Red spruce ecological sites, ecological states, and restoration pathways quantified through soil organic carbon

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Red Spruce Ecological Sites, Ecological States, and Restoration Pathways Quantified Through Soil Organic Carbon

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Thesis submitted to the Davis College of Agriculture, Natural Resources, and Design at West Virginia University in partial fulfillment of the requirements for the degree of Master of Science in Plant and Soil Sciences

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ABSTRACT

Red Spruce Ecological Sites, Ecological States, and Restoration Pathways Quantified Through Soil Organic Carbon

James Leonard

Tools used by agencies and organizations like the Forest Service (FS), the Natural Resource Conservation Service (NRCS), the Nature Conservancy (TNC), and the Central Appalachian Spruce Restoration Initiative (CASRI) to help guide red spruce (*Picea rubens*) ecosystem restoration within Central Appalachia could better address outcomes from management practices implemented in terms of soil organic carbon (SOC) stock changes. These high-elevation landscapes have a natural capacity to produce diverse ecosystem services that affect humans, animals, and plants alike. Ecological site descriptions (ESD) are an important tool used to restore impacted landscapes and provide detailed management prescriptions specific to red spruce ecological sites (ES) and ecological states occurring in the Monongahela National Forest (MNF). Previous studies have evaluated ESD utility for identifying ecologic communities and restoration pathways primarily in western rangelands, but none have focused on Central Appalachian landscapes. Research associated with SOC stocks and forest ESD is minimal. Studies have analyzed how SOC can benefit ecosystem services, yet none seek to compare SOC stocks across multiple ecological states to address both restoration pathways and management outcomes that could potentially increase SOC sequestration capacity while restoring impaired ecosystem services. 120 individual plots within the dual extent of the Spodic Shale Upland Conifer Forest (SSUCF) and Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF) ES were analyzed using soil profiles and ecosystem descriptions sampled between 2009 and 2021. Soil samples were analyzed using dry combustion to determine SOC percent
weight and further used to calculate the SOC stock to 100 cm in depth where applicable. Here, mean SOC stock, SOC stock variance, and the relationship between percent conifer canopy cover and SOC stocks of ecological states of both ES were compared and discussed. Analyses showed differences between ES total SOC (TSOC) stock \( (p < 0.0001) \), O horizon SOC (OSOC) stock \( (p < 0.0001) \), and spodic horizon SOC (SPSOC) stocks \( (p = 0.001) \), while mineral SOC (MSOC) showed no difference \( (p = .628) \) (Table 4.1). At the ecological state level, there were only two significant differences when examining TSOC \( (p = 0.038) \) and OSOC \( (p = 0.001) \) stocks (Table 4.2). The SSUCF demonstrated higher variance than the SISUHCF in TSOC stock \( (p\text{-value} < 0.0001) \) and OSOC stock \( (Table \ 4.3, \ p\text{-value} < 0.0001) \). Conversely, there was no significant difference between ES when comparing MSOC stock variance \( (p\text{-value} = 0.971) \) and SPSOC stock variance \( (p\text{-value} = 0.126) \). Regression analysis used a fixed model and showed significant effect of relative conifer percent cover on SOC stock in the TSOC \( (Table \ 5.1, \ p < 0.0001) \) and OSOC \( (Table \ 5.1, \ p < 0.0001) \) derivative. Further analysis used a mixed model and demonstrated a significant effect of ES on TSOC, OSOC, and SPSOC layers, as well as a main effect of relative conifer percent cover on OSOC when adjusted for ES and ecological state within ES \( (Table \ 5.2, \ p = 0.008) \). Our findings suggest restoration is most impactful when focusing on the SISUHCF ES based on SOC gained when restoring alternative states to the reference state condition. Improvements to DSP related to SOC are also likely to be seen in response to restoration. Using SOC as a lens through which to view management outcomes enables land managers to predict outcomes of restoration related to a wide variety of key soil-ecological metrics and DSP.
DEDICATION

I dedicate this work to all those who are curious about learning more about the earth, and those who seek to understand our place as human beings in the natural order we observe around us. This work is also for those who strive to become closer to the land, and those who seek to understand and restore the landscapes that have been heavily impacted throughout human history. Our relationship to the earth and cosmos is easy to overlook now more than ever, yet we still play a key role in influencing the trajectory of the planet. We have role to play – a role to guide the development of the planet for future generations of human beings, plants, and animals of all types. We are the caretakers of the earth, and this research is dedicated to everyone who strives to better their relationship with it to improve the conditions on earth for future generations of life.
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ABOUT THIS THESIS

This document contains six chapters in total and is organized in a specific manner to provide a logical progression of the project for the reader. Chapter 1 serves as a background introduction and familiarizes readers with the three hypotheses being asked in this research project. Chapter 2 stands as a detailed literature review of pertinent information relating to this project. Chapter 3 specifically outlines what has been done in the past by other researchers, as well as what questions have or have not been asked in relation to the scope of this experiment. Chapters 4 and 5 are standalone chapters that examine each hypothesis and are formatted for future publication. Chapter 4 specifically deals with SOC stocks and SOC stock variance as applied to red spruce ecological sites and ecological states, while chapter 5 focuses on the relationship between percent conifer canopy and soil organic carbon stocks regardless of ecological site or ecological state. Chapter 6 provides closing conclusions and a final summary of the experiment, followed by references and appendices.
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LIST OF ABBREVIATIONS

BD: Bulk density
CASRI: Central Appalachian Spruce Restoration Initiative
CMS: Cheat Mountain salamander
DOC: Dissolved organic carbon
DSP: Dynamic soil property
ES: Ecological site
ESD: Ecological site description
FS: Forest Service
MNF: Monongahela National Forest
MSOC: Mineral soil organic carbon
NFS: Northern flying squirrel
NRCS: Natural Resources Conservation Service
OC: Organic carbon
OSOC: Organic horizon soil organic carbon
SISUHCF: Spodic intergrade shale upland hardwood conifer forest
SOC: Soil organic carbon
SOM: Soil organic matter
SPSOC: Spodic horizon soil organic carbon
SSUCF: Spodic shale upland conifer forest
STM: State and transition model
TNC: The Nature Conservancy
TSOC: Total pedon soil organic carbon
CHAPTER 1: INTRODUCTION

In the late 19th and early 20th centuries red spruce (*Picea rubens*) ecosystems in the Central Appalachians were severely degraded by extensive logging operations that culminated in the 1920s and 1930s (Millspaugh, 1891; Hopkins, 1899; Stephenson, 1993). Fires were common, sometimes burning thousands of acres and consuming the thick organic layers that comprised the forest floor (Millspaugh, 1891; Hopkins, 1899; Korstian, 1937; Lafon et al., 2017), leaving most of the upland communities markedly altered (Hopkins, 1899; Stephenson, 1993; Byers et al., 2010; Nowacki and Wendt, 2010). The intensive extraction methods implemented in the Central Appalachians left a significant impact on red spruce landscapes that are still observable to this day. Disturbance was most severe where the forest burned after being logged, and as a result, most locations did not recover to their native spruce-dominated community (Byers et al., 2010).

More recently red spruce ecosystems have been managed primarily with sensitive species in mind—such as the Cheat Mountain salamander (CMS) (*Plethodon nettingi*) (Pauley, 2004; Pauley, 2006) and the northern flying squirrel (NFS) (*Glaucomys sabrinus fuscus*) (Menzel et al., 2005, 2006). However, the fragmentation of red spruce ecosystems (Adams and Stephenson, 1989; Adams et al., 2010 Beane, 2010) has isolated individual populations of CMS (Pauley, 2004; Dillard et al., 2008) and NFS (Menzel et al., 2005), making it more difficult for both species to move across the landscape. In addition to CMS and NFS, other sensitive and endangered species also rely on red spruce ecosystems for their home and are similarly affected by the lack of forest connectivity (Byers et al., 2010). Management with NFS and CMS in mind has been successful in recent years, with NFS being removed from the federal list of threatened species in 2013.

Ecological site descriptions (ESD) and their accompanied state-and-transition models (STM) have become a key tool for assessing potential pathways for restoration of
developmentally different ecological sites (ES) within a landscape (Briske et al., 2005; Bestelmeyer et al., 2009, 2010; Bestelmeyer and Brown, 2010; Duniway et al., 2010; Moseley et al., 2010). These tools identify key plant communities, soil properties and processes, and topographic attributes that make up a landscape, while offering interpretations for management-based restoration with the goal of guiding impaired ecosystems away from undesirable ecological states (Briske et al., 2005; Bestelmeyer et al., 2009, 2010). ESD are slowly being adopted for application in the eastern United States (Townsend, 2010; Drohan and Ireland, 2016), with the aim to provide a useful tool for agencies and organizations to implement forest restoration and management practices.

Not only do local organisms inhabiting these environments benefit from restoration and conservation, but other effects can be inferred beyond the local landscape. It is recognized that forest health and dynamic soil properties (DSP) can be affected positively by management strategies that ESD provide (Dunaway et al., 2010; Seeley et al., 2010). DSP are soil properties that change because of natural and anthropogenic disturbance and can be an indicator for the different functional processes inherent in the soil. DSP (such as SOC) in headwater ecosystems play a critical role in minimizing hydrologically-driven effects further downstream, such as severe flooding (Duniway et al., 2010; Lal et al., 2015), due to the relationship of organic matter (OM) to other soil properties like bulk density (BD), infiltration rate, and water holding capacity. Restoration of red spruce communities can positively influence DSP tied to important ecosystem functions and processes (Zepper et al., 2011). ESD and related management prescriptions can affect soil properties like SOC that influence drought resistance, biodiversity, nutrient cycling and transformation, and higher above- and below-ground SOC storage (see Chapter 2) (Hue et al., 1986; Duniway et al., 2010).
In West Virginia there are two completed red spruce ESD; the Spodic Shale Upland Conifer Forest (SSUCF) ES, and the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF) ES. Both ES are closely related, with similar soil forming factors influencing soil and ecological development. The main differences between these two ES lies both in the dominance of red spruce in the overstory canopy and in the soil type. Soils associated with the SSUCF are Spodosols, often accompanied by red spruce as a dominant component in the overstory canopy (USDA-NRCS, 2016a). Conversely, soils associated with the SISUHCF site are Inceptisols, with red spruce being a less prominent component—if at all—of the overstory composition (USDA-NRCS, 2016b).

By managing red spruce ecosystems using ESD, continued impacts from historic disturbance can be reduced both within the landscape and further downstream. Improved ecosystem resiliency in the Central Appalachian high-elevation forests can be attained through specific restoration pathways identified and implemented by ESD (Franzluebbers, 2002; Seeley et al., 2010). Quantifying differences or similarities among current red spruce ES and ecological states using SOC stocks as a metric can contribute to better understanding the potential restoration pathways that can improve ecosystem services and resiliency associated with red spruce landscapes of Central Appalachia. At the same time, this research can provide new knowledge of alternative red spruce ecological states that are capable of high C sequestration capacities when the reference state conditions cannot be attained feasibly.

**Hypotheses**

We hypothesize that SOC stocks between ES will be different. We also hypothesize that different ecological states within both SSUCF and SISUHCF ES will contain different SOC stocks. The reference state in the SSUCF will have higher SOC stocks than all other ecological
states, while mixed hardwood-conifer states will have lower SOC stocks. By documenting differences in SOC stocks among ecological states, ecosystem services can be inferred based on the relationship between SOC and other DSP expressed in an ES. Restoring red spruce ecosystems while managing to increase SOC stocks in Central Appalachia can provide specific on-site services such as higher C sequestration rates, greater water holding capacities, increased biodiversity, increased nutrient cycling rates, and greater overall ecosystem resiliency. These relationships can then be used to quantify and assess restoration pathways in conjunction with SOC to guide desirable state changes within an ESD state and transition model (STM). These hypotheses will be tested using four SOC stock derivatives, total pedon SOC (TSOC), organic horizon SOC (OSOC), mineral horizon SOC (MSOC), and spodic horizon SOC (SPSOC) at both the ecological state and ES analysis levels.

Three specific hypotheses were tested:

**Hypothesis 1**

Mean SOC stocks are different among ecological states both within the SSUCF and SISUHCF ES and between both ES.

\[ H_0 = \text{Mean SOC stocks are not different among ecological states within each ES} \]

\[ H_a = \text{Mean SOC stocks are different among ecological states within each ES} \]

In addition,

\[ H_0 = \text{Mean SOC stocks are not different between ES} \]

\[ H_a = \text{Mean SOC stocks are different between ES} \]
**Hypothesis 2**

The variance in SOC stock is different among ecological states both within the SSUCF and SISUHCF ES and between both ES.

$H_0 = \text{SOC stock variance is the same among ecological states within each ES}$

$H_a = \text{SOC stock variance is not the same among ecological states within each ES}$

In addition,

$H_0 = \text{SOC stock variance is the same between ES}$

$H_a = \text{SOC stock variance is not the same between ES}$

**Hypothesis 3**

SOC stock increases with increasing percent conifer canopy cover.

$H_0 = \text{SOC stocks do not increase with increasing \% conifer canopy cover}$

$H_a = \text{SOC stocks increase with increasing \% conifer canopy cover}$

In addition,

$H_0 = \text{SOC stocks do not increase with increasing \% conifer canopy cover within ES}$

$H_a = \text{SOC stocks increase with increasing \% conifer canopy cover within ES}$

**Scope of Research Objectives and Expected Outcomes**

There are three objectives and associated expected outcomes of this research.

**Objective A:** Identify differences in mean SOC stocks between red spruce ES and ecological states using site data combined with SOC content measurements
**Outcome A:** Observed differences in SOC stocks will help identify alternative states that have a high capacity for sequestering C, offering alternative options when reference conditions cannot be feasibly reached.

**Objective B:** Identify red spruce ecological states that have the widest or most narrow range of variance in SOC stocks within their respective ES.

**Outcome B:** Understand the variation of SOC stocks that different ecological states and ES contain as it relates to historic management impacts, while also identifying which ecological states are most likely to produce lasting, stable, ecosystem services.

**Objective C:** Evaluate the net SOC stock gains or losses expected when transitioning ecological states to a different state and infer ecosystem services that would benefit from such a transition.

**Outcome C:** Understanding ecosystems services that would be affected by certain management prescriptions and ecological state transitions can help better guide restoration practices while understanding SOC response.
CHAPTER 2: LITERATURE REVIEW

Red Spruce History and Current Extent in West Virginia

Red spruce is a subalpine conifer species distributed broadly across the Appalachian Mountains of the United States and into Canada (Blum, 1990). Paleobotanical research suggests a shifting red spruce population was present south of the Great Lakes along the Laurentide ice sheet approximately 18,000 years ago (Jacobson et al., 1987). As the climate began to warm further (around 6,000 years ago), red spruce was relegated to only the highest elevations of the Appalachian Mountains where the relatively modern distribution of spruce forests was seen prior to the 1700s (Jacobson et al., 1987).

By the late-1800s, timber extraction was at its peak in Central Appalachia (Byers et al., 2010). Virgin forests were clear-cut, burned, and disturbed extensively from the 1880s to the 1930s (Clarkson, 1964; Byers et al., 2010), leaving charred remains from timber refuse and rock outcrops where once stood extensive red spruce stands with thick surface horizons comprised of organic soil material. Hopkins (1899) estimated the present-day extent of red spruce in West Virginia to be as high as 607,028 ha, but by 1895 he estimated only around 91,054 ha remained. Where severe fires had occurred, hardwood species established themselves, but where the fires did not burn the red spruce seedbank completely, mixed hardwood-conifer stands developed instead (Sterling, 1920; Rentch and Schuler, 2017). After the timber boom in Central Appalachia, red spruce struggled to reestablish itself during the latter half of the 20th century, with acid deposition being a primary limiting growth factor, as seen in tree ring growth data and seedling establishment rates (Hamburg and Cogbill, 1988).

As much as 99% of native red spruce ecosystems were disturbed in some manner by logging practices (Byers et al., 2010). Today, an estimated 72,034 ha of red spruce forest exist in West Virginia (WV-DNR, 2015). It is of high priority to government agencies like the US
Department of Agriculture (USDA) and Forest Service (FS) to reestablish red spruce within its historic range in West Virginia. Red spruce ecosystems in Central Appalachia have a high species richness index that is not readily seen elsewhere on the east coast of the United States and acts as a significant biodiversity hotspot and migration corridor for countless species (Byers et al., 2010). Globally speaking, red spruce ecosystems of West Virginia receive a NatureServe designation of G2 (imperiled globally) or G3 (vulnerable globally), and rank as some of the most at-risk ecosystem types in the world (Byers et al., 2010; NatureServe, 2010).

