NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

SCIENCE ADVISORY BOARD

CARBON STORAGE CAPACITY OF FOREST SOILS IN NEW JERSEY

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EXECUTIVE SUMMARY

This report of the NJ Science Advisory Board Ecological Processes Standing Committee (EPSC) addresses charge questions focused on researching how the NJ Department of Environmental Protection might manage issues related to carbon content found within soil and its relationship to climate change.

Whereas forests of New Jersey play a critical role in sequestering carbon which plays a direct role attempts to combat climate change, our forests are under constant pressure from a variety of natural and anthropogenic factors including damaging insects, overpopulation of browse species such as white-tailed deer, the influx of invasive plant species and impacts from development.

The New Jersey Forest Service has requested assistance from the EPSC in examining this issue with the goal of addressing the following charge questions presented to the EPSC.

Charge

The NJDEP has requested that the EPSC examine how soil carbon relates to climate change, specifically:

> **Question 1**
>
> What are the primary factors that could influence soil carbon storage of forest soils, including temperature, pH, rate of decay, amount and type of soil organic matter, overstory and understory presence/absence.
>
> **Question 2**
>
> Does soil structure and function differ on post agriculture lands vs. traditional forests of various ages?
>
> **Question 3**
>
> What are the rates and factors influencing flux between forest carbon pools?
>
> **Question 4**
>
> Does repeated soil compaction affect soil carbon storage, and how does it affect it? How long does it take soil to bounce back after a single compaction? After multiple compactions?
>
> **Question 5**
>
> Related to the question about the primary factors affecting carbon storage capacity of forest soils / how site preparation can affect soil carbon soil capacity.

Based on our review of the available literature, the EPSC has concluded that the preponderance of the literature documents that organic C sequestration in forest is considered as a potential mitigation option for climate change by storing atmospheric CO2 in the tree biomass and soil organic matter. Ecosystem C inventory is essential for C accounting, control of greenhouse gas emission, forest conservation and land development programs.

While results of this review suggest that forests could be managed to increase the amount of stored carbon present in soil, if the objective is to increase carbon sequestration and storage of carbon statewide then tree planting and/or conversion of agricultural and other open lands to forest would have much larger benefits and rate of return. The committee's review of the literature identifies a variety of approaches to managing for carbon sequestration and storage purposes, including tree planting, preservation and management of existing forest lands, and conversion of agricultural lands to forest. Further, as the highest potential for carbon storage occurs in forested wetlands, opportunities to reverse/restore hydrologic function to support reforestation of wetlands should be explored.

1.0 INTRODUCTION

This report of the NJ Science Advisory Board Ecological Processes Standing Committee (EPSC) addresses charge questions focused on researching how the NJ Department of Environmental Protection might manage issues related to carbon content found within soil and its relationship to climate change. The literature reviewed as part of this charge question evaluation indicates that the forests found in the Northern United States collectively store 13 billion tons of carbon in live trees (29 percent), roots (6 percent), forest floor (9 percent), dead trees (6 percent), and soils (50 percent). About half the biomass of a live tree (dry weight basis) is sequestered carbon (Woodall et al. 2011). Through photosynthesis, live trees emit oxygen in exchange for the carbon dioxide that they pull from the atmosphere, storing the carbon in wood above ground and roots below ground as they grow. Dead trees and down logs are also reservoirs of stored carbon, which is released back into the atmosphere slowly through decomposition or rapidly through combustion (McKinley 2011, Woodall et al., 2011). Hence, carbon sequestration and storage are dynamic processes that vary with forest age, species composition and management.

The New Jersey Forest Service has requested assistance from the EPSC with the goal of addressing charge questions and providing recommendations such as future research or regulatory planning efforts. The following summarizes the charge questions presented to the EPSC.

Charge

The NJDEP has requested that the EPSC examine how soil carbon relates to climate change, specifically:

Question 1

What are the factors that could influence soil carbon storage of forest soils, including temperature, pH, rate of decay, amount and type of soil organic matter, overstory and understory presence/absence?

Question 2

Does soil structure and function differ on post agriculture lands vs. traditional forests of various ages?

Question 3

What are the rates and factors influencing flux between forest carbon pools?

Question 4

Does repeated soil compaction affect soil carbon storage, and how does it affect it? How long does it take soil to bounce back after a single compaction? After multiple compactions?

Question 5

Related to the question about the primary factors affecting carbon storage capacity of forest soils / how can site preparation affect carbon soil capacity.

2.0 OVERVIEW OF SOIL CARBON

There is an intrinsic connection between forests and soils with respect to carbon and carbon cycling. Forests accumulate carbon through their basic photosynthetic processes, and then cycle carbon both to the atmosphere and to soil through processes of decomposition. Forest soils are a vital component of most, if not all, of the United States. In the 1700's and 1800's, forest and rangeland soils were degraded across the United States at an alarming rate. This was primarily due to the conversion of forest land to agriculture, as well as unsustainable tree harvesting and grazing practices (Binkley et al., 2020). Into the 1900's and later years, as agricultural lands were abandoned, especially in the eastern U.S., forests returned. The forest land base in the U.S. has remained relatively stable at around 160 million ha since the 1920s, despite population growth.

As noted in Goerndt et al., (2016), forests currently cover approximately 42 percent of the northern United States, and collectively store 13 billion tons of carbon. Carbon in forests is distributed through live trees (29 percent), roots (6 percent), forest floor (9 percent), dead trees (6 percent), and soils (50 percent). About half the biomass of a live tree (dry weight basis) is sequestered carbon (Woodall et al. 2011). Through photosynthesis, living trees emit oxygen in exchange for the carbon dioxide that they pull from the atmosphere, storing the carbon in wood above ground and roots below ground as they grow. Dead trees and down logs are also reservoirs of stored carbon, which is released back into the atmosphere slowly through decomposition or rapidly through combustion (McKinley 2011, Woodall et al. 2011).

Ahmed (2018) notes that carbon dioxide (CO2) is one of the major greenhouse gases (approximately 72% of the total anthropogenic greenhouse gases). Further, CO2 is considered as a primary agent of global warming, and it has been estimated that CO2 is responsible for about 9–26% of the global greenhouse effects (Kiehl and Trenberth, 1997). The concentration of carbon dioxide in the atmosphere has increased from 280 ppm of the pre-industrial era (1750) to 408.84 ppm in July 2017, with an increasing rate of 2.11 ppm per year (NOAA, 2017). The dramatic rise of CO2 concentration is attributed largely to human activities, and since soil is the second largest reservoir of C in the terrestrial ecosystems, there is a strong link between soil and atmospheric C through the C cycle.

