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Plant Materials

Technical Note No. 1

Agricultural Carbon Sequestration in the Eastern Coastal Plain

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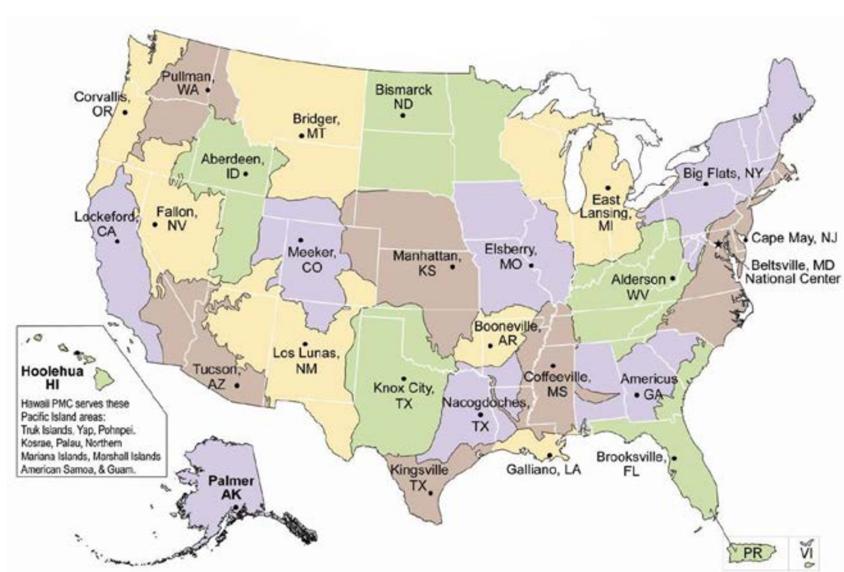
Preface

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Plant Materials Program has been involved in the collection, evaluation, selection, increase, and release of conservation plants for more than 75 years. Recent observation of and attention to the effects of climate change prompted new interest in the role of resilience in native plant materials in major land uses such as cropland, forestry, and grazing lands. Related interests in second-generation biofuel technology has also reemerged in government and private sectors. This technical note reviews the current opportunities and challenges in developing plant materials to help sequester and store atmospheric CO_2 in Coastal Plain soils specifically. Conservation planners and practitioners should be able to gain a general overview of factors involved in CO_2 sequestration including: a basic background in photosynthesis and the C cycle dynamics, considerations regarding C3 and C4 plants; comparisons between grasses and woody plants; differences between C in aboveground and belowground biomass; the foundational role that soil type plays in determining C storage potential; a description of the specific challenges of sequestration in Coastal Plain soils; major land uses such as crop production, forestry, and grazing lands; and lastly, management practices used to improve soil organic carbon (SOC) in soils including conservation tillage, cover crops, controlled burning, and fertilization. This publication was prepared to provide information needed by conservationists, producers, or consultants to help make decisions regarding the use of plant material technology in a climate change framework. For additional information on specific species of plants mentioned in this publication, please see the USDA PLANTS database at: (http://plants.usda.gov/java/) or contact the nearest Plant Materials Center or plant materials specialist (http://plant-materials.nrcs.usda.gov/contact/) and/or the Land Grant Universities that serves the State. For specific information on soils and soil health, please see USDA NRCS soils website at: (http://www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/). Also, see technical resources on the National Plant Materials Program Web site at: (http://www.plant-materials.nrcs.usda.gov/).

Location and service areas of Plant Materials Centers



Agricultural Carbon Sequestration in the Eastern Coastal Plain

Acknowledgements

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Agricultural Carbon Sequestration in the Eastern Coastal Plain

Summary and Planning Considerations

- Agriculture and forestry practices are responsible for carbon emissions but they can also play an important role in storing, or locking up carbon.

- Carbon storage is the total amount of carbon sequestered over a given number of years. It is considered a "carbon sink" if the amount of carbon stored is greater than the amount of carbon released.

- Plants differ in the way they use carbon based on how they respond to environmental conditions. High light intensities and high temperatures cause C3 plants to expend energy. C4 plants on the other hand, are more efficient than C3 plants under conditions of drought, high temperatures, and low nitrogen because they do not use O_2 in photorespiration.

- C4 grasses exist in habitats that suffer from N and water deficiency. Future climate change scenarios suggest that the severity of these limiting conditions will increase. C3 grasses respond differently to climate change scenarios, and are predicted to respond favorably to increases in atmospheric CO_2.

- It remains uncertain whether C storage in roots increases in response to elevated atmospheric CO_2 levels, however, the decomposition of roots produce beneficial products like glomalin, which ultimately increase soil and plant health and ecosystem resilience.

- Environmental factors like warmer climates, and arid or droughty conditions increase rates of erosion, decomposition, and oxidation of soil organic matter (SOM), and limit the soil's potential to sequester carbon.

- Coastal Plain soils present a particular challenge to land managers in storing and accumulating SOC pools because carbon \ additions in sandy soils are easily oxidized when inverted through tillage practices, so SOC accumulations tend to be ephemeral, and their positive effects on soil health gradual.

- Crop residue is the main carbon input in crop production systems but overall may not play that large of a role in increasing SOC, especially in deeper (> 30 cm) soil layers.

- Forests have limited N availability, and if increased could potentially improve plant responses to CO_2.

- While it takes generations to recover the C in native grassland soils, the conversion of grassland to cropland results in immediate carbon losses.

- Questionable effectiveness of reduced management practices (RMPs) such as conservation till (CT) and no-till (NT) in building SOC stores.

- When cover crops are combined with conservation tillage (CT) practices greater amounts of SOC are sequestered than by using CT practices alone.

- In most cases, controlled burning can improve SOC stocks by creating inert forms of locked-up carbon such as charcoal.

- Increasing N through supplemental fertilization is not necessary an effective strategy for improving carbon sequestration rates; or reducing GHG as a whole.

Introduction

This technical note is designed to help conservation planners apply Natural Resources Conservation Service (NRCS) practices with a focus on climate change mitigation through plant and soil management. Change in temperature and precipitation patterns and the increase in greenhouse gases (GHGs), specifically carbon dioxide (CO_2) are negatively affecting US farmers, ranchers, and forester's efforts to produce food, fiber, and fuel while protecting natural resources. The effects of climate change currently challenge USDA's efforts to support sustainable food production while preserving natural resources. This Tech Note highlights challenges and opportunities that result from climate change and the specific role plant materials may play in providing resilience and adaptation to change along the Eastern Coast of the United States from Massachusetts south to Florida.

This current Tech Note specifically focuses on:

- Definition of carbon, carbon sequestration, and carbon storage
- A general review of photosynthesis
- Different types of vegetation, and their carbon constituents (ex. lignin, cellulose)
- Soil type, and its central role in CO_2 sequestration
- Comparison between major land uses of crop production, rangeland, and forestry
- Management challenges and opportunities in producing and increasing soil organic carbon (SOC)
- Future considerations, and summary

Currently the USDA is collaborating with other agencies, state governments, and private partners to establish climate hubs focused on regional solutions for risk adaptation and mitigation to climate change. These efforts will provide farmers, ranchers, foresters, and land managers information and technological resources suited to solve their unique climate change challenges.

Carbon dioxide (CO_2) is a major greenhouse gas recognized by the scientific community for its contribution to climate change. The USDA-NRCS is making new efforts to research, map, and evaluate the role that soils and plant materials play in sequestering carbon in terrestrial systems. This Tech Note focuses on carbon and carbon sequestration in crop production, grazing land, and forestry in particular. Also discussed are the most common management practices to sequester carbon in these systems, namely, conservation tillage, cover crops, controlled burning, and fertilization.

Although climate change is a global issue affecting many social, environmental, and economic sectors at the macro level, using carbon sequestration to help take carbon out of the atmosphere is managed at the local and regional levels. This Tech Note focuses on a loosely defined region referred to as the Atlantic Coastal Plain; an area stretching from parts of Massachusetts to New Jersey and the Delmarva Peninsula, south to North Florida and west to the Florida Panhandle. The common attribute for this regional group is the predominance of underdeveloped, acidic, nutrient poor, loamy sands bordered inland by the Piedmont Plateau and reaching to sea level in the coastal zone.