**Red Spruce Importance**

Red spruce ecosystems serve as key habitat for numerous sensitive species of concern to the WV Department of Natural Resources and FS. The prominent species of concern are CMS and NFS. The CMS is listed as federally endangered and relies on interstitial spaces between rocks filled with organic soil materials for habitat; and, while not directly dependent on red spruce, CMS populations often coincide with red spruce communities growing in soils high in surface boulder cover and rock fragments (Pauley, 2004, 2006; Byers et al., 2010). The NFS is typically found in mature red spruce stands with open, well-developed understories that contain coarse woody debris (Ford et al., 2004). The main component of the NFS diet during spring and fall seasons consists of hypogeal fungi (Mitchell, 2001), which is also correlated to red spruce presence (Loeb et al., 2000). In addition to NFS and CMS, Byers et al. (2010) identified 138 globally/state-rare vascular plants and 30 rare vertebrate species that inhabit red spruce ecosystems, with hundreds of other animals, vascular and non-vascular plants, and fungi also calling these environments home. Biodiversity on the scale exhibited in the Central Appalachians is not seen in many other locations on the east coast of the US (NatureServe, 2010).
Other services provided by red spruce ecosystems are primarily related to SOC accumulated at the soil surface in O horizons, as well as SOC accumulations deeper in the subsoil. DSP like bulk density (BD), available water holding capacity, and nutrient availability are all influenced by SOC to some degree (Seely and Blanco, 2010). Ecosystem services extend beyond the local landscape through flood mitigation related to water holding capacity of soils and increased water infiltration rates.

Red spruce also influences pedogenesis, contributing to the formation of OM-rich spodic materials that accumulate in the subsoil (Fig. 2.1) (Gödde et al., 1996; Diochon et al., 2009; Nauman et al., 2015a, b). Complexed organic acids leach through the upper soil horizons and are deposited deeper in the subsoil (Lundström et al., 2000a, b). The SOC that accumulates in the subsoil is not subject to the same opportunities for microbial transformation and degradation as SOC located at the surface—effectively sequestering stable SOC and contributing to the offset of CO₂ emissions (Lal et al., 2004, 2015).

It is important to restore red spruce ecosystems within their historic extent in West Virginia to help increase landscape integrity and ecosystem resiliency of headwater locations. Changes in DSP, hydrologic functions, ecosystem processes, and C sequestration can all be improved by restoring red spruce ecosystems. Management tools such as ESD are useful in guiding restoration activities. Incorporating SOC stocks into red spruce ESD offers the possibility to better understand the effects that these stocks have on ES, ecological states, and associated ecosystem services. Understanding these interactions can aid management decisions towards implementing the highest-impact restoration and conservation practices available.
Ecological Sites and Ecological Site Descriptions

ES are defined as “a distinctive kind of land based on recurring soil, landform, geological, and climate characteristics that differs from other kinds of land and its ability to produce distinctive kinds and amounts of vegetation and its ability to respond similarly to management actions and natural disturbances” (USDA-NRCS, 2017a). An ESD is a means for describing an ES and is a tool used to implement practices to meet restoration and management goals for a landscape (Bestelmeyer and Brown, 2010). Within the last decade, provisional ESD have been implemented in forest ecosystems on the east coast of the United States (Townsend, 2010; Drohan and Ireland, 2016; Johanson et al., 2016) and are trending towards the general foundation for landscape scale management strategies used by agencies such as the NRCS, FS, and Bureau of Land Management. As a tool, ESD guide the restoration of impacted landscapes by outlining management practices suited specifically to the ES in question (Bestelmeyer and Brown, 2010).

The specificity of an ESD means that it cannot be implemented in ES other than the ES for which it was developed. Applying ESD in forest ecosystems comes with complications not fully realized, but this does not mean there is no utility involved when applied to forest ecosystems (Townsend, 2010; Drohan and Ireland, 2016; Johanson et al., 2016). Compared to ESD developed for rangeland ecosystems, fully developed ESD for forest ecosystems are not as common (Townsend, 2010). There is a need for more extensive research in applying ESD to forest ecosystems to better maximize its utility as a management tool and to better understand restoration obstacles unique to wooded landscapes. The multi-century history of varied land-use throughout the eastern US offers problems that are not seen in western rangelands, conveying a complexity that is made more difficult to interpret when significant land-use changes occur (Townsend, 2010). Therefore, careful consideration must be given when developing ESD and
delineating ES for lands that have experienced severe disturbance—as is the case for red spruce ecosystems in Central Appalachia.

**Ecological Site Description Framework**

An ES represents a combination of recurring soil, landform, geologic, and climactic influences that produce a unique group of ecological states, which are further comprised of specific community phases. ES vary from one another in that these influences produce variations in species composition, DSP, ecosystem services, and response to management practices (Briske et al., 2005; Bestelmeyer et al., 2009). For the full utility of ESD to be realized, all contributing influences must be assessed and correlated to fully understand the framework of an ES. Characterizing a landscape as such results in an identified ES concept based on soil-geomorphic properties affecting the production, composition, and resilience of an ES vegetation (Bestelmeyer et al., 2009).

An important aspect of the utility of ESD is, in part, a product of correlating one or more soil map unit components to an ES based on observable changes in soil-plant relationships, soil processes, and community composition (Duniway et al., 2010; USDA-NRCS, 2017a). Often, differences between ES and individual ecological states are due to changes in soil properties within a landscape (Duniway et al., 2010). In practice, an ES is tied to one or more soil map unit components that produce a unique vegetation type (USDA-NRCS, 2017a).

An ESD should seek to describe the overall landform, landscape position, parent material, soil features, climate, vegetation composition, and fauna inhabiting the ES (Moseley et al., 2010). Moseley et al. (2010) defines three key questions an ESD should answer: What is the ES reference conditions? How do changes in vegetation and soils occur relative to transitional pathways between both community phases and ecological states? How do reference conditions
and vegetation vary with climate, topography, and soils? These questions are not easily answerable and should be investigated through three stages of data collection: low, medium, and high intensity characterizations—each varying in the degree of characterization used to collect data and check ecological concepts (Moseley et al., 2010).

State-and-Transition Models for Ecological Site Development

The aspect of an ESD most important to management is the STM (Fig. 2.2). A STM is a broad conceptual framework used to group together vegetation and soil dynamics inherent to an ES, organized to easily implement restoration and management practices (Briske et al., 2005; Bestelmeyer et al., 2009). STM provide a way to organize and portray key boundaries that comprise ecological states within an ES, and to act as a map for management practices that should be applied to reach a desired ecological result. A STM is composed of ecological states, community phases, and transitional pathways to provide a comprehensive management plan. Triggers, drivers, and mechanisms that cause transition between states are also conceptually outlined by a STM (Brisk et al., 2008; Bestelmeyer et al., 2009).

Ecological states are temporally related plant communities and DSP that provide recurring structural and functional attributes to a given ecosystem (Bestelmeyer et al., 2009). Of the states comprising an ES, the most important is the reference state condition. A reference state can be defined as the state that can support the largest number of ecosystem services, and from which every other state in an ES can be derived (Bestelmeyer et al., 2009, 2010). Often the reference state is accepted as the “pre-European” conditions that comprised a vegetation community. In some cases—like in the eastern US—reference states are no longer easily observable (Drohan and Ireland, 2016) and an approximation of reference state conditions using historic records and other sources must be carefully determined.
Within an ecologic state there may be community phases. Community phases are specific plant communities and DSP that reoccur in an observable pattern within a state (Briske et al., 2008; Bestelmeyer et al., 2009, 2010). In the reference state there is an associated reference phase community, which imparts structural and functional qualities that determine the reference states resilience and integrity (Briske et al., 2008; Bestelmeyer et al., 2010). A community phase that occupies a position in the STM whereby transition into other alternative states can occur is called an at-risk community phase and is the least resilient phase in an ES. These community phases pose the greatest risk for transition due to management malpractice or other natural disturbances (Bestelmeyer et al., 2009).

When an at-risk phase is subjected to a trigger (i.e., events or processes that drive a state change), the at-risk phase can transition across an identified threshold boundary and become an alternative state. Triggers can be identified by changes in plant community composition or DSP inherent to a state, while transitions are the processes through which one state becomes a different state by crossing a threshold (Bestelmeyer et al., 2009). Sometimes a trigger can be anthropogenically induced—such as when clear cutting or acid deposition affects an ecosystem—or it can be a natural disturbance—like disease, infestation, or severe drought. An ecological state must cross a threshold boundary before transitioning into an alternative state, as defined by a change in specific vegetation or soil properties and processes (Briske et al., 2006; Bestelmeyer et al., 2010).

**Ecological Site Descriptions for Red Spruce Ecosystems**

Currently there exists two ESD for red spruce ecosystems in West Virginia (USDA-NRCS, 2016a, b). Both ES exist on shale geologies interbedded with sandstone that produce low pH soils and contain similar vegetation communities, although the two ES vary in vegetation composition and the degree of podzolization specific to the landscape. Both ES have similar
climactic influences and are characterized by frigid soil temperature regimes (mean annual soil temperature 0-8°C) and perudic soil moisture regimes (precipitation exceeds evapotranspiration in all months). Historic management practices are similar across both ES. Notable attributes of both ES include important conservation habitat, carbon sequestration capabilities, and other ecosystem services.

The first ESD is the Spodic Shale Upland Conifer Forest ES (SSUCF). It is represented by soils of the Spodosol soil order, with the associated soil type being the Wildell series (loamy-skeletal, mixed, superactive, frigid Typic Haplorthods) (Fig. 2.1). The SSUCF exists on many landscape positions ranging from lower backslopes to summits, and is dominantly found on steep, north-facing slopes. It is composed of an overstory canopy dominated by red spruce ranging between 30–75% of the community composition, with varying degrees of understory and midstory spruce components as well. Red spruce and eastern hemlock (Tsuga canadensis) are major components of the reference state and single reference community phase. Black cherry (Prunus serotina), red maple (Acer rubrum), striped maple (Acer pensylvanicum), mountain maple (Acer spicatum), American beech (Fagus grandifolia), American basswood (Tilia americana), white ash (Fraxinus americana), northern red oak (Quercus rubra), sweet birch (Betula lenta), yellow birch (Betula allaghaniensis), Allegheny serviceberry (Amelanchier laevis), mountain magnolia (Magnolia fraseri), and cucumber magnolia (Magnolia acuminata) comprise overstory vegetation at this ES, but exhibit less overstory dominance than red spruce or eastern hemlock. Understory shrubs at this ES include rhododendron (Rhododendron spp.), mountain holly (Ilex montana), and mountain laurel (Kalmia latifolia), while ground cover often consists of New York fern (Thelypteris noveboracensis), intermediate woodfern (Dryopteris intermedia), hypnum moss (Hypnum imponens), and liverwort (Bazzania trilobata). The reference state transitions to alternative states through logging accompanied by the presence or
absence of light fires, or it is initiated into transition through Norway spruce (*Picea abies*) or white pine (*Pinus strobus*) plantation establishment. Ecological states transitioned by logging both have spruce regeneration to some degree on site. All restoration pathways implement hardwood thinning, hardwood ringing, pesticide application, and red spruce plantings to reestablish or continue increasing understory red spruce (USDA-NRCS, 2016a).

The second ES is the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF). The soils that comprise this ES are the Mandy series (loamy-skeletal, mixed, active, frigid Spodic Dystrudepts) (Fig. 2.3), containing less podzolization in the subsoil than soils of the Wildell series. The SISUHCF can be found on all slope aspects and occurs from summits to lower backslope hillslope profile positions. Logging practices are thought to have degraded spodic material accumulations in subsoil horizons, acting in unison with prolonged hardwood cover to drive depodzolization of the subsoil (USDA-NRCS, 2016b). The SISUHCF is dominated by overstory hardwood canopy with red spruce and eastern hemlock overstory canopy consisting of less than 30%, and red maple overstory canopy consisting of up to 50%. American beech, black cherry, eastern hemlock, sugar maple, yellow and sweet birch, striped maple, and Allegheny serviceberry all share the overstory and midstory to varying degrees, with different states expressed by ecosystem composition. Red spruce regeneration is prominent in the understory and is accompanied by intermediate woodfern, New York fern, and running clubmoss (*Lycopodium clavatum*). Intensive logging and fires drive community composition in a given location, influenced strongly by how extensive the disturbance was. Ecological states affected by severe fire tend to regenerate as hardwood dominated stands with the absence of red spruce, while the absence of fire leaves the spruce seedbank intact and effectively retains a component of the overstory canopy (USDA-NRCS, 2016b). Transition from alternative states is performed by management practices similarly implemented in the SSUCF ES and include thinning, ringing, or
herbicide applications upon hardwood species to release understory spruce (USDA-NRCS, 2016ab).

Understanding SOC stock variability between red spruce ecological states is an important concept that will help build resilience and stability that an ES is likely to experience once restored to near reference conditions (Bennett et al. 2009). Incorporating clearly defined SOC stocks into both ESD and associated restoration pathways can improve efforts to enhance ecosystem services and DSP that are a function of both SOM build-up at the soil surface and OC accumulated in subsoil horizons (Gilgert and Zack, 2010; Brown and Havstad, 2016). Comparing differences between SOC stocks of red spruce ES will aid practical decision making in the MNF, improving our understanding of differences and similarities of ecological states and community phases in both ES, and increase overall management effectiveness.

**The Role of Soil Organic Carbon in Red Spruce Ecosystems**

SOM and SOC are important DSP that are highly related to one another and are often seemingly used interchangeably—even though SOM represents the *medium or compounds* for C transport into soils, while SOC represents the *actual* organic C incorporated into a soil. Both SOC and SOM influence other DSP such as BD, available water holding capacity, soil structure, aggregate stability, cation exchange, nutrient cycling rates, microbial populations, and other elemental transformations (Jobbágy and Jackson, 2000; Drenovsky et al., 2004; Essington, 2015); all of which effect an ecosystems long-term productivity and resilience (Franzluebbers, 2002; Seely and Blanco, 2010). Estimation of SOC stocks have been conducted to better understand the amount of C that can effectively be sequestered in different soils, but discrepancies over the observed variability and horizontal distribution (Jobbágy and Jackson, 2000) leaves researchers with only a general knowledge for ecosystem types and management...
prescriptions that can efficiently sequester large quantities of SOC (Heimann and Reichstein, 2008).

At the surface, organic matter is relatively abundant and continually re-incorporated into a soil (Jackson et al. 2017). SOM acts as an important source of nutrients for plants, provides energy for microorganisms and their mediated transformations, and is the medium through which C first enters the soil (Carney and Matson, 2005). At greater depths SOM inputs are more limited, and mechanisms for vertical transport (Jobbágy and Jackson, 2000) and accumulation of SOC deeper into a soil profile is determined primarily by root/shoot turnover (Lorenz and Lal, 2005), bioturbation, and leaching (Lundström et al., 2000a; Rasse et al., 2005). Humid areas with high volumes of precipitation (like West Virginia) leach dissolved organic C (DOC) in the form of microbial, hyphal, and root exudates, metabolites, waste products (Rasse et al., 2005; Lehmann and Kinyangi, 2007), and amorphous organo-metallic complexes through the surface layers and into subsoil horizons (Christ and David, 1996; Lundström et al., 2000a; Kögel-Knabner et al., 2008; Rumpel and Kögel-Knabner, 2011). Harper and Tibbet (2013) showed that SOC can be stored 5–8 m deep in a soil profile, or even deeper depending on the depth of solum (Jackson et al., 2000).