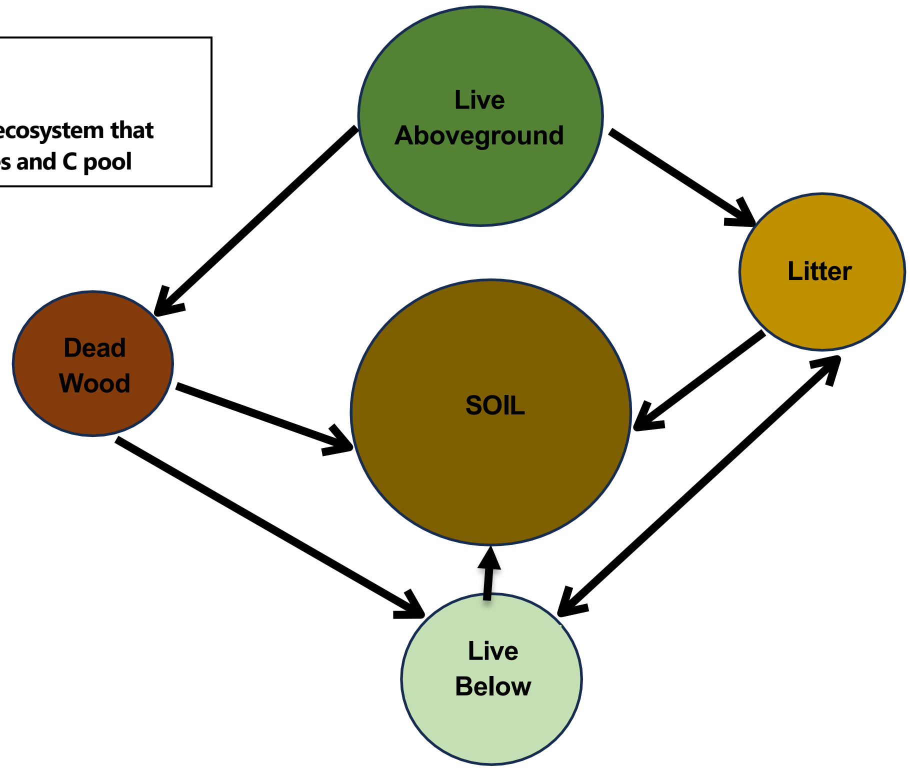
Globally, the soil C pool is about four times larger than the atmospheric pool, and consequently, any change in the flux of CO2 from soil to atmosphere has paramount importance in the balance of atmospheric CO2 (Luo and Zhou, 2006). Among different terrestrial ecosystems, forest soil contains more than two thirds of the global soil organic C reserve, although forest occupies only 30% land of the earth surface, creating the highest carbon-rich domain among different land use- based ecosystems. Atmospheric C, once fixed into plant tissues through photosynthesis, is transferred to the soil as plant litter. Part of this C is stored in soils, and the major portion is released to the atmosphere through soil respiration. Some of the stored C in soil can be sequestrated as soil organic matter and/or humus for as long as a million years (Cheng et al., 2007). As such, the potential of forest soil for long-term C sequestration is instrumental to many research efforts worldwide. In forest, soil C stock mostly derives from decaying above and belowground plant tissues and root exudates; however, the relative contribution of fine root and accompanying mycorrhizal turnover on soil C storage are considered more vital than the C in aboveground litter (Rasse et al., 2005). Microbial biomass and the community structure of bacteria, archaea and mycorrhizal fungi contribute to soil organic C stock through biomass production on one hand and releasing stored C through decomposition and respiration processes on the other. Dissolved organic carbon (DOC) is an important C pool in forest soil ecosystems, considered as a labile and more easily degradable substrate that influences the storage of C in forest soil.

3.0 QUESTION 1: WHAT ARE THE FACTORS AFFECTING CARBON STORAGE CAPACITY OF FORST SOILS?

Soil organic matter (SOM) is composed of carbon (C) combined with other elements. SOM is found and stored in multiple compartments: O horizon (litter and duff), senesced plant materials in the mineral soil matrix, microbial and root exudates, dead organisms (macro- and micro-organisms), and organic material adhering to mineral surfaces (Janowiak et al., 2017). Soil organic carbon (SOC) is a dynamic component of the soil (**Fig 3-1**), and the amount of SOC processed by microorganisms within the soil is approximate to the volume of inputs from plant detritus (Berryman et al., 2020).

Fig. 3-1.

Components of a NJ forest ecosystem that determines the carbon fluxes and C pool



Biophysical factors affect and determine the stabilization of C within soils. These factors include soil physiochemistry (pH, oxygen, nutrient, and element concentrations, temperature), species of forest vegetation, quality, quantity and rates of decay of organic inputs, soil organisms including microbial community composition, climate, and hydrography (Ji et al., 2020). Total SOC inputs are derived from the combination of autochthonous (litterfall, root turnover, root exudation of organic compounds, animal, plant, and microbial detritus) and allochthonous (external) inputs from atmospheric or hydrologic sources. Different plant species vary in their production of SOC concentrations and SOC chemical structures, which affect cycling dynamics and C sequestration. When total C inputs exceed total C decomposition, a net accumulation of soil C results (Jandl et al., 2007; Moomaw et al., 2018). SOC is lost from the soil through heterotrophic (microorganism mineralization) and autotrophic (plant root and microbial) respiration, loss via leaching, and physical loss through erosion (Ji et al., 2020). Interactions between these biogeochemical factors control soil organic carbon storage and turnover, and these interactions must be considered to ensure robust predictions of current and future SOC storage.

Soils with high SOC are characterized by substantial adsorption of carbon compounds onto mineral soil and low rates of respiration per unit of soil carbon (Doetterl et al., 2015). Ji et al. (2020) noted that the distribution of C in different soil density and particle-size fractions can be used to understand the dynamics, structure and function of SOC in soil. They found that the light fraction of SOC, which is mostly composed of undecomposed labile organic matter that originates from the degradation of plant material, is the least stable. The heavy fraction of SOC is strongly associated with soil minerals and is the most stable.

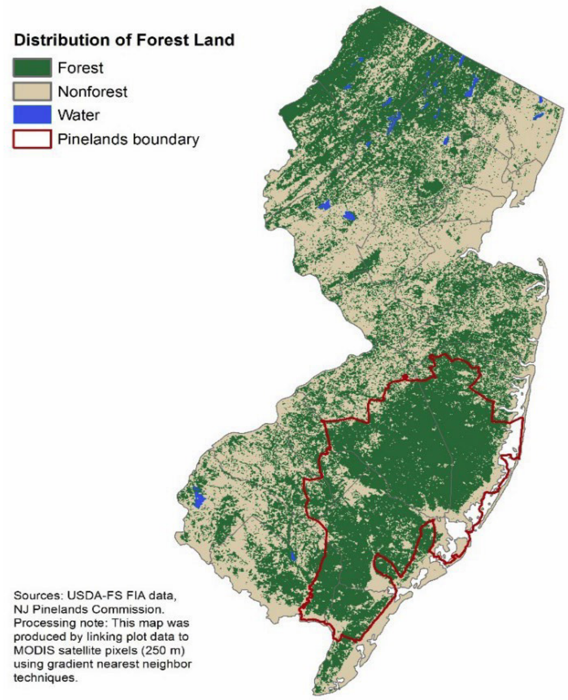


Fig. 3-2. NJ forest system (USDA 2018)

Correlations between climatic variables and carbon variables decrease significantly when relationships with geochemical predictors are removed, suggesting precipitation and temperature are secondary predictors for carbon storage, respiration, residence time and stabilization mechanisms. Natural factors, including soil texture and parent material, have been found to exert more control over SOC stocks than land use or management (Nave et al. 2021). Soil texture is a physical soil characteristic affecting the decomposition rate in soil carbon pools – for instance, clay soils can protect more carbon than sandy soils (Lal et al., 2015)

The area of New Jersey (NJ) statewide forestlands increased between 1987 (774,260 hectares) and 1999 (1,032,709 hectares), followed by a decline as of 2005 (996,821 hectares) (Lathrop et al., 2011). Estimated NJ forestland of almost 2 million acres has remained consistent since 2008 (USDA 2018).

Lathrop et al. (2011) reported that:

- The standing forest biomass carbon stock for the year 2005 was estimated to be 75,840,966 metric tons/year (with a range between 74,392,404 and 77,289,528).
- Increased standing forest carbon density caused by a maturing forest led to over an 85% increase in standing forest biomass carbon stock between 1987 and 2005.
- Taken on an annual basis, New Jersey forests increased carbon storage (in aboveground woody tissues) from a rate of approximately 1,711,440 tons/yr. between 1987 and 1999 to approximately 2,416,560 tons/yr. between 1999 and 2005
- The area of forest statewide increased between 1987 (774,260 hectares) and 1999 (1,032,709 hectares) but then declined as of 2005 (996,821 hectares).
- The total carbon stock stored in New Jersey's forests is estimated to be approximately 172,846,595 tons (with a range between 128,615,661 and 225,832,875 tons). Of the total, standing trees accounted for 44%, soil accounted for 42%, down dead wood contributed 9%, and roots contributed 4%, and shrubs contributed 0.1%,
- Standing forest carbon density (tons C / ha) is often higher in urban areas than in rural areas suggesting that urban forests have an important role in carbon sequestration.

