forest plantations with thinning and fertigation will be higher, and thus accumulate greater quantities of carbon, than those of less intensely managed plantations. Replacement of fossil fuels with biofuels and substitution of wood products to steel products are likely to have a positive impact on carbon storage. For example, steel framing requires 13 times more energy than wood framing, and aluminum framing for exterior walls is nearly 20 times as energy intensive as wood framing (Robertson and Libby 1998). Forest land owners might be able to sell more wood or sell wood at higher prices, if the prices of concrete and steel rise because manufacturers of concrete and steel have to pay for their greenhouse gas emissions.

There are two misconceptions about forest biomass and the carbon cycle. The first one is that forests do not produce net emissions of carbon dioxide (Cushman et al. 2007); this is not entirely true. It requires energy to grow, harvest, and haul the biomass to a pulpmill or sawmill or power plant. The extent to which forest products and bioenergy displace net emissions of carbon dioxide will depend on the efficiency with which they can be produced and used. The second one is that biomass fuels and fossil fuels are not different because, when burned, both release carbon dioxide. This is not true either. When biofuels are burned, the carbon released back to the atmosphere will be recycled into the next generation of growing trees (Cushman et al. 2007). Following this logic, consider that a productive forest is harvested and the site replanted with energy crops; the initial harvest will yield some long-lived products, some short-lived products, and some energy products (Figure 4). Over time, the various products will gradually decay and release their carbon to the atmosphere and some carbon will be lost from the soil because of more intensive management. The energy products harvested periodically over time will displace fossil fuels, allowing them to be left in the ground. There will also be some unburned fossil fuels because wood products typically require less energy for their production than do other materials for which they substitute. While there is an overall reduction in carbon emissions over time, the magnitude will depend on growth rate of energy crops, the efficiency of biomass substitution for fossil fuels, and many other parameters.

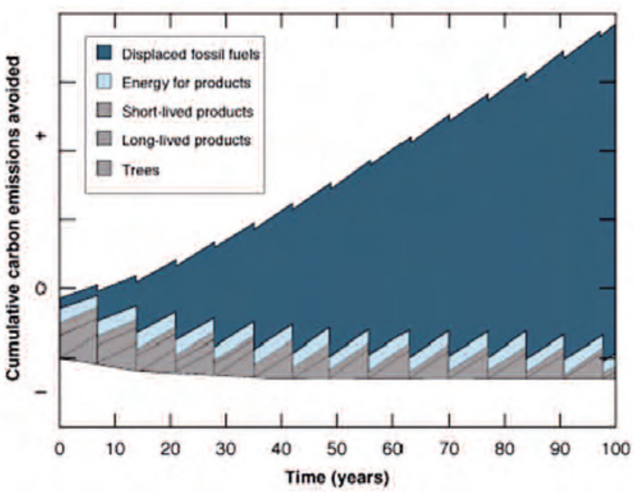


Figure 4. Forests, products, and carbon emissions avoided. *(Adapted from Cushman et al. 2007)*

In the U.S., forest carbon inventory was estimated to be ~38.5 Pg[3] consisting of 13.8 Pg of carbon in forest trees and 24.7 Pg of carbon in forest soils (Skog and Nicholson 2000). It was also estimated that forests in the U.S. sequester an average of 250 Tg carbon in trees, under-story, forest floor, and soils. In addition, net sequestration of carbon in U.S. wood and paper products and landfills (additions including net imports, minus emissions from decay and burning each year) is about 61 Tg.[4] This suggests that carbon sequestration through forests accounts for about 16% of annual GHG emissions of the U.S.[5] The U.S. south covers about 24% of country's land base and over 50% of this land (508 million acres) is forested. Forests in this region are extremely productive because of warmer climate and longer growing season. Commercially grown natural and planted pine forests in this region cover approximately 66 million acres. Using the mean annual net ecosystem productivity (NEP), Johnsen et al. (2001) noted that pine forests (508 million acres) in the Southeast sequester as much as 210 Tg carbon yr^{-1}.

Florida forest types, ownership, and output

Florida forests cover 16.1 million acres, almost 50% of total land (34.6 million acres) in the state. These forests consist of both softwood and hardwood forest types. The hardwood types, which include the oak-pine type, occupied 7.8 million acres or 50% of the State's timberland. Softwoods, which are composed of slash pine, loblolly, longleaf pine, and other pines occupied 47% of the timberland or 7.3 million acres. Non-stocked areas are made up the remaining 3% (Brown 2007; Carter and Jokela 2003). About 61% of forested lands (9.6 million acres) are owned by non-industrial private land-owners and forest industry owns about 12% of forested lands in Florida. Public agencies owned about 27% or nearly 4.2 million acres of Florida's timberland (Figure 5). As such, approximately 80% of Florida forests are under private ownership and it is important to recognize the importance of private forestlands to the state economy and prospects for carbon sequestration.

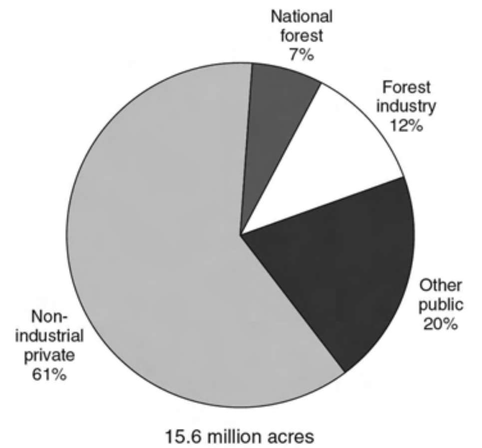


Figure 5. Area of timberland by ownership class in Florida. *(Brown 2007)*

Figures 6 and 7 show age class distributions for pine plantations and hardwood stands. Pine plantations with higher productivity rates exhibit younger age class distributions and are harvested at younger age relative to hardwood stands. While this is directly related to economic aspects of industrial forest management, it will have huge implications for carbon sequestration by harvesting and reforesting more frequently. Forests that approach maturity achieve a balance between carbon uptake in photosynthesis and carbon released back to the atmosphere from respiration, oxidation of dead organic matter, fires, and pests (Cushman et al. 2007). In other words, matured forests that are not harvested do not continue to accumulate carbon indefinitely. On the other hand, under intensive management, trees can be harvested for use in producing wood products or energy. While harvesting may result in less carbon stored in standing biomass and forest soils, wood products and biofuels produced from forest biomass can replace steel and fossil fuels. Furthermore, the land can be reforested again and additional carbon will be sequestered.

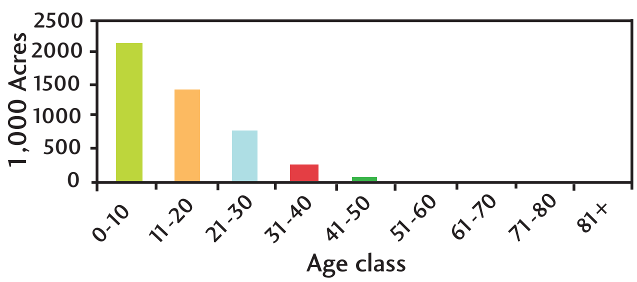


Figure 6. Age class distribution of pine forests. *(Carter and Jokela 2003)*

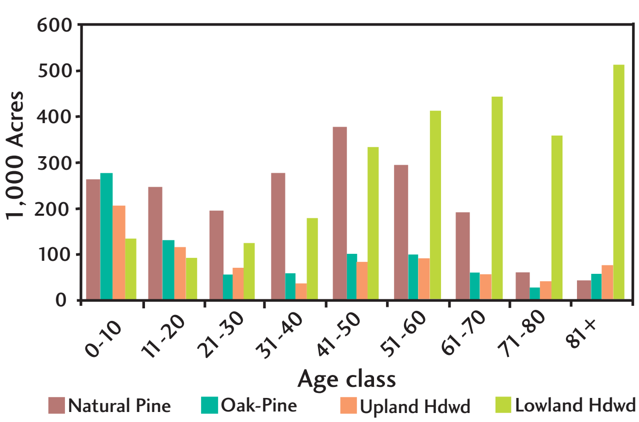


Figure 7. Age class distribution by forest type. *(Carter and Jokela 2003)*

It has been estimated that approximately 580 million cubic feet of round wood is harvested in Florida annually from both softwood and hardwood forests (Bentley et al. 2002). Approximately 81% of this output comes from softwood (pine) forests. About 52% of timber is used as pulp wood, 34% of timber is used as sawnwood, and the rest is used for veneer logs, composite panels, and other industrial uses. Since the longevity of these products is not the same, product composition will have significant implications for carbon sequestration. The net change for softwoods in 2005 involved the gross growth of 743 million cubic feet, mortality of 83 million cubic feet, and average annual net growth of 660 million cubic feet. This net growth was reduced by removals of 473 million cubic feet which yields a positive net change in the softwood resource of 187 million cubic feet. The net change for hardwoods in 2005 involved 290 million cubic feet of gross growth, mortality of 126 million cubic feet, and 163 million cubic feet of net growth. Removals of 107 million cubic feet deducted from the net growth left a surplus of 56 million cubic feet.

Estimation of biomass and carbon in Florida forests

Following Johnson et al. (2005)[6], growth, removal, and reestablishment of trees are described below. We assume that management intensities in Florida range from little intervention on low-quality lands to greater intervention on high-quality lands involving fertilization and thinning. Also, we assume that management options such as planting, fertilization, and thinning are practiced only on private forests. Drawing on published literature, estimates of stand growth and standing and harvested forest biomass are compiled. Average volume harvested per unit area is estimated by aggregating the combination of site productivity and management intensity. The weighting factor for each combination was determined from acreage distributions of management intensity and nature of forests. Following Johnson et al. (2005), we consider a base case that assumes 37% of industrial and non-industrial private forestlands are classified in the lowest productivity class, 58% in the middle productivity class, and 5% in the highest class. It is conceivable that new markets associated with carbon, bioenergy, and environmental services might stimulate landowners to switch from low-intensity to medium intensity and/or medium intensity to high-intensity management practices. In such a case, we can expect that there will be 0% in the lowest productivity class, 37% in the middle class, and 63% in the highest classification.

We assume that fertilizer is applied only for mid-intensity and high-intensity management situations, but not for low. Furthermore, the high-intensity scenario considers fertilization every four years over the rotation age (25 years) while mid-intensity scenario in-

Table 3. Timber yield under different management scenarios

	Low-Intensity	Medium-Intensity	High-Intensity
Planting density (stems acre^{-1})	726	726	726
Fertilization	None	Year 2, 16	Year 2, 5, 9, 13, 17, 21
First thinning (cmt hactare^{-1}) (at year)	0	63 (17)	59 (13)
Second thinning (cmt hactare^{-1}) (at year)	0	0	58 (19)
Final harvest (cmt hactare^{-1}) (at year)	220 (30)	175 (25)	295 (25)
Total yield (cmt acre^{-1})	89	96	130

Note: cmt = cubic meter

volves fertilization at years two and sixteen. In order to estimate carbon, it is assumed that carbon in the stem is 50% of the biomass of the stem and in the branches is 21% of stem biomass. Carbon in fine roots was estimated as twice the annual carbon production in roots. Carbon removed is estimated as the difference between carbon in the year before activity and carbon after the activity plus any carbon accumulation during the year of activity. Following Johnson et al. (2005), Table 3 presents timber yield under different management intensities. Not surprisingly, the productivity under a high-intensity management scenario is 46% higher than in a low-intensity scenario.[7]

In Florida, both slash and loblolly forests are managed as plantations that are amenable for different management practices. Considering that these plantations occupy approximately 5 million acres and 37% of these forests are under low-intensity management, 58% are under medium, and 5% are under high-intensity management, biomass yield and carbon content are estimated (Table 4). Switching from lower intensity management to higher intensity management could increase the biomass in Florida forests, because growth is increased, resulting in a larger average carbon stock within forest lands. The approximate magnitude of the potential gain in forest carbon stocks are given in Table 4.

Table 4. Carbon pool in commercial pine plantations in Florida

Management intensity	% of land under each intensity	# of acres (millions)	biomass acre^{-1} (tonnes)	Carbon acre^{-1} (tonnes)	Rotation age	Carbon acre^{-1} yr^{-1} (tonnes)	Total carbon yr^{-1} (million tonnes)
Low	0.37	5	63.5	25.42	30	0.85	1.56
Medium	0.58	5	68.5	27.42	25	1.10	3.18
High	0.05	5	92.8	37.14	25	1.49	0.37

Note: 1.4 cubic meters equals 1 tonne; in converting biomass to carbon it was assumed that moisture content would be 20% and 50% of dry biomass is carbon.

Making a simplifying assumption that forest stands accumulate biomass at a constant rate, assuming 20% moisture content, the average carbon stock over the course of a rotation would be half the dry biomass stock present at harvest. Using the numbers in Table 4, increasing management intensity from medium to high would increase the average carbon stock from 27.42 tonnes carbon per acre to 37.14 tonnes carbon per acre. Every acre switched could potentially yield 0.39 tonnes carbon per acre per year. Increased fertilizer emissions may have to be deducted when calculating these additional carbon credits. The total carbon pool associated with commercial pine plantations in Florida would be 5.12 million tonnes per year (sum of the last column in Table 4).

The remaining Florida forests (~11 million acres) may not be as productive as slash and loblolly plantations from a carbon sequestration viewpoint. In terms of biodiversity, water quality, and recreation, these forests may be more valuable than forest plantations. Binford et al. (2006) recently provide a conservative estimate of about 0.4 tonnes of carbon acre^{-1} yr^{-1} at a landscape level in the Southeastern region of the U.S. Using this estimate as a basis, forests not including commercial plantations in Florida are sequestering 4.4 million tonnes of carbon each year. Overall, we estimate the gross sequestration of Florida forests to be sequester about 9.5 million tonnes of carbon annually (5.1 million tonnes from commercial pine plantations and 4.4 million tonnes from other forests).

Estimation of carbon stored in forest products.

Wood and paper products in use and in dumps and landfills provide large pools of carbon in forests. In the U.S., the net sequestration of carbon in wood and paper products and carbon in landfills is projected to increase from 61 Tg yr^{-1} in 1990 to 74 Tg yr^{-1} by 2040. This increase is expected largely because of an increase in wood consumption and a decrease in decay in landfills compared with phased-out dumps (Skog and Nicholson 2000). Following Skog and Nicholson (2000), carbon in Florida forest products was estimated first by converting cubic feet of round wood into carbon using a factor of 270.7 kg m-3 (16.9 pounds per cubic foot). According to a conservative estimate, Florida produces 14.16 million cubic meters (~500 million cubic feet) round wood annually. This amounts to 3.8 million tonnes of carbon annually. As carbon stored in wood products typically does not count as a tradable offset (see endnote 4 for explanation), this sequestration probably will not result in offset payments to forest land owners. Therefore, it was not included in further analysis.

Economic impact of carbon credits from commercial pine forests

Calculating dollar impacts for carbon credits requires setting a baseline and quantifying carbon pool changes from that baseline. In the context of Florida's forests, however, setting a baseline is very challenging. Figure 8 presents three different baselines. Baseline A assumes that the carbon stock in a forested region may not change over time. If no significant changes in land use, management, and technology occur, this scenario is plausible. Baseline B may exist for a region that experiences changes either in management or land use such that carbon per unit area may increase, but without explicit management for carbon sequestration. Baseline C shows the converse in which carbon stocks decrease.

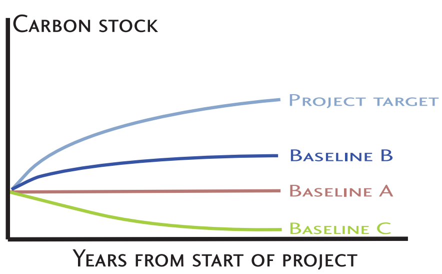


Figure 8. Carbon stock over time for different baseline scenarios.

In Florida, where a large number of forested acres are diverted for residential and other commercial purposes, Baseline C may be more realistic. Florida's land acquisition programs (e.g., Preservation 2000 and Florida Forever), which are spending approximately $1 million per day to acquire private rural lands for conservation purposes, support the argument for Baseline C. Although this type of baseline cannot be justified for public forests, it is a plausible scenario for private commercial pine forests that are managed to maximize rate of return. Therefore, any proposed project that could increase carbon stocks, by altering management intensity for example, the change in carbon stock from Baseline C could be claimed for credits. Landowners who want to continue forestry without undertaking any new projects but do not divert their land to other uses could claim the change in carbon stock between Baseline A and C.