Red spruce ecosystems are driven by environmental factors that positively influence SOM accumulation and SOC sequestration. Low average annual temperature and high average annual precipitation are attributed to these landscapes and result in conditions conducive for the build-up of SOM at the surface and continual input of DOC into the subsoil (Lundström et al. 2000a, b). The more SOM that accumulates in conifer dominated ecosystems, the more acidic the soil conditions become—acting as a positive feedback loop for red spruce regeneration and, therefore, carbon sequestration (USDA-NRCS, 2016a, b).
Spodosol Definition and Classification

Spodosols are a soil order found across the globe in both warm and cool climates; however, they never form in dry environments (Lundström et al., 2000b), being documented from subarctic tundra to polar desert environments primarily in the northern hemisphere (Blume et al., 1996). In the US, Spodosols are found primarily in humid regions like Florida, Michigan, Wisconsin, coastal environments bordering the Atlantic, the northeast, and in the Pacific-northwest—although, within the last decade this soil order has been recognized as a major component of high-elevation forest soils in West Virginia (Nauman et al., 2015a,b; USDA-NRCS, 2016a,b; Nottingham et al., 2017). Spodosol formation occurs via the podzolization pathway (Lundström et al., 2000a) and is often associated with boreal, alpine, and sub-alpine conifer and ericaceous vegetation accompanied by high volumes of precipitation (Lundström et al., 2000b; Sauer et al., 2007; Nauman et al., 2015a,b). Spodosols contain an accumulation of organic C in the form of amorphous organo-aluminum complexes with or without iron in the subsoil, referred to as spodic materials. United States Soil Taxonomy (Soil Survey Staff, 2014) defines spodic materials as having a pH in water of 5.9 or less, have an organic C content of 0.6 percent or more, and exhibit a specific hue, value, and chroma—depending on the morphology of the soil. A spodic horizon (Bs, Bh, Bhs) is an illuvial layer that is composed of 85% or more of spodic materials accumulating to a thickness of 2.5 cm or more that is not part of an Ap horizon (plowed A horizon) (Soil Survey Staff, 2014). In West Virginia, fully developed Spodosols displaying strongly-expressed spodic morphology in the subsoil tend to occur below heavily weathered eluvial horizons, but, spodic properties are also found in other soil orders like the Mandy series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts)—a spodic intergrade with weak spodic expression that does not meet spodic horizon criteria (Soil Survey Staff, 2014).
Drivers of Podzolization in West Virginia

There are multiple theories for what mechanisms drive or alter the podzolization process, but research suggests this pedogenic pathway is influenced by a suite of factors each contributing to a soils podzolization potential (Lundström et al., 2000a,b; Carney and Matson, 2005; Nauman et al., 2015a). Climate provides the prerequisite conditions that facilitates the podzolization process (Christ and David, 1996; Lundström et al., 2000a). In cool and humid environments, high volumes of precipitation contribute to the downward transport of DOC and other humic materials from the surface soil layers into subsoil horizons, effectively leeching aluminum, iron, and other base cations from minerals in the eluvial horizon (Lundström, 1993). Without precipitation, mineral weathering and translocation is slowed. DOC and organo-metallic complexes percolate through the soil profile during precipitation events following vertical and lateral preferential flow pathways, accumulating in the subsoil or leaching into streams and rivers (Rumpel and Kögel-Knabner, 2011; Kaiser and Kalbitz, 2012). DOC in soil solution is thought to be in part controlled by temperature and precipitation effects on microbial populations and leaching (Gödde et al., 1996). During winter months, snow fall is an important environmental driver allowing for continual water infiltration into the profile (Lundström et al., 2000a), and has been correlated to both red spruce occurrence and podzolization (Schaetzl and Isard, 1996; Nowacki et al., 2010; Bean et al., 2013). High-elevation red spruce ecosystems often contain moist udic to perudic soil moisture regimes and frigid soil temperature regimes that provide ideal conditions to facilitate podzolization, but on their own are not responsible for initiating the soil-forming process.

Above ground vegetation and microorganisms play a contributing role in podzolization and Spodosol genesis, driving the soil-forming process by contributing DOC to the soil solution. Conifer and ericaceous vegetation produce significant quantities of organic acids that weather
primary minerals and form organic complexes (Lundström, 1993). Root exudates and root/shoot death contribute to total organic C and SOM, although the degree of contribution is debatable (Lorenz and Lal, 2005). Humic acids, fulvic acids, and low molecular weight aliphatic and aromatic acids produced by exudates and root decomposition affect the weathering and dissolution of silicate minerals of the eluvial horizon (Lundström et al., 2000). Conifer needles and residues are strongly acidic, and OM accumulation at the forest floor is thought to contribute significantly to total DOC moving through a soil profile, accounting for an estimated 20, 30, and 50% of overall leaching from Oi, Oe and Oa horizons, respectively (Fröberg et al., 2005). Conifer needles do not degrade as quickly as broadleaf tree litter (Hobbie et al., 2007), resulting in a thick O horizon accumulation where red spruce overstory is dominant and left undisturbed. It has been suggested that O horizons may have the capacity to accumulate at faster rates than initially suspected. West Virginia O horizon accumulations estimate around 1 cm of O horizon gain per 10% gain in conifer importance (Nauman et al., 2015a).

As DOC migrates through the soil profile, microorganisms decompose organic acids resulting in further chemical changes to the soil solution. Lundström et al. (1995) found evidence of microbial decomposition of citric, oxalic, fulvic, and humic metallic complexes by passing mor layer solutions through nonsterile soil columns and measuring metal concentrations in leachates at the inlet and again at the outlet. In non-sterilized soil columns, mineral weathering was significantly greater than in sterilized columns, with a measured outlet solution pH of 7.5 verses 5.31, respectively. The biodegradation of organic acids by microbial populations seem to help regulate soil pH and facilitate precipitation of inorganic aluminum-silicate and -hydroxide phases (Lundström et al., 1995). Microbes also produce organic residues from waste products and by death and decomposition, contributing to the overall concentration of organics in a soil solution.
Ectomycorrhizal fungi associated with conifer vegetation also produce significant amounts of low molecular weight organic acids that contribute to overall soil acidity and therefore weathering/podzolization. In nutrient deficient acidic conifer forest soils, fungal symbionts use organic acid exudates to mine soil mineral grains (Jongmans et al., 1997) and acquire nutrients for their host plant in exchange for labile non-humic substances like sugars and carbohydrates (Van Schöll et al., 2008). Numerous studies document mineral tunneling by ectomycorrhizal fungi targeting feldspar mineral species for potassium/calcium, and phosphorus contained in apatite (Hoffland et al., 2005) using organic acids excreted by hypha (Hoffland et al., 2002). Hyphal weathering also facilitates the upward and downward movement of aluminum, iron, and silicon to and from the O-horizon, and is a unique strategy for dealing with aluminum toxicity (Giesler et al., 2000). Estimations of the degree that fungi contribute to the DOC pool and overall mineral weathering is also debatable—some research suggests a minimal contribution (Smitts et al., 2005) while others suggest it is a significant source of podzolization based on prolific numbers of trace-fossil tunnels and etch pits on mineral surfaces (Van Breemen et al., 2000).

Relating the podzolization process to the SSUCF and SISUHCF ES, it is important to note that while the SISUHCF ES may have experienced severe disturbance resulting in depodzolization, it is equally likely that some occurrences of this ES may never have been fully developed Spodosols like we see in the SSUCF. There are two possibilities for the occurrence of the SISUHCF ES; either (i) the SISUHCF ES will never attain the level of podzolization seen in the SSUCF ES and is naturally a spodic intergrade due to the dominance of mixed conifer-hardwood overstory vegetation; or, (ii) the SISUHCF ES is a result of depodzolization from timbering and burning practices that changed species composition and was transitioned from the SSUCF ES.
The podzolization process is a key characteristic of these landscapes and especially of these two ES. To better manage these ES it is imperative to consider how the podzolization process affects the greater ecosystem. A better understanding of how much SOC is accumulated by the podzolization process in different ecological states of both red spruce ES can influence how land managers utilize SOC as a marker for ecological health, as well as increase understanding of how SOC can affect other DSP. Viewing ecological restoration and conservation of red spruce through the lens of SOC can help land managers become more successful in both implementing and measuring restoration success.
Figure 2.1. Depiction of the Wildell soil series (Loamy-skeletal, mixed, superactive, frigid Typic Haplorthods) exhibiting SOC in the surface as OM and subsurface as spodic materials. This soil series is linked to the Spodic Shale Upland Conifer Forest ES in West Virginia. Photo credit: USDA NRCS.
Figure 2.2. State and transition model from the Spodic Shale Upland Conifer Forest (SSUCF) ES (Teets, 2013). T1A and T1B represent transitional pathways to hardwood dominated states, while R2A and R3A represent restoration pathways towards the conifer dominated reference state. T1C represents the transition into a conifer plantation state.
Figure 2.3. The Mandy soil series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts), a part of the SISUHCF ES, showing a moderate to slight degree of podzolization in the subsoil. Photo credit: USDA NRCS.
CHAPTER 3: RESEARCH GAPS

ESD research has been primarily focused on rangelands in the western United States. A small number of ESD-related studies specifically looking at forest ecosystems exist, but are limited in diversity (Townsend, 2010; Nauman et al., 2015b; Drohan and Ireland, 2016; Johanson et al., 2016). Townsend (2010) discussed development of forest-woodland ESD, focusing specifically on methods, informational inputs, and the delineation of the reference state condition, as well as the added value associated with the creation of such an ESD. Nauman et al. (2015b) focused on spatial modeling using ESD by mapping both the reference state and logged states, inferring SOC stock accumulation in O horizons, conifer importance in relation to O horizon accumulation, and discussed implications for restoration from various angles when hypothetically transitioning back to the reference state. Drohan and Ireland (2016) described provisional ES within the Northern Appalachians in reference to their STM, while also discussing important challenges for management and providing recommendations to improve the ESD development in forested landscapes. Finally, Johanson et al. (2016) classified and mapped ES groups within northern New England landscapes, giving an overview of where these ES groups may occur on the landscape and defining ecological classes with conservation decision making in mind.

No research has examined SOC stocks among ecological states occurring within an ES using SOC stock estimates or have interpreted changes to the estimated SOC stocks if one state is transitioned into another. This study seeks to fill this research gap. Continuing to expand the scope of research on ESD development in forested landscapes will play an important role in future management decisions for environments like the red spruce ecosystems of West Virginia and will further establish the need to develop ESD in forest landscapes. Better understanding of the role ESD can play in forested landscapes can, in time, refine management strategies aimed at
restoring reference conditions or mitigating past impacts, especially where significant
disturbance has taken place.

More specifically, there is also a lack of research in the application of SOC stocks tied to
forested ES and ecological states with the intent of guiding forest management decisions. Only
Nauman et al. (2015b) have estimated the spatial extent of SOC stocks in terms of ecological
states of the eastern United States, specifically for the SSUCF ES located in the MNF. Even so,
Nauman et al. (2015b) did not focus on specific states outlined in the ES STM, but rather
grouped alternative states into what are referred to as “logged states” and “transition stages”.
Most ESD research has focused on concepts like guiding scientists through the ESD creation
process (Briske et al., 2006; Briske et al., 2008; Bestelmeyer et al., 2009), delineating important
core concepts to ESD and ES (Briske et al., 2005; Briske et al., 2006; Briske et al., 2008;
Bestelmeyer et al., 2009; Bestelmeyer and Brown, 2010; Bestelmeyer et al., 2010; Moseley et
al., 2010), soil properties and processes that distinguish ES and ecological states (Duniway et al.,
2010), and ecosystem services related to DSP of ecological states (Bennett et al., 2009; Gilgert
and Zack, 2010; Brown and Havstad, 2016). More research is needed to determine how DSP and
more specifically, SOC, vary across ES and ecological states, as well as the effects that
management prescriptions aiming to build SOC stocks will have when transitioning between
alternative ecological states.

The research presented here fills some of these knowledge gaps by tying SOC stocks to
specific red spruce ecological communities. Being able to connect SOC stocks with red spruce
ecological states informs management on SOC stock gains and losses that could likely be seen
when restoration goals have been met. Not only can it inform management of changes in SOC
stocks, but it can help to better understand how other DSP will be influenced by the observed
changes to SOC.
CHAPTER 4: RED SPRUCE ECOLOGICAL SITES, ECOLOGICAL STATES, AND RESTORATION PATHWAYS QUANTIFIED THROUGH SOIL ORGANIC CARBON

Abstract

Red spruce (*Picea rubens*) ecosystems in Central Appalachia have undergone significant changes due to historical intensive logging efforts. Currently, organizations and federal agencies like the Central Appalachian Spruce Restoration Initiative, The Nature Conservancy, the Natural Resources Conservation Service, and the Forest Service are working towards restoring red spruce ecosystems to their pre-disturbance ecological status. Two red spruce ecological site descriptions (ESD) have been developed for landscape managers as restoration tools to guide implementation of management practices in these ecosystems. Soil organic C (SOC) is a key soil property in these ecological landscapes, whereby SOC is accumulated at the surface by build-up of organic matter and in the subsoil via the podzolization process. SOC influences many other dynamic soil properties (DSP) like infiltration rate, water holding capacity, elemental transformations, and cation exchange capacity, among many others. Studies have analyzed how SOC can benefit ecosystem services, yet none seek to compare SOC stocks across multiple ecological states to address both restoration pathways and management outcomes that could potentially increase SOC stocks while restoring impaired ecosystem services. A total of 120 soil profiles and their associated site conditions were described and sampled, with 15 sites attributed to each ecological state of the Spodic Shale Upland Conifer Forest (SSUCF) and Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF) ecological sites (ES). Soil samples were analyzed using dry combustion to determine SOC percent weight per horizon, and further used to estimate the SOC stock (kg/m²) held in the soil to a depth of 100 cm. Four mean SOC stock derivatives were examined, including total SOC (TSOC), O horizon SOC (OSOC), mineral SOC (MSOC), and spodic horizon SOC (SPSOC). Analyses show differences between
ES TSOC stock (p < 0.0001), OSOC stock (p < 0.0001), and SPSOC stocks (p = 0.001), while MSOC stocks showed no difference (p = 0.289). Specifically, the SSUCF contained larger SOC stocks than the SISUHCF. At the ecological state level, there were two significant differences when examining TSOC (p = 0.005) and OSOC (p = 0.0002) stocks within the SISUHCF, while there were no differences between ecological states in the SSUCF. SOC stock variance differences were only significant at the ES level of analyses in terms of TSOC stock (p < 0.0001) and OSOC stock (p < 0.0001) derivatives, with variability being larger in the SSUCF ES, while there were no variance differences in any SOC derivatives at the ecological state level. Knowing how SOC changes between red spruce ES and corresponding ecological states can help land managers to understand the impact of a restoration practice in terms of how much SOC may be gained when restoration goals for an ecosystem have been met. These changes to SOC are also reflected in the relationships SOC has with other DSP. Using SOC as a metric to predict DSP changes in these landscapes aids in a fuller understanding for the effect that restoration or other management practices may have on landscape.
Introduction

In the late 1800s and early 1900s intensive logging operations reduced red spruce forest coverage within West Virginia to roughly 12% of its historical extent (Byers et al., 2010). The widescale logging and burning not only impacted red spruce, but the entire landscapes they inhabit—including the soils that support them. Fires were common (Clarkson, 1964; Byers et al., 2010), often fully eliminating the organic soil materials that comprised the forest floor (Hopkins, 1899). The impact of the loss of organic surface layers also affected other dynamic soil properties (DSP)—such as water holding capacity—resulting in widespread flooding in the 1920s and 1930s (Byers et al., 2010).

Over the last decade ecological site descriptions (ESD) have become an important part of the restoration toolkit used by land managers across the country, initially being developed for rangeland management in the western United States (Bestelmeyer and Brown, 2010). Since then, ESD have slowly been adapted to other ecosystems like high-elevation eastern forests where red spruce is a historic component of the landscape ecology. ESD describe “a distinctive kind of land based on recurring soil, landform, geological, and climate characteristics that differs from other kinds of land and its ability to produce distinctive kinds and amounts of vegetation and its ability to respond similarly to management actions and natural disturbances” (USDA-NRCS, 2017a). ESD are used by land managers to enact highly specific management prescriptions tailored specifically for the ecological site (ES) in question. The goal of the ESD and accompanying state-and-transition model (STM) is to provide a restoration schema to help transition historically impacted ecological communities back towards their pre-European ecological status prior to disturbance, but also allow for other management goals besides restoration to the reference state condition.
In the Central Appalachian Mountains, there have been two completed ESD for red spruce forest communities. These ES include the Spodic Shale Upland Conifer Forest (SSUCF) (USDA-NRCS, 2016a) and the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF) (USDA-NRCS, 2016b), which spa approximately 50,545 ha across Randolph, Pocahontas, and Pendleton counties in West Virginia (Fig. 4.1). These ES occur side by side one another, and one often seamlessly transitions into the other. Both ES are home to species of concern, with government agencies like the Natural Resources Conservation Service and the Forest Service, as well as other non-government entities like The Nature Conservancy and the Central Appalachian Spruce Restoration Initiative working to restore these communities to some assemblance of what they once were.

**Pedogenic Properties and Processes of Red Spruce Ecosystems**

Soils correlated to Central Appalachian high elevation red spruce ecosystems are dominantly Spodosols (Fig. 4.2) and spodic Dystrudepts (Fig. 4.3) (Nauman et al., 2015a,b; USDA-NRCS, 2016a,b; Nottingham et al., 2017), although other soil types occur within the landscape too. In these landscapes spodic properties naturally develop in tandem with red spruce due to key pedogenic processes enabled by both climactic and red spruce influences. The process of podzolization, whereby aluminum and iron is complexed with organic compounds and translocated to the subsoil (Lundström et al., 2000a), leads to distinct soil morphologies and the formation of spodic properties (Figs. 4.2, 4.3). Podzolization in Central Appalachian soils proceeds exclusively under red spruce or eastern hemlock dominated forests (and associated ericaceous vegetation), driven by organic acids secreted through conifer roots and from decomposing needle litter on the forest floor (Lundström et al., 2000b; Fröberg et al., 2005; USDA-NRCS, 2016a,b).
Importantly, spodic properties are a marker for where red spruce and other conifers once inhabited historically (Nauman et al., 2015a,b). The presence of spodic properties where they should not occur—such as in hardwood forests—indicates that red spruce was present at a given location in recent past. Identifying spodic properties in soils can help to better understand the historic extent of red spruce and provide guidance for where to restore. Spodic horizons are enriched in OC that has been deposited in the subsoil. As a result, Spodosols and spodic Dystrudepts in red spruce forests are SOC accumulators—both at the surface with O horizon build up and in the subsoil with spodic property development.