A crucial factor that determines the turnover of SOC is its lability (ease of undergoing biological change or breakdown). Models of soil C fluxes often consider three SOC pools: labile C, stable C, and microbial biomass. The labile pool consists of relatively undecomposed SOC characterized by rapid turnover, which is considered sensitive to management strategies (Parton et al, 1987; Gulde et al, 2008). Labile SOC pools are composed of the light fraction and particulate organic matter, which includes partly decomposed plant debris. When organic matter is stabilized into aggregates and sorbed onto clays it becomes stable, and its stability is high when soil aggregate turnover is low.

Mean residence times of forest soil carbon can differ greatly within the soil carbon pool itself and can generally be separated by differing decomposition rates. These varying decomposition rates create three main conceptual soil carbon pools; 1.) labile pool, 2.) intermediate pool, and 3.) stable pool (Dignac et al, 2017). Both labile/intermediate pools predominantly originate from biological residues from plant, animal, bacterial and fungal matter (Dignac et al, 2017).

Labile pools can have organic matter turnover relatively fast, as quick as within a day to a year (Dignac et al., 2017). Intermediate pools can turnover organic matter within a few years to decades (Dignac et al., 2017). These pools are influenced by different soil management techniques - disturbance practices on soil have been shown to break apart soil aggregate fractions, causing a change of mean residence times (Lal et al., 2015, Grandy and Robertson, 2006a, Grandy and Robertson, 2006b, Grandy and Robertson, 2007).

The stable pool turnovers organic matter on a time scale ranging from decades to centuries (Dignac et al., 2017). This pool involves most of the soil's organic carbon and originates from both the labile and intermediate pools (Dignac et al., 2017). The stable pool is comprised of residues from plant, animal, bacterial or fungal matter, as well as deposits originating from microbial metabolic products (Dignac et al., 2017). Within the stable pool, the organic matter is located in aggregates and/or absorbed on mineral surfaces (Dignac et al., 2017). The carbon fluxes (storage and release) in these three conceptual soil carbon pools are all driven by the biotic and abiotic factors that occur within the soil organomineral matrix (Dignac et al., 2017).

This concept of lability is evolving (Berryman et al., 2020), with an acknowledgement of the complex interactions between microorganisms and soil minerals. An alternative model describing SOC lability proposes that SOC is determined by microbial accessibility across a continuum, ranging from free particulate material and dissolved organic matter (OM) to sequestered OM stabilized by association with mineral surfaces or bound within soil aggregates (Lehman and Kleber 2015). It should be noted that Nobel laureate Selman Walksman (Rutgers University) proposed a similar model in his 1936 book entitled *Humus. Origin, Chemical Composition and Importance in Nature* (Baveye and Wander, 2019).

Historically, the SOC focus was on forest floor mass or litter layer depth. However, it is now recognized that root inputs may account for five times as much SOC as aboveground sources (Jackson et al., 2017). Lability of SOC is directly affected by the composition of a forest's vegetation. Oak-hickory (*Quercus-Carya*) forest type contains more soil C than any other forest type in the contiguous U.S., accounting for 64% of forestland in the Eastern U.S. (Heath et al., 2003).

The recalcitrant nature of woody debris and its subsequent accumulation in soil is related to higher concentrations of lignin/cellulose compounds, which are less susceptible to microbial degradation (Bernal and Mitsch 2012). Studies have shown that changes in precipitation can both enhance or diminish soil C storage. Precipitation promotes the preservation of SOC, although low precipitation under drought conditions can also limit the breakdown of SOC. Conversely, vegetation growth can be limited by low precipitation, which can have negative effects on SOC inputs, including litterfall and rhizodeposition (Fröberg et al., 2008). SOC can be enhanced or depleted by an increased prevalence of wildfire. Carbon can be consumed in fires or recalcitrant black carbon can be added to the soil (Campo and Merino 2016, Bormann et al., 2008). This is especially true under anaerobic or the limited oxygen conditions, which cause SOC to accumulate with depth or in highly saturated histosol soils.

A review of soil organic C density by soil type shows the greatest C storage is in saturated histosols. The presence of the water table at or near the soil surface is a key factor in SOC organic histosol SOC sequestration (**Table 3-1**.). Histosols occur in NJ floodplain forests and lower lying forested areas, depressions, or basins adjacent to rivers and streams, often forming transitional zones between uplands and open water. NJ forested riparian wetlands cover ~697,064 acres, mostly in the Highlands and Pinelands regions (NJ State Forest Action Plan 2020).

Table 3-1. SOC density of various soil types (*Adapted from Lal (2004*).

Soil Order	Soil Order Description	Carbon density (tons $acre^{-1}$)
Histosols	Organic soils that build up over time.	1170
Gelisols	Soils of cold climates which contain permafrost.	281
Andisols	Formed in volcanic ash.	220
Spodosols	Acid soils characterized by subsurface accumulations of hummus.	191
Inceptisols	Soils that lack horizon development.	148
Mollisols	Deep, high organic layer typically 60-80cm of depth created by plant roots. Common in grasslands.	134
Vertisols	High in swelling clays, displays cracks when dried.	133
Oxisols	Defined soil profiles, highly weathered.	128
Alfisols	Clay enriched subsoil, and high fertility. 'Alf' refers to aluminum and iron.	125
Ultisols	Known as red clay soils, common in tropics.	124
Entisols	Least soil horizon development.	42
Aridisols	Dry soil, common in deserts, horizon development.	38
Rocky land		17
Shifting sand		4

High soil moisture decreases the diffusion of oxygen, which slows microbial breakdown of SOC; these lower decomposition rates build up histosols over time. Although other terminal electron acceptors (nitrate, sulfate) can be substituted for oxygen, some steps in microbial breakdown of complex C molecules require oxygen. Therefore, turnover of SOC in hydric (saturated) soils is slow, and SOC accumulates. Lockaby et al. (1996) found hydroperiod to be a dominant factor influencing degradation of leaf litter in a Georgia floodplain forest. Flooding stimulated lignin and cellulose loss rates that convert litter to SOM. After 23 months, 16-48% of original lignin remained in flooded litter microcosms, while non-flooded controls retained 70% of original lignin. In the anoxic soils of freshwater wetlands, some of the carbon sequestered in the soil is offset by an increased production of methane, which is a far more potent greenhouse gas than CO2 (Dalmagro et al., 2019, Villa and Bernal 2018).

Soil clay content is a key factor in soil carbon sequestration. While sand-sized particles (>60 mm) exhibit weak bonding affinities to SOM, clay-sized particles (<2 mm) provide a large surface area and numerous reactive sites where SOM can be sorbed by strong ligand exchange and polyvalent cation bridges (Sposito et al., 1999). Where there are abundant reactive surfaces of clay minerals, soil carbon can form complexes with a low turnover rate, which leads to C stabilization (Torn et al., 1997). There are also differences between different clay minerals. Soil turnover times associated with bonding of SOM to smectite were found to be four times longer than SOM bonding than to kaolinite (Wattel-Koekkoek et al., 2003).

Soil pH varies due to climate, soil buffering, nitrogen deposition, and plant cover. Globally, soil buffering is largely controlled by temperature and water balance (Slessarev et al., 2016), as in relatively arid regions soil pH is usually buffered by carbonates (Bowman et al., 2008), and pH is lower in low versus high latitudes. In the context of C storage, soil pH is known to be negatively correlated with SOC density, suggesting that low pH benefits the accumulation of organic matter (Zhou et al., 2019). Hong et al. (2019) suggests that this is because pH values are lower when soils rich in organic matter produce organic acids.