Table 5 presents a plausible conservative estimate of dollar impacts of carbon credits for private forest landowners under different management intensities. For example. if all pine plantations are assumed to be managed under moderate intensity, it is shown that landowners could receive approximately $80 million each year towards carbon credits. On the other hand, if all pine plantations are managed under low intensity, landowners could receive about $62 million each year towards carbon credits. We believe that pine forestry operations in Florida do not cause significant leakages either domestically or internation-

Table 5. Expected revenue from commercial pine plantations (5 million acres) for carbon credits under different management intensities

Management intensity	Carbon $acre^{-1}$ yr^{-1} (tonnes)	Total carbon yr^{-1} (million tonnes)	Unit price of carbon $acre^{-1}$ (tonnes)	Total revenue ($ in millions)
Low	0.85	4.23	14.68	62.21
Medium	1.10	5.48	14.68	80.53
High	1.49	7.42	14.68	109.05

Based on a value of $4 Mg^{-1} CO_2eq, and 1 tonne of carbon = 3.67 tonnes of carbon dioxide.

ally because their output is not large enough to influence the supply behavior of timber producers outside of Florida. Furthermore, while carbon credits from pine plantations are justified based on the expected conversion to alternate land uses, these are in practice for decades and no new leakage is anticipated. As such this analysis does not consider a leakage decrement to projected carbon stocks. It should be noted that carbon credits associated with forest products are not considered in the analysis because of the complexity and variation in longevity or substitutability of products. Inclusion of carbon payments associated with forest products would result in higher profitability for forest landowners. Future research could address this important issue.

Challenges and opportunities for forest carbon sequestration in Florida

There are several challenges to maintaining and increasing existing levels of forest carbon sequestration in Florida. One of the major challenges for maintaining and enhancing forest carbon stocks is the future loss of forestlands to the large and increasing demand for residential land. By 2060 Florida's population is expected to be 35 million, and approximately 7 million more acres of rural land (forest and agricultural lands) will be converted to urban development (Zwick and Carr 2006). Any loss of forestland means less carbon accumulation in the field and less stock of carbon stored in forest products. Another challenge is limited market opportunities for small diameter wood. Forest landowners in the past were encouraged through federal policies (Conservation Reserve Program, for example) to create high-density forest plantations. With limited markets for small diameter wood, landowners are unlikely to undertake necessary silvicultural practices such as thinning. Accordingly, there has been a huge build up of small diameter wood and standing dead wood. This has not only resulted in an increase in wildfire hazard, but it is known to have a detrimental long-term impact on forest health and composition. Finally, wildfires, hurricanes, and pests (Southern Pine Beetle[8]) pose great threats to Florida's forests and thus to carbon sequestration. While we do not have control over hurricanes, measures such as prescribed burning can minimize threats from wildfires and pest attacks.

Because Florida forests are highly productive and amenable for more intensive management, there are several opportunities to increase forest carbon sequestration. Use of genetically improved seedlings, fertigation, and other innovative silvicultural operations make it possible to double the productivity of commercial plantations. This improvement will not only reduce the conversion of forestlands to other uses but also bring marginal agricultural land into forestry. Furthermore, recent research indicates that carbon and bioenergy markets and associated forest thinning operations are shown to increase the profitability of commercial forestry (Andres et al. 2007). Participation in carbon markets can provide additional stimulus for converting marginal agricultural land into forestry.

Environmental benefits such as improvement in biodiversity, soil conservation, air quality, and water quantity or quality associated with carbon sequestration projects can be significant (Feng et al. 2004). These co-benefits must enter as negative costs in analyzing the cost of carbon sequestration (Richards 2004). While internalizing these co-benefits along with carbon payments is challenging, their inclusion is critical for policy development. Public Demand for these co-benefits is on the rise. Shrestha and Alavalapati (2004) found that households in the Lake Okeechobee watershed expressed a willingness to pay more than $900 million to see a moderate improvement in air quality, water quality, and biodiversity. Explicit policies targeting payments for these co-benefits would further stimulate forest carbon sequestration.

Several opportunities exist to create additional carbon pools. Undertaking forestry on marginal pasture and range lands is one option. Studies suggest that there is a possibility for afforesting 5% of the 7.4 million acres of pasture and range land in Florida. Assuming that low intensity management is possible, it is possible to add 0.31 million tonnes of carbon per year which translates into $4.6 million revenue. Additional opportunities include (1) improving net carbon sequestration in products and landfills by shifting product mix to a greater proportion of lignin-containing products, which decay less in landfills, (2) increasing product recycling, and (3) increasing product life. Currently, the majority of round wood in Florida is used as pulpwood whose longevity is short. Carbon markets are shown to increase the rotation length of timber thereby producing greater proportion of sawnwood (Stainback and Alavalapati 2002), whose longevity is very high. Thus, carbon markets will likely increase the amount of carbon stored in Florida's solid wood products.

Food security, escalating prices of cattle feedstock, and other environmental concerns have prompted criticism of the use of corn and soybeans for biofuels. It seems that there is less opposition over the use of forest biomass for bioenergy and biofuels. In fact the use of small diameter woody biomass for bioenergy not only improves the health and profitability of forests but also offsets carbon emissions by replacing fossil fuels (Alavalapati et al. 2006). Cellulosic ethanol technology, when it becomes cost competitive, is expected to provide great opportunity for forest biomass utilization as biofuel.

Conclusions

Florida's forests, both public and private forests, play a key role by sequestering about 9.5 million tonnes of carbon annually, not accounting for harvest and tree death. Private forest landowners could realize $62 million yr^{-1} from carbon credits even if we assume that plantations are managed with low intensity. They could realize about $80 million yr^{-1} from carbon credits associated with commercial pine forestry with medium management intensity, and more than $100 million with high intensity. If emissions associated with fertilizer application in medium intensity management are included in carbon credit calculations, this value would be lower. This number could be higher if carbon credits associated with forest products and their use or substitution for energy intensive products such as steel and aluminum are considered. Future loss of forestlands for urban development, wildfires, hurricanes and pest attacks are the major challenges for the sustainability of these forests and thus for carbon accumulation. Through proper management it is possible to increase the amount of carbon sequestered in Florida's forests and forest products. This includes innovation and adoption of biotechnologies in forestry, silvicultural operations, and technologies in bioenergy and forest products.

Opportunities for greenhouse gas reduction through biofuels in Florida

Alan Hodges

Energy use is an essential economic activity in industrialized societies. Burning of fossil fuels for energy emits greenhouse gases. Internationally, per capita rates of primary energy use are strongly associated with economic development. The U.S. has the highest level of energy use in the world, contributing to the high standard of living and quality of life, with unprecedented mobility in private vehicles, and highly reliable electric power. Annual energy use in the U.S. is currently about 100 quadrillion British Thermal Units (BTU), or about 350 million BTU per person, and total energy expenditures are about 7% of gross domestic product (GDP). Although energy use per dollar of GDP has declined steadily since 1970, in inflation-adjusted terms, further efficiency improvements and conservation are still needed to reduce reliance on costly dwindling supplies of fossil fuels from politically unstable regions, and to reduce impacts on the environment, including emissions of pollutants and greenhouse gases contributing to global climate change.

Use of biofuels such as ethanol, biodiesel, biogas, wood and various waste materials, has frequently been suggested as an important option for reducing greenhouse gas (GHG) emissions by replacing fossil fuels such as coal, petroleum and natural gas (e.g., U.S. EPA 2006). Renewable energy sources, including biomass, wind, geothermal and hydropower, have grown rapidly in recent years, but collectively still represent only about 6% of U.S. energy consumption. Wood and waste materials together represent the largest segment of non-hydro renewable energy, and use of biomass for energy has nearly tripled in the past 15 years.

As with any fuel, combustion of biofuels directly releases CO_2, however, this is offset by carbon uptake during the growth of the plant. Biofuels are derived from biomass accumulated in living plants through photosynthesis. The net carbon emissions for biofuels over the entire lifecycle of production and use may include substantial fossil fuel energy required for harvesting, processing, transportation and distribution, and also energy embodied in equipment and infrastructure. Therefore, it is important to consider these indirect effects of biofuels for a successful long term public policy regarding GHG management. The purpose of this paper is to provide an assessment of the potential for GHG reduction or offsets by biofuel production in the forestry and agriculture sector in Florida.

Energy, forestry, and agriculture in Florida

Florida is the fourth largest state in the U.S., with a population of over 18 million, and a gross state product of over $670 billion. It is also among the most rapidly growing regions of the country, with the population projected to nearly double by the year 2050. Total energy consumption in Florida in 2003 was 4,288 trillion BTU in equivalent heat energy units, with the largest share for transportation (33%), followed closely by residential (30%), commercial (24%), and industrial (13%). The most important fuels used for energy production were petroleum (45%), followed by coal (17%), natural gas (17%), nuclear (7%), and biomass wood and waste materials (4%), together with imported electric power (8%) (U.S. DOE/EIA State Energy Data 2003). Energy-related GHG emissions in Florida were estimated at 239 million tonnes CO_2eq, or 4.2% of the total for the U.S. in 2001 (U.S. DOE/EIA 2004).

The state of Florida has a large forestry and agricultural sector, with direct sales of forestry and agricultural products and services around $57 billion, and total output impacts of food and fiber products, allied manufacturing, inputs and services approaching $100 billion annually (Hodges et al. 2006). Total area for agricultural crop and pastureland in Florida was about 8.4 million acres (3.4 million ha) in 2002 (USDA/ERS), and the area of forestland was estimated at 16.2 million acres in 2003 (6.6 million ha) (Carter and Jokela 2003). In general, abundant rainfall and water resources, and year-round growing conditions for crops are favorable for biomass production in Florida, but poor soils may limit yields and require high inputs of fertilizers.

Biomass has a number of characteristics that affect its competitiveness with fossil fuels. The biomass resource is generally dispersed across the landscape, so it must be collected and concentrated into a useful form. Its high bulk and relatively low energy density means that it is not economically feasible to transport the material for long distances. Biomass is variable in composition and energy value across different species or provenances. Air-dried biomass is typically 20–30% moisture, which affects the yield of useful energy from combustion because of the latent heat of vaporization. The energy content of wood ranges from 6 to 9 thousand BTU per pound (dry weight basis), which is lower than coal (10,250 BTU lb^{-1}). Another drawback is that biomass may be available only seasonally, due to weather conditions, slope or site factors that affect access to the resource. An advantage of waste biomass is its low or even negative cost, i.e., there is a demand for disposal, and prices for wood and waste fuels have remained very stable over time. Biomass combustion has low emissions of pollutants such as NO_x, SO_2, Hg, and, of course, net GHG emissions of the fuel itself are zero.

Ethanol and biodiesel

Ethanol is currently the most important biofuel in the U.S. for use in transportation motor fuels, usually blended with gasoline at rates of 10–85%. Ethanol serves as a replacement for gasoline, and as an oxidant additive that reduces pre-ignition, improves combustion efficiency, and reduces emissions of nitrogen oxide pollutants. Ethanol is produced by conventional fermentation technology from materials containing starches or simple sugars. Corn (maize) is the principal feedstock used for ethanol production in the U.S., which now exceeds 6 billion gallons (22.7 billion liters) annually, or about 4.3% of total gasoline use. Ethanol production has grown rapidly in response to a variety of generous federal government incentives and subsidies for corn production, and a tax credit of $.51 per gallon for blending with gasoline, as well as strong market demand in the face of high gasoline prices. The extensive use of corn for ethanol production in the U.S., now accounting for about 14% of total corn production, has lead to increased food prices and structural adjustments in the agricultural sector. Many other potential feedstock materials and conversion technologies are being investigated for ethanol production.

Biodiesel is another important biofuel that is growing rapidly in the U.S. and Europe. Biodiesel is made by transesterification to make methyl esters of vegetable oil from oilseed crops such as soy, peanut, sunflower, and canola (rapeseed), or from recycled cooking oil from restaurants. Production of biodiesel in the U.S. is growing rapidly, reaching 75 million gallons (284 million liters) in 2005 and was expected to further double or triple in 2006 (National Biodiesel Board). Soy oil extracted from about 1.5% of the U.S. soybean crop is used for biodiesel. Biodiesel fuel use is greater in Europe, where diesel automobiles are more popular.

In Florida, there is currently no fuel ethanol production, although several plants are under development with public support (FL DEP). Biodiesel is being produced in relatively small quantities from waste cooking oil in Florida. A difficulty for use of liquid biofuels in Florida is the lack of transportation and distribution infrastructure. As of 2006, there were only 12 filling stations that sold ethanol or other alternative fuels (U.S. DOE/EIA State Energy Profile for Florida). The state had over 17,000 alternative fueled vehicles in use in 2003, but most of these were equipped for using liquefied petroleum or compressed natural gas fuels. Shipping of ethanol to Florida from plants in the Midwest is costly because it must be transported by truck, rail tank car or barge, since the ethanol is corrosive to pipelines.

A variety of alternative sugar-bearing feedstocks have been considered for conventional ethanol production in Florida, including sugarcane, sorghum, and citrus by-products (Rahmani and Hodges 2006). Brazil has demonstrated that sugarcane can be a successful biofuel crop. Sugarcane is cultivated in South Florida on about 400,000 acres (161,875 ha), primarily in the Everglades Agricultural Area, with dry matter yields exceeding 25 tonnes acre^{-1}, and sucrose content of 11%. Ethanol yields of 595 gallons acre^{-1} (5,565 l ha^{-1}) could potentially produce up to 238 million gallons (901 million liters) annually (Table 6). The cost of ethanol produced from sugarcane in Florida is estimated at $2.25 gallon^{-1} ($0.59 l^{-1}), including growing, harvesting, and processing. This cost is not competitive with ethanol produced from corn. Moreover, under current U.S. sugar price supports and import tariffs, which maintain domestic sugar prices above $.20 per pound, it is not economically attractive for producers to utilize sugarcane for ethanol (Shapouri et al. 2006).

Sweet sorghum is grown on about 100,000 acres (28,328 ha) in Florida, and has a po-

Table 6. Potential fuel ethanol production from Florida crops

Resource/Crop	Total Area (acres)	Ethanol Yield (gal acre^{-1})	Potential Ethanol Production (million gal yr^{-1})	Median Unit Cost ($ gal^{-1})
Sugarcane	400,000	595	238.0	2.25
Corn	70,000	405	28.4	1.82
Sweet Sorghum	100,000	302	30.2	3.00
Citrus Molasses	na	–	1.8	2.50

Source: Rahmani and Hodges 2006

tential ethanol yield of 302 gallons acre^{-1} (2,825 l ha^{-1}), or 30 million gallons (114 million liters) annually, at a cost of about \$3.00 gallon^{-1} (\$.79 l^{-1}). The citrus industry is one of the largest sectors of agriculture in Florida, with over 750,000 acres (303,521 ha) of groves managed. About 90% of the orange crop is processed for juice, producing over 5 million tonnes annually of by-products such as peels, seeds, and molasses, which are high in fermentable sugars. All of these byproducts currently have existing uses in well-established markets for animal feed, essential oils, and beverage grade ethanol. However, if demand warranted, 40,000 tonnes of citrus molasses could be used to produce about 1.8 million gallons (7 million liters) of fuel grade ethanol, at a cost of \$2.50 gallon^{-1} (\$.66 l^{-1}). Corn is not a major commodity in Florida, but is currently grown on about 70,000 acres (28,328 ha), and could potentially be utilized to produce up to 28 million gallons (107 million liters) of ethanol annually (Table 6). To put this in perspective, Floridians consumed 8.6 billion gallons of gasoline in 2006 (FL DEP).

Cellulosic ethanol

There is a consensus that sustainable production of ethanol in the long run will have to utilize cellulosic materials such as wood and various waste products, rather than food crops which have well-developed markets for competing uses. The technology for cellulosic ethanol production has been the focus of intense research for nearly 20 years by the U.S. DOE National Renewable Energy Laboratory and several universities. The first pilot scale plants for cellulosic ethanol (1 million gallons yr^{-1}) are now under development by several companies. There is a great deal of uncertainty about when cellulosic ethanol will become commercialized at full scale. The consensus is that production in significant volumes will not occur until after 2015. The problems with the cellulosic ethanol process are both technical and economic. Cellulose is an extremely tough material, reinforced by lignin, which is difficult to break down into simple sugars and other constituents. The principal processes for accomplishing this are enzymatic, chemical (dilute acid hydrolysis), and thermal. The enzymatic process is currently uneconomic because of the high cost of enzymes, which are produced by microbiological cultures. Another difficulty is that most of the sugars derived from cellulose are pentoses (5-carbon), which are generally not suitable for conventional fermentation by yeasts (*sachromyces* sp.). In any case, eventual production of fuel ethanol from cellulosic feedstocks will likely be determined by technical factors, rather than by resource availability.