The Carbon Cycle

Carbon is an element found in all living organisms and is essential for life. It helps form organic molecules, creates stable bonds between atoms, and links to other carbon atoms to form a millions of different compounds. Through the carbon cycle, when living organisms such as plants die or decay, this carbon is released into the soil and respired back into the atmosphere in the form of CO_2.

In soils, carbon may be in elemental, inorganic, or organic forms. Elemental carbon takes the form of charcoal, soot, graphite, and coal. Inorganic carbon is derived from the geologic parent material (the base rock) and is found in calcite or dolomite, while organic carbon is found in plant litter and humus.

Along with the biological process of decay, other sources of CO_2 are animal respiration, and anthropogenic (human) sources such as agricultural and forestry practices (deforestation), land use change, fossil fuel combustion, and industry pollution. While agriculture and forestry practices are responsible for carbon emissions, they can also play an important role in storing, or locking up carbon.

What is Carbon Sequestration and How Does it Work?

According to the Department of Energy, carbon sequestration is the provision of long-term storage of carbon in the terrestrial biosphere, underground, or the oceans so that the buildup of CO_2 (the principle greenhouse gas) concentration in the atmosphere will reduce or slow (Lal et al., 2007).

Carbon sequestration naturally occurs through the process of photosynthesis when CO_2 from the atmosphere is stored in vegetative biomass and soil organic matter until it is eventually returned to the atmosphere through decomposition or respiration. Carbon sequestration is a temporary state in the carbon cycle that can be measured annually by the amount of CO_2 that is stored in above and below ground biomass. Carbon storage is the total amount of carbon sequestered over a given number of years, and is considered a “carbon sink” if the amount of carbon stored is greater than the amount of carbon released (EPA, 2010).

Photosynthesis in C3 and C4 Plants

Photosynthesis occurs in two stages: a light reaction stage where chlorophyll electrons gain charged particles from water molecules that are split into hydrogen (H) and oxygen (O) atoms. This process results in the formation of oxygen gas (O_2) that is released through the open stomata.

The second stage of photosynthesis is the process of CO_2 fixation where CO_2 from the atmosphere combines with the sugar ribulose diphosphate. The product of this reaction combines with hydrogen produced in the first stage to form PGAL (phosphoglyceraldehyde), the “building blocks” of more complex molecules such as monosaccharide sugars or starch. The processes in stage one only takes a fraction of a second to complete and the second stage is complete within minutes of light entering the leaf’s mesophyll tissue (Capon, 1990).

There are two photosynthetic pathways that allow plants to obtain energy (sugars and starches) through the Calvin Cycle. The C3 and C4 pathways are distinguished by the number of carbon atoms that occur as the result of adding CO_2 to a 5-carbon sugar. C3 plants use oxygen catalysts to get their CO_2 directly from the atmosphere. C4 plants do not have these enzymes and so store this carbon in a 4-carbon organic acid away from the presence of atmospheric oxygen. Through additional steps, the 4-carbon compound in a C4 plant is broken down to CO_2 and entered into the Calvin cycle.

Plants differ in the way they use carbon based on how they respond to environmental conditions. C3 grasses grow best at 15–25˚C (59–77 ˚F), and 30–40˚C (86–104˚F) is the optimal temperature for C4 grasses (Nelson, 1996). High light intensities and high temperatures cause C3 plants to spend energy on oxygen catalysts during a process called photorespiration, and are thus relatively inefficient under those conditions. C4 plants on the other hand, are more efficient under conditions of drought, high temperatures, and low nitrogen, because they do not use O_2 in photorespiration.

Therefore C4 grasses such as millet (*Pennisetum glaucum*), maize (*Zea mays*), and sorghum (*Sorghum bicolor*) have evolved to grow in warmer, water-stressed climates while C3 plants such as wheat (*Triticum sp*.), rice (*Oryza sativa*), and barley (*Hordeum vulgare*) grow in more temperate zones. The geographic range of both C4 and C3 plants often overlap, yet C4 species are much more common in the Southern United States, subtropics, and tropics. While C4 plants represent only 3% of flowering plants, roughly one third of all photosynthesis on land is attributable to C4 plants.

Globally, grass species are more or less equally divided between C4 and C3 species. In the Southern Atlantic Coastal Plain state of Florida however, C4 species make up 80 percent of grass species present. The existence of a large population of C4 grasses could negatively affect the amount of carbon that can be stored in future carbon-rich scenarios, as C4 plants, unlike C3 plants, do not significantly respond to increases in atmospheric carbon, and may also have a negative response to CO_2 enriched environments (Allen et al., 2006; Parton et al., 2001).

As we see, geography and climate play a significant role in determining whether C3 or C4 plants predominate in a region, and by extension, the potential for carbon sequestration. Nevertheless, the potential for carbon sequestration is determined by many factors besides geography and climate; such as by soil type, plant species, land use, and management practices.

Carbon Content of Vegetation

The carbon content of plants is consistent across a wide variety of plant species (Magnussen and Reed, 2004) and can be quickly estimated by using the following equation:

$$C = 0.475 \times B$$

(C = carbon content by mass; *B* = oven-dry biomass)

Throughout the day the carbon economy of the plant is not static, and as some carbon is fixed, some carbon is also lost through respiration. Approximately 30–50 % of the carbon fixed per day can be lost through respiration (Poorter et al., 1990). Total carbon content of vegetation is determined by plant species characteristics such as whether or not the plant uses C3 or C4 pathways for photosynthesis; if it is a hard or softwood, if it is fast or slow growing; if it is native or introduced; and even by the plant material’s state of decomposition. A variety of vegetative classes in all states of decomposition (including litter and woody debris) should be used to determine total ecosystem carbon. Herbs, shrubs, and even mosses contribute to total carbon pools (Magnussen and Reed, 2004) and should not be overlooked.

Approximately 90% of a plant’s dry weight is the result of photosynthesis (Poorter et al., 1990). Vegetative biomass is made of a wide variety of biochemical combinations of complex carbohydrates, waxes, terpenes, lignin, and tannin. The assortment of these chemicals is dependent upon the plant species and its particular growth stage. In regards to C sequestration, cellulose and lignin play the most important role.

Table 1. Plant products resulting from plant metabolism.[1]

CO_2+H_2O+Light (Photosynthesis)	Soil minerals
Sugars	• Lignin (cell walls)
• Starch (stored food)	• Fats
• Pectin (binds cell walls)	• Proteins
• Cellulose (cell walls)	• Pigments
	• Hormones
	• Vitamins
	• Alkaloids
	• Tannin

[1]/ Modified from Capon (1990)

Cellulose: Thousands of glucose molecules created from photosynthesis form long chains to form cellulose, a complex carbohydrate that is the basic component of plant cell walls (primary walls). With age, cell walls thicken by adding additional layers of cellulose. Once incorporated into the structure of the plant, cellulose is not broken down into component glucose units for the plant's future energy needs (starch performs that function). Cellulose makes up 40–50% of the dry weight of plants.

Lignin: As plants mature (lignification), a hardened amorphous substance called lignin forms deposits on the cellulose surface, eventually encapsulating the cellulose in a hard layer called a secondary wall. Each newly-formed wall layer is formed within the last. Unlike cellulose, lignin is not composed of carbohydrate (sugar) monomers but complex polymers of aromatic alcohols. Cellulose fibers (microfibrils) work in concert with lignin to provide the plant's structure. Cellulose provides a structural and load-bearing weave, while lignin fills the spaces in the cellulose fibers, providing stiffness and rigidity. Lignin not only helps provide plant structure, but because it is hydrophobic, it prevents the absorption of water in cell walls, thus facilitating water transport in vascular tissues. Plants also produce lignin in response to mechanical damage or infection (Pedersen et al., 2005).

Lignin plays an important role when determining cellular partitioning of carbon in whole-plant C allocation budgets. It also plays an important role in litter chemistry, as litter with greater amounts of lignin will be more resistant to microbial decomposition, thus reducing decomposition rate and increasing soil carbon sequestration (Tuskan, n.d; Wedin, 2004).

***Plant Degradation*:** Under all situations, a living or dead residue of either grass, forb, or legume is left on the soil surface or incorporated into the soil, eventually adding carbon to the soil. This plant residue will degrade at rates dependent upon their various carbon constituents.