Inputs of labile C have been known to decrease soil C storage through a priming effect. Two different priming mechanisms have been proposed (Kuzyakov et al., 2000). In the first, extracellular enzymes released by labile OM accelerate the breakdown of SOC (Craine et al., 2007). According to this mechanism the C subject to remineralization is carbon that shares similar nutrient stoichiometry as the newly added OM. A second mechanism, termed "nutrient mining", uses the labile OM as an energy source to mine more stable SOM. Overall, the addition of labile C to soil carbon pools may lead to the remobilization of SOM pools with long residence times, and this results in a net loss of carbon from soil (Dijkstra et al., 2013).

Stabilized SOC within aggregates, through sorption on mineral surfaces at depth or in recalcitrant materials such as char, is thought to be an ecosystem property: a property that is the result of an exchange of material or energy among different pools and their physical environment. Soil aggregate formation is an example of physical protection for soil organic carbon stabilization, a key process that contributes to forest soil carbon balances (Lal et al., 2015). Consequently, there are several interacting pathways to stabilize soil C that involve microbial accessibility and chemical recalcitrance (Barryman et al., 2020). Soil C storage could resist losses as the result of a perturbation, or they could be resilient and recover SOC lost due to a perturbation. The stability of any pool depends on the magnitude of, and controls on, its inputs and outputs. The inputs are the quantity and quality of C fixed by the primary producers and altered by abiotic processes (**Table 3-2**); the outputs are controlled by microbial accessibility and microbial activity:

- **Changes affecting *quantity of OM inputs***—shifts in productivity due to removal or addition of biomass,
- **Changes affecting *quality of OM inputs***—change in species, allocation of production (belowground versus aboveground); transformation of biomass by pyrolysis,
- **Changes affecting *microbial accessibility***—destruction of aggregates; destabilization of redox-active minerals; inputs of active minerals (e.g., ash deposition); changing the OC saturation state; changes to the quality and quantity of SOC inputs, which could affect priming (stimulation of decay of stabilized SOC); changes in the distribution of SOC with depth through erosion and deposition, leaching, bioturbation, and other influences,

- **Changes affecting *microbial activity***—change in soil temperature and moisture, nutrient availability, freeze-thaw patterns, oxygen availability (i.e., redox), pH, or salinity; change in nutrient status from additions of substances such as herbicide or additions of N and sulfur from acid deposition.

Vulnerability of SOC to change depends on the factors that potentially may force the change (e.g., climate change, fire regime shift, invasive species, disturbance); furthermore, there are usually interactions among forcing variables (Barryman et al., 2020). The addition of fertilizing nutrients to mineral soils, through either nutrient management or N deposition, can result in gains, losses, or no change in SOC stocks; the outcome depends on many factors, not all of them known (Blagodatskaya and Kuzyakov 2008; Jandl et al., 2007). The mechanisms leading to an SOC increase are not well understood but are thought to differ from the direct effects of N fertilization (Binkley et al., 2004; Forrester et al., 2013), and effects of forest fertilization on SOC have been found to be site specific.

Table 3-2. Disturbance Factors Affecting SOC Sequestration (*Adapted from Barryman et al., 2020 and references therein*)

Disturbance	Potential Positive Effects	Potential Negative Effects
Fire	Creation of heat-altered C (soot, charcoal, Biochar) collectively called pyrogenic C	Mineralization of surface OM reduces total SOC inputs; Significant SOC loss when soil temperature exceeds ~ 150 °C; Erosion exposes deeper C to decomposition processes
Harvesting		C input quantity via forest floor and root OM inputs reduced as the stand regenerates, reducing SOC. Harvesting potentially disturbs soils and reduces the amount of woody C inputs. Changes in seedling species versus mature canopy species may affect soil C inputs and microbial processes
Nutrient Additions	Most studies show an increase in SOC stocks after nutrient additions; SOC increases under higher available N; N-fixing species associated with higher forest SOC – reported to be ~12–15 g C/ 1 g N fixed; Herbicide application shown to have a positive impact on C storage aboveground, but negative impact on belowground C	
Tree Mortality	Changes rate and type of OM matter input to soil – initially increases C inputs	Over time, decomposition occurs. C inputs decrease
Invasive Species	Can alter nutrient and C cycling and soil physical properties	Impacts on SOC largely system- and plant-dependent

Changes in the vegetation within NJ forests will undoubtably affect the quantity and quality of future soil carbon inputs. A few meta-analyses and review articles conclude that the net effect of tree harvest is a reduction in SOC, with the type of forest and soil type determining the magnitude of C loss (Jandl et al., 2007; Johnson and Curtis 2001; Nave et al., 2010). Nave and others (2010) reported an 8% average reduction in SOC stocks after harvesting for the forest and soil types studied. Forest mortality events reorganize the detritus pathways over multiple years, impacting SOC formation. Invasive species or exotic pests can eventually cause forest mortality. A NJ example occurred in the Pine Barrens, where defoliation by the gypsy moth (*Lymantria dispar*) reduced C storage at the landscape scale (Clark et al., 2010). However, many species invasions result in lesser disturbance than mortality events by affecting only a few trees, or by causing defoliation without killing the tree. Lack of forest seedling and sapling survival has been described for forests in the mid-Atlantic region.

Miller and McGill (2019) found NJ forest average seedling density/m^2 to be 0-0.25 and sapling density/m^2 to be 0-0.1, with slightly higher density in small, isolated patches in the southern coastal plain. Seedling densities less than 0.25 stems/m^2 (2,500 stems/ha) and sapling densities less than 0,1 stems m^2 (1,000 stems/ha) are often cited as insufficient (Abrams and Johnson, 2012; Bressette, Beck, and Beauchamp, 2012; Russell et al., 2017) to ensure forest regeneration (Miller and McGill 2019). They associated this low density with stand composition and characteristics, stressors, and climate change. Stressors, showing high overlap with each other, included human modified land cover, percent cover of invasive plants and deer density. Climate change variables were less important factors in sapling density, with only a minor negative effect related to percent precipitation. Patterns of similarity for trees and seedlings was lowest in the mid-Atlantic states, particularly metropolitan area spanning central New Jersey, and forests dominated by oak and pine in the canopy tended to differ in their seedling species (Miller and McGill 2019). These researchers note that this region in NJ is a zone of major transition from southeast warm-adapted species (e.g., oak, hickory and southern pines) to more northerly cold-adapted species (e.g., northern hardwoods and conifers).

3.1 Climate Effects and Forest Soil Carbon

Generally, global precipitation trends can be summarized as "wet getting wetter and dry getting drier" (Trenberth, 2011), suggesting that state changes are affecting forest ecosystems. Radiocarbon dating studies of soil carbon age have shown that carbon turnover times vary along temperature gradients, which suggests that temperature and climate are factors regulating soil carbon sequestration (Trumbore et al., 1996). Globally, soil carbon varies as a function of precipitation and temperature (**Fig. 3-4**), with high soil carbon associated with excess precipitation and/or low temperatures (Minasny et al., 2014).

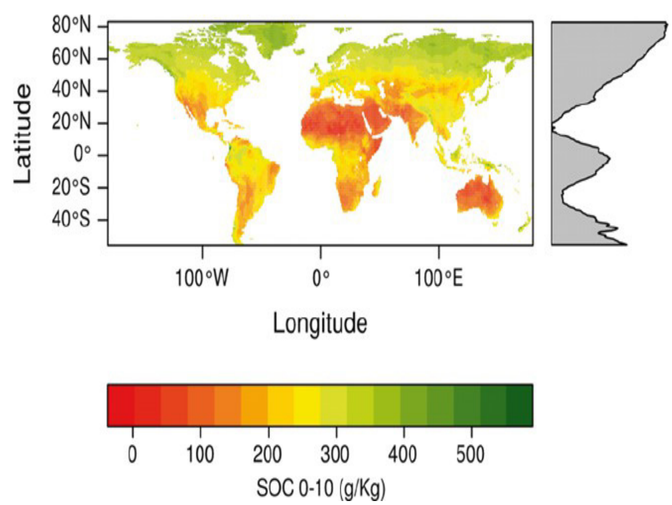


Figure 3-4. A global map of soil organic carbon (SOC) 0-0.1m. SOC was modeled as a function of precipitation, temperature, slope, parent material, vegetation, slope, and latitude. Figure from (Minasny et al., 2014).