**SOC Relationships to other DSP and Implications for Restoration**

SOC has been studied intensively and is correlated to many DSP (Jobbágy and Jackson, 2000; Drenovsky et al., 2004; Essington, 2015). DSP like water holding capacity, infiltration rate, cation exchange capacity, BD, and many others are significantly influenced by SOC. Increases to SOC act to reduce BD, increase cation exchange capacity, increase infiltration rates, improve soil structure and stability, and increase water holding capacity, just to name a few. In short, SOC positively influences DSP, such that by managing landscapes to increase SOC sequestration other DSP are positively changed too. Predicting changes to SOC stocks and the functioning of DSP that have a relationship to C can help land managers understand how a landscape is likely to be affected by a management practice contained in an ESD and further implemented in practice.

Incorporating clearly defined SOC stocks into both ESD and associated restoration pathways can improve efforts to enhance ecosystem services and DSP that are a function of both SOM build-up at the soil surface and SOC accumulated in subsoil horizons (Gilgert and Zack, 2010; Brown and Havstad, 2016). Understanding SOC stock differences between red spruce
ecological states is an important concept that will help build resilience and stability that an ES is likely to experience once restored to near reference conditions (Bennett et al. 2009). The reference state can be defined as the ecological state that can support the largest number of ecosystem services, and from which all other alternative states in an ES can be derived (Bestelmeyer et al., 2009, 2010). This implies DSP related to the reference state condition are functioning at their greatest capacity within the ES, and that as restoration occurs in an alternative state its related DSP and ecosystem services improve as reference state conditions are achieved. In red spruce forests of Central Appalachia, restoring an alternative red spruce state to the reference state condition means increasing the amount of red spruce in the overstory via some management method (USDA-NRCS, 2015a, b). Consequently, this means an increase to the podzolization process and the development or enhancement of spodic properties.

By correlating SOC stocks to red spruce ES and ecological states, the application of ESD becomes more impactful to land managers. The distinction between these ecological communities is often subtle in terms of vegetation composition (USDA-NRCS, 2015a, b) (Fig. 4.4, 4.5), but, regarding soils, they are strikingly different (Figs. 4.2, 4.3) and contain unique management possibilities. Differences in SOC stocks between ES and ecological states can be used to land managers’ advantage by exploiting the natural soil processes so closely tied to the Central Appalachian red spruce landscape to better implement restoration and conservation resources. SOC and other DSP related to SOC can act as a lens through which to view relationships between restoration management practices and resulting changes to DSP in a landscape.
Materials and Methods

Study Area

The SSUCF and SISUHCF ES are found within Pocahontas, Pendleton, and Randolph counties in West Virginia, and are considered part of the Eastern Allegheny Plateau and Mountains (MLRA 127), which is itself a part of the Appalachian Plateau Province (USDA-NRCS, 2016a,b) (Fig. 4.1). The SSUCF and SISUHCF ES occur in acid shale geologies with interbedded sandstone and siltstone on the Chemung and Hampshire formations (WVGES, 1968). A wide range of landforms make up these landscapes but are generally dominated by steep mountain slopes accented by narrow valley bottoms. Slope shape varies greatly, from simple linear mountain slopes to complex undulating hills. Significant microtopography in the form of tip and mound features are commonly present. Both ES range in elevation from approximately 870–1300 m, and range in slope gradient from 3–80% (USDA-NRCS, 2016a,b). Most of the year it is overcast (~81 days of clear sky per year), and annual precipitation can be upwards of 127 cm (USDA-NRCS, 2016a,b), yielding a perudic moisture regime. The greatest precipitation rates occur in the summer months, although precipitation and temperature vary with landscape position and topography. Mean annual temperature across both sites is around 7°C and receives an average of only 119 frost-free days per year. The total footprint these two ES encompass is estimated to be around 50,715 ha (cite NRCS here, e.g., SSURGO or WSS or the ESD, as the source for this figure?), although these sites have not been mapped with full certainty (Nauman et al., 2015a).

Plant communities of both ES are similar, consisting of mixed hardwood-conifer stands that include beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), striped maple (*Acer pensylvanicum*), yellow birch (*Betula alleghaniensis*), sweet
birch (*Betula lenta*), mountain magnolia (*Magnolia fraseri*), cucumber tree (*Magnolia acuminata*), red spruce, Allegheny serviceberry (*Amelanchier laevis*), and eastern-hemlock (*Tsuga canadensis*). Understory species occur in the form of regenerating species listed above, but also include intermediate woodfern (*Dryopteris intermedia*), New York fern (*Thelypteris noveboracensis*), lesser roundleaved orchid (*Platanthera orbiculate*), indian cucumber (*Medeola*), trillium (*Trillium*), Canada mayflower (*Maianthemum canadense*), common yellow oxalis (*Oxalis stricta*), partridgeberry (*Mitchella repens*), running clubmoss (*Lycopodium clavatum*), three-lobed bazzania (*Bazzania trilobata*), and splendid feather moss (*Hylocomium splendens*). Soils in these landscapes grade from shallow to moderately deep depending on hillslope profile position, and commonly contain evidence of podzolization (USDA-NRCS 2016a,b). The Wildell series (Loamy-skeletal, mixed, superactive, frigid Typic Haplorthods) characterizes the SSUCF ES, while the Mandy series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts) is indicative of the SISUHCF ES. The primary differences between the two ES are the amount of red spruce in the canopy and the degree of podzolization exhibited in the soil. When landscapes like this experience significant disturbance spodic properties produced through podzolization are quick to degrade, being lost to erosion and other degrading influences in only a matter of decades (Barrett and Schaetzl, 1998; Nauman et al. 2015b).

**Previously Sampled Pedons and Acquired Data**

This study was performed within the area encompassing the dual SSUCF and SISUHCF ES extent (Fig. 4.1). This same extent has been used in previous studies (Nauman et al., 2015a,b) such that data previously collected by West Virginia University, the Forest Service, and the Natural Resources Conservation Service from 2009–2015 was available for use in this research. Three types of data were used in this study: (i) morphological descriptions of previously
characterized soil profiles; (ii) vegetation data from research plots; and (iii) measured SOC for pedon samples that have been analyzed in the lab. A total of 27 pedons that occurred within a described ecological state (NRCS, FS, Nauman et al. 2015a,b) and were previously sampled were available for inclusion. Many previously described pedons by the Natural Resources Conservation Service and Forest Service that were located within the dual ES extent were not sampled and therefore not included in this experiment.

Sample Selection

Sample locations were selected using a stratified random sampling design. Previous work by Nauman et al. (2015b) led to the development of a map that delineates the reference state condition of the SSUCF ES, but groups alternative ecological states in both ES as “logged stages” and “transition stages” that have been disturbed in the past. This assumes all locations within the study footprint that are a part of the SISUHCF were transitioned from the SSUCF reference states by past logging consequences. The Nauman et al. (2015b) map defines spodic intensity (spodic, spodic intergrade) and above-ground cover type (conifer, mixed, hardwood) modeled from other sources. This map was further reclassified to display locations by spodic intensity for use in this project—regardless of above-ground vegetation – with a total random sample pool of 323 points generated. Of these 323 random points a total of 15 pedons per ecological state for each ES were used in the final analysis, totaling 27 previously described pedons and 93 newly excavated pedons during this project (n = 120). The possible 323 sample locations provided a larger sample pool from which to draw samples and descriptions. Upon arrival to a proposed location, if the vegetation community depicted an ecological state needed for analyses then the plot was sampled and described, while if the research site did not meet the above-ground vegetation community requirements, then the sample location was rejected. If,
once excavated, the soil did not express field described spodic properties associated with the ES, then the sample site was also rejected. Only sites containing both the necessary ecological communities and soils expressing spodic properties representative of either ES were included in this project.

New sample locations were distributed across the extent of both the SSUCF and SISUHCF ES (Fig. 4.4). The plantation ecological states in both ES were excluded from analysis due to the difficulty in identifying representative locations. To reach a total of 15 pedons per ecological state in the SSUCF ES, 31 newly excavated Spodosols were described and sampled, while for the SISUHCF ES a total of 62 newly excavated spodic-Dystrudepts were described and sampled.

**Field Sampling and Description Methods**

Experimental unit, sampling, and description methods closely follow those implemented by Nauman et al. (2015a,b). Each location deemed suitable for sampling had both a soil description and vegetation description completed. The overall research plots were 20 x 20 m. Each plot contained a soil profile in the center of the plot, and four small satellite soil profiles specifically targeting O horizon depths (Appendix A). Coordinate locations were collected in the plot by placing a handheld global positioning system unit capable of <3 m accuracy in WAAS mode directly upslope of the soil profile. Within the 20 x 20 m plot overall species were recorded including plants within the visible surroundings, with absolute canopy cover recorded for each species in the plot and relative canopy cover calculated later.

The whole plot was divided into four equal quadrants with each quadrant containing a single O horizon depth observation (five total O horizon observations per plot including the soil pit) that captures the depths in cm of the Oi, Oe, and Oa horizons when present, and contributes
to an average O horizon thickness calculation for each site. All percent cover estimations were conducted using ocular estimation with the help of visual aids displaying percent composition of a specific area contained in Shoeneberger et al. (2012).

At the center of each plot a soil pit ~1 x 1 m square was excavated using hand tools to lithic contact or 100 cm in depth, whichever was more shallow. Once fully excavated, the pit face was cleaned to expose the soil horizonation, color, structure, and other properties, and was photographed for documentation. A pedon description was completed using official Natural Resources Conservation Service pedon description methods (Schoeneberger et al., 2012), with close attention being paid to spodic morphology. Spodic intensity—a subjective field-based estimation of the degree of podzolization—was estimated based on the smeariness exhibited by horizons in the profile, as well as other metrics used to describe spodic morphology such as color requirements and horizon thickness (Soil Survey Staff, 2014).

Each horizon was sampled from soil materials displaying homogenous property expression and placed into a thick-walled plastic sample bag. Once the description and sampling were completed, excavated profiles were field classified based on the field-characterized soil morphology to the nearest soil series possible since particle size distribution and other important lab data usually used to classify a soil were not examined.

**Laboratory Methods**

To obtain SOC content and SOC stock estimates, soil samples from both mineral and organic horizons were treated similarly. For both mineral and organic horizon samples large roots and large rocks were removed by hand prior to processing. Mineral soil samples were crushed with a mortar and pestle to break up aggregates and passed through a 2 mm sieve to remove all rock fragments and roots. Next, a 0.5 g subsample of all soil samples was acidified
using 1M HCl with 1:2 (m:V) solid:solution ratio in order to degas any inorganic carbon
contained in soil samples. Then, soil samples were dried in the lab oven at 70°C for 48 hours to
remove excess moisture. The SOC content was determined for both mineral and organic soil
materials using 0.08 g of the acidified and dried subsample using the Elementar Vario MAX
Cube (Hanau, Germany) by dry combustion (Nelson and Sommers, 1996). The Elementar Vario
MAX Cube measures total C, S, and N in each sample recorded as percent weight. The SOC
content for each soil was combined with BD estimates from a pedotransfer function developed
by Yoast (2015) from soils in the greater geographic area to produce a total SOC stock for each
pedon. SOC stock was calculated to a depth of 100 cm, or to the depth of lithic contact if
shallower than 100 cm, using the equation (USDA-NRCS, 2017b):

\[ SOC_{stock\ pedon} = \sum_{i}^{n} (SOC_{i} \times BD_{i} \times Thickness_{i} \times (1 - CFrags_{i}/100)) \]

where \( SOC_{i} \) is the OC content of a specific horizon represented as a fraction. \( BD_{i} \) is the estimated
BD of the specific designated horizon based on horizon texture. \( Thickness_{i} \) is the thickness of the
specific horizon in cm. \( CFrags_{i} \) is the total volume of course fragments found in the specified
horizon written as a percent of the whole. \( \sum_{i}^{n} (...) \) represents the sum of each horizon contained
in the total soil profile to a depth of 100 cm or lithic contact to give the estimated SOC stock of
the pedon.

**Statistical Analysis**

All data were analyzed using JMP and SAS software (JMP®, Version Pro 16.0, SAS
2012). Significance criterion alpha for all tests was set to 0.05. All continuous response data
were screened for normal distribution of residuals using the Shapiro-Wilk W test in JMP.
Analysis was conducted on four response variables, corresponding to four SOC stock and
variance derivatives from collected data; (i) total SOC (TSOC) stock, up to 100 cm in depth or to lithic contact if less than 100 cm; (ii) O horizon SOC (OSOC) stocks, comprised of all O horizons occurring at the surface of the soil; (iii) mineral SOC (MSOC) stocks, including all horizons below any O horizons at the surface down to 100 cm or lithic contact if less than 100 cm; and (iv) spodic horizon SOC (SPSOC) stocks, including only spodic horizons designated Bh, Bhs, or Bs to a depth of 100 cm or lithic contact if less than 100 cm.

To compare mean SOC stocks and stock variance across ES and ecological states a natural log transformation was applied to the TSOC, OSOC, and SPSOC stock data to correct for right-skewness. In the case of MSOC stocks, a square root transformation was used to correct for right-skewness. Two null hypotheses were tested: (i) SOC stocks do not differ among ecological states of each ES and between ES; and (ii) SOC stock variance does not change among ecological state and between ES. The first hypothesis was tested using a mixed effects model ANOVA with ES and ecological state considered fixed effects in the model, and ecological states nested within their related ES. Year sampled was considered as a random effect and ANOVA was followed by the slicing method of multiple comparisons on least square (LS) means, where ecological states were compared within each corresponding ES using Tukey-Kramer adjustment. The second hypothesis test included the Levene test statistic at the level of ES. Further, the Levene test was also used to evaluate equality of variances among ecological states within each ES separately.

During lab analysis soil standards for the Lobdell series (Fine-loamy, mixed, active, mesic Fluvaquentic Eutrudepts) were used to check accuracy of SOC measurements. A total of 98 Lobdell standards were analyzed over the course of the lab work, with one standard for each 12 samples run. The Lobdell standard has lab measured C of 2.77%. After 98 Lobdell standards were analyzed, our calculated mean C was 3.01%, with a standard error of 0.057.
Results

SOC Stocks

The mixed effects model identified a significant effect of ES on TSOC, OSOC, and SPSOC stocks. Specifically, the SSUCF had higher SOC stocks than SISUHCF in mean TSOC stock (p < 0.0001), OSOC stock (p < 0.0001), and SPSOC stock (p = 0.001) (Table 4.1). Conversely, there was no significant difference between ES when comparing MSOC stocks (p = 0.289; Table 4.1). In addition, TSOC stocks (Table 4.2, p = 0.005) and OSOC stocks (Table 4.2, p = 0.0002) demonstrated differences at the ecological state level. Ecological states differed in TSOC and OSOC stocks only within the SISUHCF ES (Figs. 4.7, 4.8) and are denoted with letters next to LS means in Table 4.2, such that groups that do not share the same letter are statistically different (Figs. 4.7, 4.8). The ecological states of the SSUCF did not contain significant differences and are therefore were not denoted similarly to the SISUHCF.

In terms of TSOC stock, the Reference State had higher SOC than the Logged and Burned State with Cherry Seedbank, but was not different from other alternative states in the SISUHCF (Fig. 4.7). In comparison, OSOC stocks in the Reference State was higher than all other ecological states except the Logged State with Cherry Seedbank, which itself was similar to the other ecological states (Fig. 4.8). SPSOC and MSOC showed no differences among ecological states of either ES. When comparing mean OSOC and MSOC we find OSOC accounts for a larger proportion of the overall TSOC stock than the MSOC stock in the SSUCF ES (Table 4.1). The SISUHCF does not follow this same trend, as the greatest proportion of the SOC is contained in the MSOC layer with exception for the Reference State in which OSOC accounts for the greatest proportion of SOC.
In terms of untransformed SOC stocks, the SSUCF ES has the highest arithmetic mean SOC for every soil layer type except for MSOC (Table 4.1), although, the MSOC layer only had a mean of 0.46 kg/m² greater in the SISUHCF than in the SSUCF. In the SISUHCF ES, the Reference State contained the highest mean SOC stocks in the TSOC (35.86 ± 2 kg/m²) and OSOC (20.69 ± 1.2 kg/m²) (Table 4.2). For the MSOC and SPSOC stocks the Logged State with Cherry Seedbank contained the highest mean SOC stocks with 21.91 ± 1.2 kg/m² in the MSOC layer and 8.00 ± .5 kg/m² in the SPSOC (Table 4.2). The Logged and Burned State with Cherry Seedbank contained the lowest mean SOC stock in the TSOC (23.45 ± 1.3 kg/m²) and OSOC (7.17 ± .4 kg/m²) and was second lowest in mean MSOC (16.29 ± .9 kg/m²) stock (Table 4.2).