Bardgett (2005) suggests 3 levels of degradation:

1	very easily degradable	labile, low molecular weight	sugars, amino acids	readily used by microbes
2	moderately degradable (intermediate)	moderately labile	cellulose, hemicellulose	less readily available
3	not easily degradable	most recalcitrant fraction	lignin, structural materials	not readily available

Essentially the goal is to intensify production by keeping the land covered with biomass yearlong and eliminating any winter or summer fallow periods. Along with adding SOC to the soil, intensification through increased cropping and decreased soil disturbance will help slow the rate of SOC mineralization/oxidation (Wang et al., 2010).

Grasses: C4 grasses possess characteristic traits that allow them to respond positively to increases in atmospheric CO_2 including:

- higher water use efficiency (WUE)
- higher CO_2 fixation rate than C3 grasses
- more efficient PEP carboxylase enzyme in mesophyll cells of C4
- better N–use efficiency

(Moore et al.)

Despite these apparent physiological advantages, most C4 grasses exist in habitats that already suffer from N and water deficiency, and in future climate change scenarios these conditions are predicted to become extreme. Thus, it is commonly thought that rising global temperatures will limit any positive response C4 grasses might have to increased atmospheric CO_2. In addition, interaction among factors such as temperature extremes + fire suppression + over grazing may ultimately create more limiting conditions in C4 than C3 grasses.

C3 grasses are limited by photorespiration, a counter-productive process in which oxygen is used during photosynthesis and carbon and nitrogen are lost. Conversely, photorespiration has very little impact on C4 grasses. Temperature does influence photorespiration rates, and generally photorespiration is greater in climates with higher temperature than lower temperature (Nelson, 1996). In response to warmer temperatures, C3 grasses close their stomata to reduce water loss, thereby also cutting off the entranceway that carbon dioxide uses to enter the leaf. This ultimately results in decreased photosynthetic output. Yet despite these inherent limitations, the C balance in C3 grasses is still positive because net photosynthesis increases 3–5 times the rate of photorespiration (Nelson, 1996).

Table 2. Comparison of cell wall composition in C_4 grasses[1], and primary vs secondary walls in grass and dicots[2].

Chemical Composition[3]	Maize (stover)	Sorghum	Miscanthus	Switch-grass	Sugarcane (bagasse)
Cellulose	27–40	21–45	28–49	28–37	35–45
Hemicellulose	25–34	11–28	24–32	25–34	25–32
Lignin	9–15	9–20	15–28	9–13	16–25
	Primary Wall		**Secondary Wall**		
	Grass	**Dicot**	**Grass**	**Dicot**	
Cellulose	20–30	15–30	35–45	45–50	
Hemicellulose	-	-	-	-	
Lignin	minor	minor	20	7–10	

[1]/ Adapted from Van der Weijde et al. (2013)
[2]/ Adapted from Vogel (2008)
[3]/ Percent of dry matter.

Ultimately, C3 grasses have the opposite response in climate change scenarios, and are predicted to respond favorably to increases in atmospheric CO_2; increasing productivity 58% in crops, 44% for trees, and 42% for herbaceous species (Wedin, 2004).

Fast-Growing vs Slow-Growing Plants: Fast-growing grass and fast-growing herbs have higher CO_2 uptake during photosynthesis than their slower-growing counterparts (Atwell et al., 1999). When attempting to determine net carbon gain, it is important to also account for carbon loss through shoot and root respiratory loss (whole-plant respiratory loss). Fast growing herbs lose more through shoot respiratory CO_2 loss than their slow-growing counterparts, however total gross photosynthetic CO_2 gain is greater in fast-growing herbs (Atwell et al., 1999).

Root and Shoot Gains and Losses: Generally, there are four main ways roots supply C to soils:

- Quantity of root detritus (amount due to root sloughing and root death)
- Quality of root detritus (influences turnover rate and varies with species and location of root in soil profile)
- Release of root exudates (influencing microbe activity and metabolism rate of root detritus)
- C transfer to root symbionts (allocation of carbohydrates to mycorrhizal fungi)

(Tresder, 2005)

It remains uncertain whether C storage in roots increases in response to elevated atmospheric CO_2 levels. Current research is more certain that as atmospheric CO_2 increases, photosynthesis, aboveground biomass, and root biomass all increase. Runion et al. (2009) find that the C entering from root exudation or sloughing of root cells may not add significant carbon to the soil as these inputs are easily degradable. However, byproducts of decomposition, like the sticky protein glomalin, permeate the soil and contain 30–40% carbon (Wright and Nichols, 2002).

Additionally, glomalin helps form soil aggregates, coats hyphae of fungi, helps plants access and retain nutrients and water, and most importantly, helps roots resist microbial decay (Nichols, 2007). Thus a root's lifespan (longevity) and ultimately the C flux in soil is determined by root quality and the ability or inability of soil microbes to metabolize extra root C.

A large portion of carbon allocated to roots appears to be dedicated to fine root production specifically (Tingley et al., 1996); but it is largely unknown how these fine roots contribute to C and N cycling. Also

Table 3. Comparison of α-cellulose, lignin, and ash content in select non-woody and woody plant materials as determined by position on the plant stalk or branch.[1]

Chemical Composition	Location on Plant[2]	Kenaf	Giant Reed[3]	Miscanthus	Switch-grass	Cotton	Olive Tree	Almond Tree
		Species						
α-Cellulose Content (%)	B	43.8	37.7	43.7	42.6	43.8	41.7	40.7
	M	42.6	36.7	41.8	41.4	42.2	40.7	39.7
	T	40.2	34.4	39.1	41.0	40.1	38.1	37.1
Lignin Content (%)	B	15.5	20.5	28.5	-	17.6	21.5	27.3
	M	15	18.5	27.7	-	15.4	19.4	26.5
	T	13.4	16	26.7	-	13.4	17	25.7
Ash Content (%)	B	4.1	4.9	2.1	-	3.5	2.0	2.2
	M	4	4.4	1.9	-	3.7	1.9	2.4
	T	3.6	4.3	1.7	-	3.4	1.8	2.3

[1]/ Adapted from (Ververis et al., 2004)
[2]/ Location on the plant stalk or branch is represented by B = base; M = middle; and T = top.
[3]/ Data in the study were not significantly different between reed internode and reed node samples, thus reed samples of stalk represent internode samples.

uncertain is the role mycorrhizal associations play. Together, fine roots and mycorrhizal fungi often contribute equal or greater amounts of organic matter to the soil than aboveground biomass (Zak et al., 2000).

Studies indicate that fertilizing with N can help increase the amount of carbon in roots. Elevated levels of CO_2 increased shoot and root growth of *Quercus robur* seedlings when combined with high N fertilization (Maillard et al., 2001). This study also suggests that oak seedlings in low N soils will not benefit from increases in atmospheric CO_2.This finding is particularly important in the context of considering future carbon sequestration potential in N-limited Coastal Plain soils.

Table 4. Estimated root residue produced by a variety of crops.[1]

Crop	Estimated Root Residue (lb/ac)
Native prairie	15,000–30,000
Italian ryegrass	2,600–4,500
Winter cereal	1,500–2,500
Corn	3,000–4,000
Red Clover	2,200–2,600
Spring cereal	1,300–1,800
Soybeans	500–1,000
Cotton	500–900
Potatoes	300–600

[1]/ Adapted from (Magdoff and Van Es, 2008)

Soil Type

Soils play a central role in any discussion of carbon sequestration. The global soil organic carbon (SOC) pool is over three times that found in the atmosphere (Lal, 2002; Unkefer et al., 2001). Not only is the soil C pool larger than both the vegetative and atmospheric C pool, but soils undergo the largest fluxes in the carbon cycle (Schlesinger and Andrews, 2000). It is estimated that 61 to 62 gigatons (1 gigaton = 1 million metric tons) are lost from the soils to the atmosphere per year through soil organic matter oxidation or erosion alone (Soil Carbon Center, 2010). By some estimates, to balance the amount of C lost to the atmosphere per year through land use change and fossil fuel use, an annual residual sink of ~2–4 Pg (1 Pg = 1 billion metric tons) is needed (Beedlow, 2004). This number represents over ~3–6 times the estimated current annual terrestrial sink in plants and soils combined.