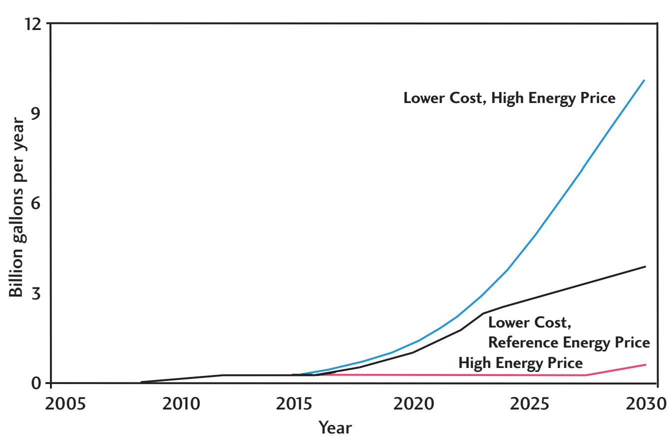


Figure 9. Projected production of ethanol from cellulosic materials in the U.S., 2005–2030 *(U.S. DOE/AEO 2007)*

According to forecasts by U.S. DOE, under the baseline scenario of lower cost and reference energy prices, cellulosic ethanol production in the U.S. would reach about 4 billion gallons, roughly equivalent to current ethanol production from corn, by 2030 (Figure 9) (U.S. DOE/EIA, AEO 2007). Under most favorable scenario of low cost of production and high energy prices, cellulosic ethanol production would reach about 10 billion gallons by the year 2030. U.S. consumption of gasoline in 2006 was over 140 billion gallons (U.S. DOE/EIA).

Lifecycle analysis of biofuels

A number of studies have examined the lifecycle costs, energy balance, and emissions for ethanol and biodiesel production and use, exclusive of emissions associated with land use conversion. In a recent paper, Hill et al. (2006) evaluated the economic and energetic costs for growing corn or soybeans. The analysis considered inputs such as fertilizers, chemicals and farm machinery, as well as the conversion to biofuel, transportation and distribution, coproducts used for animal feed (corn distillers dried grains and solubles [DDGS], soy meal), farm emissions of CO_2 and N_2O, mitigation of CH_4 emissions, and the energy equivalent value of biofuels. It was found that soy biodiesel had a net energy balance of 93% (i.e., an energy output/input ratio of 1.93:1), and reduced greenhouse gas emissions by 41% compared to petroleum diesel. By comparison, the benefits of ethanol from corn were rather modest, with a net energy yield of 25% and reduction in greenhouse gas emissions of only 12% versus reformulated gasoline. The authors point out that even if all the corn produced in the U.S. were used for ethanol, it would meet only 12% of total gasoline motor fuel demand, so clearly this can be only a partial or transitional strategy.

Lifecycle emissions of GHG for several types of biofuels were compared to gasoline using a lifecycle analysis model known as Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) (Wang 2005). The model considers both direct and indirect inputs for biofuel and fossil fuel production and distribution, a so-called "wells to pump" analysis. It was found that the largest emission reductions of about 85% were obtained from cellulosic ethanol, while much smaller emission reductions were provided by corn-ethanol (18 to 29%), depending upon the type of vehicle and fuel mix. In a review and meta-analysis of numerous published studies, Farrell et al. (2006) estimated a most likely reduction of 13% in GHG emissions from corn-ethanol compared to gasoline; however, there was a very wide range in values, from a 20% increase to a 32% decrease, depending upon the definitions of system boundaries, input parameters, and assumptions about coproduct credits, without including impacts from land use change. Cellulosic ethanol would have substantially better environmental performance than conventional corn-ethanol, with total GHG emissions of 11 g MJ^{-1} compared to 83 g MJ^{-1}, due to the lower fossil fuel inputs required.

Delucchi (2006) evaluated total lifecycle GHG emissions for several types of biofuels produced from various feedstocks compared to conventional gasoline and diesel fuels. The study used cumulative emission factors (CEF), rather than the global warming potential (GWP) advocated by IPCC, to express the CO_2 equivalence of all greenhouse gases. This system uses somewhat different weightings for various gases, particularly fluorocarbons, and accounts for some additional gases and particulates. For light duty vehicles, the greatest CO_2 equivalent emissions reductions were found for natural gas (synthesis gas) produced from wood (68%), followed by methanol (M85) produced from wood (49%), ethanol (E90) produced from grass (44%), and ethanol from corn (2%). For heavy-duty vehicles such as trucks, methanol and ethanol had similar results, and biodiesel from soybeans provided a 50% reduction in GHG compared to petroleum diesel. Somewhat larger emissions reductions were shown for the fuel cycle portion of the lifecycle, as high as 82% for synthesis gas. It was projected that greater emissions reductions would be obtained in the future, due to technological improvements, with total lifecycle emissions reductions for ethanol from grass increasing from 44% in 2010 to 71% in 2040, and soy-biodiesel emissions reductions increasing from 49% to 87%, respectively.

Brazil has become a world leader in fuel ethanol produced from sugarcane, with current production rivaling that in the U.S., as a result of a longstanding policy promoting renewable fuels and energy independence (raw sugar in Florida at left). Since sugarcane is a major crop in Florida, the Brazilian experience is a useful example of the potential for a sugarcane-ethanol industry in the U.S. The energy balance and GHG emissions of ethanol produced from sugarcane in Brazil have been evaluated for a typical plant producing the both sugar and ethanol (Dias De Oliveira et al. 2005). Ethanol yields from sugarcane are significantly higher than for corn (5,565 vs. 3,788 l ha^{-1}), and while energy inputs for cultivation of this demanding crop are also higher (36 vs. 20 GJ ha^{-1}), the net energy requirements for sugarcane processing are much lower than corn (3.6 vs. 41.6 GJ l^{-1}) due to the use of crushed cane (bagasse) as fuel for process heat and electric power co-generation. The net energy balance of sugarcane-ethanol was estimated at 3.7, or more than three times that for corn-ethanol. Total CO_2 equivalent emissions from sugarcane-ethanol were estimated at 3.12 Mg ha^{-1}, or 0.46 to 0.57 kg per liter of ethanol. For corn-ethanol, the comparable CO_2 emissions ranged from 1.39 to 1.46 kg l^{-1}. An analysis of the ecological "carbon footprint" for sugarcane-ethanol indicated that about 0.63 ha would be required for sugarcane production and CO_2 assimilation of the emissions from a typical automobile for one year. An important environmental constraint for sugarcane-ethanol is the large volumes of water required for cane washing, which creates a high biochemical-oxygen-demand (BOD) wastewater for disposal. In Brazil, the wastewater is generally applied to sugarcane fields, and has some benefit for irrigation and fertilization, but this may not be possible in the more sensitive environment in Florida, especially in the Everglades Agricultural Area of South Florida. Treatment of wastewater would substantially decrease the net energy balance and increase the net CO_2 emissions.

Recent reports have asserted that diversion of food crops for biofuel production has significantly reduced global supplies and increased prices for food commodities, leading to expansion of cultivated area on marginal land, burning and clearing of native forest and grassland habitats (Fargione et al. 2008; Searchinger et al. 2008). It is shown that land use change to crop cultivation results in a very large release of carbon stored in vegetation and soils, termed the "carbon debt", which nullifies the carbon offset benefits of biofuel substitution for fossil fuels for many years. Due to the rather inelastic demand for food and feed grains, it is estimated that the U.S. policy supporting a dramatic increase in ethanol production will potentially divert corn from 12.8 million hectares, leading to an increased cultivated land area of 10.8 million hectares in Brazil, China and India (Searchinger et al. 2008). Thus, biofuel production from food crops may have significant leakage effects. In Florida, this would also apply to sugarcane diverted to ethanol production, although the demand for sugar is somewhat more elastic, since there are more substitutes for sweeteners. Production of switchgrass or other cellulosic biofuel crops would not have such leakage effects, particularly if occurring on abandoned farmlands (CRP lands) with little carbon storage.

Biogas

Biogas is a biofuel consisting of methane and other non-combustible gases (CO, H_2S) that are produced by anaerobic fermentation of livestock manure, municipal wastewater sludge (biosolids), landfill wastes, and other organic liquid or slurry wastes. Biogas may substitute for petroleum natural gas in domestic heating, industrial heat and power, or as a compressed gas for transportation fuel. An important drawback of biogas is its relatively low energy density, with heating value about 70% of natural gas, due to a lower content of CH_4. Also, biogas may contain substantial amounts of corrosive sulfur compounds that require cleanup with expensive scrubbers before it can enter gas distribution networks or be used in internal combustion engines. Biogas production requires the construction of large containment vessels (digesters) and means for gas collection and storage. Biogas is largely an undeveloped resource in the U.S., but it has been extensively exploited in China, India, and other developing countries through small-scale village and on-farm systems. An exception is the capture of gas from closed landfills, where the cost of the containment system is incorporated in the sunk costs for the landfill. Biogas is commonly used from landfills for "green power" programs by electric utilities.

The logic for capture and use of biogas is very compelling from the standpoint of GHG reduction, since CH_4 has over 20 times greater global warming potential than CO_2. There is a strong economic opportunity for biogas to replace natural gas, because of its recent rapid increase in prices in the face of growing demand and limited domestic supplies. Natural gas is now the preferred fuel for industrial heating systems and electric power generation, because of its clean-burning characteristics and flexibility for peaking power gas turbine systems. Unlike petroleum, natural gas is primarily tapped from domestic sources because it is expensive and difficult to transport overseas in liquefied natural gas (LNG) tankers. Methane captured from renewable sources and beneficially used would offset an equivalent amount of natural gas.

The total methane resources in Florida were estimated at 502,000 tonnes yr^{-1}, including 457,000 tonnes from landfills, 19,000 tonnes from livestock manure management, and 26,000 tonnes from domestic wastewater treatment systems (Milbrandt 2005). The estimated production of biogas from improved management of livestock wastes was based on inventories of dairy and beef cattle reported in the Census of Agriculture (USDA/NASS). Biogas was not included, however, in the estimated total GHG mitigation potential for biofuels, since livestock wastes were evaluated in the report by Wilke, and landfill and wastewater systems are not part of the agricultural and forestry sector.

Biomass combustion/gasification for electric power generation and heating systems

One of the most promising opportunities for greenhouse gas reduction in the forestry and agriculture sectors is the production of energy crops, woody biomass, and various byproducts/waste materials for direct combustion or gasification to replace coal, natural gas and oil currently being used for heat and power generation. There are large resources of unutilized wood waste byproducts available currently, as well as roundwood and thinnings produced from forest plantations, and high yield dedicated energy crops such as poplars *(Populus)*, willows *(Salix)*, and *Eucalyptus* have been developed. Wood product mill residues such as bark, sawdust, chips and trimmings are extensively used in the forest products industry to meet internal needs for process heat energy and electric power.

Electric power generation is the single largest source contributing to GHG emissions in the U.S. Electric power plants accounted for 47% of all energy consumed in Florida. CO_2 emissions from electric power generation in Florida were 130 million tonnes in 2005, representing 5.2% of the total for the U.S., including 60 million tons from coal, 35 million tonnes from natural gas, 32 million tonnes from petroleum, and 2 million tonnes from combustion of municipal solid waste (USDOE/EIA, 767/906). Carbon dioxide emissions by electric generators in the Florida Reliability Council region, which includes most of the state except the western panhandle, are projected to increase to 199 million tonnes in 2030, an increase of 1.8% annually (USDOE/EIA, AEO 2007).

In 2005, Florida had a peak summer electric power capacity of 53,220 megawatts. The state's per capita electricity consumption is among the highest in the U.S. because the long, hot summers pose a high demand for air conditioning (USDOE/EIA State Energy Profile for Florida). Electric power usage has also increased significantly because of the growing importance of electricity in the information economy. In the Florida Electric Power Reliability Coordinating Council, electric generating capacity is forecast to grow to 78 gigawatts in 2030, an increase of nearly 40% above current levels, and total electricity generation is expected to increase to 349 billion kilowatt-hours (BkWhr), representing average annual growth of 2.0%. (USDOE/EIA, AEO 2007). Generation from renewable sources is projected to increase to 1.55 BkWhr, with 86% from wood, other biomass, municipal solid waste and landfill gas. Electric generation from wood and other biomass fuels produced by the forestry and agricultural sectors would increase by 56% between 2005 and 2030 under baseline projections. Because of concerns about GHG emissions and global climate change, nuclear power is now having a renaissance, with a number of new units under development in Florida although there remain concerns about safety and long-term radioactive waste disposal.

Biomass-fired electric power generation currently exists at about 1000 locations in the U.S. where there is a favorable combination of biomass resources and energy demand, mainly in New England, California, and throughout the southeast and north central regions. About two-thirds of this generating capacity is in the forest products industry, using byproducts or waste materials. Many facilities are integrated with industrial operations for combined heat and power, simultaneously generating electricity and using the waste heat for industrial processes. There are about 10 electric utility power plants that currently co-fire biomass together with coal at rates up to 15% of the fuel mix. However, a limitation of biomass fuels is the typically higher mineral content, which results in a greater volume of residual ash for disposal, and may cause problems with slagging in co-combustion applications.

A preferred technology for biomass-fueled electric power generation is the integrated gasification combined cycle system (IGCC). A virtue of this system is a two-fold greater thermal-electric conversion efficiency by utilizing part of the waste heat from combustion (e.g., 40% vs. 20%). A gas combustion turbine powers the primary electric generator, and a turbine powers a secondary generator with steam generated from the waste heat. Conventional combustion turbines have the lowest cost at about $300 dollars per kilowatt capacity, while biomass IGCC systems are about $1,500 per kW, and coal IGCC systems are around $1,250 kW^{-1}. The cost of flue gas desulfurization at coal plants is about $124 kW^{-1} capital cost, and $.0096 kWh^{-1} in operating and maintenance costs. Biomass is lower in capital costs than nuclear, fuel cells, solar thermal and photovoltaic systems (U.S. DOE/EIA, AEO 2006).

Projections of energy supply and use in the U.S. are provided by the U.S. Department of Energy National Energy Modeling System, a comprehensive technical-economic model that accounts for global macroeconomic conditions, technological change and penetration in various end-user markets (DOE/EIA 2006). Under the reference case scenario, which is considered the most likely, electric power from biomass electric capacity is projected to increase from about 7 gigawatts (GW) currently to 10 GW in 2020. Most of the increase is expected from combined heat and power. Under the "high renewables" scenario, which assumes a variety of legislative incentives, technical advances and favorable markets, biomass electric power would be marginally higher. Under the most optimistic scenarios that consider the possibility of legislation that would require 20% of renewable sources in electric utilities generation assets, the so-called "renewable portfolio standard" (RPS), biomass-fueled electric generation would rise nearly ten-fold, to around 70 GW by the year 2020 (Figure 10).