Within the SSUCF, the Reference State contained the highest mean SOC stock in only the OSOC stock component (41.21 ± 2.3 kg/m²), while the Logged State with Cherry Seedbank had the highest mean SOC stock in the TSOC (59.86 ± 3.4 kg/m²), MSOC (22.72 ± 1.3 kg/m²), and SPSOC (10.56 ± .6 kg/m²) pools (Table 4.2). The lowest mean SOC stock in all C pools can be attributed to the Logged State with Beech Seedbank, except for SPSOC and MSOC pools of which the Reference State contained the lowest mean stocks (Table 4.2).

**SOC Stock Variance**

Considering both ES, the SSUCF contained the widest range of observed SOC stock in all pools except the SPSOC (Table 4.1). The widest observed SOC stock range in the SSUCF was for the Logged State with Cherry Seedbank in the OSOC (87.79 kg/m²), although the TSOC (87.25 kg/m²) and MSOC (84.70 kg/m²) stocks are also similarly wide in range (Table 4.2). In the SISUHCF, the widest ranging TSOC stock was in the Reference State which had a range of 57.749 kg/m². The Reference State also has the greatest variability in OSOC stock (51.189 kg/m²), while the Logged State with Cherry Seedbank varied greatest in the MSOC layer (54.51
kg/m$^2$). The Logged and Burned State ranged 19.907 kg/m$^2$ in the SPSOC layer, with the Logged State with Cherry Seedbank closely following (19.896 kg/m$^2$).

The Levene test identified significant differences of variance between ES in TSOC and OSOC derivatives. The SSUCF had higher variability (SD = 23.43) than the SISUHCF (SD = 12.91) in TSOC stock (Table 4.3, p < 0.0001). Similarly the SSUCF (STDV = 21.41) had higher variability than SISUHCF (SD = 9.32) in OSOC stock (Table 4.3, p < 0.0001). Conversely, there was no significant difference between ES when comparing MSOC stock variance (Table 4.3, p = 0.971) and SPSOC stock variance (Table 4.3, p = 0.125). Levene analyses within each ES demonstrated that neither ES exhibited significant differences among ecological states SOC stock variation in all four SOC stock components (Table 4.4).

**Discussion**

**SOC Stock Differences Between ES and Among Ecological States**

SOC stock differences between ES were significant for all SOC derivatives except MSOC (Table 4.1), generally supporting our initial hypothesis. Our first hypothesis posed that ecological states and ES are different in terms of SOC stocks. This hypothesis was shown to be partly true in that there is difference between ES in SOC stocks in all derivatives except MSOC, while at the ecological state level SOC stocks were different in only the SISUHCF ES. Our second hypothesis was proven to be partially true as well, in that SOC stocks show variance differences in the TSOC and OSOC derivatives at the ES level but not the ecological state level of analysis.

Spodosols and spodic intergrades are taxonomically different in terms of the amount of spodic properties contained in soil horizons (Soil Survey Staff, 2014; USDA-NRCS, 2015a, b). Spodic intergrades like the Mandy series by definition do not meet the same criteria as a
Spodosol like the Wildell series, and therefore it follows that differences should appear in SPSOC between the two ES. In most cases the SSUCF had a greater component of red spruce in the overstory than in the SISUHCF, so the SSUCF ES correspondence with greater OSOC stocks is not unexpected considering O horizon formation is partly dependent on needle litter build up associated with conifer vegetation (Fröberg et al., 2005; Hobbie et al., 2007).

When comparing ecological states, the OSOC stock contributes a greater proportion to the TSOC stock estimate in all states of the SSUCF (Table 4.2). Diochon et al. (2009) found when examining red spruce reference stands in Nova Scotia, Canada, that approximately 50% of SOC is held within the combined O horizons and upper 20 cm of mineral soil. Tewksbury and Van Miegroet (2007) reported that the OSOC of their study area in spruce-fir ecosystems on the Tennessee and North Carolina border accounted for 12% of the SOC stored in the upper 50 cm of soil. Comparatively, the SSUCF Reference State mean OSOC stock represents 75% of the TSOC, while 58% of the TSOC stock in the SISUHCF Reference State can be attributed to the OSOC stock when calculated to 100 cm. Our OSOC stock estimates are significantly higher than what is reported by Diochon et al. (2009), even when excluding SOC from the upper 20 cm of mineral soil from our calculated SOC stock. In the SISUHCF ES, only in the Reference State does the OSOC stock account for the greatest proportion of the TSOC stock estimate (58%). The mean MSOC stock for each alternative state of the SISUHCF was greater than the mean OSOC stock, accounting for the majority of SOC stock in alternative states.

Garten et al. (1999) reported an average OSOC stock of 35 Mg C ha in high elevation spruce-fir plots within the southern Appalachians. Tewksbury and Van Miegroet (2007) calculated 20.8 ± 6.6 Mg C ha in spruce-fir ecosystems on the Tennessee and North Carolina border with similar Inceptisols containing spodic properties, often classifying as Dystrochrepts or Haplumbrepts – although 70% of the soils they sampled were <50 cm deep. In both cases they
found MSOC stocks to be proportionally greater to TSOC than OSOC. These past research estimates are small when compared to our mean OSOC estimates of 357 ± 20.3 Mg C ha in the SSUCF and 115 ± 7 Mg C ha in the SISUHCF ES.

Other researchers have found similar SOC stocks representative of east coast spruce-fir forests, although our measurements show a higher degree of SOC sequestered in West Virginia red spruce ecosystems. Miller et al. (2004) assessed an average SOC stock of 112 Mg C ha in well-drained spruce-fir soils of south-west Virginia, while Kern (1994) estimated an average of 201 Mg C ha for Halpumbrepts of spruce-fir ecosystems – both of which are far less than our estimated average TSOC for both the SSUCF (529 ± 30 Mg C ha) and SISUHCF (293 ± 16.7 Mg C ha). This comparison is limited in the sense that the previously mentioned researchers only calculated SOC to 50 cm depth, while here we calculated SOC stocks to 100 cm where applicable, so it follows that our calculations would contain higher SOC stock estimates. Tewksbury and Van Miegroet (2007) also estimated SOC storage in spruce-fir ecosystems and found an average of 211 Mg C ha, ranging from 166 to 241.5 Mg C ha. These measurements are relatively close to red spruce ecosystems in Central Appalachia, although West Virginia spruce forests seem to offer a higher degree of SOC sequestration.

These comparative findings could assert two things: (i) SOC is accumulated at a greater quantity within the deep mineral layers in red spruce soils not fully realized by past research, and (ii) Central Appalachian red spruce forests of West Virginia have the capacity to sequester greater amounts of SOC in O horizons than in other areas of the eastern United States and Canada.

The significant differences between TSOC, OSOC, and SPSOC derivatives of both ES likely is due to the added degree of disturbance experienced by the SISUHCF ES. The SISUHCF is characterized by intense fires in some ecological states, and this is reflected by overstory
hardwood dominance and lack of red spruce regeneration after the spruce seedbank was burned (USDA-NRCS, 2015b). Further, the logged states in the SISUHCF always have a greater mean OSOC stock than in their corresponding logged and burned state (Table 4.2). When timber is cut it removes the forest canopy and changes the thermal environment of the soil (Bekele et al., 2007), potentially altering the nutrient dynamics and accelerates mineralization (Diochon et al., 2009). Thermal soil changes as well as greater hardwood canopy cover regeneration post-harvest encourages regressive development via depodzolization, caused by the lack of continued dissolved OC and SOM inputs from coniferous vegetation (Barrett and Schaetzl, 1998). In contrast to our hypothesis, mean MSOC and SPSOC stocks in both ES are lowest on average in the Reference State when compared to alternative states of each ES, but highest in terms of OSOC stocks. We would expect the reference states to have higher SPSOC since increasing podzolization is correlated with increasing conifer vegetation (USDA-NRCS, 2015a, b), but this trend is not apparent based on our data. Observed variation in SOC derivatives across ES and ecological states are likely a product of some unquantified influence, and we hypothesize further that this variation is attributed to historic disturbance regimes that differ spatially.

There are numerous reasons for why SOC stocks observed in WV may be greater than previous mentioned literature. We sampled by horizon to a depth of 100 cm where applicable, whereas many of the other researchers sampled by depth increments down to 50 cm mineral soil (Diochon et al. 2009; Kolka et al., 2014), while Bradford et al. (2012) only collected from O horizons and down to 10 cm of mineral soil. The obvious difference in SOC calculated to 100 cm in this study verses 50 cm in other studies likely contributes to our SOC stock estimated being higher. Another important difference involves sampling by depth verses by horizon. Sampling based on depth ranges assumes soil properties do not change within the selected depth, whereas sampling by horizon is not limited by this constraint. Differences in sampling techniques may
also influence how much SOC is calculated and is another possible reason for observed
differences between this study and other past research. In this study we estimated BD using a
pedotransfer function designed by Yoast (2015), so this factor in the SOC calculation is likely
different across studies and may add to the observed discrepancies among mentioned studies.
SOC stocks may also be influenced differently due to parent material type. Most mentioned
studies were conducted in coarser soil materials higher in sand content, while our study locations
are dominantly silt loams of finer texture. Sampling methods also likely play a role in observed
differences between our calculations and other past research. Most cited studies used a soil core
to collect soil materials which can limit morphological descriptions of the soil in that, for
example, rock fragments cannot be easily observed in a representative manner. In this study we
hand excavated pedons to 100 cm so a more complete description could be made. Another
probable factor to observed differences lies in the personal subjectivity of the describer – for
example, one describer may evaluate rock fragments higher or lower than what actually is
contained in the soil, which can significantly affect the SOC stock calculation.

It seems clear how intense fires affect OSOC stocks, but the variation—or lack of
variation—in SPSOC stock remains unexplained. Further, differences among SOC stock
derivatives in the SSUCF ES do not follow a clear trend. The reference state condition has the
highest mean OSOC stock and is attributed to higher conifer canopy cover, so it would be
reasonable to assume the SPSOC stocks should be higher too. Again, these unexplained
differences are likely attributed substantially to disturbance history, as not every hillslope was
affected similarly. Logging intensity was likely greater in one location versus another, making
determining the impact that a certain location experienced nearly impossible to discern at present
time. It is possible that the most direct way of determining the degree of disturbance may lie in
the O horizon composition—or lack thereof—because this metric is most readily affected being at the soil surface, but this hypothesis needs further testing for confirmation.

**SOC Stock Variance Differences Between ES and Among Ecological States**

Variance differences of each SOC stock derivative were only significant at the ES level of analysis in terms of TSOC stock and OSOC stock (Table 4.3). MSOC and SPSOC did not exhibit variance differences between ES when analyzed. Further, no differences among ecological states within their relative ES were seen either (Table 4.4). F ratios support variance differences between ES, where F ratios close to 1 do not exhibit variation attributed to random chance, while higher values explain variance differences not attributed to random chance (Tables 4.3 and 4.4). Variance differences are likely due to the fact that OSOC comprises a significant portion of TSOC in these ecosystems, so any loss or addition to the O horizons at a given location is reflected further in the TSOC.

The SSUCF ES had the greatest range in observed SOC stocks, especially when considering the TSOC and OSOC stocks. The Reference State displayed the greatest range in OSOC stock, encompassing a difference of 85.3 kg C m\(^{-2}\) between the highest and lowest values (94.5 ± 5.4 kg C m\(^{-2}\) and 9.2 ± .8 kg C m\(^{-2}\), respectively) (Table 4.2). Diochon et al. (2009) compares findings from multiple past researchers showing that OSOC stocks generally range between 30-60 Mg C ha for coniferous forests of the North America. Again, this range attributed to past researchers represents only a fraction of the OSOC stock the SSUCF Reference State accumulates (412 ± 23.5 Mg C ha), and still falls short of the mean OSOC stock for the SISUHCF Reference State (207 ± 11.8 Mg C ha).

The Logged State with Cherry Seedbank in the SSUCF contains a high outlier expressed as a buried O horizon in one of the sample locations. Since the O horizon was buried and no
longer a surface O horizon it was included in the MSOC stock. This outlier brings the range of MSOC in the Logged State with Cherry Seedbank to 81.31 kg C m² between the highest (88.2 ± 5.1 kg C m²) and lowest (7 ± 0.4 kg C m²) measured values. The importance of this outlier is it shows a significant effect that historic disturbance likely created. Whether by tree throw or short-term mass colluvial movement, the historic O horizon and accompanying Spodosol was buried, effectively preserving the SOC once existing at the surface—now covered in 60 cm of colluvial materials. This occurrence is not unique, as multiple buried O horizons were described over the course of this study across different locations. The outlier here provides a glimpse of the significance that historic disturbance had, and how it may reflect in a soils morphology and corresponding SOC stock. It also supports the idea that SOC stocks in these environments can vary substantially, effectively limiting an accurate SOC stock estimate.

The SISUHCF ES did not display nearly as great of range in SOC stock as the SSUCF does (Table 4.2). Similar to the SSUCF, the SISUHCF Reference State showed the greatest range in OSOC stock, ranging a total of 51.19 kg C m² among observations between the highest and lowest values (53.8 ± 3.1 kg C m² and 2.65 ± .2 kg C m², respectively). In general, the logged states showed a wider range in TSOC than in the logged and burned states. It is interesting to note that between both ES the SPSOC stocks showed the narrowest range of variability, while also containing a mean SPSOC stock that is similar across ES. This similarity is also displayed in terms of mean SPSOC stocks across ecological states of each ES as well. The narrow range of variation in the SPSOC stocks among ecological states and between ES could suggest that SOC that is stored in spodic horizons is more stable in the face of significant disturbance like logging or fires. Miesel et al. (2012) mentions that mineral soils are poor conductors of heat, and therefore any significant effect on SOC in the upper mineral horizons is generally limited to the first 5 cm, although this varies with extended exposure and higher
temperatures (Neary et al., 1999). In relation to our study, this assertion supports our findings in that MSOC stocks showed no difference between ES – with one of the biggest developmental differences being severity of fires between ES. Further, these findings also could support the notion that, from a developmental standpoint, these two ES may actually be one ES based on SPSOC variance similarities. The high range in OSOC variation seems indicative of the fact that surface O horizons are much more susceptible to disturbance influences than SPSOC stocks held below ground (Bradford et al., 2012; Miesel et al., 2012; Kolka et al., 2014).

**Restoration Implications Using SOC to Guide Forest Management**

If land managers know how much SOC they can expect to gain or lose when implementing a management prescription in these ES then they can target red spruce communities that offer the highest return regarding restoration resources available. Reference state conditions are often the goal for restoration and based on the data from this study the Reference State of both ES contains the greatest SOC stocks in the O horizons. SOC benefits numerous other DSP like water holding capacity and infiltration rate, and BD among others (Jobbágy and Jackson, 2000; Drenovsky et al., 2004; Essington, 2015), and focusing on accumulating SOC in O horizon may advance DSP improvement resulting from restoration. A unique aspect of Central Appalachian high elevation red spruce ecosystems when compared to other similar ecosystems in the eastern US is their ability to seemingly accumulate greater quantities of SOC at the surface in the form of O horizons. Aiming for reference conditions in restoration can build surface SOC reserves and improve DSP that form a relationship with SOC.

ESD implement management practices that form restoration pathways between ecological states. In the SSUCF and SISUHCF management practices encouraging restoration are similar in that in both ES red spruce is release from the understory by hardwood thinning
combined with underplanting of red spruce saplings (USDA-NRCS, 2016a, b). Based on our calculations regarding the SSUCF, when restoring the Logged State with Cherry Seedbank back to the Reference State an average of 40.7 ± 2.3 Mg C ha can be gained in O horizon accumulation, and when restoring the Logged State with Beech Seedbank back to the Reference State an average of 126 ± 7.2 Mg C ha can be gained in O horizon accumulation (Fig. 4.9). In terms of the SISUHCF ES, restoring from the Logged and Burned State with Cherry Seedbank to the Logged State with Cherry Seedbank can offer a gain on average of 51.5 ± 2.9 Mg C ha, while restoring from the Logged State with Cherry Seedbank to the Reference State averages 83.7 ± 4.8 Mg C ha in O horizon gains once restoration goals have been met. Regarding the beech states of the SISUHCF, when restoring from the Logged and Burned State with Beech Seedbank to the Logged State with Beech Seedbank an average of 7.5 ± .4 Mg C ha is gained, while restoring from the Logged State with Beech Seedbank to the Reference State accumulates an average of 114.6 ± 6.5 Mg C ha in the O horizons (Fig. 4.10). These findings are supported by Nauman et al., (2015b) assertion that on average in these ES O horizon response to conifer importance values equates to a 0.96 cm gain for every 10% increase of conifer importance. By increasing red spruce and other conifer vegetation in the overstory O horizons grow thicker and amass more SOC, and in consequence positively influence related DSP in these landscapes.