Along with soils, geography plays a significant role in determining the variability in SOC pools. Arid and warm climates have smaller C pools, and tend to have limited ability to sequester carbon. This is largely caused by environmental factors that increase rates of erosion, decomposition, and oxidation of soil organic matter (SOM) in these regions. Temperate grasslands have been found to contain more carbon when compared to tropical forests (Greenland,1995; Allen et.al, 2006) and arctic, boreal, and temperate regions have the greatest concentrations of SOC. The boreal forest contains large C pools because microbes responsible for breaking down and decomposing carbon are largely absent from the soil, in contrast to the humid tropics, where soil respiration from microbes is greatest.

Table 5. Soil partitioning of carbon inputs into fractions[1,2]

Fraction Layer[1]	Input[2]	Turnover Rate (years)[1]	% of Total SOM[1]
"active"	live microbial biomass, material with low C:N ratios, recent litter inputs	1–5	2–8
"slow"	Particulate organic matter with high carbon:nitrogen ratios, high lignin, other organic compounds resistant to decomposition, influenced by tillage	20–50	40–60
"passive"	chemically stable compounds, humin, humic acid of humus, least influenced by management practices	>1000	30–50

[1]/ Adapted from Wedin (2004)
[2]/ Adapted from Fisher and Binkley (2000)

SOC is one component of SOM, and is estimated to make up 58% of SOM (Pluske et al., 2013). While SOC is the carbon contained within SOM, the latter also contains many elements that are components of organic compounds such as hydrogen (H), oxygen (O), and nitrogen (N). SOM can be separated into 3 fractions: 1) active; 2) slow; and 3) passive (see Table 5). As plant matter decomposes and is incorporated by soil biota, most of the carbon is released back to the atmosphere, and some is stored.

The central role that soils play in the C cycle, in C sequestration, and long-term C storage cannot be underestimated. Soil types differ widely in their ability to retain soil CO_2 pools due to the soil's inherent properties. Increased atmospheric C helps stimulate vegetative biomass growth through "the fertilizer effect", however these above and belowground gains are tempered and limited by various feedback mechanisms in the soil. Just as a plant can sequester only a finite amount of C, soils too have a saturation point after which no further C can be stored.

Carbon is transferred to the soil from the plant's root exudates, root death, and dead plant debris including dead leaf, twigs, and branches. Each of these carbon sources decompose on different timelines (turnover times) that is species specific. For example, depending on the species under investigation, the fine roots alone may live for days or years (Beedlow, 2004).

These topics are not exhaustively discussed here but are meant as an introduction to the central role that soils play in determining the fate of carbon inputs in total C budgets.

Description of Coastal Plain Soils

Coastal Plain soils are loose, acidic, infertile, and poorly developed. These soils are primarily well-drained, loamy-sand soils that often become poorly drained towards the coastal lowlands. The area is dominated by Ultisols, with suborders of Udults and Aquults most predominant. Udults are freely drained and humus poor soils. Aquults occur in wetter areas in the coastal plain where in winter and spring, ground water is close to the surface.

Coastal Plain soils present a particular challenge to land managers in storing and accumulating SOC pools. Carbon additions in sandy soils are easily oxidized when inverted through tillage practices, so SOC accumulations tend to be ephemeral, temporary gains (Novak et al., 2009). It remains uncertain to what extent more recalcitrant forms of carbon can be added and retained in these easily C-saturated soils. Soil amendments such as biochar have been used to counteract the inherent low soil fertility in Coastal Plain soils and have increased soil organic carbon, cation exchange capacity (CEC), and pH levels (Ducey et al., 2012).

Other greenhouse gases (GHGs) exist outside the scope of this technical note, and may have a greater influence on climate change than carbon. There is a high percentage of N_2O lost through denitrification because of the high acidity (low pH) characteristic of the Coastal Plain soils (Weier and Gilliam, 1986). This is significant because nitrous oxide molecules remain in the atmosphere for 120 years and pound for pound, contribute 300 times more to atmospheric warming than carbon (EPA, 2014).

Table 6. Comparison of SOM across various forest climate zones according to soil texture.[1]

Forest Climate Zone	Soil Texture Index	Soil Organic Matter ($Mg\ ha^{-1}$)
Boreal	loamy	121
	sandy	87
Temperate	clayey	74
	loamy	206
	sandy	204
Tropical	clayey	234
	loam-clay	90
	loamy	121

[1]/ Adapted from (Vogt et al., 1995).

C Sequestration in Major Land Uses

Crop Production

Cropland continues to occupy the largest percentage of global land area (Wang et al., 2010) and is well positioned to play a central role in any effort to reduce land degradation, increase terrestrial vegetation, and increase SOC. In the United States, 40% of total land area is dedicated to agriculture (Franzluebbers, 2010).This potential is both an opportunity and a challenge. The United States has lost 5 billion metric tons of carbon from cultivation (Lal et al., 1999) and agriculture and land-use change contribute to 20% of global anthropogenic CO_2 emissions. (Wang et al., 2010). Nevertheless, improving the carbon efficiency of crop production systems can be done relatively quickly, with no negative environmental impacts, while increasing soil health, productivity, and ultimately farmer income (Unkefer et al., 2001).

Crop residue is the main carbon input in crop production systems. The greatest amount of residue in order of magnitude is found in corn production > wheat > soybean. Other important sources of residue are: sorghum, cotton, rice, sugarcane, barley, sugarbeat, potato, oats, and sunflower (Blanco–Canqui and Lal, 2009). Crop residues can play a positive role in maintaining or increasing SOC pools if managed effectively. Competing uses for crop residue, such as for biofuel feedstocks, animal feed, or industrial raw material threatens their use as a C source.

__Key Concept:__ Fertilizer Effect- the assumption of a positive plant or crop response from an increase in atmospheric CO_2 levels.

Intensive land management practices such as deep tillage and cultivation disturbs soil aggregates, increases residue decomposition rates, and reduces subsequent C stores. Management of these residues is discussed further in this Tech Note in the section entitled Management Practices to Improve SOC.

Forestry

The factors that determine level of C sequestered in forests are: 1) species of tree; 2) management practice; 3) soil type; 4) regional climate; and 5) topography (EPA, 2010). Again, the amount of C sequestered will not be uniform across regions or even individual fields so estimates will have to be based on local conditions, species, and the age of the stand. Old growth forests and secondary forests also have complex dynamics concerning C cycling. For example, after 80 years of secondary regrowth in tropical forest sites, previously disturbed forests have less ability to sequester C than old-growth forests. Although aboveground biomass approached that of old-growth forests, belowground biomass took longer to recover and many old-growth species could not recolonize forests (Martin et al., 2013). This study finds that larger landscape level drivers negatively affected seed dispersal and recruitment of old-growth species such as habitat fragmentation and loss of animal seed carriers.

Competition and resource availability also help determine the total carbon allocation in forests. These factors in turn affect:

- Plant growth
- Litter quality and decomposition rates
- Carbon and nitrogen sequestration
- Plant–atmosphere gas exchange

Seasonal changes within the year play a significant role in determining C storage rates, as senescence of leaves will reduce sequestration rates most notably in the extreme northern and southern latitudes. Thus due to less seasonal growth rate variability, the rate of carbon sequestration in trees increases, in general, as you approach the tropics. Deciduous trees lose their leaves each year while coniferous needles can last up to 8 years or more (Beedlow, 2004). Additionally, the rate of carbon storage in trees slows down with age, and after approximately 80 years of aging (depending on species), growth slows, and C reaches a saturation point and levels off.

Increased levels of CO_2 in the atmosphere will not necessarily increase a forest's long-term C storage due to other offsetting factors such as N availability, air pollution, and C processing dynamics (Beedlow et al., 2004).

Forests have limited N availability, and if increased could potentially improve plant responses to CO_2. For example, biomass of white oak (*Quercus alba*) was increased 85% in nutrient-poor soil by increasing CO_2. Root/shoot biomass ratios were three-fold higher in high N treatments compared to low N treatments (Tingey et al., 1996).