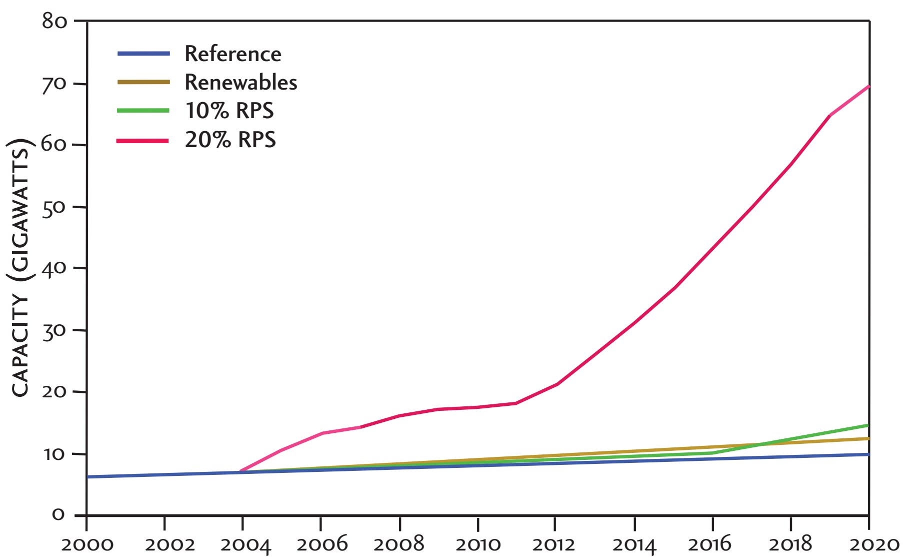


Figure 10. Power production from dedicated dry biomass co-firing as determined under different RPS scenarios. Includes electricity generation and industrial co-generation. *(U.S. DOE/EIA 2006 AE021002)*

Estimates of potential biomass resources have been developed for each state and county in the U.S. by the National Renewable Energy Laboratory and University-based researchers, using information on soil types and crop productivity, together with average harvest/collection and transportation costs (Walsh et al. 2000). Quantities of agricultural and forestry residues, perennial energy crops (switchgrass, hybrid poplar, willow), mill wood wastes and urban landscape debris were estimated across a range of delivered price levels. At the highest price level of $50 dry tonne^{-1}, a total of 9.5 million metric tons (MMT) would be available in Florida, including 4.60 MMT of urban wood wastes, 2.68 MMT of mill wastes, 1.27 MMT of switchgrass grown on Conservation Reserve Program (CRP) lands, and nearly 1 MMT of forest and crop residues. This assumes that existing USDA rules regarding harvesting of forage crops on CRP lands would be relaxed. At the lowest price level of $20 tonne^{-1}, 2.76 MMT of mainly urban wastes would be available, and at the intermediate price levels the supply would be 6.52 to 6.78 MMT.

Further development of biomass power will require fine-scaled evaluation of resource availability at a local level. As part of a USDA-Forest Service funded project, a research team in Florida has conducted a screening of socioeconomic and resource data in 13 states of the southern U.S. to identify counties that have a high suitability for wood energy development based on available forest and urban wood waste biomass, population density and growth, personal income and income growth, and the existence of power generation facilities. Five counties in Florida (Clay, Nassau, Alachua, Leon, Santa Rosa) were identified as highly suitable, and detailed assessments of woody biomass supply were conducted using geographic information systems (GIS) to analyze collection and transportation costs for logging debris, forest thinnings, and urban wood waste. A supply curve for Florida shows the quantity of a wood biomass that could be supplied to central plants over a range of prices (Figure 11). These results indicate that at a price of \$50 tonne^{-1} there would be about 5.5 million dry tonnes of biomass available.

The total quantity of woody biomass resources in Florida was estimated from forest inventories and surveys of forest product manufacturers conducted by the U.S. Forest Service (USDA-FIA). The estimates include non-merchantable logging residues, stumps, forest thinnings, urban wood, and annual removals of pulpwood (Table 7). The delivered cost for each resource represents the average costs determined in the case studies noted above, and ranged from \$23 tonne^{-1} for urban wood, reflecting the fact that this resource has a low opportunity cost, to \$54 tonne^{-1} for pulpwood, reflecting the market value for this resource. The total quantity was estimated at over 8 million metric tons annually. Based on typical unit energy values (14.92–16.15 million BTUs tonne^{-1}), the total annual energy potential of this resource would

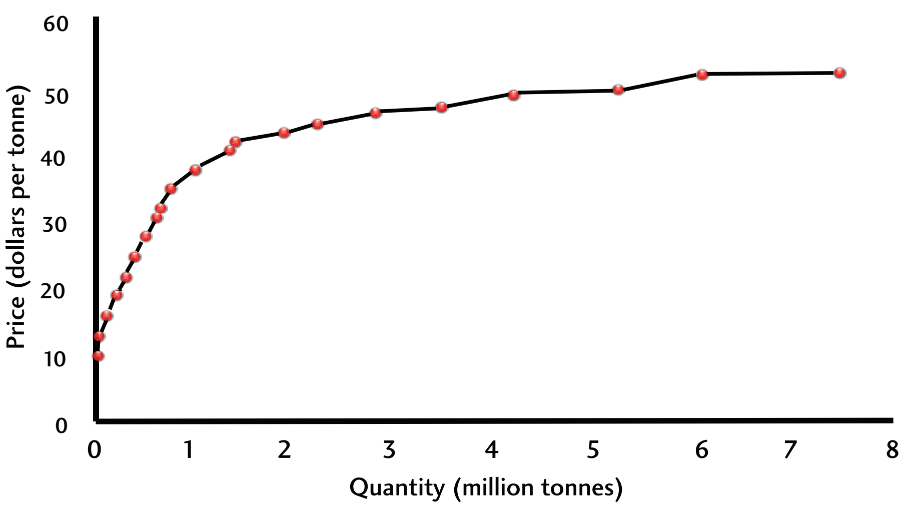


Figure 11. Supply curve for woody biomass logging residues, forest thinnings, pulpwood and urban wood in Florida.

Table 7. Florida Woody Biomass Resource Quantity, Price and Energy Value.

Resource	Annual Quantity (1000 Mg tons)*	Average Delivered * Cost (\$ Mg^{-1})	Unit Energy Value (million BTU Mg^{-1})*	Total Energy Value (trillion BTU)*
Logging residues	1,522	45.69	15.58	23.7
Stumps	555	43.77	14.92	8.3
Forest thinnings	157	43.77	14.92	2.4
Pulpwood	4,105	54.29	16.15	66.3
Urban wood	1,877	23.18	14.92	28.0
Total	**8,217**			**128.7**

**dryweight basis.*

Source: USDA-Forest Service, Forest Inventory and Analysis, Timber Product Output, compiled by Matt Langholtz, University of Florida (2006).

exceed 128 trillion BTUs (135.8 Pj). These results are broadly comparable to those from Walsh et al. (2000).

There also exists a large volume of wood product mill residues such as bark, sawdust, and chips, about 2.5 million dry tons annually, however, nearly all of this is already used in the forest products industry for by-products or fuel for heat and power generation (USDA-FS, TPO).

Total biofuel potential and carbon offsets

The estimated total potential carbon offsets by biofuels in Florida are summarized in Table 8, based on the resources discussed previously, including logging residues, forest thinnings, urban tree debris and pulpwood (USDA-FS), crop residues (Milbrant 2005), energy crops (Walsh et al. 1999), and ethanol (Rahmani and Hodges 2006). The woody biomass, energy crops and crop residues were assumed to replace a mix of coal, oil and natural gas for electric power generation, while ethanol substitutes for gasoline motor fuel, and methane replaces natural gas. The share of each resource that could reasonably be expected to be captured or utilized, based on technical and economic constraints, ranged from a low of 30% for pulpwood, which has existing markets for other non-fuel uses, to 90% for urban tree debris, which has a negative cost for disposal. The net additional biofuel value or additionality of carbon offsets represents the difference between total potential utilization and the current utilization. For example, mill residues are already utilized at a high level (70%). With all resources converted to common heat energy values, the total energy value of biofuels was estimated at nearly 98 Pj. This energy would represent a displacement of 7.4 million tonnes CO_2eq of fossil fuel emissions, representing a possible market value of $29.4 million at $4 Mg^{-1} CO_2eq. Crop residues, logging residues and forest thinnings, urban tree debris and pulpwood each could contribute to CO_2eq displacement in excess of 1 million metric tons, while captured methane, energy crops and ethanol would each amount to less than one million tons. These estimates do not account for the fossil fuel greenhouse gas emissions associated with biofuel production, processing and transport. Pulpwood, forest thinnings, logging debris and urban waste wood would have

Table 8. Summary of near-term potential annual energy value and carbon offsets by biofuels in Florida

Resource/Material	Total Potential Annual Yield (Units)	Share of Resource Currently Utilized	Share of Resource Potentially Utilized	Net Additional Biofuel Utilized (units)	Total Heat Energy (Pj)	Fossil Fuel CO_2eq. Displaced (Gg)
Crop Residues	3,263 Gg	5%	50%	1,468	23.2	1,762
Logging Residues and Thinnings	1,679 Gg	5%	75%	1,175	19.3	1,465
Urban Tree Debris	1,877 Gg	10%	90%	1,502	23.6	1,793
Pulpwood (Timberland)	4,105 Gg	10%	30%	821	14.0	1,061
Energy crops (switchgrass on CRP lands)	1,268 Gg	0%	50%	634	10.0	761
Ethanol (Sugarcane, Sorghum, Corn, Citrus By-Product)	1,130 ML	1%	30%	328	7.7	516
Total					**97.9**	**7,360**

very small lifecycle emissions while crop residues and dedicated energy crops may have somewhat higher emissions due to additional fertilization requirements. Overall, the lifecycle greenhouse gas emissions for biofuels would reduce the net emissions displacement by perhaps 10%.

Conclusions

- Energy demand in Florida will continue to grow rapidly, more than doubling by the year 2030, with greenhouse gas emissions increasing accordingly, unless aggressive measures are taken to substitute biofuels for fossil fuels, and to promote energy conservation. Electric power generation is the largest use of energy in Florida, and per capita electric power consumption is among the highest in the nation.
- Substantial volumes of fuel ethanol could be produced from sugarcane in Florida, following the successful example of the Brazilian sugar industry; however, this is currently not economically attractive under U.S. sugar policy, which supports high domestic sugar prices. Lifecycle analyses indicate that the net energy balance and greenhouse gas reduction for ethanol from sugarcane is much better than for corn, especially for milling operations integrated with cogeneration plants that utilize the fiber portion of sugarcane for process heat and surplus electric power generation.
- The potential for ethanol production from corn, sorghum and citrus byproducts is very small since these commodities are not produced in large volume in Florida or already have competing uses. Biodiesel fuel production from oilseed crops such as soybeans has a better net energy balance and greenhouse gas reduction than ethanol, but has very limited potential in Florida.
- Development of technology for ethanol production from low cost and abundant cellulosic feedstocks has enormous potential; although serious technical and economic barriers make the outlook for this technology very uncertain, and the consensus forecast is that widespread commercialization is at least 10 years away.
- Use of biogas captured from landfills, wastewater treatment plants, and livestock wastes for on-farm energy needs are compelling because of the high global warming potential of methane.
- Inventories of forest biomass residues, byproducts and waste materials indicate that Florida may have an additional unutilized supply in excess of 5 million dry tons annually. In many cases, delivered costs of woody biomass for electric power generation, at \$23 to \$54 per metric tonne or \$1.55 to \$3.36 per million BTUs, are competitive with coal and natural gas in Florida Expansion of biomass power systems will depend upon local resources and economic conditions, government incentives, and environmental compliance costs.

Total potential annual greenhouse gas emission reductions from fossil fuel displaced in the near term by biofuels in Florida are estimated at 7.4 million tonnes of CO_2 equivalent, representing a possible market value of \$29.4 million at \$4 Mg^{-1} CO_2eq. This estimate does not consider leakage and lifecycle emissions associated with production of biofuels, but these are expected to be relatively small, amounted to only about 10 percent of the carbon displaced

Opportunities for reducing greenhouse gas emissions through livestock waste management in Florida

Ann C. Wilkie

Management of livestock wastes can affect greenhouse gas emissions through attenuating both methane and nitrous oxide emissions, as well as by displacing carbon dioxide emissions from fossil fuel use that can be avoided through biogas production and use. Methane is naturally produced from the anaerobic decomposition of livestock manure and is a potent greenhouse gas with 21 times the greenhouse warming potential of CO_2, on a mass ratio basis (U.S. EPA 2007). Nitrous oxide is naturally produced as a result of the nitrogen cycle where organic nitrogen in manure and urine undergoes nitrification and denitrification. Nitrous oxide is an even more potent greenhouse gas, with a greenhouse warming potential 310 times that of CO_2 on a mass ratio basis (U.S. EPA 2007). Unfortunately, estimates for N_2O emissions are uncertain and methods to reduce these emissions are not well developed. In contrast, methods for reducing CH_4 emissions have received more attention. Anaerobic digestion in a closed vessel allows microbial degradation of manure to biogas containing CH_4. Biogas can be used as a renewable fuel to displace fossil fuel consumption, which not only lessens CH_4 emissions from manure management but also lowers fossil CO_2 emissions.

Methane emissions from livestock include enteric emissions and manure management emissions (IPCC 1996). Enteric emissions of CH_4 occur principally from the ruminant activity in cows (dairy and beef) and are a function of feed quality and intake. Other than reducing cow numbers, there is little opportunity to reduce enteric CH_4 emissions. In contrast, CH_4 emissions from livestock manure management are impacted by chosen management options. EPA (2007) estimates that manure management contributed 41.3 Tg of CO_2eq from CH_4 emissions and 9.5 Tg of CO_2eq from N_2O emissions to the U.S. greenhouse gas emissions inventory in 2005. Liquid handling of manure and long-term manure storage increase CH_4 emissions. Dry handling systems, dry storage, and short-term storage lower CH_4 emissions. Anaerobic digestion of manure with biogas capture can result in lower CH_4 emissions, yet some leakage of biogas (estimated to average 1%) prevents complete elimination of CH_4 emissions from livestock manure management.

IPCC (1996) has developed methods for estimating greenhouse gas emissions from livestock manure management that account for climate, animal type, regional development, and management practices. Generally, the number of animals, the average manure volatile solids (VS) production, and the maximum methane yield (Bo) of the VS are combined with an emission factor to estimate methane emissions. Emission factors have been developed based on both scientific studies and measurements, as well as through model development and calculations. The emission factors vary with region, climate, animal type, and manure handling, thus adding a level of uncertainty to greenhouse gas emissions estimates. For cattle, IPCC (1996) has developed both Tier 1 methods (simple) and Tier 2 methods (more complicated) for estimating emissions.

Emissions from Florida manure management

Livestock production in Florida includes both confined animal operations and pastured animals. The increase in production and concentration of intensive livestock operations along with increased urbanization of rural regions has resulted in greater awareness and concern for the proper storage, treatment, and utilization of livestock manure. Pastured animals offer limited opportunity for managing livestock manure to lessen greenhouse gas emissions. The principal opportunities for altering manure management, therefore, occur in dairy and poultry operations with confined livestock.

Most dairies in Florida use hydraulic flushing for manure collection and short-term storage in manure pits, followed by frequent land-application of liquids onto croplands. The temperate weather conditions and long growing season eliminate the need for long-term manure storage caused by frozen ground or lack of a standing crop. For temperate regions with liquid manure handling and short-term storage, IPCC (1996) suggests a CH_4 emission factor (Tier 1) for dairy cows of 54 kg head^{-1} yr^{-1}.

For poultry in Florida, manure is handled using dry manure management methods. In the broiler industry, sawdust bedding is usually added to the barns and several flocks of broilers may be raised before the manure is removed and stockpiled, at least annually. In poultry layer production, manure is collected under cages in deep pits with annual removal, collected on bedding or scraped from the barn daily. The amount of time that poultry manure is stockpiled prior to application onto croplands is variable. The University of Florida Institute of Food and Agricultural Sciences (Jacob and Mather 2004) estimates that annual litter production from producing 140 million broilers amounts to 1 million tons of used litter (manure and bedding). For temperate regions with dry manure handling and stockpiling, IPCC (1996) suggests a CH_4 emission factor for poultry of 0.117 kg bird^{-1} yr^{-1}.

Table 9 gives the CH_4 emission estimates for confined dairy and poultry production with their CO_2 equivalent global warming potential. It appears that greenhouse emissions from broilers are more than twice that of dairy cows, while the layer population produces about one-sixth of the emissions of dairy operations.

Table 9. Estimated methane emissions from manure management of confined animal populations in Florida

Animal Type	Number of Animals[1]	CH_4 Emission Factors[2] kg animal^{-1} yr^{-1}	CH_4 Emissions Gg yr^{-1}	CO_2 Equivalent Tg CO_2 yr^{-1}
Dairy cows	135,000	54	7.29	0.153
Poultry layers	10,700,000	0.117	1.25	0.026
Poultry broilers	139,800,000	0.117	16.36	0.343
Total			**24.90**	**0.523**

[1] NASS (2005), [2] IPCC (1996).