Alternatively, not only can SOC stock predictions be made on restoration practices, but identification of ecological states most suited to intensive management such as logging can also be made based on ecological state SOC stock characteristics. Targeting alternative states with the lowest SOC stocks—especially regarding O horizon C—allows for mitigation of disturbance related impacts, as selecting for logging in these lower SOC alternative states are likely to have less effect on DSP related to SOC. In order to limit impacts felt by DSP at the landscape level we suggest logging operations be limited to ecological states containing the lowest SOC stocks,
which effectively relegates these operations to the SISUHCF ES, and more specifically, the logged and burned alternative states of the ES. Selection of these ecological states over other states with greater SOC accumulations in the O horizon also benefits at-risk species such as the NFS, which is correlated to red spruce landscapes and thick O horizons (Loeb et al., 2000; Mitchell, 2001; Ford et al., 2004; Byers et al., 2010).

Restoration resources are often scarce, so decisions made about where to implement the resources are important. Based on our data we suggest that restoration target the SISUHCF. The SISUHCF contains statistically different SOC stocks among ecological states, whereas, the SSUCF does not. Since the SSUCF does not stand to gain as much SOC from restoration, and it already contains very high SOC stocks regardless of ecological state, restoration is more impactful in the SISUHCF. The affect of restoration in this ES leads to higher SOC sequestration, but also can lead to further changes in related DSP like water holding capacity or soil structure when reference state conditions have been reached (Bennett et al. 2009; Gilgert and Zack, 2010; Brown and Havstad, 2016). Intentionally targeting SOC poor ecological states for red spruce restoration means greater SOC gains when restoration is met. Restoring to the Reference State in the SISUHCF is important because it has the highest SOC stocks when compared to alternative states of the ES, while also gaining more SOC on average when compared to a restoration made in the SSUCF. Although, there can still be a case made for restoration within the SSUCF. Since the SSUCF has the capacity to sequester such large amounts of SOC, keeping it sequestered is important. Where red spruce is sparse in the SSUCF ES, restoration to the Reference State may not add a significant portion of C to the SOC pool, but it may help to ensure that SOC already sequestered is not lost as the overstory canopy species fluctuates over the course of decades. Ensuring that there is enough red spruce in the overstory to
at least sustain SOC accumulated in the past may prove as important as gaining new SOC from restoration of the SISUHCF.
References


Figure 4.1. Dual extent of Spodic Shale Upland Conifer Forest and Spodic Intergrade Shale Upland Hardwood and Conifer Forest ES within the boundaries of the Monongahela National Forest.
Figure 4.2. The Wildell soil series (loamy-skeletal, mixed, superactive, frigid Typic Haploorthod) is correlated to the Spodic Shale Upland Conifer Forest ES in West Virginia. This soil shows a strong degree of podzolization in the subsoil.
Figure 4.3. The Mandy soil series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts) is correlated to the Spodic Intergrade Shale Upland Hardwood and Conifer Forest ES, showing a moderate to slight degree of podzolization in the subsoil.
State-and-Transition Models

Figure 4.4. State and transition model from the Spodic Shale Upland Conifer Forest ES (Teets, 2013). T1A and T1B represent transitional pathways to hardwood dominated states, while R2A and R3A represent restoration pathways towards the conifer dominated reference state. T1C represents the transition into a conifer plantation state.
Figure 4.5. State and transition model for the Spodic Intergrade Shale Upland Hardwood and Conifer Forest ES (Teets, 2013). Four types of ecological states occur in this ES: reference state, logged states, logged and burned states, and a plantation state.
Pedon Locations

Figure 4.6. Soil and ecosystem point locations used in analysis, broken down by source
### Ecological Site SOC Means and Least Square SOC Means

<table>
<thead>
<tr>
<th>Stock Derivative</th>
<th>ES</th>
<th>N</th>
<th>Mean (kg/m²)</th>
<th>LS Means</th>
<th>LS SEM</th>
<th>F Ratio</th>
<th>DFDen</th>
<th>p-value</th>
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*Table 4.1. Raw means and transformed least square means for both ecological site by different soil layer analyses.*
**Ecological State SOC Means and Least Square Means**

Table 4.2. Raw means and transformed least square means for ecological states of both ecological sites by soil layer. Differences at the ecological state level were only detected within the SISUHCF regarding total SOC and O horizon SOC stock pools. These differences are denoted using “a”, “ab”, and “b” to discern among ecological states.

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<tr>
<th>Stock Derivatives</th>
<th>ES</th>
<th>Ecological State</th>
<th>Mean (kg/m²)</th>
<th>Range (kg/m²)</th>
<th>SEM</th>
<th>Effect p-value</th>
<th>Sliced p-value</th>
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<th>LS SEM</th>
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Figure 4.7. Plot of least square means for Ln transformed TSOC stocks listed by ecological states of both SSUCF and SISUHCF ES. Letter designations denote statistical differences observed between ecological states.
Figure 4.8. Plot of least square means for Ln transformed OSOC stocks listed by ecological states of both SSUCF and SISUHCF ES. Letter designations denote statistical differences observed between ecological states.
**Ecological Site  SOC Stock Variance**

Table 4.3. Levene test for SOC stock variance difference between ecological sites. Stock variance is different in total SOC stocks and O horizon SOC stocks.

<table>
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<tr>
<th>Soil Layer</th>
<th>ES</th>
<th>N</th>
<th>Std Dev</th>
<th>F Ratio</th>
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<th>Levene p-value</th>
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<td>SSUCF</td>
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<td>21.771</td>
<td>118</td>
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<td>SISUHCF</td>
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<td>OSOC (kg/m²)</td>
<td>SSUCF</td>
<td>45</td>
<td>21.41</td>
<td>30.321</td>
<td>118</td>
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<td>75</td>
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<td>SPSOC (kg/m²)</td>
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</table>
**Ecological State SOC Stock Variance**

Table 4.4. Levene test for SOC stock variance difference between ecological states. No difference in variance was detected among ecological states within either ecological site based on multiple comparisons analysis.

<table>
<thead>
<tr>
<th>Soil Layer</th>
<th>ES</th>
<th>Ecological State</th>
<th>N</th>
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O Horizon SOC Stock Gains or Losses from Restoration and Disturbance

Figure 4.9. State and transition model for the SSUCF, excluding the plantation state. This figure represents the mean O horizon SOC (Mg/ha) that could be gained or lost when transitioning to/from the Reference State.

Figure 4.10. State and transition model for the SISUHCF, excluding the plantation state. This figure represents the mean O horizon SOC (Mg/ha) that could be gained or lost when transitioning among ecological states.
CHAPTER 5: CONIFER CANOPY COVER INFLUENCE ON SOIL ORGANIC CARBON ACCUMULATION IN CENTRAL APPALACHIAN RED SPRUCE FORESTS

Abstract

High elevation red spruce (*Picea rubens*) ecosystems in Central Appalachia have experienced significant changes caused by historic intensive logging efforts beginning in the latter half of the 19th century and ending in the early-20th century. Organizations and federal agencies are currently working towards restoring red spruce ecosystems to their historic pre-disturbance status. Two Central Appalachian red spruce ecological site descriptions (ESD) have been developed for landscape managers as a restoration tool to guide implementation of management practices in these ecosystems. Soil organic carbon (SOC) is an important dynamic soil property (DSP) in red spruce landscapes, whereby SOC is accumulated at the surface by build-up of organic matter and in the subsoil via the pedogenic process of podzolization. SOC influences countless other DSP like infiltration rate, water holding capacity, elemental transformations, and cation exchange capacity, among many others. Studies have analyzed how SOC can benefit DSP and ecosystem services, yet none specifically use SOC stock measurements as a means for expressing changes to DSP or other functional processes. How conifer canopy cover relates to SOC stocks in these red spruce ecosystems is not fully known given the long history of intensive management in the region, but this relationship could help landscape managers better realize changes to DSP and other ecological metrics that are likely to be seen once restoration goals have been met. A total of 101 soil profiles and corresponding ecosystems within the Spodic Shale Upland Conifer Forest (SSUCF) ecological site (ES) and the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF) ES were described and sampled to assess SOC stock interaction with relative percent conifer canopy cover. Soil
samples were analyzed using dry combustion to determine SOC percent weight per horizon, and further combined to estimate the SOC stock (kg/m²) held in the soil to a depth of 100 cm where applicable. Four different SOC stock derivatives including total SOC (TSOC), organic horizon SOC (OSOC), mineral SOC (MSOC), and spodic horizon SOC (SPSOC) were regressed with relative conifer canopy cover estimates without regard for ES or ecological state. Initial regression analysis showed a significant positive slope relationship between relative conifer percent cover and TSOC (p < 0.0001) and OSOC (p < 0.0001) layers. Further analysis used a mixed model to control for ES and ecological state as fixed effects, with year sampled as a random effect. The generalized linear mixed model identified a significant interaction between ES and relative conifer percent cover on OSOC stocks (p = 0.024), with SISUHCF having a positive slope relationship and SSUCF had negligible slope. Relative conifer percent cover did not show significant relationships with any other SOC analysis layers in these ecosystems. Understanding how conifer percent cover relates to SOC stocks in these ecosystems can allow land managers to predict changes to SOC stocks and related DSP when restoration practices are applied, while also offering a glimpse into the disturbance history of a landscape and the effects these disturbances had on how SOC is accumulated or lost. The correlation between conifer percent cover and SOC stocks in Central Appalachian red spruce ecosystems leaves more to be explained than initially thought.
Introduction

In the late-1800s and early-1900s intensive logging operations reduced red spruce forest coverage in West Virginia to an estimated 12% of its historical extent (Byers et al., 2010). The widescale logging and burning not only impacted red spruce, but also the entire landscapes they inhabit – including the soils they are formed from. Fires were common (Clarkson, 1964; Byers et al., 2010), in some cases eliminating the thick build-up of organic soil materials that comprised the forest floor (Hopkins, 1899). Changes like these affect the way red spruce forests and their accompanying soils provide invaluable ecosystem services, as was exhibited by widescale early-20th century flooding (Byers et al., 2010) resulting from intensive logging.

Over the last decade, ecological site descriptions (ESD) have become an important part of the restoration toolkit used by land managers across the country, initially being developed for rangeland management in western states of the US (Townsend, 2010). Since then, ESD have slowly been adapted to other ecosystems like eastern forests where we find red spruce as a historic component of the landscape ecology. In the Central Appalachian Mountains, there have been two completed ESD for these red spruce forest communities (USDA-NRCS, 2015a, b). These ecological sites (ES) include the Spodic Shale Upland Conifer Forest (SSUCF) and the Spodic Intergrade Shale Upland Hardwood and Conifer Forest (SISUHCF), spanning some 50,545 ha across Randolph, Pocahontas, and Pendleton counties in West Virginia (Fig. 5.1). These ES often transition into one another across the landscape, making differences between the two seemingly unrecognizable at times. Both ES are home to species of concern such as the northern flying squirrel (Menzel et al., 2005, 2006) alongside many others (Byers et al., 2010), with government agencies like the Natural Resources Conservation Service and Forest Service and other non-government entities like The Nature Conservancy and the Central Appalachian
Spruce Restoration Initiative working to restore these red spruce communities to some assemblance of what they once were.

**Pedogenic Properties and Processes of Central Appalachian Red Spruce Ecosystems**

Soils correlated to Central Appalachian red spruce ecosystems are Spodosols (Fig. 5.2) and spodic-Dystrudepts (Fig. 5.3) (Nauman et al., 2015a, b; USDA-NRCS, 2016a, b; Nottingham et al., 2017). In these landscapes spodic properties naturally develop in tandem with red spruce as a result of key pedogenic processes fostered by both climactic and conifer influences. Low average annual temperature and high average annual precipitation are attributed to these landscapes (USDA-NRCS, 2016a, b) and result in conditions conducive for the build-up of soil organic matter (SOM) at the surface and continual input of dissolved organic C into the subsoil (Lundström et al. 2000a, b). The podzolization process, whereby aluminum and iron are complexed with organic compounds and translocated to the subsoil, leads to distinct soil morphologies and the formation of spodic properties (Figs. 5.2 and 5.3). Both conifer and ericaceous vegetation produce significant amounts of organic acids that weather primary minerals and form organo-metallic complexes with aluminum and iron that help to drive the podzolization process in high-precipitation environments (Lundström, 1993; Lundström et al., 2000a). Podzolization in Central Appalachian soils proceeds exclusively under conifer and ericaceous dominated forests with components of red spruce or eastern hemlock (Nauman et al., 2015a, b).

Importantly, spodic properties produced by the podzolization process are a marker for where red spruce and other conifers once historically inhabited (Nauman et al., 2015a, b). The presence of spodic properties where they should not occur (hardwood forests) indicates that red spruce inhabited a given location in recent past. Identifying spodic properties in soils can help to
better understand the historic extent of red spruce in the past and provide guidance for where to restore red spruce into the overstory canopy (Nauman et al., 2015a, b).

In West Virginian red spruce ES, organic matter (OM) accumulates both at the surface in the form of O horizons and in the subsoil forming spodic properties contained in Bh, Bhs, and Bs horizons (Figs. 5.2 and 5.3). Root/shoot death contributes to total organic C and OM build up as well (Lorenz and Lal, 2005). Conifer needle litter does not degrade as quickly as broadleaf tree litter (Hobbie et al., 2007), resulting in thick O horizon accumulations where red spruce overstory is dominant and left undisturbed (USDA-NRCS, 2016a). Other contributors to the totality of the podzolization process involve ectomycorrhizal fungi that acquire nutrients by “mining” coarse-silt and fine-sand sized mineral grains of feldspar using low molecular weight acid exudates to dissolve the minerals (Jongmans et al., 1997; Landeweert et al., 2001).

Conversely, these same ecosystems are subject to varying degrees of depodzolization, which can occur to soils that undergo significant disturbance, like from historic logging and severe fires (Barrett and Schaetzl, 1998; Nauman et al. 2015b; USDA-NRCS, 2016b). The removal of conifer vegetation from the forest canopy also removes the influences that drive the podzolization process in these landscapes. Without conifer vegetation in the ecosystem community, podzolization ceases and the opposite process of depodzolization begins. As a result of this change in pedogenic pathway, previously deposited organic C complexes are lost from the subsoil and organic soil materials at the soil surface that contributed to the once proceeding podzolization process. As fires eliminated the red spruce seedbank hardwood stands regenerated in place (Byers et al., 2010). Continued hardwood cover leads to the depodzolization of an already podzolized soil, since inputs supporting this pedogenic pathway cease to exist (USDA-NRCS, 2016b). The build-up of organic material at the surface of the soil and resulting spodic
properties in the subsoil seem to be a function of conifer vegetation and historic disturbance history, and is central to the understanding the differences between the SSUCF and SISUHCF ecological communities (USDA-NRCS, 2016a, b).

**SOC Stocks as a Function of Conifer Canopy Cover**

As conifer vegetation in the overstory increases, so increases the amount of needle litter on the forest floor. Conifer needles and accompanying residues are strongly acidic, and OM accumulation at the forest floor is also thought to contribute significantly to the total dissolved organic C moving through a soil profile, further affecting the podzolization process (Fröberg et al., 2005). It has been suggested that O horizons may have the capacity to accumulate at faster rates than initially suspected. West Virginia O horizon accumulations estimate around 1 cm of O horizon gain per 10% gain in conifer importance (Nauman et al., 2015a). Limited research seems to suggest that as conifer vegetation plays a more important role in the overstory it contributes more to O horizon development, producing at times thick folistic epipedons (USDA-NRCS, 2016a). Thicker O horizons means more decomposing organic materials at the soil surface that contribute further to SOC accumulation as the subsurface development of spodic properties and spodic horizons.

The more SOM that accumulates in conifer dominated ecosystems, the more acidic the soil conditions become—acting as a positive feedback loop for red spruce regeneration and, therefore, carbon sequestration (USDA-NRCS, 2016a, b). In these ecosystems, restoring red spruce means increasing the amount of red spruce in the overstory by creating canopy gaps, as well as under-planting red spruce seedlings (USDA-NRCS, 2016a, b). In the SSUCF and SISUHCF ES red spruce dominance in the overstory is correlated with spodic expression, forming Spodosols where conifer cover is dominant. The opposite is true for the SISUHCF ES.
Significant reductions to the red spruce overstory reduce acidic SOM inputs, driving the depodzolization process. This is further exacerbated by hardwood regeneration and lack of continued inputs of dissolved organic C leaching into the subsoil.