Litton et al. (2007) refer to several common surrogates that have been the preferred methods to measure amount of C sequestration in forests including:

- Interannual allocation of resources at individual plant, tissue, and cellular levels
- Dry matter production with changing resource ability
- Evaluating patterns of biomass accumulation in above and belowground plant components (root vs. shoot)
- Net primary productivity (NPP)

Table 7. Distribution of carbon stored in forest ecosystem[1]

Location	% carbon stored
Soil	59
Tree & Roots	31
Forest Floor (litter)	9
Understory	1

[1]/ Adapted from (Birdsey, 1992)

Papermaking: Fiber length and cell wall thickness influences paper's mechanical strength along with the lignin and cellulose content of raw plant materials. The greater the lignin content of the plant material, the greater the energy and chemicals required in the pulping process, thus the less it desirable for papermaking (Ververis et al., 2004). Because non-woody plants have lower lignin content than woody soft and hardwoods, there is a growing interest in using non-woody species for sources of pulp and paper raw materials.

For the purposes of determining potential C-sequestration in both woody and non-woody plants, it should be noted that cellulose, lignin, and ash content all decrease significantly when moving from the base of the stalks or branches to the top of individual plants (Ververis et al., 2004). Also, the chemical composition that makes some plants (especially non-woody plants) desirable to the papermaking industry are opposite those that favor long-term C storage.
In management strategies that use hardwood sources for pulp production , selection of plant material will be determined on slenderness ratio, flexibilitiy coefficients, and Runkel ratios. ((For more information consult: Ververis et al. (2004)).

***Conifers (softwood) vs Deciduous (hardwood)*:** The greater the lignin and cellulose content in a plant, the woodier it is, and the longer it will take to break down and release stored carbon. Generally, the carbon content of softwoods is less than hardwoods, and early wood (EW) ("Spring Wood"), has less carbon than late wood (LW) (wood produced toward the end of the growing season) (Bertaud and Holmbom, 2004). Secondary walls in LW tend to be thicker than EW, and fiber length is longer in softwoods like spruce (*Picea abies*) when compared to hardwoods such as birch (*Betula verrucosa*). Hardwood merchantable roundwood (pulpwood and sawtimber) has greater weight in green tons than pine merchantable roundwood. This species-specific delineation is important because it determines carbon accumulations by the ton; the same unit in which CO_2 is traded in financial markets.

In terms of land use types, SOC stocks in forests are similar to grasslands, and are greater than annual and perennial croplands. If a forest is converted to cropland, the losses of C per unit area can be 20–100 times greater than before the conversion (Batjes, 1999) and losses are mainly due to changes in the aboveground biomass.

Table 8. Carbon accumulation in metric tons/ac/yr for three different softwoods and one hardwood common in Southeast Coastal Plain.[1,2]

Carbon Accumulation in Metric Tons per Acre per Year[1]				
	Years Since Planting			
Species	**0-5**	**6-10**	**11-15**	**16-20**
Loblolly Pine	1.51	1.86	6.99	6.17
Slash Pine	1.51	1.75	6.52	5.83
Longleaf Pine	1.4	1.51	5.24	4.78
Oak (Hardwood)	1.63	2.48	2.07	2.07

[1]/ Carbon accumulation per acre is dependent on density of planting. These numbers represent dense planting (>250 stems per acre). Adapted from (Current et al., 2007)
[2]/ These figures are taken from Chicago Climate Exchange (CCX) tables.

US greenhouse gas inventories consider five different storage pools when determining C stocks in forests: 1) total aboveground biomass, 2) below ground biomass, 3) dead wood, 4) litter, 5) and SOC (EPA, 2010). Changes in soil and soil carbon from forestry management practices are complex and have not been studied in detail. Regionally, soils are highly variable, and often the reference condition does not date back far enough to compare carbon flux processes in current conditions. Additionally, in the case of Northeastern forests, current forest composition is largely determined by legacies of colonial farming dating back 200 years. The implication is that a long history of human induced disturbances such as deforestation, logging, and fire has lead to a predominance of early and mid-successional taxa that are more vulnerable to disease, invasive species competition, and climate pressures like drought. This lack of resilience may limit a forest's composition, function, and potential for C sequestration (Thompson et al., 2013).

Nevertheless, it can be generally said that harvesting does not significantly affect carbon stocks in the soil in the long term if the land is replanted to trees (Kimble et al., 2003). If the forest is burned and replaced with pasture, most of the carbon that the soil lost in the burn is returned within a year after conversion, and almost entirely restored within eight years of conversion (Batjes, 1999).

Fire, especially intense wildfires, can have a negative effect on soil carbon by reducing aboveground biomass and altering the physical and chemical properties of the soil. Volatilization of organic matter typically occurs between 200–315° C (Knicker, 2007) and could be prevented with the use of managed, controlled burns. In this case, the most important factor in returning C to forest soils after disturbance is the species of plants that re-colonize the changed landscape.

Planting nitrogen fixing legumes after a prescribed fire helps increase SOC by creating better soil fertility. Forests with poor soil fertility have been shown to have lower sequestration rates when compared to forests that have had nutrients added (Oren et al., 2001). Also, by increasing N inputs to forest systems that are chronically N-limited, stand productivity increases along with litter fall and root decomposition (Jandl et al., 2006).

Timber harvesting can contribute to C losses as only 23% of the wood that is harvested is marketable (Wang et al., 2010), while the remaining plant material is either burned or left to decompose. Gains in C storage from harvested forest products should be seen as a temporary sink, as eventually the products will degrade and return to the C cycle. Paper has a half-life of approximately 4 years, and building materials and furniture have a half-life of approximately 65 years (Beedlow et al., 2004).

Table 9. Average Amount of Carbon Sequestered for Various Biomes (tons/ac) [1]

Biome	Plants	Soil[2]	Total
Cropland	1	36	37
Temperate Forests	25	43	68
Temperate Grasslands	3	105	108
Wetlands	19	287	306
Desert/Semi-desert	1	19	20
Boreal Forests	29	153	182

[1]/ Adapted from (Gorte, 2009).
[2]/ Measured down to 1 m (meter)

Strong coastal storms and hurricanes can also impact changes in above ground biomass by toppling trees, breaking limbs and branches, and adding debris to the soils. When selecting tree species for reforestation in the Coastal Plain, land managers should consider which species demonstrate the highest wind resistance and survival during storm events.

Due to limited research, the exact carbon content of wood for most tree species remains unknown; Table 16 and 17 lists estimated values for a number of North American species in the Coastal Plain. Although slightly variable, the accepted current estimate, on average, is that one acre of forest trees can sequester approximately 410,000 lbs of CO_2 (American Forests, 2015). Another estimate finds that 1 ton of carbon can be sequestered in roughly 2.2 tons of wood (Batjes, 1999) and that pine plantations in the southeast are capable of storing approximately 1 ton of carbon per acre per year (EPA, 2015). More accurate assessments of carbon storage for individual species can be determined by using online carbon calculators provided by the USDA Forest Service Climate Change Resource Center: http://www.fs.fed.us/ccrc/topics/urban-forests/ctcc/.These calculators use DBH (diameter at breast height) x the species growth factor to determine the approximate age of the tree.

Improving forestry practices through selective cutting, increased stocking, reducing erosion and soil disturbance, increasing rotational length, and creating multi-age stands to enhance biological diversity, can help improve carbon stocks in forest regimes.

Grazing Lands

Grazing lands is a common term used to define rangeland, pastureland, grazed forestland, native and naturalized pasture, hayland, and grazed cropland (NRCS, 2013). Approximately 70% of the world's agricultural area is dedicated to rangelands and pasture (Conant, 2010). Rangelands account for 10–30 percent of the world's SOC and make up roughly half of all US grazing lands (Schuman et al., 2002). In the US, grazing land is mostly concentrated in the West, with only minimal pasture and range in the southeast Coastal Plain; mainly in Florida. Yet in Florida, more land is dedicated to grazing land than to cropland, covering about 5.5 million acres (Clouser, 2009).

The main factors affecting carbon sequestration in grazing lands are grazing intensity, burning, fertilization, and restoration practices (Mortenson et al., 2004). Other significant factors affecting CO_2 sequestration include length of growing season, temperatures, and even cloudiness (Suyker et al., 2003).

These climate factors play a large role in determining biomass production, thereby affecting the amount of carbon directly fixed or returned indirectly to the soil as plant litter. Soussana et al., (2004) calculated the annual net ecosystem production (NEP) of grassland at 1–6 t C $ha^{-1}yr^{-1}$. This figure is dependent on radiation, temperature, water regime, nutrient status, and age of sward. Suyker et al. (2003) found that moisture stress and timing of stress had a significant negative effect on carbon sequestration over a three-year prairie study.