Biogas potential from confined livestock manure in Florida

The production and use of biogas from livestock manure offers an opportunity for reducing CH_4 emissions from manure management as well as avoiding greenhouse gas emissions from fossil fuels that are displaced through biogas use. When biogas is combusted, like fossil fuels, it produces CO_2. However, the carbon in this CO_2 originated from atmospheric CO_2 that was recently fixed into plant matter. Biogas production and use, therefore, repre-

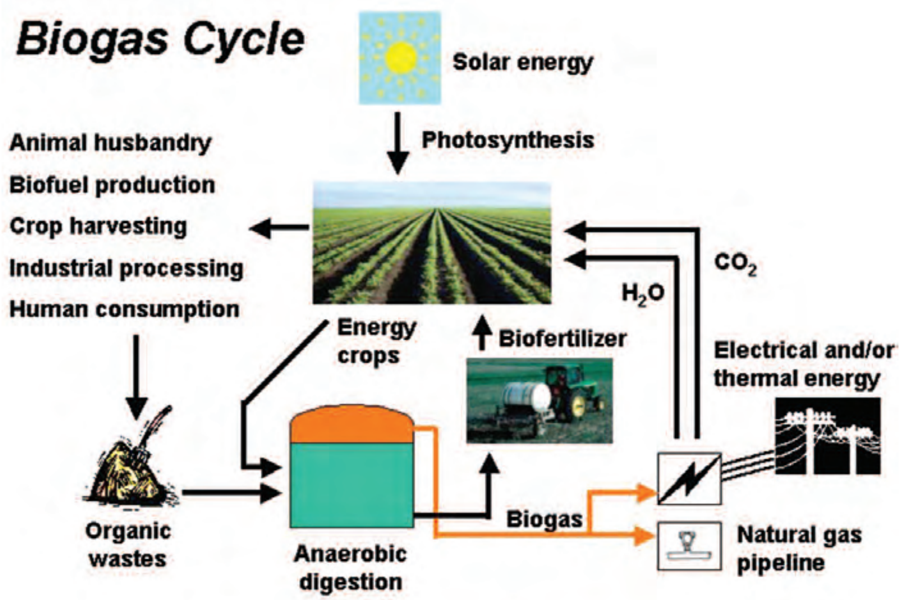


Figure 12. The biogas cycle.

sents a closed renewable carbon cycle that does not contribute to increased greenhouse gas emissions (Figure 12). In effect, anaerobic digestion is a carbon dioxide neutral process. Local biogas production and use also reduces emissions associated with transporting fossil fuels from distant sources.

The production of biogas from animal manure is not a novel application of anaerobic digestion and many successful biogas facilities are in place at swine and dairy operations throughout the U.S. (AgSTAR 2007). Generally, manure collected from animal housing is diluted to a slurry and pumped into an enclosed heated vessel where a mixed culture of anaerobic microorganisms consume the degradable fraction of the manure and convert it to biogas, a mixture consisting principally of CH_4 and CO_2. On average, the manure is retained in the vessel for 15 to 30 days. The biogas is conveyed from the vessel and can be used in place of natural gas. Often, the biogas is used to provide hot water for on-site use and generate electricity for sale, though the methane in biogas can be used for any natural gas application. In addition, the process is effective for conserving plant nutrients, reducing manure odor, and lowering pathogen levels (Wilkie 2005). The effluent from the digester retains soluble plant nutrients and an inert fiber residue, both of which have positive agronomic properties. Digester effluent can be recycled to cropland as nutrient-rich biofertilizer, reducing the demand for synthetic fertilizers that are produced using less sustainable methods with significant CO_2 emissions. Also, digester effluent could be used to grow algae for biodiesel production, providing another renewable fuel for on-farm use to displace fossil fuels and further reduce greenhouse emissions from livestock operations.

The production of biogas from confined animal operations in Florida provides opportunities as well as challenges. First, the use of flush water at Florida dairies greatly exceeds water use in less temperate climates and results in large volumes of dilute wastewater. Most of the applications of anaerobic digestion have been at dairies with dry scraped manure handling where there is controlled addition of dilution water. Conventional digesters are not suitable for very dilute manure wastewaters and the cost of heating the wastewater can exceed the biogas potential in the waste. Fortunately, recent developments in digester technology have extended the application of anaerobic digestion to such dilute wastewaters. An ambient temperature fixed-film digester (Figure 13), designed specifically for Florida conditions, has been demonstrated for treatment of the liquid fraction of flushed dairy manure (Wilkie 2003).

In contrast to dairy manure, manure from confined poultry operations is quite dry and cannot be pumped without significant water addition. Broiler manure contains significant quantities of bedding and application of biogas production using broiler litter has not

been demonstrated at commercial scale. Layer manure conversion to biogas has been demonstrated commercially on a limited basis. The high level of ammonia and the requirements for dilution water offer challenges to poultry manure digestion. In spite of limited full-scale demonstrations, poultry manure has a high biogas potential and merits consideration as a renewable resource for biogas production.

Table 10 gives the estimated methane production potential from anaerobic digestion of dairy and poultry manure in Florida. Table 10 also gives an estimate for the amount of fossil CO_2 that could be avoided if the methane was used to replace natural gas consumption. It is apparent that the amount of fossil CO_2 emissions avoided by production and use of biogas is comparable to the manure management CH_4 emissions (on a CO_2eq basis) and in the case of layers it is actually greater. The conversion of manure to biogas mitigates GHGs by reducing fugitive methane emissions and fossil CO_2 emissions.

Figure 13. Fixed-film anaerobic digester.

Table 10. Estimated methane production potential from biogasification of manure from confined animal populations in Florida and the resulting reduction in fossil CO_2 emissions

Animal Type	Number of Animals[1]	CH_4 Production Factors[2] m^3 $animal^{-1}$ yr^{-1}	CH_4 Production million m^3 yr^{-1}	CO_2 Displaced[3] Tg CO_2 yr^{-1}
Dairy cows	135,000	440	59.40	0.117
Poultry layers	10,700,000	1.48	15.84	0.031
Poultry broilers	139,800,000	1.05	146.79	0.288
Total			**222.03**	**0.436**

[1] NASS (2005). [2] Estimated from ASAE (2005). [3] Assumes biogas displaces natural gas.

Revenue from biogas and carbon credits

On-farm biogas production in Florida has been limited by low energy costs, the cost of capital, the uncertainty of animal production, and lack of public awareness. These factors are rapidly changing and opportunities exist to implement biogas production from manure. Still, the value of fertilizer and soil-amendment by-products are low and cash flow to cover investments must come principally from the sale (or savings) of energy. A further opportunity for income occurs in the sale of carbon credits (AgCert 2007; ECC 2007), where companies purchase greenhouse gas reductions to compensate for their own emissions. The trading of carbon credits is an emerging global market and provides an opportunity to improve the economics of biogas projects. Economies of scale could also be realized with centralized digesters in areas with a large concentration of livestock operations.

Table 11 . Estimated value of carbon credits and methane production from biogasification of confined livestock manure in Florida

Animal Type	Sum of GHG reductions Tg CO2 yr-1	CH_4 Production million m^3 yr^{-1}	Value of Carbon Credits[1] \$ yr^{-1}	Value of CH_4 [2] \$ yr^{-1}
Dairy cows	0.270	59.40	$1,079,074	$16,779,312
Poultry layers	0.057	15.84	$229,585	$4,473,353
Poultry broilers	0.632	146.79	$2,527,304	$41,465,239
Total	0.959	222.03	$3,835,964	$62,717,904

[1] *Based on a value of \$4 Mg^{-1} CO_2eq.* [2] *Based on \$8 per 1000 cft of natural gas (EIA, 2007).*

Table 11 shows the estimated value of carbon credits and methane produced from biogasification of confined livestock manure. The sum of greenhouse gas (GHG) reductions is the sum of the CH_4 emissions from manure management avoided (on a CO_2eq basis) from Table 9 and the displaced CO_2 emissions from biogas use in Table 10. The carbon credit, at a value of \$4 Mg^{-1} CO_2, adds about 5% to the revenue projection of biogas sales (as natural gas). The value of carbon credits is expected to rise and the cost of energy is expected to increase, improving the potential revenue stream for biogas production.

Co-digestion and integrated biorefineries

Combining wastes from animal manure with other regionally available wastes and feedstocks is called co-digestion. Co-digestion offers opportunities for on-farm biogas facilities to increase revenues from tipping fees (fees charged for accepting waste products) as well as from the enhanced production of biogas. Food and yard wastes from surrounding communities and commercial establishments are suitable for co-digestion. Co-digestion can also help improve the waste characteristics by changing the moisture or nutrient content of the waste to beneficial levels.

By-products from ethanol and biodiesel production can also be used in co-digestion (Wilkie 2006). Florida is unlikely to have significant ethanol production from corn, while cellulosic ethanol production will not be able to capitalize on a feed market from non-grain by-products. Condensed solubles from stillage evaporation and spent yeast at cellulosic ethanol plants could be transported to biogas plants for co-digestion. Biodiesel production results in crude glycerol and spent washwater by-products that have high biogas yields and are suitable for co-digestion.

Another opportunity for biogas production from confined animal manure occurs in the context of integrated biorefineries where animal production is located close to ethanol or bio-diesel production facilities. Feed from ethanol byproducts can be used in animal production with minimal drying and storage, while biogas from manure and spent yeast can power the ethanol plant. Spent oilseed cake from biodiesel production can be used in animal feed rations, with manure, crude glycerol, and spent washwater used for biogas production. Excess biogas can be sold as fuel or electricity. The synergies from integrating animal production with biorefineries can offer savings in energy conservation and improved efficiencies to lower feed and energy costs.

Biogas from other wastes and biomass

Manure is by no means the only suitable feedstock for biogas production. Wastes from food processing can also be used as a renewable feedstock. Waste from meat production, dairy processing, breweries, canneries, seafood processing, aquaculture production, juice processing, beverage production and sugar production can all be converted to biogas. There are also many biomass crops that could be used as feedstocks for biogas production. Nutrients from crop conversion can be returned to the cropping system for a truly sustainable renewable energy production system, which can displace greenhouse emissions from fossil energy consumption. Finally, high rates of algae and aquatic weed production in Florida offer additional feedstocks for biogas production, with the additional benefit of removing nutrients from surface waters.

Conclusions

Management of livestock manure can result in substantial emissions of greenhouse gases, especially methane. The principal opportunities for reducing GHG emissions occur in concentrated dairy and poultry operations. The estimated methane emissions from manure management of confined animal populations in Florida total 24.9 Gg CH_4 yr^{-1}, which is equivalent to a global warming potential of 0.523 Tg CO_2 yr^{-1}. The conversion of manure to biogas reduces these CH_4 emissions and avoids CO_2 emissions from fossil fuel use that is displaced by biogas use. The estimated methane production potential from anaerobic digestion of dairy and poultry manure in Florida is 222 million m3 CH_4 yr^{-1}. If this methane were used to replace natural gas, approximately 0.436 Tg CO_2 yr^{-1} of fossil CO_2 emissions would be avoided. In addition to the energy value (or savings), this two-pronged attack on GHG emissions offers a potential for additional revenue from the sale of carbon credits to help finance biogas installations. Higher energy costs and greater recognition of the value of environmental benefits are improving opportunities for renewable biogas production. Tipping fees from taking local organic waste into on-farm biogas plants can improve revenue prospects and increase biogas production through co-digestion. Wastes from ethanol and biodiesel production can also be used in co-digestion. Animal production can be integrated with biorefineries to improve by-product utilization and energy use efficiencies.

Role of Florida soils in carbon sequestration

Sabine Grunwald

Soils store substantial amounts of carbon. Approximately 1,500 Pg C is stored in the upper 1 m of soil in the world (Schlesinger 1997), and the sequestration of carbon in soils has been suggested to counteract rising atmospheric CO_2 emissions. It has been estimated that the total global soil carbon pool is four times the biotic pool and about three times the atmospheric pool (Lal 2004). Hence, even relatively small changes in soil carbon storage per unit area could have a significant impact on the global carbon balance. Major reservoirs and fluxes of the global carbon cycle are shown in Figure 14. Of these, the oceanic carbon reservoir is the largest but least reactive, and the atmospheric reservoir, although the smallest, is the most critical one since it drives global warming. Emissions of CO_2 from soils through decomposition processes (via heterotrophic respiration) are thought to be on the order of 50 Pg C yr^{-1} with additional losses of about 10 Pg C yr^{-1} from disturbances such as fire. The soil organic carbon content may range between ~3–250 kg m^{-2}. The soils reservoir is complex due to many overlapping ecosystem processes that continually reshape this pool. Thus, much uncertainty exists to accurately characterize soil carbon across larger regions. With the exception of the fossil fuel reservoir, each reservoir at times behaves as either a source or a sink of carbon.

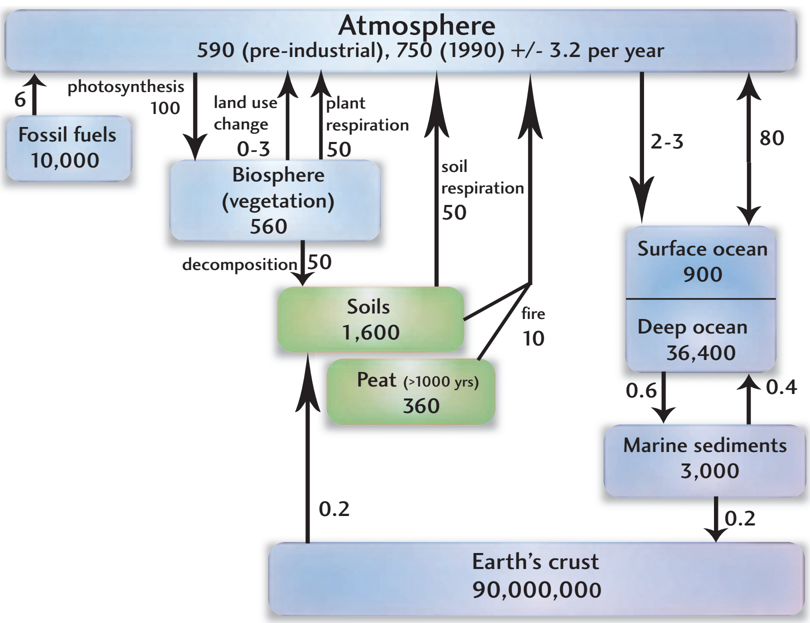


Figure 14. Major reservoirs and fluxes of the global carbon cycle. Numbers in boxes are given in Pg C (1 Pg C = 10^{15} g C) and fluxes in Pg C yr^{-1} (modified after Jacobson et al. 2004). Note that the actual numbers vary slightly with different estimates, and are used here only as guides to the levels of fluxes and pools.

Soil carbon variation in space and time

In most soil profiles, organic matter is highest near the soil surface, where most plant litter is added, and then declines with increasing depth. The spatial variation of soil carbon across a landscape is large, ranging from a few (1–20 m) to a few hundred meters (300–500 m). The variability in soil carbon is dependent on multiple factors including land use management, land cover (vegetation), composition of leaf and root litter, parent material/geology, soil type, topography, hydrology/soil moisture, climate, microbial activity, fire, disturbances and others. The rate of soil carbon storage is modulated by regulating mechanisms among labile and recalcitrant pools based on processes of organic matter decomposition, mineralization, and aggregation. Recalcitrant carbon resides for longer periods of time in soils (10–35 years or longer) and is protected from microbial and chemical processes. Whether the soil is a source or a sink of carbon depends on the balance between the carbon's recalcitrance and cycling. The sequestration of carbon in recalcitrant form is desired in order to reduce the likelihood that soil carbon is recycled back into the atmosphere, thus adding to atmospheric CO_2.

The time scale of recalcitrant soil carbon change is in the order of years, whereas the labile carbon pool changes at a more rapid rate (in the order of weeks-months). Turnover or residence times for the carbon reservoirs range from over 100 years in the sediment reservoir, $100^{-1}000$ years for peat and soil carbon, less than 10 years for microbial and labile carbon, less than 3 years for atmospheric CO_2, and less than one year for ocean biomass. Time affects whether inputs and outputs are at equilibrium, and temporal scale influences the relative importance of various effects on production and decomposition.

Carbon sequestration refers to the provision of long-term storage of carbon in the terrestrial biosphere, underground, or in the oceans so that the buildup of anthropogenic CO_2 concentration in the atmosphere will be reduced or slowed. It is important to distinguish between "potential", "attainable" and "actual" carbon sequestration in soils (Ingram and Fernandes 2001). The potential is defined by factors that set the physico-chemical maximum limit to storage (e.g., mineralogy, depth). The attainable is set by factors that limit the input of carbon to the soil system (e.g., climate, vegetation). The actual is set by factors that reduce carbon storage (e.g., drainage, tillage). Assessment of actual and potential soil carbon storage across a landscape is constrained by the variability and interaction among multiple landscape factors that are responsible for the large variability in soil carbon. Thus marketing soil carbon is partly determined by labor and capital costs involved in measuring spatial variability in soil carbon at landscape scales, and the long time periods required to sequester carbon in soils. However, rapid, cheap and accurate soil sensing methods and geospatial soil carbon modeling can overcome these limitations (cf. Grunwald 2006).