Temperature has received significant attention in the literature, because most studies conclude that global warming will reduce soil carbon, assuming that soil respiration rates will be stimulated more than the rate of primary productivity (Rustad et al., 2001). Metabolic processes, such as primary production and respiration, can be increased by rising air temperatures (Tait et al., 2013). This is typically shown through what is known as the Q10 effect, where primary production is usually doubled with every 10 degrees C of air temperature rise (Tait et al., 2013). However, this effect can be variable depending on plant species, which is therefore also dependent on-site location (Tait et al., 2013). Carbon fixation via primary production is a key ecosystem function, which could ultimately offset the carbon balance in a forested ecosystem. Increasing air temperatures can cause plant growth to decrease, and can cause decomposition processes to increase, resulting in an overall net loss of carbon in an ecosystem (Riedo et al., 2000, Coughenour and Chen, 1997). Specifically, chronic increased air temperature can have detrimental effects to the northeastern U.S. Jenkins 1999 conducted a study in the northeastern U.S., utilizing TEM 4.0, a terrestrial biosphere model, and found that net primary production predictions are limited by temperature, suggesting that temperature is one of the most important controllers of predicted productivity in this area. This can therefore directly affect the carbon cycle within these forests, potentially creating a net loss of carbon (Jenkins 1999). In summary, long-term increased air temperature can have effects to primary production and therefore the forest carbon balance. As an example, over the long-term, increased temperature can enhance respiration rates, causing a decline in the primary production of the sub-canopy, which in turn can affect the landscape effects on the carbon balance (Ren et al., 2007).

If this proves to be the case, loss of soil carbon would be a climate feedback mechanism, with warming increasing SOC mineralization thereby increasing soil carbon dioxide atmospheric effluxes, leading to enhanced warming. However, research is currently inconsistent on the extent that warming will affect soil carbon stocks. For example, an extensive analysis of changes in carbon content in relation to soil warming experiments showed no statistical change in carbon stocks with warming (van Gestel et al., 2018). Some studies suggest that recalcitrant carbon is not very responsive to temperature increases, and under this scenario, warming would not trigger significant loss of SOC (Thornley 2001).

Climate change, overharvesting, and catastrophic wildfire have emerged as the greatest concerns. Effects on SOC degradation is expected to be more severe when two or more of these disturbances interact with each other. Quantity and quality of OM inputs will be impacted as warming temperatures and shifting precipitation regimes will lead to transitions in forest and rangeland plant communities (Clark et al., 2016). Microbial accessibility may be impacted as temperature and moisture changes alter rates of mineral complexation and leaching. Finally, microbial activity itself is sensitive to changes in temperature and moisture availability. In addition to changes directly tied to climate, increases in CO2 concentration could alter plant productivity, affecting the quantity of C inputs to soil, as well as the relative contributions of roots and shoots to SOC, potentially increasing root-derived OM inputs (Phillips et al., 2012). Some have also shown that litter quality will change or that species shifts could take place which change the quality of C inputs to soil (MacKenzie et al., 2004).

4.0 QUESTION 2: SOIL STRUCTURE/FUNCTION IN POST-AGRICULTURAL LANDS VERSUS TRADITIONAL FORESTS

The concept of soil structure is closely linked to the distribution of pore sizes. The larger pores (or macropores) facilitate the transport of gases and water, the growth of roots and the movement of soil fauna. Macropores originate from the arrangement of soil aggregates and from the creation of biopores by decaying roots and earthworms burrowing through the soil. As an example, larger and stable aggregates tend to produce larger pores, which is why the mean weighted diameter (MWD) of aggregates is considered a measure of soil structure. If soils have a high bulk density, meaning they are more compacted with a lower porosity, then they have the potential to have a lower carbon content (per weight). In general, many studies have shown that soil organic carbon concentrations decrease as bulk density increases (Fukumasu et al., 2022, Kätterer et al., 2006, Meurer et al., 2020). As depth increases within a soil profile, generally there is a decrease in total porosity coupled with an increase in moisture content, causing compaction and bulk density to increase with soil depth (Shah et al., 2017, Chaudhari et al., 2013).

Compaction collapses macropores and increases bulk density. These effects are magnified when the stability of soil aggregates is low. In a recent pair-comparison between soil structure under natural and managed conditions (e.g., agricultural land use), the amount of macropores, aggregate stability and mean weight diameter of aggregates was up to two times, and the rate of water infiltration and the amount of macropores up to three times, larger in natural than in managed soil structure (Or et al., 2021). These differences have a cascading effect on many soil processes leading to carbon storage and protection. Over time, afforestation modifies soil structure to resemble morphologically and functionally natural soil structures at equilibrium with a given climate and soil type.

4.1 Background

Forest soils in temperate and boreal regions show vertical differentiation of soil horizons with most of the nutrients and carbon (50-60%) concentrated in the top 0.2 m of the mineral soil (Jobbagy and Jackson, 2000). These soils typically have an abundance of roots and exhibit high faunal and microbial activities. The vertical extent of the root system is a function of topography, soil texture, and the depth of the groundwater table (Ehrenfeld et al., 1992; Sainju and Good, 1993; Fan et al., 2017). The abundance of soil fauna, roots and organic matter catalyzes the formation of soil aggregates, which tend to be stable and organized hierarchically. That is, small aggregates and labile carbon are contained in larger aggregates, whereas small aggregates are formed predominantly by more recalcitrant organic carbon associated with the colloidal mineral fraction (< 53 μm). This type of structural organization often leads to an increase in porosity in larger aggregates, a phenomenon that has been described using fractal geometry (Giménez et al., 2002). In addition to stable aggregates, forest soils have a well-connected network of macropores that ensure fast exchanges of water and gases between the soil and the atmosphere (Or et al., 2021; von Wilpert, 2022).

In contrast, soil structure in agricultural soils is regularly remolded and homogenized by tillage (Or et al., 2021). Soil fragments (i.e., the equivalent of soil aggregates in disturbed soils) resulting from cultivation have simpler pore systems (Chun et al., 2008), greater bulk density (Giménez et al., 2002) and sequester less carbon (Six et al., 2002; Devine et al., 2014) than aggregates from similar soils under forest. The extra aeration introduced by cultivation results in the fast (one or two decades) loss of soil organic carbon (Poeplau et al., 2011). Furthermore, tilled layers tend to be compacted (i.e., greater bulk density and penetration resistance) and contain fewer and less stable macropores than the subsoil (Ehlers, 1975; Messing et al., 1997). A characteristic of agricultural soils is that macropores in the tilled region and the subsoil constitute two largely disconnected systems (Logsdon et al., 1990).

4.2 Length of time for reversion of soil structure damage in agricultural lands to forest soil structure

According to data in Table S1 compiled by Jones and Schmitz (2009), it takes forest soils an average of 42 years to recover from perturbations induced by agriculture production. This average recovery period is the same as the average recovery of forest ecosystems when other perturbations, such as deforestation, logging, and hurricane/cyclone, are included in the calculation (Jones and Schmitz, 2009). Although these estimations are helpful as general guidelines, the time it takes for a soil to return to pre-perturbation conditions depends on climate, soil type, the soil property(ies) used to assess recovery, and soil depth (surface vs subsurface soil). Thus, the following analysis focuses on the speed of decompaction and carbon accrual in soils when land use is reverted from agriculture to forest.