Most carbon sequestration in grazing land occurs in the top 30cm of soil. Root litter is the largest carbon input to the soil (Soussana et al., 2004) and grasses, especially many tropical species, produce a large amount of deep-rooted biomass. Fast growing perennial grasses like switchgrass and miscanthus offer management solutions that are able to sequester 3 times the carbon as conservation tillage (Khanna et al., 2007).

Converting grazing lands to cropland may result in a 95% aboveground and 60% belowground loss in C. When compared to cropland, grassland grazing systems create less soil disturbance and therefore carbon is better stabilized. Another advantage is that grazing lands can be managed with fewer inputs and on larger scales than cropland. Nevertheless, the intensity and duration of grazing should be closely monitored so as not to reduce sequestration rates (Franzluebbers, 2010). At this time, data have not consistently determined whether grazing itself has an overall positive or negative effect on SOC (Rice and Owensby, 2001).

Measuring the effectiveness of management changes on C sequestration in grassland can be more challenging than in crop production or forestry because:

- sequestration rates are slower
- difficulty in measuring change
- benefits widely-distributed across many landowners
- practices may be more varied
- costs of implementation are poorly quantified
- science is less complete

(Conant, 2010)

While it takes generations to recover the C in native grassland soils, the conversion of grassland to cropland results in immediate carbon losses. Soussana et al., (2004) found that regaining lost carbon is a slow process taking several decades. In a long-term study where cropland was converted to native grasses, regression analysis was used to estimate that it would take approximately 100 years for the SOC to reach levels in the native prairie to 60cm depth (Potter et al., 1999). When converting grassland back to forest, the gains and losses of carbon are not as certain, and are largely dependent on soil type and climate.

Table 10. Geometric mean of SOC to 1 meter depth in Coastal Plain for major land uses.[1]

	Land Use				
Region	**Crop-land**	**Forest**	**Pasture**	**Rangeland**	**Wetland**
	Mg SOC/ha				
NJ, DE, PA, VA, MD, WV	121	159	132	—	738
VA, NC, SC, GA	173	302	341	—	494
GA, FL, AL, MS	279	183	339	342	420
	Mt SOC yr^{-1}				
Estimated Amount of CO_2 Sequestered/yr SOC under (RMPs)[2]	45–98	25-102	13–70	—	—

[1]/ Adapted from (West et al., 2013)
[2]/ Adapted from (Lal et al., 2009). Recommended Management Practices (RMPs) here consists of the use of reduced till (RT) and no till (NT). These data represent potential gains.

Biofuel Production

The Energy Independence and Security Act of 2007 made production of advanced biofuels a priority. Second generation biofuels consist of grasses like switchgrass (*Panicum virgatum*) and giant miscanthus (*Miscanthus* x *giganteus*). Second generation biofuels are produced in a CO_2 neutral fashion from the lignocellulosic biomass of fast growing woody plants like poplar (*Populus* spp.) and willow (*Salix* spp.) (Potters et al., 2010).

Current breeding strategies focus on increasing stem biomass yields and cell wall polysaccharide content while reducing lignin content (Van der Weijde et al., 2013). These biofuel feedstocks will be grown ideally with less inputs on marginal soils, thus cultivar selection and development should focus on increasing resiliency, resource efficiency, and stress-tolerance.

Management Practices to Improve SOC

While soil, vegetation type, rainfall, and climate play a significant role in determining C flux in the SOC pool, the greatest influence on carbon sequestration in the Coastal Plain is management practices. Generally speaking, increasing the soil organic carbon (SOC) pool improves soil quality and increases agricultural productivity. Because the SOC pool is the primary component of soil organic matter (SOM) levels, the best way to encourage or increase carbon sequestration in soils is through the conservation of plant material in the field. While vegetation does not contain a C pool as large as soil, it is mainly *through* plant materials that soil carbon pools are managed. Many of these conservation measures are already known in resource management systems (RMS). They include the use of minimum and no-tillage; increased use of manure and fertilizer application; use of cover crops, mulching, and high-residue plants; crop rotations; and optimized irrigation practices.

Table 11. Comparison of the percent of soil organic matter (SOM), pH, and percent of plant-available water capacity under no tillage (NT) and conventional tillage (CT) practices.[1]

Tillage Type	% SOM	pH	Plant-Available Water Capacity (%)
No Tillage (NT)	5.4	7.8	28.5
Conventional Tillage (CT) (heavy disk harrow)	4.0	8.0	24.4

[1]/ Adapted from (Magdoff and Van Es, 2008).

Given enough time, the conversion of cropland to perennial grass systems or managed pasture will increase levels of SOC (Post and Kwon, 2000; Follett et al., 2009). The potential for sequestration will vary widely depending on geography, climate, and species of plant used. Follet et al. (2001) found SOC stocks increased significantly after 5 years by converting cropland to a perennial grass cover in the Great Plains. However, during a 10 year SOC study performed in a sandy Coastal Plain soil, there was no significant change in SOC by depth when converting a cool season grass sod (tall fescue/red fescue) to warm season grasses (Miller and Dell, 2012). In this particular study, it appeared that SOC pools in sandier soils were already saturated from a previous history of cool season C3 turfgrass.

Under optimal growing conditions and the use of restoration practices like conservation tillage or no tillage, it is clear positive gains of SOC can be made at least in the top 20 cm of the soil profile in either cropland or perennial pastures (Franzluebbers, 2010). Achieving positive SOC additions to lower soil horizons > 20 cm is more problematic, especially as one moves south into sandier soils.

Under less than optimal growing conditions, it is likely to take many years before SOC levels increase. Management practices such as no-till should be considered within a whole suite of strategies aimed at reducing carbon losses. Even if widely adopted, any one strategy on its own may not achieve significantly improved results. For example, Schlesinger and Andrews (2000) suggest that even if management practices like no-till were implemented on a large scale, the result would only be a 1 percent change in total CO_2 emissions**.** This should be understood in the context that 12–20 percent of total global CO_2 is due to tropical deforestation alone (EPA, 2010; Van der Werf et al., 2009).

Conservation Tillage

The most commonly discussed way to sequester carbon in crop production systems is by minimizing soil disturbance using reduced or no-till methods. SOC decreases rapidly with tillage, gradually leveling out at a newer, lower equilibrium (Mann, 1986). Conservation tillage should be seen as a long-term investment for crop production systems. The benefits to conservation till are slow to manifest, and typically takes between 9–15 years for significant SOC accumulation (Novak et al., 2009). These gains are only within the top few cm of the soil, where the residue breaks down, and may not effect soil accumulation for the whole soil profile. Follett et al. (2009) note that when sampled below the depth of 30 cm, reduced tillage (RT) showed no evidence of promoting C gain. In fact, in some cases total SOC under no-till (NT) (0–60 cm) did not differ from plow tillage (PT).

Conservation tillage (CT) has been successful in rebuilding SOC in cotton production fields in South Carolina in the 0–3 cm depth, after 6 years. However, lack of residue mixing in the 3–15 cm depth resulted in SOC decline (Novak et al., 2009). In short, surface gains by CT in the shallow surface depths are often offset by SOC losses at lower depths.

Cover Crops

Cover crops are often interplanted with cash crops (intercropping); grown as a weed-suppressing nurse crop; as a relay crop to add nutrients to a subsequent cash crop; or as a temporary residue cover to reduce wind and water erosion. Cover crops are also convenient tools for farmers who are looking for quick cover for temporary periods when either cash crops

Table 12. **The effect of rotations upon SOC accumulation for various commodity crops after changing from conventional tillage (CT) to no-tillage (NT) for various production systems.**[1]

Crop System	SOC Accumulation = Mean Increase in SOC		Average Soil Depth	Average Duration of Experiments Years
	grams M^2	lb M^2		
Continuous Monoculture	704	1.55	21	16
Rotation (no wheat fallow)	710	1.57	22	13
Continuous Corn	932	2.05	25	23
Rotation Corn (no corn + soybean)	603	1.33	22	16
Continuous Wheat	293	0.65	15	12
Rotation Wheat (no wheat fallow)	630	1.39	20	10
Wheat-fallow	142	0.31	23	19
Continuous Soybean	542	1.19	21	10
Rotation Soybean	790	1.74	23	11

[1]/ Adapted from (West et al., 2001)

could not be planted or there is a break in the production schedule when other crops cannot grow (winter).