Factors that control soil carbon storage

Chemical, biological and physical processes continually transform organic matter added to soils in the form of plant and animal detritus. The rate of soil carbon accumulation varies greatly among soils, reflecting the influence of environmental factors on soil forming processes:

Soil carbon = *f* {climate—hydrology and temperature; land cover;
land use management; organisms; soils; parent material/geology; topography;
and natural and anthropogenic stressors such as fires and tropical storms}

Climate and soil carbon in Florida The high precipitation rates (up to >1,600 mm annually) and high temperatures (avg. annual temp. from 14.5°C to 29.5°C) tend to accelerate decomposition explaining the relatively low organic matter content (0.5–3%) found in many Florida topsoils. However, high precipitation leads to accelerated leaching of organic material from the topsoil to the subsurface soil where carbon-rich material accumulates in form of spodic horizons, which may range from few centimeters to several meters in thickness. The relatively high water table, albeit fluctuating, in many locations across Florida favors the formation of such spodic horizons that are found in flatwoods and depressions. High precipitation rates in low landscape positions along with high water table have formed many wetlands and freshwater marshes across Florida. The high biomass production of emergent marsh vegetation in conjunction with low decomposition rates favors the accumulation of soil organic matter.

Florida experiences more thunderstorms than any other state or region in North America, and the rainfall from these storms is a major portion of the total precipitation in the state. Hurricanes often yield 125 to 300 mm of rain over affected areas. Excessive, high-intensity rains are associated with tropical thunderstorms and hurricanes, which accelerate vertical transport processes (e.g., movement of soil carbon) along the soil profile.

Hydrologic manipulation, in particular drainage (e.g., in south Florida's Everglades Agricultural Area), has lead to oxidation of organic soil material and subsidence of soils. Rates of regional subsidence in the Everglades have been estimated at 2.5 cm yr^{-1} in drained areas (Snyder et al. 1978). The peat accretion rate during the last 1,000 years has been assessed of about 0.16 cm yr^{-1}, less than one tenth the subsidence rate. Other assessments in a Florida freshwater marsh in south Florida suggest a maximum accretion rate of 1.1 cm yr^{-1} (Reddy et al. 1993). Florida is occasionally afflicted with drought, despite being one of the wettest states. Drought conditions favor wildfires that impact thousands of acres every year causing severe losses of CO_2 into the atmosphere.

Land cover/land use (LC/LU) management and soil carbon in Florida Major LC/LU in Florida include: Mesic Uplands (Prairies, Hardwood Pine Forests, and Hammocks) (22.92%); Freshwater Wetlands (22.01%); Aquatic/Open Water (18.10%); Agriculture (14.74%); Urban (9.73%); Disturbed Communities / Transitional (6.73%); Xeric Uplands (2.62%), Marine Estuaries (2.51%); and various other types (0.55%) (Florida Fish and Wildlife Conservation Commission 2003). Major agricultural crops include citrus (385,312 ha; central Florida), sugarcane (211,571 ha; south Florida), improved pasture (1,199,463 ha), unimproved pasture/woodland pasture (57,458 ha), row/field crops (567,672 ha; corn, potatoes, cotton, beans, hay and grasses), and other agriculture (90,706 ha; various tree groves, nurseries, and specialty farms, vegetables). Rice production is a minor crop in Florida (7,711 ha), although this does contribute to CH_4 emissions (U.S. EPA, 2006). Depending on the LC/LU management, soil carbon storage (topsoil and subsoil) in Florida may follow the general trend: wetlands > pinelands > rangeland/grassland ~ urban > improved pasture > upland forest > crops. Besides carbon-rich topsoils and O horizons major proportions of soil carbon may be also found in subsurface horizons on Spodosols, in particular under upland forest, pinelands, and pastures. However, many other site-specific factors may also impact soil carbon accumulation including soil moisture conditions, geographic location, topography, and climate.

Historically, wetlands covered much larger areas in Florida than today. Drainage of the Everglades changed south Florida from a subtropical wetland to a human-dominated landscape with a strong retirement, tourism and agricultural economy. As a result, the current Everglades (~ 8,240 km^2) is about half its original size. The northern portion of the historic Everglades was drained, which is now the Everglades Agricultural Area that is used mainly for sugarcane, mixed vegetables and sod production. Soils in the EAA are formed in organic material that is rich in carbon throughout the soil profile with soil depths ranging from about 50 to 130 cm. The subsidence and soil carbon loss in the EAA is substantial with about 1.5 cm of soil lost each year due to oxidation. Subsidence of soil profiles changes the bulk density and decreases the carbon content in the remaining soil. A major portion of the EAA is expected to go out of production or be moved to adjacent mineral soils since these soils are becoming too shallow to be cropped.

In Florida, there is potential to shift towards land uses that tend to sequester soil carbon. This would either require shifting agricultural sites into rangeland/grassland, pineland and wetlands or intensifying production with a focus on energy crops. Given the sensitivity of Florida's landscape and competing land use interests (e.g., urbanization, food production, recreation, and conservation) this may be an option on marginal land. The rapid urban growth in Florida is expected to increase CO_2 emission due to higher energy consumption, but may have a positive effect on soil carbon sequestration if agricultural lands under intensive tillage are converted into residential areas.

Soil characteristics and soil carbon in Florida There are specific soils that tend to accumulate carbon in the subsoil at comparable rates to the topsoil. These soils, called Spodosols (Figure 15), are extensive throughout Florida. The spodic, carbon-rich subsurface horizons of Spodosols tend to have a high proportion of recalcitrant carbon with a dominance of organo-metallic complexes. A combination of specific landscape properties promotes the formation of Spodosols including little to no clay content (sand-rich soils), acidification, generation of reactive by-products, release of metals through weathering, high precipitation and vertical leaching, and redistribution of soil components. A fluctuating water table has been suggested as essential to form Spodosols in the southeastern U.S. In Florida soils, a substantial proportion of soil carbon is stored in the subsoil in form of recalcitrant carbon that may reside for hundreds to thousands of years. Weatherable minerals are scarce in the clastic units of the Pleistocene and younger but more abundant in the Miocene aged sediments. Quartz is overwhelmingly dominant in sand and silt fractions, but does not bond well with organic materials. Soils of this region are nearly devoid of weatherable aluminum (Al)- and iron (Fe)-bearing minerals. The source of metals for carbon interactions and spodic horizon formation in these southeastern U.S. coastal plain soils come from secondary metal oxides, primarily Al. Since many Florida soils are slightly acidic the organic acids promote to dissolve Al-oxides, which in turn promote the formation of Spodosols. The metals and organics may migrate together as complexes or separately from the topsoil into the subsurface soil forming an eluvial horizon (E horizon) (Figure 15). An illuvial, carbon-enriched spodic horizon (Bh) is subsequently formed.

The drainage and soil moisture status in Florida's soils are highly variable and dependent on parent material, topography, and physiography. Soils of the Panhandle and northern to central peninsula formed predominantly in sandy to loamy marine and fluvio-marine parent materials show a variety of drainage conditions. Sand-rich soils along with nearly level topography favor rapid infiltration of rainfall that lead to excessive leaching of materials including leaching of metals, organic material and metal-organic complexes.

Major soils that accumulate soil organic carbon are Histosols, Spodosols, and Mollisols. Histosols are soils that consist of more than 12–18% organic carbon and half of the upper 80 cm of soil is organic material. They form in depressional areas and floodplains and are typically found in wetlands. Spodosols are common on flatwoods, flats, and depressions. Spodosols contain a spodic subsurface horizon (>10 cm to few m) enriched in Al or Fe and organic materials. Mollisols are mineral soils that have a dark surface horizon (>25 cm) enriched in soil organic matter. Most upland soils (e.g., Alfisols and Ultisols) show a more or less expressed surface horizon (A horizon) enriched in organic matter.

Parent material/geology and soil carbon in Florida The Florida Plateau consists of a core of metamorphic rocks. Eocene, Oligocene and Miocene (>2 million yrs.) limestones occur at varying depth throughout the entire state. Deposits in Florida that have been assigned to the Pleistocene (10,000–2 million yrs.) vary greatly in extent and composition with a dominance of limestones in the southern part and siliceous sandy materials or finer-textured stratified marine sediments elsewhere. In locations where soils have been formed close to limestone bedrock or along erosional phases (e.g., Cody Scarp) inorganic soil carbon content in the subsoil may be found. However, the acidic nature of most Florida soils justifies the assumption that total carbon and organic carbon are essentially equivalent.

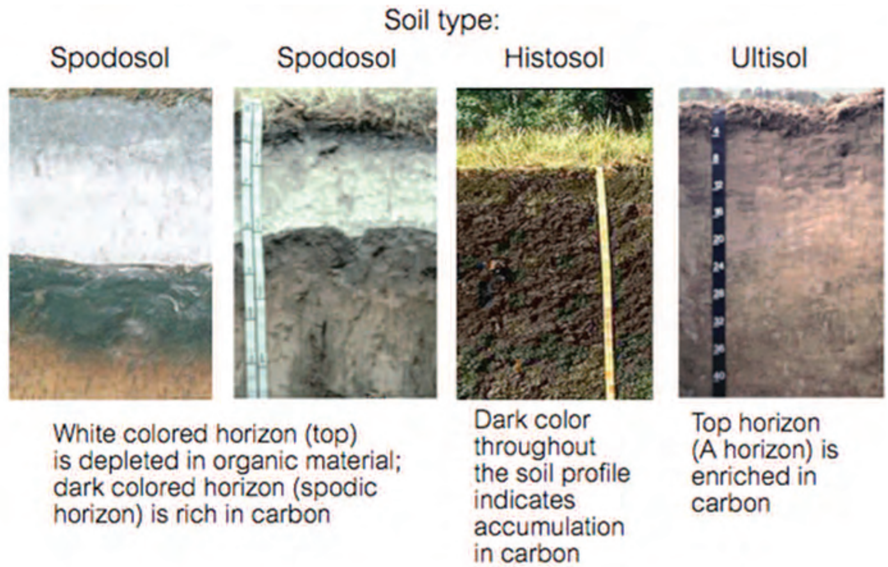


Figure 15. Photographs of soil profiles that show accumulation of organic carbon *(Photographs: Natural Resources Conservation Service—National Soil Survey Center)*

Lithologically, the majority of soils are formed in sandy to loamy marine-derived sediments. Sand is the dominant particle size fraction in many Florida soils with less proportion in the silt and clay fractions. In Florida soil, texture is not favorable to bond with organic matter forming organo-mineral complexes; thus, organic carbon may be easily leached from upper soil layers, which leads to carbon enrichment in subsurface layers.

Topography and soil carbon in Florida While elevations range only from 0 to 105 m above sea level across Florida, microtopography has major impacts on hydrologic patterns in Florida and subsequent formation of soil organic carbon. Flatwoods and associated landforms (flats) occur in about 50% in Florida and are typically broad, nearly level, flat areas that are poorly drained and tend to accumulate soil organic matter. Despite the high sand content, soils in flatwoods, depressional areas and flats have the potential to sequester large amounts of carbon relative to agricultural land. Due to needs of a growing population in Florida those hydric soils are threatened to decline. Organic soils (Histosols) may contain to over 80% organic matter. Wetlands have the ability to sequester large amounts of carbon in soils on a relatively small area with sequestration rates between 0.1 to 1 tonne C ha^{-1} yr^{-1} (Watsen et al. 2000). This positive effect may be counteracted by CH_4 emission from wetlands in subtropical/tropical regions. Schipper and Reddy (1994) observed CH_4 production rates from 0.3 to 1.1 g m^{-2} d^{-1} in various Florida wetlands. The annual carbon loss in the top 24 cm of soil varied between 0.68 and 3.7% of total carbon. Methane production accounted for about 70% of the carbon losses. Assuming an average rate of 0.85 g CH_4 m^{-2} d^{-1} emissions this would translate into 0.0103 Pg CO_2eq yr^{-1} for the total area of Histosols in Florida.

Storage of carbon in Florida Soils

Florida covers about 152,506 km^2 and major soil orders are Spodosols, Entisols, Ultisols, Alfisols, and Histosols (Table 12). Almost all soil carbon stocks in the literature are reported in units of kg m^{-2} up to a specific soil depth to represent the three-dimensional nature of soils. Typically, the unit of CO_2eq is not used to report soil carbon data for various reasons. Wetland soils (Histosols), prominent in Florida, may emit a major proportion in form of CH_4, which can fluctuate substantially in space and time. Since CH_4 has a 21-times higher global warming potential than CO_2, the effects on the carbon budget can be significant. Given these constraints we report soil carbon stocks for Florida in CO_2eq while all other data are reported in commonly used units.

The mean soil organic matter content standardized to a depth of 1 m (OC^{-1}) across all soil types is 28.4 kg m^{-2} CO_2eq and 42.6 kg m^{-2} CO_2eq across the whole soil profile (OC-P) variable for different observation locations (Table 12). Florida soils that show the highest OC-P are Histosols with 223 (STD: 138.4) kg m^{-1} CO_2eq sequestering large amounts of carbon on a relatively small area. Other soils that are high in soil carbon are Inceptisols, Mollisols and Spodosols. However, only Spodosols are extensive throughout Florida. Spodosols not only sequester carbon in the topsoil but also major proportions are stored in

Table. 12. Mean soil organic carbon content and standard deviations (STD, in parenthesis) in different soils across Florida based on calculations by G.M. Vasques and S. Grunwald. Values are reported in CO_2eq.

Soil Orders	Areal Coverage of Soils (%)	OC-1 (kg m^{-2} CO_2eq)[2]	OC-P (kg m^{-2} CO_2eq)[3]
Alfisols	11.6	20.4 (16.9)	29.9 (22.8)
Entisols	22.7	17.7 (31.4)	21.9 (16.7)
Histosols	9.9	189.7 (86.4)	223.0 (138.4)
Inceptisols	0.6	48.3 (38.3)	58.7 (34.5)
Mollisols	2.0	51.2 (40.2)	59.9 (37.0)
Spodosols	29.4	32.4 (21.3)	59.1 (42.1)
Ultisols	17.3	15.0 (13.0)	27.7 (20.9)
	Total — 93.51	**Mean — 28.4 (40.3)**	**Mean — 42.6 (51.0)**

Data sources: Florida Soil Characterization Dataset; and State Soil Geographic Database (STATSGO)—Natural Resources Conservation Service

[1] *Remaining coverage is water*

[2] *OC^{-1}: Depth-weighted organic carbon content up to 1 m depth*

[3] *OC-P: Depth-weighted organic carbon content across the whole soil profile (up to a max. depth of 2 m)*

the subsoil in form of spodic horizons. Stone et al. (1993) found 17 g of soil organic carbon kg^{-1} (STD: 12) in the Bh (spodic) horizon and 8.5 g kg^{-1} (STD: 5) in the Bh (spodic) horizon based on 244 sampled profiles across Florida. These carbon contents were similar to organic carbon concentrations in topsoil (A horizons) of 19 (STD: 20) g kg^{-1}. Similarly, Gholz and Fisher (1982) assessed soil organic carbon in slash pine *(Pinus elliottii)* plantations with different ages (2 to 34 yr. old) in northern Florida and found no significant differences in soil organic carbon in the topsoil as compared to the spodic horizon. The soil carbon amounts in Spodosols in Florida are substantial. Batjes (1996) found comparable amounts of carbon in comparable Podzols (FAO-UNESCO soil units, 1 m depth) with mean 24.2 C kg m^{-2}. The range of mean soil organic carbon across the world was from 3.0 C kg m^{-2} (Yermosols) to 25.4 C kg m^{-2} (Andisols).

According to Guo et al. (2006), which used STATSGO data to assess soil carbon across the whole U.S., Histosols have the highest potential to sequester carbon with mean soil organic carbon of 97.6 (STD: 50.3) kg m^{-2} followed by Spodosols with mean soil organic carbon content of 9.9 (STD: 5.2) kg m^{-2} standardized to a depth of 1 m. Interestingly, Florida ranks highest among all conterminous U.S. states in terms of soil organic carbon (Guo et al. 2006). Given the landscape conditions in Florida, Histosols, and Spodosols are most prominent throughout the state and provide ample opportunities to sequester carbon. Hydrologic management and changing climate patterns such as increased precipitation due to frequency and intensity of tropical storms/hurricanes and a rising water table as well as anthropogenic manipulation of hydrology have the potential to increase the sequestration of carbon in Florida soils.