4.3 Soil Carbon Content

Soil carbon content increases when land use switches from agriculture to either afforestation (Guo and Gifford, 2002; Paul et al., 2002; Laganière et al., 2010) or secondary forest (Foote and Grogan, 2010; Poeplau and Don, 2013). Increases in soil carbon content often leads to lower bulk density values (Or et al., 2021), and greater aggregate stability (Devine et al., 2014) and soil microbial biomass and activity (Sussyan et al., 2011). The rapid recovery of bulk density in the topsoil, where most of the carbon in forest soils is concentrated, suggests that soil carbon could be restored relatively quickly. However, carbon restoration is in general a slower process than carbon degradation. For example, within two decades from deforestation, agricultural soils may lose between 30-50% of soil carbon, whereas it may take 50-60 years to restore the same amount of carbon when land is reverted to forest (Guo and Gifford, 2002, Poeplau et al., 2011). Carbon accrual rates are greater near the surface, in soils with clay contents larger than 33% (clay particles stabilize organic molecules by forming complexes), and in temperate climates where the balance between biomass production and rate of decomposition is more favorable than in either boreal or subtropical climates (Laganière et al., 2010).

4.4 Summary

Secondary forests growing on former croplands lead to regeneration of soil structure and accrual of soil carbon. Near the surface of the soil, increases in macroporosity, the formation of more stable aggregates, and gains in soil organic carbon can be detected one or two decades after the change in land use. These processes move downward at rates that are determined by climate, soil water content, clay content and pH. Different modeling exercises predict that full recovery of soil structure/carbon content across the soil profile takes in the order of 100 years. These estimates and empirical evidence suggest that the average recovery time of forest growing on former agricultural soils is longer than the 42 years derived by Jones and Schmitz (2009).

5.0 QUESTION 3: WHAT ARE THE RATES AND FACTORS INFLUENCING FLUX BETWEEN FOREST CARBON POOLS

Forest carbon products are produced by autotrophic (vegetation) members within the forest ecosystem. When the live forest organisms die (leaf drop, root exudation, animal carcass, microbial death, and lysis), and release carbon (C) compounds, the C becomes available to organisms controlling decomposition processes. As carbon compounds are decomposed, the potential exists for this carbon to form new compounds within the soil compartment. Biogeochemical factors such as soil type, vegetation species composition, temperature, oxygen concentrations, precipitation and hydrograph that affect any of these compartments will determine the C fluxes and sequestration potential for a specific forest system. New Jersey Forest Service (NJFS) recognizes 5 compartments of forest C storage: 1) above-ground biomass, 2) below-ground biomass, 3) deadwood, 4. litter and 5) soils (Newell and Vos., 2012, IPCC, 2006). Biogeochemical interactions within and between these compartments determine the amount of C stored within each compartment (**Table 5.1**). The total C content of a specific forest is constrained by the physical size of the forest, whose estimated acreage will differ depending on measurement metrics [field surveys versus satellite imagery (Heath et al., 2003)].

Table 5-1. Summary of Effect of Various Factors on Soil Organic Carbon (SOC)

metric	relationship with SOC	explanation
temperature	↑ → ↓	high temperatures increase reaction rates, and enhance turnover of SOC
precipitation	↑ → ↑	generally, high precipitation is associated with high SOC at a global level, as it increases C production, and increases prevalence of hydric soils
high water table	↑ → ↑	high water tables slow the decomposition of SOC due to low oxygen availability
lability	↑ → ?	land management strategies often increase the amount of labile SOC, however effects on recalcitrant carbon are less clear
clay content	↑ → ↑	high soil clay content increases protection of SOC through sorbtion by clay minerals
pH	↑ → ↓	high SOC is associated with low pH as soils rich in SOC produce organic acids
labile C addition	↑ → ?	Addition of labile carbon to soils, can often lead to declines in SOC due to priming effects.
soil type		Soil orders often reflect SOC content, and parent material and climate can play a role in SOC

The movement of carbon from one pool to another is considered a flux. UNH (2008) estimates some of the following measures of flux between carbon pools, on a worldwide basis:

- Removal from the atmosphere plants through photosynthesis 560 Petagram (Pg) of C/year

- Release of CO_2 back to the atmosphere through plant respiration 60 Pg of C/year
- Release of CO_2 back to the atmosphere through soil respiration 60 Pg of C/year

Domke et al. (2018) estimate that the aboveground carbon stock in the United States is 14,941 teragrams of carbon in aboveground pools, 2,923 teragrams of carbon in belowground biomass, 2,570 teragrams of carbon in dead wood, 2,680 teragrams of carbon in leaf litter, and 28,774 in soil.

6.0 QUESTION 4: DOES REPEATED SOIL COMPACTION AFFECT SOIL CARBON STORAGE, AND HOW DOES IT AFFECT IT?

Data on soil structure recovery from compaction in forest soils are mostly from northern Europe and pertain to damage induced during various forest operations (Hildebrand and Schack-Kirchner, 2002; von Wilpert, 2022). An exception to this trend is the work of Piché and Kelting (2015) who measured the recovery of physical properties on forest successions on agricultural fields in eastern New York. Compared to fields under agriculture, 5-10 years of forest development was sufficient for the soil structure of the top 7 cm to achieve a new state, with a 24% decrease in bulk density and a 31% increase of macropores greater than 50 μm. However, the legacy effect of compaction by tillage was still present in the subsoil 55-60 years after agriculture abandonment, as evidenced by an increase in soil strength that peaked 15 cm below the surface (depth of tillage) in forest fields regardless of age. Faster recovery at the surface (~10 years) compared to the subsoil (> 40 years) was also reported in relation to the use of heavy machinery in forest operations (Schaffer, 2022). Mohieddinne et al. (2019) estimated that the decrease of penetration resistance to pre- compaction values at 30 cm depth would take between 54 and 74 years, depending on soil type. Similarly, Maloney et al. (2008) estimated that for soils under secondary forest in Georgia, it would take 83 years to achieve pre-perturbation bulk density values in the topsoil (0-10 cm) and 165 years at 30-40 cm depth.

Studies on recovery from a single compaction event are less common, but the few reports that are available in the literature show similar patterns/times of recovery. Bottinelli et al. (2014) felled trees and air-lifted them away from experimental plots at two sites prior to compacting the soil with two passes of a wood-loaded forwarder followed by seeding of an oak monoculture. Immediately after the compaction event, the soil macroporosity decreased more than 90% in the top 7 cm, and about 50% at 30-45 cm. Two or three years after compaction, only macroporosity in the top 7 cm of the soil showed some recovery caused by the growth of roots and the action of physical processes such as wetting and drying and freezing and thawing. A similar experiment using agricultural equipment detected signs of macropore recovery at the surface after two years, but not sufficient to be statistically significant (Keller et al., 2021). A literature review suggests that an axle load of 10 Mg compact down to soil 50 cm and the effects persists for decades (Hakansson and Reeder, 1974). Cases of compaction to a depth of 1 m caused by heavy loads and/or by traffic on wet soils have been reported (Hakansson and Reeder, 1974), which implies a longer recovery time than the ones discussed in this report.

7.0 QUESTION 5: LAND USE MANAGEMENT PRACTICES - HOW DOES SITE PREPARATION AFFECT SOIL CARBON SOIL CAPACITY

Prior to discussion of effects of different land use practices on soil organic carbon, it is useful to discuss the soil carbon fraction in the context of the overall distribution and cycling of carbon in forests. In forests, above ground and below ground biomass are the primary sources of soil carbon (Ahmed 2018). The amount of carbon stored in soil is highly affected by soil litter and the processes affecting its production and decomposition (Walkiewicz et al., 2019). Soil carbon accounts up to two thirds of the carbon stored in the system (Adamowicz and Keca 2019), and although cycling rates may vary, carbon is stored within this compartment for a longer duration via formation of stable aggregates (Cardoso et al., 2013, Stamati et al., 2013). Hence there is a considerable body of literature focusing on the effects of land use practices on carbon storage and sequestration in forests, much of it focused on carbon storage in soils. These land use practices are generally oriented around actions to clear land in preparation for some land use activity, whether that is selectively or broadly removing trees for development or clearing for agricultural use. However, it is the forest above that results in carbon sequestration.