When cover crops are combined with conservation tillage (CT) practices greater amounts of SOC are sequestered than by using CT practices alone (Causarano et al., 2006). Intercropping can be used to keep the ground covered between rows as well as exploit the vertical space in the canopy, if a climbing legume is used.

Adding plant-derived material into the soil in the form of cover crops creates its own set of challenges. This green manure will inevitably create greater microbial growth and biotic N-demand, resulting in N immobilization and less available nutrients for any subsequent crop (Zak et al., 2000). Thus, timing of cover crop termination and residue management also become important considerations.

Residue of non-leguminous cover crops, particularly grasses, has higher carbon and lignin content and takes longer to break down. Cover crops higher in lignin provide energy for microorganisms and reduce the rate of microbial immobilization (Zak et al., 2000) while increasing moisture retention and cation exchange capacity of soils.

Residue for leguminous cover crops have a lower C:N ratio so do not increase SOM as readily as grasses. Legumes tend to break down quickly, making easily digested proteins and sugars more readily available to microbes. Nevertheless, leguminous cover crops have higher levels of N and can act as a fertilizer source, increasing total plant biomass and reducing the need for additional N input (Wang et al., 2010), especially in elevated atmospheric CO2 scenarios (Wedin, 2004).

Brassicas decompose more quickly than grasses, and slower than legumes, taking up as much N as grasses, but making N more available to the subsequent crop (Clark, 2010). An ideal situation for building SOC would be some combination of grasses, forbs, and legumes in a mixture with a C:N ratio of at least 25:1. Having C content greater than or at this ratio will ensure that N is not immobilized and adequate levels of C are being returned to the soil (Clark, 2010).

Table 13. Comparison of cover crop and pasture grass biomass and their estimated carbon content.

Crop	Biomass[1] lb/ac	Carbon Content[2] lb/ac	Nitrogen lb/ac
Hairy Vetch (*Vicia villosa*)	3,260	1,549	141
Crimson Clover (*Trifolium incarnatum*)	4,243	2,015	115
Austrian Winter Pea (*Pisum sativum*)	4,114	1,954	144
Rye (*Secale sp.*)	5,608	2,664	89
Sunn hemp (*Crotalaria juncea*)	4,500-10,000[a] 8,000-14,000[b]	~2,138-4,750	90-180[a] 120-200[b]
Velvet Bean (*Macuna pruriens*)	2200-4000[b]	~1,045-1,900	40-60[b]
American Jointvetch (*Aeschynomene americana*)	2000-4000[a] 4000-8000[b]	~950-1,900	50-100[a] 40-100[b]
Cowpea (*Vigna unguiculata*)	4000-6000[a]	~1,900-2,850	50-90[a]
Alyce clover (*Alysicarpus vaginalis*)	1500-3500[a] 3000-8000[b]	~713-1,663	15-20[a] 40-150[b]
Sorghum-sudan (*Sorghum bicolor*)	6500-9500[a]	~3,088-4,513	55-80[a]
Bahiagrass (*Paspalum notatum*)	3000-8000[a] 3,000-10,000[c]	~1,425-3,800	55-140[a]
Switchgrass (*Panicum virgatum*)	30,000	14,250	

[1]/ Dry weight of above ground plant material.
[2]/ C = 0.475* B where C is carbon content by mass, and B is oven-dry biomass.
[a]/ (Newman et al., 2007).
[b]/ (Rich et al., 2009).
[c]/ (Newman, 2011).

Controlled Burning

Management practices for grazing lands and forests such as controlled burning may cause short-term effects on C pools. During burning soil temperature can reach 150–220˚C from 1 to 5cm depth (Batjes, 1999) and large amounts of carbon can be returned to the atmosphere. Nevertheless, less intensive controlled burns (< 80˚C) can be used as a management tool to reduce fuel loads, reduce the number of high-severity wildfires (flame temperatures > 800˚C), and reduce mortality in larger trees. In most cases, controlled burning can improve SOC stocks through creating inert forms of locked-up carbon such as charcoal. Thus, to enhance sequestration during burning, closely manage burn schedules to keep fuel loads and fire intensities low, and using long, slow burning. In addition, returning as much residue to the soil surface as possible as surface mulch also would enhance sequestration (Lal, 2004).

Fertilization

Improving nutrient content and soil fertility can help increase SOM (Batjes, 1999) in grazing land and forests. An important consideration when determining carbon stock in grazing systems is the fact that much of the nitrogen in the vegetation is removed (>370kg N $ac^{-1}yr^{-1}$) (Soussana et al., 2004). Interseeding with nitrogen fixing legumes may improve SOC by increasing aboveground biomass (Mortenson et al., 2004). Nevertheless, too much nitrogen use may increase primary productivity but decrease SOC stock by increasing the rate of mineralization. Thus, gains from fertilization in grassland and grassland conversion are not certain.

These long-term carbon stores are slow to develop, occur only in shallow soil horizons (< 30 cm) and appear to reach saturation points dependent upon species, temperature, soils, and climate (Jenkinson,

Table 14. Comparison of C:N ratios for various mulches and cover crops.[1]

Mulch Material	C:N ratio
Chicken Manure	9:1 to 20:1[b]
Soil Humus	10:1[a]
Green Legumes	12:1[b]
Legume Residues	23:1[b]
Green Grass	40:1[b]
Grain Straw/Dry Grass	80:1[b]
Pine Needles	225:1[b]
Sawdust	400:1[a]
Cover Crop	**C:N ratio**
Young Rye Plants	14:1[c]
Rye at Flowering	20:1[c]
Hairy Vetch	10:1 to 15:1[c]
Crimson Clover	15:1[c]
Corn Stalks	60:1[c]

[1]/ Adapted from (Cockx and Simonne, 2003).
[c]/ (Sullivan, 2003).

Table 15. Percent of total organic carbon (TOC) accumulation for various types of fertilizer practices.[1]

Fertilizer Application	TOC accumulation %
OM	26.6
½ OM + N	26.1
NPK	23.2
NP	22.6
PK	18.7
NK	13.9
CK	11.7

[1]/ Adapted from (Gong et al., 2009).

1988). In one long-term grassland study (> 120 yr) there was no difference in SOC content or C:N ratios in the top 23 cm of soil between fertilized and unfertilized plots (Jenkinson, 1988). In another study, SOC increased 5 years after conversion from tilled crop production to native grasses in the Great Plains, but only in the top 2.5cm of soil with N-fertilizer. Without fertilizer, there was no SOC increase (Reeder et al., 1998).

In forests, nutrients in soils are often limited, especially N, and this can limit the amount of carbon sequestered in forest wood (Oren et al., 2001). However, adding extra N to the soils may not always have a positive outcome. A study done by Nadelhoffer et al. (1999) has shown nitrogen added to forest soils was eventually lost through water runoff or through denitrification to the atmosphere and had little effect on C sequestration. Also, Sonnleitner et al. (2000) showed that increasing CO_2 concentrations and N deposition increased leaf and needle biomass with evidence of a synergistic effect, however the extent of the positive impact was largely dependent on soil type, with greatest gains in nutrient limited sandy soils as opposed to calcareous soils.

Nitrogen additions increase water use efficiency (WUE) in agricultural crops and forest stands, increasing growth, leaf area, and lengthening the time a leaf might photosynthesize under water-stressed conditions (Sonnleitner et al., 2000). However, in the same study, adding N enhanced evapotranspiration (ET) by 16% in sandy, acidic soils, while decreasing ET by 6.5% in calcareous soils. In nutrient poor or droughty soils, plants can be expected to allocate additional resources like N to root growth instead of above-ground shoot biomass (Sonnleitner et al., 2000). Generally, increasing nitrogen concentration in plants leads to a higher rate of photosynthesis but also increased rates of respiration (Poorter et al., 1990). Therefore, it does not necessarily follow that increasing

N through supplemental fertilization would be an effective strategy for improving carbon sequestration rates; or reducing GHG as a whole.