Based on comprehensive mapping of wetland soils in the Everglades (1,341 sites), the topsoil (0-20cm) mean carbon stored is 53.7 (STD: 17.9) kg C m^{-2}, and the floc/detritus layer mean carbon stored is 9.1 (STD: 7.77) kg C m^{-2} (Reddy and Grunwald 2007). These values are comparable to the mean organic carbon content of Histosols of the world with a mean of 77.6 kg C m^{-2} for soils up to 1 m depth (FAO-UNESCO soil units) (Batjes 1996). These data indicate that soil carbon storage in wetlands is higher when compared to carbon sequestered in spodic horizons in subsurface soils. Florida's historic, natural landscape stored much carbon in soils because wetlands, flatwoods and flats were much more extensive than today. Many of these wet (hydric) sites were lost to agricultural, forest and urban lands. Reversing these land uses to more natural conditions would have the potential to sequester large amounts of carbon in soils on a relatively small land surface area.

Land management practices and their potential to sequester soil carbon

There is concern that the effect of climate and land use change on soils will exacerbate the problem of increasing CO_2 in the atmosphere, but through optimized management soils can play a part in mitigating increasing CO_2 levels. Paustian (2006) suggested that a net accumulation of carbon presently occurs in terrestrial vegetation and soils, at a rate of about 2 Pg C yr^{-1}. While the net terrestrial accumulation of carbon is small relative to the annual fluxes of carbon between the atmosphere and land, it is significant in relation of the net change in CO_2 in the atmosphere. In other words, if the terrestrial carbon sink was to disappear, and everything else remained equal, the rate of growth of CO_2 in the atmosphere would increase by more than 50% from about 3.2 to more than 5 Pg C yr^{-1}. The contribution of soils to the overall carbon sink is still uncertain. Since both biomass production (hence, carbon inputs) and decomposition (hence, carbon losses) are affected by changes in temperature, precipitation and CO_2 concentrations, the interactions and feedbacks controlling the terrestrial carbon balance are complex and difficult to predict. It is well established that the conversion of native ecosystems (e.g., forests, grasslands and wetlands) to primarily agricultural uses has led to significant losses of carbon from terrestrial ecosystems, on the order of 120–180 Pg C or more over the past 150–300 yrs. from vegetation and soils combined worldwide (Houghton 1999). Converting grassland and forest to arable agriculture typically results in the loss of about 30% of the organic carbon present in the soil profile (Davidson and Ackerman 1993). From soils alone, estimates of historical losses over the same period are 50–100 Pg C. Soil organic carbon losses reported in subtropical and tropical environments often match or even surpass those observed under temperate conditions. In subtropical and tropical environments, shifting cultivation systems appear to conserve more soil organic carbon than forestlands permanently cleared for cultivation. This offers the opportunity to reverse trends by adapting land use and resource management practices.

Globally, agricultural soils have been estimated to have the capacity to sequester carbon at rates of 0.06 Pg C yr^{-1} during several decades (Cole et al. 1996). The realization of this potential carbon sequestration would not be trivial since it would offset roughly one-tenth of the current emission from fossil fuels. In the U.S., annual gains in soil carbon from improved agricultural practices have been estimated at 0.14 Pg C yr^{-1} (Houghton et al. 1999). In tropical humic climate (Brazil) it was shown that soil carbon differed by management with 4.33 kg m^{-2} soil organic carbon under forest, 5.85 kg m^{-2} (pasture, 5 yrs.), and highest with 6.12 kg m^{-2} (pasture, 81 yrs.) (Neill et al. 1998). Hutchinson et al. (2007) pointed out that the humid tropics have considerable potential to sequester carbon with 4–9 Mg C ha^{-1} yr^{-1} in the terrestrial ecosystem and potential soil carbon accumulation rates (20–25 year rotation) of 50 Mg C ha^{-1}.

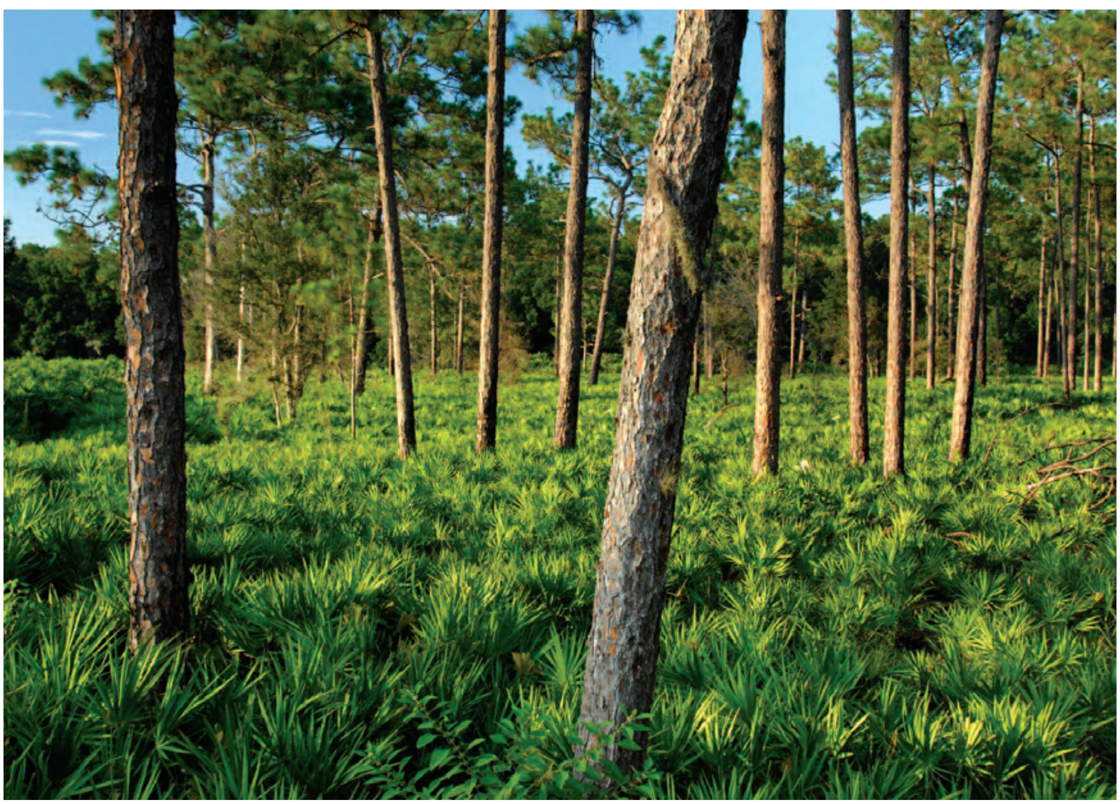
Many land use practices, some involving land use changes, have shown to increase soil organic carbon and have thus received considerable attention for their possible role in climate change mitigation. Guo and Gifford (2002) presented a comprehensive meta-analysis (74 publications) documenting the effect of land use on soil carbon stocks. They found that soil carbon declined after land use changed from pasture to plantation ($^{-1}$0%), native forest to plantation ($^{-1}$3%), native forest to crop (-42%), and pasture to crop (-59%). Soil carbon increased after land use changes from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%), and crop to secondary forest (+53%). Houghton et al. (1999) assessed that the net emissions of C from land use change (1850–1995) in south and southeastern Asia under subtropical/tropical climate was 43.5 Pg C and the clearing of forest for permanent cropland released 33.5 Pg C, about 75% of the total C. The rate at which carbon may accumulate in soil and the length of time for soil carbon sequestration is highly variable among land use. Average rates of soil carbon accumulation for forest and grassland establishment after agricultural use were 33.8 and 33.2 g C m^{-2} y^{-1}, respectively (31 studies reviewed by Post and Kwon 2000), with maximum rates of 105 g C m^{-2} y^{-1} found under subtropical conditions shifting from agriculture into moist forest (Brown and Lugo 1990).

Carbon sequestration in managed soils occurs when there is a net removal of atmospheric CO_2 because carbon inputs are greater than carbon outputs. Soil carbon sequestration has additional appeal because practices that enhance soil carbon also improve soil quality and soil fertility, thus enhancing several ecosystem services. Most important to note is that unlike other carbon sequestration pathways soil sequestration provides long residence times (hundreds to thousands of years). After crop residues, roots and organic amendments enter soils, carbon resides shortly (for few months to years) in labile soil fractions, and finally becomes a long-time constituent (for hundred of years) of recalcitrant organo-mineral complexes. The quantity and quality of carbon entering soil as well as the interaction of this carbon with the soil biophysical environment are major factors determining the rate and duration of soil carbon sequestration.

General practices that enhance soil organic carbon

Land use shifts

- Land uses that enhance soil organic matter (e.g., forest, wetlands)
- Land uses that are adjusted to high water table and/or wet conditions (e.g., grassland, wetlands, and aquatic refugees)
- Energy crops that have the ability to sequester large amounts of carbon in biomass, root system and soils
- Constrain rice cultivation (to limit CH_4 emissions)
- Mixed cropping systems that combine annual and perennial plants (e.g., silvopasture)
- Preservation of forestlands and agroforestry offer promise as alternative land-use practices to enhance terrestrial carbon sequestration



Reduced tillage / reduce soil disturbance

- Conservation and no-tillage practices enhance decomposition and soil carbon accumulation; and stabilize soil aggregates

Fertilization

- Increases nutrients in soils; stimulates biomass production and root growth; enhances photosynthesis and crop residues

Soil amendments

- Compost, manures, organic wastes, mixed organic fertilizers and biosolids (sewage sludge) enhance soil organic matter content in soils (and improve soil quality/fertility, ability to retain water and nutrients, and formation of organo-mineral aggregates)

Optimized crop rotations / treatment of residues

- Use of legumes in crop rotations
- Use of cover crops (grasses of legumes)
- Rotations of crop-pasture
- Retention of crop residues / green manuring

Water management / irrigation practices

- Maintenance of a high water table (e.g., seepage irrigation is the most common irrigation method in south Florida on muck and sandy soils, and consists of maintaining a water table perched on an impermeable layer)
- Reduction of drainage (e.g., water management in EAA)
- Wastewater (from treatment plants) for irrigation; wastewater treatment lands

Manure / waste management

- Optimize manure management
- Solid systems are preferred over liquid systems (liquid systems tend to encourage anaerobic conditions and produce significant quantities of CH_4, whereas solid waste management produce little or no CH_4)
- Constrain enteric fermentation (pigs/horses are preferred over cattle, sheep and goats, because ruminants have the highest CH_4 emissions among all animal types)

Land resource management activities

- In residential/recreational areas designate land uses that have the potential to sequester carbon (e.g., ponds, wetlands)
- Avoid use of extensive impermeable surfaces in residential areas because such surfaces do not support carbon sequestration and accelerate storm runoff
- Establish constructed wetlands that store soil organic matter on a relatively small area
- Enlarge riparian forest buffers

Scenarios

Florida soils could potentially sequester significantly more carbon by increasing the coverage of specific soil types, as shown in Figure 16. Histosols covering about 15,098 km^2 account for 2.86 Pg CO_2eq across Florida and show the greatest potential to increase soil carbon storage, and these can be created through the construction of wetlands. Increasing the area covered by Histosols of 1% (1,525 km^2) would result in a gain of 0.29 Pg CO_2eq considering a 1 m soil profile translating into $1,156 million. According to Reddy et al. (1993) the accretion rate on nutrient-enriched wetland sites with long hydroperiods is about 1.1 cm yr^{-1} and it would take about 90.9 years to build up a 1 m profile. In contrast, on unenriched sites with shorter hydroperiods the accretion rate is lower with about 0.25 cm yr^{-1} and it would take about 400 years to accrete a 1 m profile (Reddy et al., 1993). Assuming an average CH_4 emission of 0.85 g m^{-2} d^{-1} (Schipper and Reddy, 1994) the methane emissions for a 90.9 year period are estimated at 0.095 Pg CO_2eq and over a 400 year period 0.418 Pg CO_2eq. Thus, contrasting soil carbon accretion and methane emissions from wetlands under the 90-year scenario would result in 0.194 Pg CO_2eq accretion in soil; however, under the 400 year scenario would result in -0.129 Pg CO_2eq emitted into the atmosphere. Considering a Global Warming Potential factor for CH_4 of 21 (U.S. EPA 2006), this raises some concerns. Moreover, there would be significant costs associated with the construction of wetlands to generate these soils. Thus, it may be more realistic to consider the formation of a 1 cm soil layer across an area of 1,525 km^2 that would translate into a carbon value of $11.6 million, assuming an average accretion rate of soil organic matter of 1 cm yr^{-1} and $4 Mg^{-1} CO_2eq.

It may also be possible to increase the area of Spodosols from its present value of about 33,837 km^2, representing a soil carbon base of 1.45 Pg CO_2eq across Florida. A 1% increase would result in sequestration of 0.04 Pg CO_2eq considering a 1 m soil profile translating into $197.8 million. However, it is not known how long it would take to form Spodosols. Other soils (e.g., Ultisols, Entisols) have more limited potential to sequester carbon.

Creation of soil types is constrained by several factors. Specifically, the coarse scale soil data used for these scenarios do not fully account for the spatial variability of soil carbon controlled by various landscape factors (e.g., hydric conditions, land use) across Florida. More detailed soil datasets would be required for an in-depth analysis. Moreover, this approach does not consider many land management factors such as manure management, field burning of agricultural residues, land ownership, and N_2O emissions.

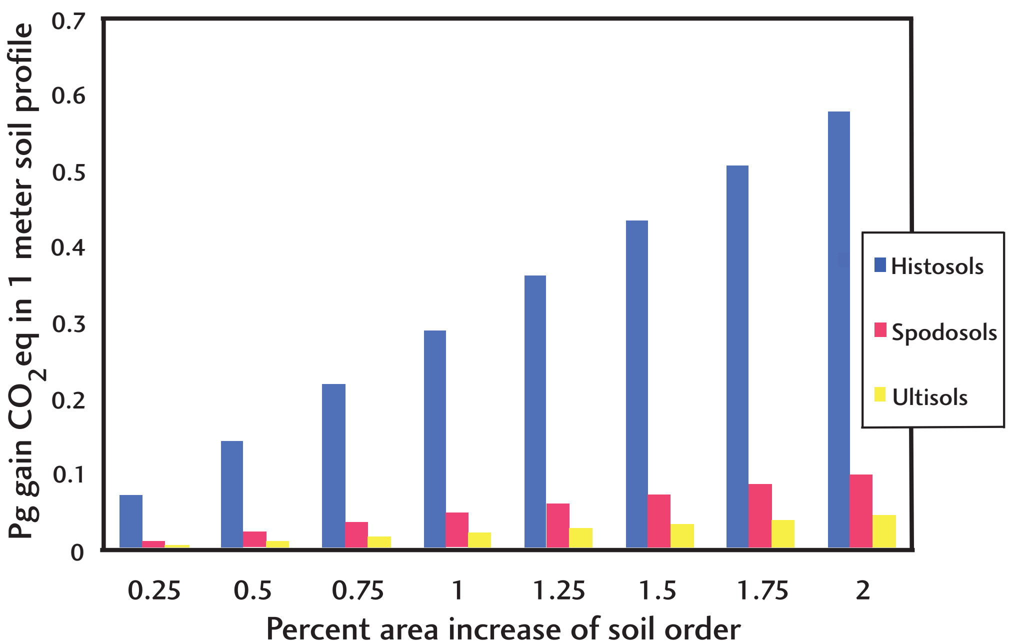


Figure 16. Scenarios to assess gains in soil carbon by increasing the coverage of different soils across Florida. Calculations are based on a standardized 1 m soil profile.

Perhaps the most valuable strategy in the near term is to increase the carbon sequestration of existing soils through management practices. Fransluebbers (2005) estimated soil organic carbon sequestration rates of 153.7 ((168.4) Mg CO_2eq km^{-2} yr^{-1} in the southeastern U.S. by changing land use practices from conventional to no-tillage. If we assume that 50% of agricultural lands in Florida were converted to no-tillage, this would translate into an annual gain of 1,723,077 Mg CO_2eq yr^{-1}, or an economic value of $6.9 million, at $4 Mg^{-1} CO_2eq. No doubt each crop would entail different advantages and disadvantages, and a more detailed analysis may result in a higher carbon value of no-till. Because no-tillage offers generally improved nutrient and water retention, as well as avoided GHG emissions, this relatively small carbon additionality offers another incentive for farmers to employ conservation tillage.