Table 7-1 summarizes the potential effects of different land use practices on soil organic carbon (SOC) storage and sequestration in forests. The summary provides a general treatment and different forest types in New Jersey are known to vary widely with respect to their carbon (C) storage potential.

Table 7-1 Evaluation of literature sources regarding land use practices on SOC

Land Use Practice	Effect on Carbon Storage or Sequestration	Citation
Selective tree removal* * Refers to management practice of selectively reducing the density of the forest in a given area.	Decreases SOC by 24%	Cardoso et al. 2013
	50% decrease in soil C but low impacts on C stocks	Walkiewicz et al. 2021
	Decreases SOC stocks	Ahmed 2018
	Substantial decrease in forest C stock	Ahmed 2018
	Decreases (Reduces C input)	Pouyat et al. 2020
	Decrease in C input, decrease in forest C stocks, and reduces C sink capacity	Adamowicz and Keca 2019
	Reduces SOC from 60–100+ cm in depth by an average of ~18% (harvest)	Gross and Harrison 2019
Other tree harvesting practices	Reduces SOC stocks by 25%	Gross and Harrison 2019
	Reduces C input	Pouyat et al. 2020
	Silvicultural drainage on hydric soils is to reduce soil C stocks, but productivity may also be enhanced, which can increase soil C	Pouyat et al. 2020

Land Use Practice	Effect on Carbon Storage or Sequestration	Citation
	Decreases SOC stocks	Ahmed 2018
Agriculture	50-75% less C stock than native forest	Cardoso et al. 2013
	Decreased SOC stocks by ~50%	Gross and Harrison 2019
	Conversion of land to agriculture can result in depletion of SOC stock by up to 40-50%	Lathrop et al. 2011
	Agricultural soil has 2.19-times lower SOC content than the forest soil	Guttieres et al. 2021
	Has less carbon concentration than forest soils	Adamowicz and Keca 2019
	Converting land to cropland results in greater losses of SOC than conversion to pasture	Pouyat et al. 2020
	No-till practice on the lands under corn–soybean cropping rotation could sequester about 2% of the annual anthropogenic emissions of CO2 emissions in the U.S	Schlesinger and Amundson 2018
	Reduced agricultural intensity increases SOC	Pouyat et al. 2020
	Monoculture plantations reduce SOC	Chen et al. 2020
	No or minimum tillage increases of 44% total organic carbon in soil compared to conventional tillage.	Hossain 2021
Fire Management	Impact on soil disturbance is dependent on a variety of factors (fire temp, duration, etc.)	Ahmed 2018
	Charcoal left behind from prescribed fires may be effective in sequestering C in soils	Pouyat et al. 2020
	Reduces SOC storage, however, repeated prescribed fires can have benefits for SOC, such as building more stable forms of SOC	Pouyat et al. 2020
Biochar	Applications could store 0.7 Pg C/year	Schlesinger and Amundson 2018
	Can be used to increase SOC on forest, rangeland or mine sites. Biochar additions to soil can also promote SOC formation and stabilization.	Pouyat et al. 2020

Land Use Practice	Effect on Carbon Storage or Sequestration	Citation
	Can increase the total soil carbon content by 26% in the presence of litter, support long-term carbon sequestration, enhance soil quality, and remediate soil pollution	Cui et al. 2021
	A potentially important mechanism to store carbon in stable forms	Davies et al. 2020
	Reduces SOC oxidation and if 10% global net primary production were pyrolyzed, 4.8 Gt C/year would be bound in the produced charcoal	Adamowicz and Keca 2019
Fertilization	In a study on *Molinia caerulea* litter, N fertilization increases the N and decreases the C concentration	Walkiewicz et al. 2021
	In N-fertilized experiments, eCO2 generally increased both plant biomass and SOC	Terrer et al. 2021
	The stimulation of soil respiration by P addition in cropland may be linked to the significant increase of soil organic carbon	Feng and Zhu 2019
Conservation	Protection of natural forests through the use of intensively managed forests may also benefit C sequestration	Pouyat et al. 2020
	Protected areas/protecting forest biodiversity can benefit carbon sequestration	Shifley et al. 2016
	Van Veen and Paul (1981), have recognized long ago that the equilibrium level of soil organic carbon (SOC) is more dependent on the extent of protection than on the composition of the plant residues added to soil.	Stamati et al. 2013
Restoration	Afforestation can increase the quantity of carbon sequestered in trees	Shifley et al. 2016
	Recovery of SOC with reforestation of agricultural lands occurs	Pouyat et al. 2020
	Conversion from crop to secondary forest increased SOC stocks by 53% *However, deep soil SOC could be lost*	Gross and Harrison 2019

7.1 Selective Tree Removal and Other Tree Harvesting Practices

While selective tree removal and other tree harvesting practices may affect the amount of carbon sequestration and storage by 1) removing biomass directly storing carbon, and 2) eliminating or reducing the ability of the forest to sequester carbon from the atmosphere. With respect to carbon flow, selective tree and understory thinning has multiple effects on forest systems. These include:

- Direct reduction in the amount of carbon stored in plant biomass.
- Reduction in carbon sequestration by removing live vegetation.
- Reduction in soil organic matter feeding existing microbial communities, and component loss in soil fertility due to decreased nutrients, cation exchange capacity, and percent moisture.
- Decrease in longer term storage of carbon in the soil fraction as microaggregates.
- Potential short-term erosion of soils if not immediately replanted, causing export of carbon via runoff and further reduction of soil organic carbon.
- Vegetative community and ecosystem impact beyond carbon cycling but which indirectly affect it, such as watershed impacts, wildlife impacts and altered soil characteristics allowing for invasion of nuisance species.

The extent of any impacts obviously would be related to the magnitude of the clearing event, as well as the age of the forest impacted, the regeneration time and success of any trees replanted, and the forest community type (e.g., pitch pine forest or red maple swamp). The carbon cycle within forest plantations, wood lots and other areas subject to forestry management would similarly be affected by silviculture and tree thinning.

A key difference between selective tree removal and other harvesting practices is that selective tree removal may improve forest productivity over time, encouraging substantial amounts of timber biomass over time, and therefore allowing for greater sequestration and storage of carbon, at least until harvest. Evaluation of effects of one land use practice versus another is difficult unless the entire life cycle of the process is considered.

7.2 Agriculture

Historical clearing of forests for agricultural production in New Jersey resulted in long term changes to the characteristics and productivity of what were once forest soils. Fertility of agricultural lands still managed for crop production in New Jersey is maintained by supplying outside energy and inputs in the form of fertilizers, irrigation, and in some cases, pesticides. In some parts of the state, lands are maintained for agricultural use by the property owner primarily as a tax credit since agricultural lands are assessed at a lower rate than commercial or residential land uses. The benefits of carbon sequestration and storage are still greater than if these areas were developed with impervious cover, but agricultural lands in New Jersey generally provide less carbon storage and sequestration compared to remaining forests. Cardoso et al. (2012) summarized the benefits of agricultural conversion to forests on carbon storage.

Specifically:

- Agricultural lands support 50-75% of the carbon stock of native forests.
- The soil organic component may be 50% or less than that of forest soils prior to agricultural conversion.
- No or minimum tillage may significantly increase storage of soil organic carbon relative to conventional tillage, but also requires energy input.
- Carbon sequestration and storage may vary with different food crops grown but focusing on certain crop types to offset carbon loss would not be effective. Agriculture generally

requires crop rotation to avoid soil fertility loss and accumulation of pests.