Materials and Methods

Study Area

The SSUCF and SISUHCF ES are found within Pocahontas, Pendleton, and Randolph counties in West Virginia, and are considered part of the Eastern Allegheny Plateau and Mountains (MLRA 127), which is itself a part of the Appalachian Plateau Province (USDA-NRCS, 2016a,b) (Fig. 5.1). The SSUCF and SISUHCF ES occur in acid shale geologies with interbedded sandstone and siltstone on the Chemung and Hampshire formations (WVGES, 1968). A wide range of landforms make up these landscapes but are generally dominated by steep mountain slopes accented by narrow valley bottoms. Slope shape varies greatly, from simple linear mountain slopes to complex undulating hills. Significant microtopography in the form of tip and mound features is commonly present. Both ES range in elevation from approximately 870–1300 m, and range in slope gradient from 3–80% (USDA-NRCS, 2016a, b). Most of the year it is overcast (~81 days of clear sky per year), and annual precipitation can be upwards of 127 cm (USDA-NRCS, 2016a,b), yielding a perudic moisture regime. The greatest precipitation rates occur in the summer months, although precipitation and temperature vary with landscape position and topography. Mean annual temperature across both sites is around 7°C and receives an average of only 119 frost-free days per year. The total footprint these two ES encompass is estimated to be around 50,715 ha, although these sites have not been mapped with certainty (Nauman et al., 2015a).
Landscapes in both ES contain similar vegetation consisting of mixed hardwood-conifer stands including beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), striped maple (*Acer pensylvanicum*), yellow birch (*Betula alleghaniensis*), sweet birch (*Betula lenta*), mountain magnolia (*Magnolia fraseri*), cucumber tree (*Magnolia acuminate*), red spruce, Allegheny serviceberry (*Amelanchier laevis*), and eastern-hemlock (*Tsuga canadensis*). Understory species occur in the form of regenerating species listed above, but also include intermediate woodfern (*Dryopteris intermedia*), New York fern (*Thelypteris noveboracensis*), lesser round-leaved orchid (*Platanthera orbiculate*), indian cucumber (*Medeola*), trillium (*Trillium*), Canada mayflower (*Maianthemum canadense*), common yellow oxalis (*Oxalis stricta*), partridgeberry (*Mitchella repens*), running clubmoss (*Lycopodium clavatum*), three-lobed bazzania (*Bazzania trilobata*), and splendid feather moss (*Hylocomium splendens*). Soils in these landscapes grade from shallow to moderately deep depending on hillslope profile position, and commonly contain evidence of podzolization (USDA-NRCS 2016a,b). The Wildell series (Loamy-skeletal, mixed, superactive, frigid Typic Haplorthods) characterizes the SSUCF ES, while the Mandy series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts) is indicative of the SISUHCF ES. The primary differences between the two ES is the amount of red spruce in the canopy and the degree of podzolization exhibited in the soil. When landscapes like this experience significant disturbance spodic properties produced through podzolization are quick to degrade, being lost to erosion and other degrading influences in only a matter of decades (Barrett and Schaetzl, 1998; Nauman et al. 2015b). Each ES also varies in the amount of red spruce found in the overstory of their related ecosystem communities, with some ecosystems ranging from little to no red spruce cover—whether it be overstory or
understory—to thick overstory red spruce stands plentiful in understory regeneration (USDA-NRCS, 2016a, b).

Previously Sampled Pedons and Acquired Data

This study was performed within the area encompassing the dual ES extent (Fig. 4.1). This same extent has been used in previous studies (Nauman et al., 2015a,b) such that data previously collected by West Virginia University, the Forest Service, and the Natural Resources Conservation Service from 2009–2015 was available for use in this research. Three types of data are used in this study: (i) morphological descriptions of previously characterized soil profiles; (ii) vegetation data from research plots; and (iii) measured SOC for pedon samples that have been analyzed in the lab. A total of 27 pedons that fall within a described ecological state (NRCS, FS, Nauman et al. 2015a,b) and have been previously sampled are available for inclusion. Many previously described pedons by the NRCS and FS that are located within the dual ES extent were not sampled and therefore not included in this experiment.

Sample Selection

Additional sample locations were selected using a stratified random sampling design. Previous work by Nauman et al. (2015b) led to the development of a map that delineates the reference state condition of the SSUCF ES, but groups alternative ecological states in both ES as “logged stages” and “transition stages” that have been disturbed in the past. This assumes all locations within the study footprint that are a part of the SISUHCF were transitioned from the SSUCF reference states by past logging consequences. The Nauman et al. (2015b) map defines spodic intensity (spodic, spodic intergrade) and above-ground cover type (conifer, mixed, hardwood) modeled from other sources. This map was further reclassified to display locations by
spodic intensity for use in this project—regardless of above-ground vegetation—with a total sample pool of 323 points generated. Of these 323 points a total of 93 newly excavated pedons were described and sampled during this project (refer to Chapter 4), and 8 previously described pedons (NRCS, FS) included as well (n = 101). New sample locations were distributed across the extent of both the SSUCF and SISUHCF ES (Fig. 5.4), with 31 newly excavated soil profiles described and sampled from the SSUCF, and 62 newly excavated soil profiles described and sampled from the SISUHCF ES.

Field Sampling and Description Methods

Experimental unit, sampling, and description methods closely follow those implemented by Nauman et al. (2015a,b). Each location deemed suitable for sampling had both a soil description and vegetation description completed. The overall research plots were 20 x 20 m. Each plot contained a soil profile in the center of the plot, and four small satellite profiles specifically targeting O horizon depths (Appendix A). Coordinate locations were collected in the plot by placing a handheld global positioning system unit capable of <3 m accuracy in WAAS mode directly upslope of the soil profile. Within the 20 x 20 m plot overall species were recorded including plants within the visible surroundings, with absolute canopy cover recorded for each species and relative canopy cover calculated later.

The whole plot was divided into four equal quadrants with each quadrant containing a single O horizon depth observation (five total O horizon observations per plot including the soil pit) that captures the depths in cm of the Oi, Oe, and Oa horizons when present, and contributes to an average O horizon thickness calculation for each site. All percent cover estimations were conducted using ocular estimation with the help of visual aids displaying percent composition of a specific area contained in Shoeneberger et al. (2012).
At the center of each plot a soil pit ~1 x 1 m square was excavated using hand tools to lithic contact or 100 cm in depth, whichever was shallowest. Once fully excavated, the pit face was cleaned to expose the soil horizonation, color, structure, and other properties, and photographed for documentation. A full pedon description was completed using official NRCS pedon description methods (Schoeneberger et al., 2012), with close attention being paid to spodic morphology. Spodic intensity—a subjective field-based estimation of the degree of podzolization—was estimated based on the smearing exhibited by horizons in the profile, as well as other metrics used to describe spodic morphology such as color requirements and horizon thickness (Soil Survey Staff, 2014).

Each horizon was sampled from areas displaying homogenous property expression and placed into a thick-walled plastic sample bag. Once the description and sampling were completed, excavated profiles were field classified based on field characterization of soil morphology to the nearest soil series possible since particle size distribution and other important lab data usually used to classify a soil were not examined.

**Laboratory Methods**

To obtain SOC content and SOC stock estimates, soil samples from both mineral and organic horizons were treated similarly. For both mineral and organic horizon samples large roots and large rocks were removed by hand prior to processing. Samples were crushed with a mortar and pestle to break up aggregates and passed through a 2 mm sieve to remove all rock fragments and roots. Next, a 0.5 g subsample of all soil samples was acidified using 1M HCl with 1:2 (m:V) solid:solution ratio in order to degas any inorganic carbon contained in soil samples. Then, soil samples were dried in the lab oven at 70°C for 48 hours to remove excess moisture. SOC was determined for both mineral and organic soil materials using 0.08 g of the
acidified and dried subsample using the Elementar Vario MAX Cube (Hanau, Germany) by dry combustion (Nelson and Sommers, 1996). The Elementar Vario MAX Cube produced total C, S, and N in each sample given as percent weight. The SOC content for each soil was combined with BD estimates from a pedotransfer function developed by Yoast (2015) from soils in the greater geographic area to produce a total SOC stock for each pedon. SOC stock was calculated to a depth of 100 cm or lithic contact if shallower than 100 cm using the equation (USDA-NRCS, 2017b):

\[
SOC_{stock\ pedon} = \sum_{i}^{n} (SOC_i \times BD_i \times Thickness_i \times (1 - CFrags_i/100))
\]

where \(SOC_i\) is the OC content of a specific horizon represented as a fraction. \(BD_i\) is the estimated BD of the designated horizon based on horizon texture. \(Thickness_i\) is the thickness of the specific horizon in cm. \(CFrags_i\) is the total volume of course fragments found in the specified horizon written as a percent of the whole. \(\sum_{i}^{n} (...)\) represents the sum of each horizon contained in the total soil profile to a depth of 100 cm or lithic contact to give the estimated SOC stock of the pedon.

**Statistical Analysis**

All data were analyzed using JMP and SAS software (JMP®, Version Pro 16.0, SAS Institute Inc., Cary, NC, ©2015; SAS®, Version 9.4, SAS Institute Inc., Cary, NC, ©2002-2012). Significance criterion alpha for all tests was set to 0.05. All response variables were screened for normal distribution of residuals using the Shapiro-Wilk W test in JMP. Analysis was conducted on four response variables, corresponding to four SOC stock derivatives from collected data; (i) TSOC stock, up to 100 cm in depth or to root-limiting layer if less than 100 cm; (ii) OSOC stocks, comprised of all O horizon horizons occurring at the surface of the soil;
(iii) MSOC stocks, including all horizons not comprised of organic soil materials at the surface down to 100 cm or root-limiting layer if less than 100 cm, and; (iv) SPSOC stocks, including all spodic horizons designated Bh, Bhs, or Bs to a depth of 100 cm or root-limiting layer, if less than 100 cm. To test the null hypothesis that SOC does not depend on relative conifer percent cover, we regressed SOC stock derivatives on percent relative conifer canopy cover in simple linear regression. A natural log transformation was applied the TSOC stocks, OSOC stocks, and the SPSOC stock data sets to correct for right-skewness of the data, while square root transformation was used to correct right-skewness in the case of MSOC stocks. For the purpose of linear regression each pedon within each ES was considered independent of each other. The linear regression was done on data from both ES combined.

Further, categorical effects of ES and ecological states within ES (hypothesis 1) and continuous effect of relative conifer percent cover (hypothesis 3) were collectively used in a final mixed model to predict SOC while adjusting for the other effects in the model. The generalized linear mixed model (Gaussian distribution on transformed response) accounted for main effect of ES and ecological states within ES, relative conifer percent cover, and for interaction of ES and relative conifer percent cover, while year sampled was a random effect.

During lab analysis soil standards for the Lobdell series (Fine-loamy, mixed, active, mesic Fluvaquentic Eutrudepts) were used to check accuracy of SOC measurements. A total of 98 Lobdell standards were analyzed over the course of the lab work, with one standard for each 12 samples run. This Lobdell standard has a lab calculated percent C of 2.77. After 98 Lobdell standards were run our calculated mean percent C was 3.01, with a standard error of 0.057.
Results

Initial regression analysis using a fixed model shows significant effect of relative conifer percent cover on SOC stock in the TSOC (Table 5.1, p < 0.0001; Fig. 5.5) and OSOC (Table 5.1, p < 0.0001; Fig. 5.6) pools. Initial fixed model regressions (Figs. 5.5, 5.6, 5.7, 5.8) did not account for influences from ES, ecological state, or year sampled. Adjusted R² values were highest for TSOC and OSOC (.20 and .31, respectively), and lowest for MSOC and SPSOC (-.006 and .02, respectively). Further analysis using a mixed model demonstrated a significant effect of ES on SOC stock for TSOC, OSOC, and SPSOC pools when adjusted for relative conifer percent cover. There was a main effect of relative conifer percent cover on OSOC when adjusted for ES and ecological state within ES (Table 5.2, p = 0.008). However, only in the OSOC layer a significant interaction of ES and relative conifer percent cover was observed (Table 5.2, p = 0.024; Fig. 5.9). Adjusted R² values were highest for the SISUHCF in the TSOC and OSOC derivatives (.22 and .30, respectively). Remaining adjusted R² values attributed to MSOC and SPSOC derivatives in the SISUHCF as well as all SOC stock derivatives for the SSUCF were less than a tenth of a percent (Figs. 5.9, 5.10, 5.11, and 5.12). All other analyses showed no significant effect of relative conifer percent cover and its interaction with ES on SOC stock pools when adjusted for each other, and for ecological state within ES (Figs. 5.10, 5.11, and 5.12).

Discussion

Relationships Between SOC Stocks and Conifer Vegetation

To our knowledge, there is no comparable research that has examined SOC stocks with varying levels of conifer cover in similar or even dissimilar ecosystems. Based on previous research in West Virginia (Nauman et al., 2015a,b) and our experience working in these high-
elevation red spruce ecosystems, our expectation was that SOC stocks would increase with increasing conifer cover. In line with our hypothesis, initial regressions found TSOC and OSOC were the only SOC derivatives to be statistically related to conifer canopy cover (Table 5.1, Figs. 5.5, 5.6, 5.7, and 5.8). These four initial regressions grouped all sample pedons together without concern for ecological state and ES to capture conifer canopy influence. These findings suggest that with every percent increase to relative conifer cover a response of .39 kg C m² OSOC was seen (untransformed data using arithmetic values with significant lack of fit).

In Central Appalachian ecosystems OSOC makes up the dominant proportion of TSOC in the SSUCF and Reference State of the SISUHCF ES (Chapter 4, Table 4.1 and 4.2), therefore, OSOC most directly produce commensurate changes in TSOC (Chapter 4, Table 4.1 and 4.2). The fact that MSOC and SPSOC were not significantly affected by an increase in the percent relative conifer canopy cover (Figs. 5.7 and 5.8) may further support the idea that disturbances like logging and fires have less effect on MSOC and SPSOC stocks in comparison to the OSOC stocks (Miesel et al., 2012; Kolka et al., 2014). SPSOC is held in deep mineral horizons, effectively insulating it from effects of logging and fires (Kolka et al., 2014), whereas the OSOC stocks are held at the soil surface and are most susceptible to drastic disturbances (Bradford et al., 2012; Miesel et al., 2012; Kolka et al., 2014). Miesel et al. (2012) mentions that mineral soils are poor conductors of heat, and therefore any significant effect on SOC in the upper mineral horizons is generally limited to the first 5 cm, although this varies with extended exposure and higher temperatures.

Further, a mixed model controlling for ES, ecological state, and year sampled showed that percent relative conifer cover had a statistically significant relationship with OSOC stocks but no other SOC derivatives, not even TSOC (Table 5.2). Interestingly, the SISUHCF showed a
greater positive relationship between conifer percent cover and all SOC stock derivates than in the SSUCF (Figs. 5.9, 5.10, 5.11, and 5.12). The mixed model showed that the SISUHCF ES was driving the positive relationship based on the interaction between relative conifer canopy cover and SOC derivatives, while the SSUCF did not show a similar significant relationship and had negative slopes in the TSOC, MSOC, and SPSOC derivatives (Figs. 5.9, 5.10, 5.11, and 5.12). When viewing relative percent conifer cover and SOC derivative plots we can see an almost random plotting of points within the SSUCF. For example, the fact that one pedon in the SSUCF contains upwards of 80 kg C m² in the OSOC layer corresponding to ~30% relative conifer canopy cover while another pedon in the same ecological state contains ~20 kg C m² corresponding to nearly 100% relative conifer canopy cover in the OSOC layer shows just how much variability these ES contains (Fig. 5.9). This degree of randomness also seems apparent in TSOC and SPSOC stock derivatives, which leads us to believe that disturbance history of these ES principally affects SOC stock variation.

**Disturbance History Effects on SOC Stocks and Future Management Implications**

The SSUCF and SISUHCF ES have undergone drastic changes in the course of the last two centuries related to past logging and burning management regimes. Logging and fires play a substantial role on how SOC is accumulated and retained in forest ecosystems. Kolka et al. (2014) looked at the effect of fires on forest floor C (O horizon C) in mixed forests of Minnesota and found across all plots that mean SOC losses in the forest floor averaged 9.7 Mg ha. Further, Kolka et al. (2014) found C pools to be higher in unburned reference plots. In their burned sites Kolka et al. (2014) found that approximately 65% of SOC held in O horizons were lost by fires. Nave et al. (2011) found similar results showing around 67% of SOC was lost from the O
horizon C pool after fires, while no change was found to MSOC. Bradford et al., (2012) estimated a 74% decrease to O horizon C pools and no change to mineral C pools in Minnesota.