Summary and outlook

As population levels in Florida increase there will be high demand for land to produce food, fiber and biomass, and other products. Important decisions will have to be made to manage Florida's land resources in a manner to balance such demands in context of a global economy and climate warming that requires contributions to reduce carbon emissions and sequester carbon in soils and other ecosystem components. Florida's unique landscape characteristics combining subtropical climate, high precipitation rates, high water table, nearly flat to gently sloping terrain facilitate enhancing the amount of carbon stored in soils, which can be controlled by land management activities and hydrologic manipulations. An impediment to soil carbon storage as an instrument to mitigate rising GHG emissions is the relatively long response time and difficulty assessing soil carbon variability that is modulated by multiple interacting environmental landscape factors. However, carbon sequestered in soils provides long-term storage that supports sustainable management of land resources and enhanced ecosystem services.

Although rough estimates for soil carbon in Florida were presented above (Table 12), they do not fully account for the spatial variability of soil carbon. More research is necessary to fill these gaps to assess the spatial and temporal variability of soil carbon, investigate the impact of changing climate (hydrology) and rising temperatures on soil carbon, and conduct soil carbon monitoring to assess carbon sequestration rates across Florida. Protocols for rapid and accurate mapping of soil carbon using soil sensors (e.g., visible/near infrared diffuse reflectance spectroscopy) need to be developed to provide baseline information for carbon budgets and markets. Advanced geostatistical methods can be employed to reduce the costs of soil coring and uncertainty of assessment of soil carbon stocks across larger landscape units. Carbon simulation models can be adapted to Florida's landscape conditions to model carbon flux, variability of soil, and terrestrial carbon across various ecosystem types. The model outputs could then feed into carbon trading systems.

Summary conclusions and carbon market prospects for forestry and agriculture in Florida

Stephen Mulkey

Overview of participation in carbon markets

The preceding reports show that Florida is uniquely endowed to become a leader in greenhouse gas mitigation through the effective management of forestry, agriculture, and natural ecosystems. Florida's unique landscape combining subtropical climate, high precipitation rates, high water table, and nearly flat terrain facilitate carbon storage in soils. Similarly, due to favorable radiant energy balance year round, afforestation and reforestation are appropriate climate mitigation strategies. Overall, the state's huge acreage devoted to forestry and agriculture represents an untapped potential for the development of climate mitigation projects and a new source of revenue. Realizing this potential requires that policy makers consider competing land uses and their potential consequences. Sustainable resource use through land use policy can be driven partly by the economic incentive provided by carbon markets, but for these markets to function effectively there must be transparent and comprehensive accounting of carbon sequestration, reversal, and leakage. Mitigation projects must be designed over spatial and temporal scales consistent with the goals of GHG mitigation over this century and beyond, with explicit consideration of market forces in land use decisions. State agencies, especially the Florida Department of Environmental Protection, could establish appropriate accounting and best-practices procedures, and provide a mechanism for certification of verifiers. Current projections of urban population growth within Florida are not consistent with either the goals of sustainable development or maximizing the opportunity for climate mitigation through land management. Appropriate environmental safeguards are essential to insure that the methods of mitigation maintain or enhance the long-term health of Florida's ecosystems. To the extent that enhanced carbon sequestration is consistent with the maintenance of ecosystem services, creation of carbon offsets through appropriate land use is a significant step toward monetizing these services for inclusion in the human economy.

Forestry

Gross growth of Florida forests, before deducting for harvest and tree death, is about 9.5 million tonnes of carbon annually. Because virtually none of these forests are managed explicitly for carbon sequestration, it is clear that more intense management could make this number significantly higher. New markets related to carbon, bioenergy, and environmental services could stimulate landowners to adopt more intensive management, significantly increasing timber yield. Examples of management strategies to accomplish this include planting density, fertilizer application, and thinning. Because timber yield is but one estimate of carbon sequestration in forested landscapes, it is important to validate management schemes with direct measures of CO_2 flux (e.g., Binford et al. 2006), and develop time-specific landscape carbon budgets including all sources of leakage. Critical to the use

of forests and woodlot waste for bioenergy for power production is that the frequency and intensity of harvest be adjusted to maintain soil nutrients and forest productivity. Given such safeguards, it is likely that managing Florida forests for participation in carbon markets will result in significant positive environmental co-effects, especially the maintenance of watershed-based ecosystem services. Innovative forestry practice involving biotechnologies and substitution of energy-intensive products with long-lived wood products provide additional opportunities to maximize the role of forests to achieve greenhouse gas emissions mitigation. The greatest single threat to carbon sequestration and sustainability of Florida's forests comes from the state's rapid urban development and sprawl. Other significant threats include wildfires, hurricanes and pest attacks, which may be more frequent with ensuing anthropogenic climate change.

Biofuels

Substitution of fossil fuels with biofuels holds significant promise for reducing GHG emissions as Florida's energy demand grows to more than double by 2030. Inventories of forest biomass residues, byproducts and waste materials indicate that Florida may have an additional unutilized supply in excess of 5 million dry tonnes annually. In many cases, delivered costs of woody biomass for electric power generation are competitive with coal and natural gas in Florida. Expansion of biomass power systems will depend upon local resources and economic conditions, government incentives, and environmental compliance costs. Other significant near-term opportunities include power generation with biogas from farm residues and municipal solid and liquid waste. Total methane resources in Florida are estimated to be 502,000 tonnes yr^{-1}. Given that there is little or no potential for reversal, the near-term carbon-offset value of Florida biofuels is high (7.4 Tg) before leakage is accounted for. The environmental co-effects associated with biofuel production can be negative through the effects of such land use on biodiversity. It is important that preservation of Florida's critical ecosystems and species be part of management plans as we move toward a low-carbon economy and biofuel production increases.

Technological and market forces are significant obstacles to realizing the carbon offset potential for ethanol production. Although Florida has the resources to produce significant quantities of ethanol from sugarcane, current U.S. sugar policy supporting higher prices for domestic sugar makes this an unlikely source of biofuel. Lifecycle analysis of GHG emissions shows that ethanol derived from sugar is superior to ethanol derived from corn, especially for milling operations integrated with cogeneration plants that utilize sugarcane fiber to produce heat and electricity. Corn, sorghum and citrus byproducts are produced in small quantities or have competing uses in Florida, and thus are limited near-term opportunities for ethanol production. Combined, these sources of carbohydrate-derived ethanol could offset about 3.5% of Florida's demand for gasoline (2006 data), assuming they are produced at maximum potential. Although biodiesel has a better net energy balance than ethanol, these crops have very limited potential in Florida. Cellulosic ethanol produced in Florida could meet a significant portion of Florida's transportation needs, but development of the technology and infrastructure for mass production is likely 10 years away. Until a demonstration plant is in operation, we feel that any estimate of production capacity would be specious. Regardless of the feedstock for production of ethanol, lifecycle analysis of GHG emissions is the crucial determinant of the viability of ethanol as a substitute for fossil fuel. Where indicated, lifecycle assessment must include agriculturally produced N_2O emissions and emissions associated with land conversion.

Livestock waste

Manure management is a primary tool for methane mitigation through the agricultural sector, and in Florida the greatest opportunities occur in concentrated dairy and poultry operations. The estimated methane emissions from manure management of confined animal populations in Florida total 24,900 tonnes CH_4 yr^{-1}, which is equivalent to a global warming potential of 0.523 Tg CO_2 yr^{-1}. Use of this methane as biogas for power generation has three advantages through (1) avoided direct emissions of methane from livestock waste, (2) displacing fossil natural gas used for power generation, and (3) income from the sale of this gas to the natural gas market. In addition to these advantages, the sale of carbon credits offers an additional revenue stream to help finance biogas installations.

Soils

While highly heterogeneous, on average Florida soils have the highest organic carbon content in the conterminous U.S. Climate mitigation through soil management is a long-term and complex ecological problem because soil has a long response time for carbon storage and multiple interacting landscape factors affect soil carbon storage. With the state's high precipitation, carbon tends to be sequestered in lower horizons through leaching, leaving the upper horizon capable of receiving additional carbon. Significantly, organic carbon deposited in the subsoil of Florida Spodosols and Histosols is sequestered for long periods and is less prone to reversal. Over several decades, hydrologic modifications such as wetland creation and raised water tables hold potential for increasing subsoil carbon sequestration. Note that wetlands naturally produce methane, which decrements the GHG mitigation potential of these soils.

In the near term, modified crop cultivation can enhance topsoil organic carbon retention while reducing N_2O emissions associated with agriculture. Specific recommendations for such practice include conservation tillage (low-till or no-till), fertilization with soil amendments derived from compost, manures, biosolids and other organic wastes, and optimized crop rotations to improve nutrient retention. Land use policy to maximize carbon retention should look to increase the acreage of forest and wetlands, and match land use to local water table conditions so as to minimize drainage in sandy or muck soils. Additional land management activities that sequester carbon include creating residential and recreation areas that sequester carbon (e.g., wetland meadows and forested wetlands), maintenance of wetlands, and enlarging riparian buffers. Important positive environmental co-effects of climate mitigation through soil management include improved soil nutrient content and greater soil biodiversity.

Potential market value

Data from these reports show that the near-term potential sequestration of carbon and avoided emissions for selected components of forestry and agriculture could offset 16.98 Tg CO_2eq yr^{-1} (Table 13). Biofuels, biomass, and energy crops represent the largest potential of the components considered in this report. While this is only about 7% of Florida CO_2 emissions (255.4 Tg CO_2, based on 2004 data), it more than offsets the projected annual rate of CO_2 emissions increase, which may be as high as 2% under high rates of economic growth. The preceding reports have used a low value of \$4 Mg^{-1} CO_2eq, which has been typical of the U.S. voluntary market. In contrast, Figure 17 shows that these components would be valued at about \$340 million annually under realistic carbon market prices of \$20 Mg^{-1} CO_2eq. Based on values seen in the European market, once meaningful federally mandated caps are in place, it is reasonable to expect values of \$20 to \$45 Mg^{-1} CO_2eq. A market price of \$30 Mg^{-1} CO_2eq would increase the near-term annual value of these components to \$510 million.

Properly defining additionality for a given activity ensures that the net impact on the global atmosphere is one of reduction of GHGs for a specified length of time. If deemed appropriate to count total gross carbon sequestration, then pine forestry would be valued according to the accounting in Table 5 of this report. A more conservative interpretation would use only new carbon acquired due to shifts in management practice, as shown in Table 13. The additional carbon acquired from medium and high intensity management represents an effective reduction of GHGs for the length of the rotation, 25 years.

It is important to note that the data in Figure 17 do not include the value of these components associated with more traditional markets. For example, the market value of bio-

Table 13. Summary emissions offset potential from components of Florida forestry and agriculture

Activity	Near-term carbon offset potential (Tg CO2eq yr-1)
Biofuels, biomass, and energy crops	7.36
Agricultural biogas	0.96
Conservation tillage on 50% of aglands	1.72
Shifts to medium and high intensity pine management[9]	5.8
Afforestation of 5% of range and pastureland	1.14
Total	**16.98**

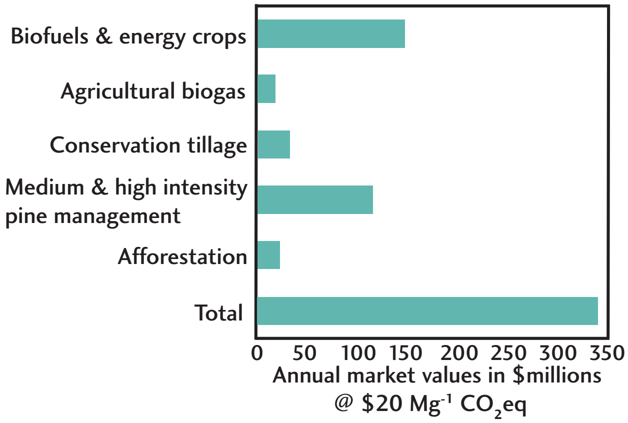


Figure 17. Annual carbon market value for the components of Table 1.

gas as a replacement for fossil natural gas would amount to an additional $62.7 million annually (Table 11). Similarly, sale of crop and logging residues as fuel would be worth $49 million per year at $10 per dry ton. Additionally, reduced fuel costs from implementation of conservation tillage would be a savings of $14 million per year. Including these values with the numbers in Figure 17, the total annual value of these components of forestry and agriculture is about $465 million.

The components shown above represent near-term, feasible amendments that could be implemented within the next 5 years. The data shown in Table 13 considerably understate the potential for participation of Florida forestry and agriculture in a low carbon economy. For example, pine forestry is only one component of industrial and managed forestlands in Florida. Management of other forest types and inclusion of long-term sequestration in new forest products, assuming that these products displace products produced with fossil fuels, would provide additional value. Similarly, when cellulosic ethanol becomes feasible, this would add a major economic component to the agricultural sector. Land use shifts and hydrologic manipulations have significant potential to improve soil carbon stocks in Florida.

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Notes

1. According to IPCC protocol, all gases are converted to a common metric known as CO_2 equivalents (CO_2eq), expressed in teragrams (Tg or million tonnes) or megagrams (Mg).

2. A recent report notes that growing tree plantations to remove carbon dioxide from the atmosphere to mitigate global warming could trigger environmental changes that outweigh some of the benefits. Those effects include water and nutrient depletion and increased soil salinity and acidity, said the researchers (Jackson et al. 2005).

3. A teragram (Tg) is equal to one million metric tons (tonne). A petagram (Pg) is equal to one billion metric tons (tonnes). There is 1 Tg of carbon in ~130 x 1 million cubic ft of wood or 2.2 x 1 billion board ft of softwood lumber.

4. Although carbon stored in forest products can be significant, it is not currently qualified for market transaction. Some argue that carbon in wood products is a flow of wood and is expected to continue to be produced in the absence of markets for greenhouse gas (GHG) emission credits. In other words, carbon in wood products is baseline, and not additional, and does not count as an offset. However, carbon stored in wood products and credits associated with displacement of fossil fuels and steel with forest products can be considered as societal benefits.

5. U.S. EPA (2007) noted that total emissions of the U.S. in 2005 equal to about 1978 Tg of carbon. One tonne of carbon is equal to 3.67 tonnes of carbon dioxide.

6. Johnson et al. (2005) use data from North Carolina Tree Nutrition Cooperative. We assume that growth and yield data from North Carolina reflect Florida's situation and used in this to estimate carbon accumulation.

7. The net impact of carbon sequestration through high-intensity management may not be this high because of the carbon emissions associated with fertilizers and thinning practices during high-intensity management. If nitrogen fertilizer use is increased, nitrous oxide emissions will increase. Nitrous oxide is a potent greenhouse gas and the warming effect of the increased nitrous oxide emissions should be subtracted from the benefit of increasing carbon sequestration. Using the Intergovernmental Panel on Climate Change (IPCC) 2006 default rate that 1% of nitrogen in fertilizer is directly emitted as nitrous oxide, assuming 385 pounds of urea applied per fertilization, and urea being 46.4% nitrogen by weight, this would mean 1.76 pounds of nitrogen would be directly emitted as nitrous oxide per acre, per fertilization. One pound of nitrogen makes about 1.57 pounds of nitrous oxide, and a pound of nitrous oxide has 296 times the warming effect of a pound of carbon dioxide Converting to metric tons, each application of fertilizer could result in direct nitrous oxide emissions of 0.3775 metric tons carbon dioxide equivalent per acre. (Source: Gordon Smith, EDC Feb. 14, 2008)

8. In the U.S. South, the average annual tree mortality due to Southern Pine Beetle was estimated to be about 100 million board feet of sawtimber and 20 million cubic feet of growing stock.

9. The value for medium and high intensity management of pine plantations is derived from data in the preceding report on forestry, and represents a conservative interpretation of the additionality provided by this practice. This is obtained from shifting 1.85 million acres to medium intensity from low intensity management, and switching 2.9 million acres to high intensity management from medium intensity. This results in annual increases in onsite carbon stocks of 0.25 and 0.39 tonnes carbon per acre on medium and high intensity management, respectively. The total carbon sequestration value of these shifts in management intensity would be $116.8 million per year for 25 years at a market value of $20 Mg^{-1} CO_2eq. Note that this estimate does not include decrements due to use of fossil derived fertilizer and other sources of leakage associated with management practice.

Credits

Executive Summary

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