7.3 Fire and Soil Carbon

Fire and its management vary between forest types in New Jersey. Forest fires are a natural part of ecosystems, including many of the vegetation communities in the New Jersey Pinelands. But even within the Pinelands the burn cycle of vegetation communities may vary significantly between vegetation type, and stand characteristics, ranging from 15-40 years (USDA 2022). With climate change, nationwide there have been a series of severe uncontrolled wildfires over the past decade that, in addition to causing widespread ecological and economic destruction, have released tons of carbon into the atmosphere. The management of forests for long term ecological health and to retain carbon in the soil and vegetation should be considered with respect to the potential impacts from severely intensively destructive wildfires. For example, litter is an essential component of forest health (Walkiewicz et al., 2019) including storage of carbon. Programs aimed at reducing fuel loadings that build up to catastrophic levels by their nature reduce the amount of litter accumulating on the forest floor. Dixon et al. (2019) notes that the application of frequent prescribed fire regimes will not significantly decrease soil carbon and may, in fact, increase it.

Review of the literature suggests the following salient points concerning forest fire and its effect on carbon sequestration and storage:

- Soil disturbance from fire and its ultimate impacts on soil carbon is dependent on many variables including the temperature of the fire, its duration, fuel loadings, type of litter, soil moisture and soil texture.
- Remaining charcoal can be effective in sequestration of carbon by soils.
- Fire management may reduce soil organic carbon storage, but long-term prescribed burns may be helpful in stimulating forest productivity, thereby enhancing sequestration and storage long term (usually measured in hundreds of years [Meunier and Sutheimer, 2022]). Charcoal and ash are sources of potash, which often encourage rapid regrowth of vegetation in burned areas. Datta (2021) notes that the effects of forest fire are either beneficial or disastrous, depending on the severity of the fire. Low impact burning can stimulate more beneficial herbaceous flora and increase the nutrients available to plants.

7.4 Soil Amendments

Various soil amendments can be considered for both forested and agricultural soils to encourage sequestration and storage of carbon into soils. These include biochar application, as well as fertilizers such as phosphorus addition. Studies have shown amendments to be effective in increasing the amount of soil carbon sequestered and stored (Cui et al., 2021, Davies et al., 2020, Schlesinger and Amundsen 2018, Pouyat et al., 2020). However, in considering their effectiveness in reducing atmospheric impacts of CO_2 and GHG emissions, the entire life cycle cost should be considered. Soil amendments considered are summarized below.

7.4.1 Biochar

Biochar is charcoal produced from plant matter and stored in the soil as a means of removing carbon dioxide from the atmosphere (Schlesinger and Amundsen 2018). Several studies (see Table 3-1) have indicated the potential for biochar application to increase carbon storage of agricultural soils. Biochar is made from slow pyrolysis at 450 and 550ºC, and thus requires energy to produce (Aysu et al., 2013). A full life cycle analysis of the energy source and its carbon emissions would need to be prepared to understand whether biochar can efficiently remove carbon from the atmosphere. For example, pyrolysis is produced through electricity. If the source of the electricity is coal-fired plants, then the associated carbon emissions would need to be considered in the analysis of the effectiveness of biochar in managing atmospheric carbon.

7.4.2 Fertilization

Similarly, application of nitrogen and/or phosphorus fertilizers have been shown to increase the carbon storage potential of soils. In a sense this is mimicking natural processes that occur after forest fires. However, like the application of biochar, the effectiveness of fertilizer application in carbon sequestration and storage would need to consider the full life cycle cost of developing and applying the product. For example, the product life cycle for phosphate fertilizer would need to account for the carbon emissions associated with mining the phosphorus, the transportation of the ore to the fertilizer manufacturing plant, manufacturing costs to crush and refine the ore, subsequent packaging and shipment (by truck or rail) to distribution centers, and costs associated with distribution itself (unloading, moving within wholesale or retail stores). All that is prior to the act of applying fertilizer to agricultural lands by farm equipment.

The life cycle "costs" in terms of carbon emissions for nitrogen fertilizers would be even greater due to the use of petroleum products in their production. In a modern plant, nitrogen fertilizer is produced from natural gas. In several transformation steps, natural gas, primarily methane, is upgraded by combination with nitrogen from the air to form nitrogen fertilizer. As a result, fossil fuel consumption is required to generate the soil amendment that is aimed at increasing carbon sequestration and storage.

7.4.3 Conservation and Reforestation

While carbon being stored in forest products, such as furniture, or lumber used in homes or other structures, may act as longer-term carbon sinks, these sinks do not provide continuous sequestration as do living trees. Any forest system is a living dynamic wherein the carbon component as well as water and nutrients are cycled continuously between the atmosphere, tree tissue, and the soil. The rates of exchange vary between media. For example, forest soils may leach carbon depending on rainfall, pH, soil texture and a host of other factors related to climate, location, fire frequency/history and human disturbance or management. Management of those factors may "temporarily" influence the amount of carbon retained in the soil, but the overall carbon sink is mostly influenced by the presence of living trees.

The articles reviewed collectively indicate that while land use practices may affect the amount of carbon sequestered and stored in forest soils, the impact of these practices overall is less significant than reforestation. Many of the proposed management practices are not sustainable since they rely on external inputs that generate atmospheric carbon themselves (Schlesinger 2019). For example, while mapping soil organic matter (SOM) in forests may provide useful information on management of publicly owned forests, the emphasis on management of these areas is less important than increasing or retaining the amount of forested area used for carbon sequestration storage.

While increasing biomass in existing forests does not necessarily increase soil carbon (Adamowicz and Keca 2019), allowing trees to regrow on areas not currently supporting them clearly would (White 2017, Adamowicz and Keca 2019). Clearly agricultural soils do not sequester or store as much carbon as mature forests, regardless of forest community type or even successional stage. Thus, positive effects of conservation and reforestation on carbon sequestration and storage would be far greater than for the other land use practices reviewed.

8.0 CONCLUSIONS

Based on our review of the available literature, the EPSC has concluded that the preponderance of the literature documents that organic C sequestration in forest is considered as a potential mitigation option for climate change by storing atmospheric CO2 in the tree biomass and soil organic matter. Ecosystem C inventory is essential for C accounting, control of greenhouse gas emission, forest conservation and land development programs.

Soil microbial biomass and community structure are extremely crucial for regulating dynamics of soil organic C and subsequent emission and storage in soil. Stability of soil organic C is coupled with various biogeochemical processes in the soil and therefore regulated by multiple biotic and abiotic factors. Thus, the link between different pools and processes are crucial for understanding the soil C storage and stability. Soil organic matter in the deep soil layers is potentially stable due to long residence time and surrounding soil properties. The accumulation of these highly processed C is influenced by the translocation of dissolved organic carbon (DOC) through the soil profile. Plant biomass can also be a major determinant of the vertical distribution of C in soil, through above and belowground C allocation patterns. Similarly, root activities such as incorporation of structural coarse roots, mycorrhizal fine roots and hyphal mycelium can influence the vertical distribution of organic C. The effect of clay content on soil C stability is well established, particularly in deeper layers with higher proportion of protected organic molecules. Although a large portion of fine root C returned to atmosphere through root and rhizomicrobial respiration, root residues can stay in soils for long time compared to aboveground litter and thus contribute significantly to the SOC stock. Priming process can impact soil C stock negatively. Fresh litter and root may also stimulate the microbial activities that leading to rapid decomposition of old C in soil, creating an antagonistic effect on the storage of soil organic C. Advanced analytical techniques can be instrumental for explicit understanding of these complex interactions at ecosystem level. Overall, the interdependency of various soil C pools and processes is a fundamental determinant of storage and stability of forest soil.

While results of this review suggest that forests could be managed to increase the amount of stored carbon present in soil, if the objective is to increase carbon sequestration and storage of carbon statewide then tree planting and/or conversion of agricultural and other open lands to forest would have much larger benefits and rate of return. The committee's review of the literature identifies a variety of approaches to managing for carbon sequestration and storage purposes, including tree planting, conservation, and management of existing forest lands, and conversion of agricultural lands to forest. Further, as the highest potential for carbon storage occurs in forested wetlands, opportunities to reverse/restore hydrologic function to support reforestation of wetlands should be explored.

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