If we apply the same C losses to the SSUCF and SISUHCF using SOC stock averages estimated in this study (Chapter 4) we find the possibility for significant losses of SOC in these ecosystems due to fires. Using the higher estimate of Bradford et al. (2012) and the lower estimate from Kolka et al. (2014), if the SSUCF Reference State experienced severe fires an average of 308 ± 17.4 Mg C ha to 231.7 ± 13.2 Mg C ha could be lost from O horizons alone (Chapter 4, Table 4.2). Using the example of our highest observed OSOC stock in this ES (1024 Mg C ha), a 74% loss as Bradford et al. (2012) suggests would equate to 758 ± 43.2 Mg C ha in lost SOC from the O horizon alone. In the SISUHCF the average loss in O horizon C from intense fires using the same estimate equates to between 153 ± 8.7 Mg C ha and 75.3 ± 4.3 Mg C ha is lost from the Reference State (Chapter 4, Table 4.2). While understanding what the actual OSOC these ES contained before extensive disturbance is impossible, these losses can help us form a picture for what could have been.

In the SISUHCF, historic fires are believed to have been more severe, burning O horizons and removing the red spruce seedbank entirely at times (USDA-NRCS, 2016b). No remaining red spruce seedbank means no further red spruce regeneration, and as a result, a causal change to overstory species composition occurs once an area has regenerated—mostly dominated by hardwood species (Sterling, 1920; Rentch and Schuler, 2017). In the SSUCF, fires were not as severe, leaving the spruce seedbank intact (USDA-NRCS, 2016a). Differences in logging and burning intensity directly influences the degree of red spruce regeneration seen in each ecological state of both ES (NRCS-USDA, 2016a, b).
Prior to historic logging in Central Appalachia, a specific area may have had a high red spruce component in the overstory canopy with SOC stocks reflective of long periods of podzolization without disturbance, but post timbering, this same area would have been left barren of vegetation with conifer vegetation removed and podzolization effectively ceasing. The post-harvest process of depodzolization combined with varying degrees of succeeding spruce regeneration means that there are two different possible processes occurring spatially in unison: i) regressive development via depodzolization occurring with no further podzolizing inputs due to a lack of red spruce and red spruce seedbank to drive podzolization temporally; and, ii) regressive development via depodzolization occurring initially but the red spruce component in the seedbank retained, effectively reinitiating podzolization when red spruce reestablishes itself (Fig. 5.13). The degree these two regressive pathways affect the SOC pool are substantial and would explain why some high conifer stands contain comparatively low SOC stocks, while another location within the same ecological state may show the opposite relationship.

Accounting for how conifer vegetation correlates to SOC stocks is difficult at best since we know spodic properties can be held in a soils pedomemory for substantial amounts of time following disturbance (Nauman et al., 2015a, b); however, the upper portion of the soil generally undergoes the most impact from logging and fires (Bradford et al., 2012; Miesel et al., 2012; Kolka et al., 2014), leaving a disconnect between aboveground disturbances and belowground consequences.

By correlating SOC stocks to conifer canopy cover, land managers can get an idea for how much SOC might be gained when restoring red spruce into the canopy. Land managers can set target goals for SOC stock gains in red spruce landscapes and know how much red spruce they need to restore into the overstory to reach their SOC stock goal. As previously mentioned,
our findings suggest that with every percent increase to relative conifer cover during restoration a further $0.39 \pm 0.02$ kg C m$^2$ (3.96 ± 0.23 Mg C ha) is gained on average (estimate uses untransformed data and arithmetic values with lack of fit). Increasing conifer cover by 20% during restoration would therefore capture on average $7.8 \pm 0.44$ kg C m$^2$, or, $78 \pm 4.4$ Mg C ha in OSOC once restoration goals have been met. This estimate is supported by Nauman et al. (2015b) assertion that in these ES O horizon response to conifer importance values equates to a 0.96 cm gain for every 10% increase of conifer importance. Taken together, increasing conifer percent cover leads to increased O horizon development and increased OSOC sequestration.

From our analysis we calculated the average SOC in kg/m$^2$ per cm of O horizon, finding that in locations without red spruce regeneration – indicative of severe historic fire presence (NRCS-USDA, 2015b) – OSOC averaged 1.76 kg C m$^2$ per cm. Alternatively, locations with red spruce regeneration present in the understory contained 2.33 kg C m$^2$ per cm, .57 kg C m$^2$ more on average. Other considerations regarding endangered and threatened wildlife such as the northern flying squirrel are correlated to the amount of red spruce in the overstory canopy (Loeb et al., 2000; Mitchell, 2001; Ford et al., 2004; Byers et al., 2010). Restoration decisions with sensitive species in mind forces land managers to implement management practices that aim to reach a specific goal of red spruce canopy cover. In these types of situations where a clear goal is established, a SOC stock could be paired with the management plan to further support reasoning for restoration in terms of probable changes to observed DSP on site and the benefits to sensitive species gained once restoration goals are met.

References


Extent

Figure 5.1. Dual extent of SSUCF and SISUHCF ES within the boundaries of the Monongahela National Forest
Soil Series

Figure 5.2. Wildell soil series, a loamy-skeletal, mixed, superactive, frigid Typic Haplorthod, correlated to the SSUCF ES in West Virginia. This soil shows a strong degree of podzolization in the subsoil.
Figure 5.3. The Mandy soil series (Loamy-skeletal, mixed, active, frigid Spodic Dystrudepts), correlated to the SISUHCF ES, showing a moderate to slight degree of podzolization in the subsoil
Pedon Locations

Figure 5.4. Soil and ecosystem point locations used in analysis, broken down by source
Regression Analysis

Table 5.1. SOC regressed on relative conifer percent without regard to ecological site. Total SOC and O horizon SOC show significant slope of regression. Table corresponds to Figs. 5.5, 5.6, 5.7, and 5.8

| Response                  | Term                | Estimate | Std Error | t Ratio | Prob>|t|   |
|---------------------------|---------------------|----------|-----------|---------|------|-----|
| Ln Total SOC              | Intercept           | 3.296    | 0.067     | 49.15   | <.0001 |
|                           | Relative Conifer %  | 0.011    | 0.002     | 5.1     | <.0001 |
| Ln O Horizon SOC          | Intercept           | 1.933    | 0.125     | 15.43   | <.0001 |
|                           | Relative Conifer %  | 0.027    | 0.004     | 6.87    | <.0001 |
| Sqrt Mineral SOC          | Intercept           | 4.315    | 0.154     | 27.95   | <.0001 |
|                           | Relative Conifer %  | -0.003   | 0.005     | -0.59   | 0.560 |
| Ln Spodic Horizon SOC     | Intercept           | 1.872    | 0.085     | 22.11   | <.0001 |
|                           | Relative Conifer %  | 0.005    | 0.003     | 1.84    | 0.069 |

Table 5.2. SOC was modeled using ES, ecological states within ES, relative conifer percent, and interaction of ES and relative conifer percent as fixed effects, while year sampled was a random effect. Total O horizon SOC stock demonstrates significant relationship of ES with relative conifer percent cover on SOC. Table correspond to Figs. 5.9, 5.10, 5.11, and 5.12.

<table>
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<th>Response</th>
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<th>DFDen</th>
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<td>Relative Conifer %</td>
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Figure 5.5. Regression of Ln transformed total SOC stocks and relative conifer percent canopy cover.

Figure 5.6. Regression of Ln O horizon SOC stocks with relative conifer percent canopy cover.
Figure 5.7. Regression of Ln mineral SOC stocks with relative conifer percent canopy cover.

Figure 5.8. Regression of Ln spodic horizon SOC stock with relative conifer percent canopy cover.
Figure 5.9. Model of relative conifer percent cover on O horizon SOC stocks controlling for ES, ecological state, and year sampled. The interaction of ES and relative conifer percent cover on SOC stock was significant.

Figure 5.10. Model of relative conifer percent cover on total SOC stocks controlling for ES, ecological state, and year sampled. The interaction of ES and relative conifer percent cover on SOC stock was not significant.
Figure 5.11. Model of relative conifer percent cover on mineral SOC stocks controlling for ES, ecological state, and year sampled. The interaction of ES and relative conifer percent cover on SOC stock was not significant.

Figure 5.12. Model of relative conifer percent cover with spodic horizon SOC stocks controlling for ES, ecological state, and year sampled. This interaction was not significant in either ES.
Wildell-Mandy Developmental Pathway

Figure 5.13. Developmental pathway for the Mandy series as outlined by the SISUHCF ESD
CHAPTER 6: CONCLUSIONS

The purpose of this research project was to provide land managers concerned with red spruce restoration a potentially useful method to interpret restoration and management outcomes. Using SOC as a lens to interpret these restoration or conservation outcomes allows for the better utilization of restoration resources often limited by funding or manpower. Nauman et al. (2015a, b) determined where to target red spruce restoration – using the presence of spodic properties in soil to determine historic extent – but now we can further adjust our methods to select for not only where red spruce likely occurred in the past, but also which current red spruce communities will respond most strongly to restoration initiatives in terms of SOC. Our results showed that there are significant differences in TSOC, OSOC, and SPSOC stocks between the SSUCF and SISUHCF ES, while also further identifying differences among ecological states within the SISUHCF. We also showed TSOC and OSOC stocks to be highly variable between ES but not among states within their related ES. Finally, we found correlation between percent conifer cover and OSOC stocks primarily related to the SISUHCF ES. These findings help to better represent the effects of restoration practices on SOC stocks in these Central Appalachian ecosystems. Not only can we now understand how these ES restoration and transitional pathways result in SOC stock changes, but we can also interpret these SOC stock changes in unison with DSP relationships to infer expected changes once restoration goals have been met.

At this point it is critical to address a consequential issue regarding the SSUCF and SISUHCF ES. We know these landscapes and ecosystems experienced significant disturbance that altered ecological trajectory in various ways (NRCS-USDA, 2016a, b). Although, the question remains: which Mandy soils (SISUHCF ES) are true Mandy soils, and which Mandy soils are depodzolized Wildell soils (SSUCF ES)? The difference between the two lies in
whether a given Mandy series is a temporal expression of the series or a spatial expression of the series. There is no doubt that the Mandy series naturally occurred in areas where red spruce historically existed sub-dominantly alongside eastern hardwood species – this would be the natural occurrence of the spatial Mandy. However, we also know that regressive development via depodzolization as a result of intensive logging accompanied by fires initiated the loss of spodic properties in Spodosols—sometimes more, sometimes less—and these soils we would consider a temporally expressed Mandy. Developmentally speaking, there are two manners through which to get to the same Mandy series: (i) natural development with a minor or moderate red spruce component in the overstory produces just enough spodic properties in the soil to alter the soils morphology (spatial Mandy), and (ii) depodzolization of the Wildell series by severe disturbance (i.e. loss of spodic properties from the soil, a temporal Mandy) (Fig. 6.1).

These differences are significant in that they present a problem in the context of the structure upon which ESD are based. If a soil is a temporal Mandy then at one point it was a Wildell soil, and, therefore, it is reasonable to assume that these soils given enough time and restoration resources can re-podzolize enough to classify as a Spodosol in the future. This essentially means breaking the rules of ESD, since one ES is supposed to be different from another ES, and as such, cannot be transitioned into another. These two ES are related in that both ES share similar developmental trajectories, although one deviating from the other due to disturbance. Taken as such, it would be possible to restore a temporal Mandy soil and corresponding ecosystems back to its historic Wildell status. Consequently, a question that begs an answer is: are there two distinct ES or is there only one ES? An interpretation of NRCS ESD supports the idea that there are two ES, but as delineated in their corresponding ESD there is no room for the possibility of spatial verses temporal Mandy expression—one being historic Wildell
soils that could be restored. Only by further research can this issue be deciphered. We hypothesize this could be done by measuring aluminum extracted from the subsoil in Bs and Bw horizons to compare to aluminum concentrations observed in present day Wildell series. Mandy series with higher aluminum concentrations that are similar to that seen in Wildell series can be shown to be temporally expressed Mandy soils, and as such, can be targeted for restoration in hopes to set the soils trajectory back toward its historic soil type by encouraging podzolization.

There is much room for future research into questions surrounding SOC in Central Appalachian red spruce ecosystems. The aforementioned issue between temporal or spatial Mandy expression is only one example, and it may have significant implications for future restoration possibilities. Other possible future research could compare O horizon thickness with different SOC stock types (i.e. SPSOC, TSOC, MSOC), or, further regress O horizon thickness with conifer percent cover. SOC stocks or O horizon thickness could be modeled and mapped within the current extent of the Monongahela National Forest, further aiding management. Referencing our data and calculated SOC stocks or O horizon thickness with known years that land parcels were recorded being logged could also help express how O horizon or spodic properties are developed and retained, or to what degree they may be affected by disturbance. Further research into how soils in these landscapes respond to fire could be conducted using the presence of charcoal alongside OSOC stocks, while integrating specific disturbance types into the analysis may also shed light on how SOC, O horizons, and spodic properties were affected by historic disturbance. Another possibility for further research and analysis could occur by creating SOC depth curves that express SOC stocks by depth in the profile, helping further understand the vertical distribution of SOC in these landscapes. Finally, an analysis between Mandy and Wildell...
series by horizonation targeting different horizon types comparatively could increase our understanding for how SOC is fractionated through the soil profile in these environments.

These landscapes contain a history rich in stories that soil scientist and ecologists seek to interpret and express. Red spruce landscapes in Central Appalachia have come a long way, experiencing the logging boom of the mid-19th century and succeeding fires that burned in some cases for months on end, effectively casting the dark night sky in a bright red hue. Acid deposition further impaired red spruce recovery throughout much of the 20th century, but now, the red spruce foothold is again well established in Central Appalachia, giving hope to future generations who want to see these ecosystems returned to their historic magnificence and improve or retain the important ecosystem services and habitat these ecological communities provide. As a result of this research, we think Central Appalachian red spruce ecosystems are capable of accumulating far greater SOC stocks than previously supposed. Leon Minckler, a 20th century red spruce restoration enthusiast once said, “A typical spruce tree is born, lives, and dies in a soil literally created from its ancestors”. He could not have been more correct.
Figure 6.1. Developmental pathways for Wildell and Mandy soils as affected by disturbance. Two forms of Mandy soil exist, one naturally occurring that we refer to as the spatial Mandy, and an anthropogenically developed version, what we refer to as the temporal Mandy.
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Appendix A. Experimental Unit – Plot Layout

APPENDICES
Appendix B. NRCS Modified Pedon Description Form
Appendix C. Other SOC Analyses Documentation

Total SOC Stocks

![Plot of least square means for Ln transformed TSOC stocks for both SSUCF and SISUHCF ES](image)

*Figure C1. Plot of least square means for Ln transformed TSOC stocks for both SSUCF and SISUHCF ES*
Figure C2. Plot of least square means for Ln transformed TSOC stocks listed by ecological states of both SSUCF and SISUHCF ES. Letter designations denote statistical differences between ecological states.
Figure C3. Box plots of TSOC stocks within the SISUHCF ES listed by ecological state
Figure C4. Box plots of TSOC stocks in the SSUCF ES listed by ecological state.
O Horizon SOC Stock

Figure C4. Plot of least square means for Ln transformed OSOC stocks of both SSUCF and SISUHCF ES
Figure C6. Plot of least square means for Ln transformed OSOC stocks by ecological states of both SSUCF and SISUHCF ES
Figure C7. Box plots of OSOC stocks for the SISUHCF ES by ecological state
Figure C8. Box plots of OSOC stocks for the SSUCF ES by ecological state
Mineral SOC Stocks

Figure C9. Plot of least square means for square root transformed mineral SOC stocks of both SSUCF and SISUHCF ES

Figure C9. Plot of least square means for square root transformed mineral SOC stocks of both SSUCF and SISUHCF ES
Figure C10. Plot of least square means for square root transformed MSOC stocks by ecological states of both SSUCF and SISUHCF ES.
Figure C11. Box plots of MSOC stocks for the SISUHCF ES by ecological state
Figure C12. Box plots of MSOC stocks for the SSUCF ES by ecological state
Figure C13. Plot of least square means for Ln transformed SPSOC stocks of both SSUCF and SISUHCF ES.
Figure C14. Plot of least square means for Ln transformed SPSOC stocks by ecological states of both SSUCF and SISUHCF ES
Figure C15. Box plots of SPSOC stocks for the SISUHCF ES by ecological state.
Figure C16. Box plots of SPSOC stocks for the SSUCF ES by ecological state
Appendix D. Lobdell Standard C% Statistics

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<td>Lower 95% Mean</td>
<td>2.8999926</td>
</tr>
<tr>
<td>N</td>
<td>98</td>
</tr>
<tr>
<td>Sum</td>
<td>295.367</td>
</tr>
<tr>
<td>Minimum</td>
<td>2.557</td>
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<tr>
<td>Maximum</td>
<td>6.668</td>
</tr>
<tr>
<td>Range</td>
<td>4.111</td>
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