Conclusion

Many groups in the United States promote better land management of the terrestrial biosphere as the principle means of reducing carbon emissions (IGBP, 1998; USDOE, 1999; IPCC, 2001). This idea appreciates the central role that vegetation can play in influencing SOC pools, while recognizing also, that the US is committed to finding voluntary and market-based solutions to meet climate goals. Although soil carbon pools play a much larger role in total atmospheric C budgets than terrestrial vegetation, it is mainly through vegetation that we can manage these C pools (Unkefer, 2001).

The IPCC identified carbon sequestration through terrestrial vegetation as one of the most effective options for reducing GHG emissions (Wang et al., 2010). We can currently sink 2.6 billion tonnes of carbon per year using land as a carbon sink, while we lose approximately 9.4 billion tonnes per year through fossil fuel burning, cement production, and land-use change (CDIAC, 2014). Thus, we currently sequester only 27.6% of anthropogenic carbon emissions each year through soils and vegetation. It remains uncertain how much we can improve the amount of CO_2 in long-term terrestrial sinks as C sequestered in vegetation and soils is time-sensitive/dependent, requires continued, careful management, and is not permanent.

Wang et al. (2010) observe that it takes approximately 25–50 years to restore 66–90 PgC (1 petagram (Pg) = one billion metric tonnes) of historic C loss. For some perspective, the combination of land-use changes, combustion of fossil fuels, and cement manufacturing resulted in the addition of 441.5 PgC between the years 1850–2000 (CDIAC, 2014). That is to say, by applying the most appropriate land management for C storage in soils over the next 25–50 years, we can restore approximately 15–20% of anthropogenic CO2 released since 1850. Another finding by the CDIAC (2014) found the estimated cumulative emissions of carbon dioxide for all sources for 2012 alone was 9.67 billion tonnes.

It should be noted that while our ability to sequester carbon through reforestation, more efficient crop and livestock production, and improving soils can help reduce carbon emissions to the atmosphere, better land management should not be seen as a panacea. Efforts to restore the health of forests and soils must be coupled with efforts to reduce industrial and fossil fuel emissions, lest any gains made should be offset or negated.

This Tech Note is not exhaustive, and the topic of carbon sequestration is broad in scope, deep in detail, and rich in research. Thus, this publication hoped to highlight the major opportunities and challenges in the select land uses of cropland, forestry, and grazing land in the Coastal Plain from the Mid-Atlantic south to Northern Florida. Other land uses, such as wetlands, sequester more CO_2 than cropland, forest, and pasture combined (Table 10) but fall out of the scope of this review and so where not detailed here.

As atmospheric carbon and global temperature increase, many gains made by more sustainable management practices may be lost when higher temperatures increase rates of SOM mineralization, most notably in permafrost. Positive predictions of carbon sequestration will be seen in the North, while it is still unclear how tropical carbon sinks will perform (Batjes, 1999). Some researchers have predicted a diminishment of C4 plants with an increase in atmospheric carbon as C4 grasses have evolved under low carbon conditions. Continual logging and deforestation in the tropics further threaten future potential for improved forestry and rangeland practices to make a significant dent in emissions. The increased popularity of waste removal from harvested fields for biofuel production further threatens to decrease carbon stocks.

The main challenge to carbon sequestration in cropland, forestry, and grazing land is that it is not permanent. Any losses in carbon can only be restored after several decades of management, and success will be largely dependent on geography, climate, and species of plants used. As other options will need to be explored, more research should be conducted on alternatives such as urban forestry. Urban forests have a great potential for carbon sequestration and may store even more C than rural forests (Batjes, 1999).

Beyond the scope of this review, but also very important to the gains of future carbon stocks, is the role that other GHGs play in management strategies. For example, 74% of total N_2O emissions in the US come from agricultural soil management; with an additional 5% from the breakdown of livestock manure and urine. Agricultural activities are predicted to increase to almost 80% of total N_2O emissions by the year 2020 (EPA, 2014). Management strategies that promote the fertilization of forests and grazing land to increase carbon stocks may simultaneously increase N_2O emissions, thereby canceling out or losing any intended benefits from sequestering C. These tradeoffs and negative/positive feedback loops are ubiquitous in the study of C and N cycle stores and emissions. Thus, overreliance on vegetation alone as a potential C sink is shortsighted, and a more comprehensive approach of reducing emissions while storing C should be emphasized in all private and public sectors.

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Table 16. Total CO_2 stored (lb/tree for 80 yrs) ranked highest to lowest for select trees in the South and Coastal Plain[1].

Scientific Name	Common Name	South	Coastal Plain
		-------------lb/tree for 80yr----------	
Quercus alba	white oak	84,930	na
Quercus phellos	willow oak	54,295	48,658
Quercus nigra *	water oak	53,961	39,211
Quercus laurifolia *	laurel oak	na	49,390
Acer saccharinum	silver maple	45,654	na
Platanus occidentalis, *	sycamore	na	42,150
Quercus virginiana *	live oak	na	40,235
Ulmus alata	winged elm	39,168	na
Prunus spp.	black cherry	34,145	na
Acer saccharum	sugar maple	28,661	na
Acer rubrum	red maple	27,971	17,872
*Magnolia grandiflora**	southern magnolia	21,256	17,788
Betula nigra	river birch	19,997	na
Pinus taeda *	loblolly pine	17,500	35,077
*Liquidambar styraciflua**	sweetgum	na	16,533
Juniperus virginiana	Eastern red cedar	14,232	22,334
Malus spp.	crabapple	8,894	na
Cornus florida *	dogwood	6,997	3,763
Ilex opaca	American Holly	6,652	9,558
*Lagerstroemia indica**	crape myrtle	3,301	na

[1]/ Results were organized highest to lowest amount of total CO_2 for 80 years for species in the "South". The "South" in this particular carbon calculator represented states from NJ south along Coastal Plain, south to Florida, and west to Mid-Texas. "Coastal Plain" referred to a tree climate zone from Charleston, SC, to Tallahassee, FL, across the gulf coasts states specifically located on the coast. Please refer to USFS Tree Carbon Calculator for more detail: http://www.fs.fed.us/ccrc/topics/urban-forests/ctcc/

Table 17. Total CO_2 stored (lb/tree for 5; 20; 40; 60; 80 yrs) ranked highest to lowest for select trees relevant to the Mid-Atlantic and Southeastern Coastal Plain[1]

		Amount of total lb/tree CO_2 stored at 5; 20; 40; 60; and 80 years				
		---years---				
Scientific Name	**Common Name**	**5**	**20**	**40**	**60**	**80**
Quercus alba	white oak	78	3,631	23,839	71,346.0	84,930
Quercus phellos	willow oak	69.3	3,511	16,907	36,741	54,295
Quercus nigra	water oak	144	3,972	19,053	44,644	53,961
Quercus laurifolia	laurel oak	89	3,664	14,947	30,746	49,390
Acer saccharinum	silver maple	236	5,022	23,471	45,654	45,654
Platanus occidentalis,	sycamore	40	1,541	8,589	22,256	42,150
Quercus virginiana	live oak	344	5,971	16,865	28,539	40,235
Ulmus alata	winged elm	155	10,410	39,168	39,168	39,168
Prunus spp.	black cherry	150	7,776	34,145	34,145	34,145
Acer saccharum	sugar maple	355	5,738	15,528	25,653	28,661
Acer rubrum	red maple	155	2,033	11,438	27,971	27,971
Magnolia grandiflora	southern magnolia	21.6	842	6,184	21,256	21,256
Betula nigra	river birch	159	5,390	19,997	19,997	19,997
Pinus taeda	loblolly pine	22	1,844	12,113	17,500	17,500
Liquidambar styraciflua	sweetgum	112	2,959	10,541	16,064	16,533
Juniperus virginiana	Eastern red cedar	66	1,474	6,967	14,232	14,232
Malus spp.	crabapple	149	4,139	8,894	8,894	8,894
Cornus florida	dogwood	47	2, 232	6,997	6,997	6,997
Ilex opaca	American Holly	31	497	2,792	6,652	6,652
Lagerstroemia indica	crape myrtle	5	1,016	3,301	3,301	3,301

[1]/ Please refer to USFS Tree Carbon Calculator for more detail: http://www.fs.fed.us/ccrc/topics/urban-forests/ctcc/