PINEMAP

Mapping the future of southern pine management in a changing world

Forest Soils: Soil Respiration as an Indicator of Forest Health

Healthy soils are essential to vigorous, productive, and resilient forest systems. Soils make up the uppermost layer of earth's surface and are comprised of a mixture of rock, minerals, and organic materials. It is the medium for which forest trees grow. However, healthy forest soils are much more than that. Forest soils are complex, living communities comprised of numerous and diverse microflora and fauna interacting among themselves and with mineral and organic constituents. The soil community carries out a range of crucial physiological processes that directly influence tree vigor, health, and resilience.

SOIL HEALTH IS DEFINED AS THE ABILITY OF SOIL TO:

Sustain life *for plants, organisms, humans, and ecosystems*

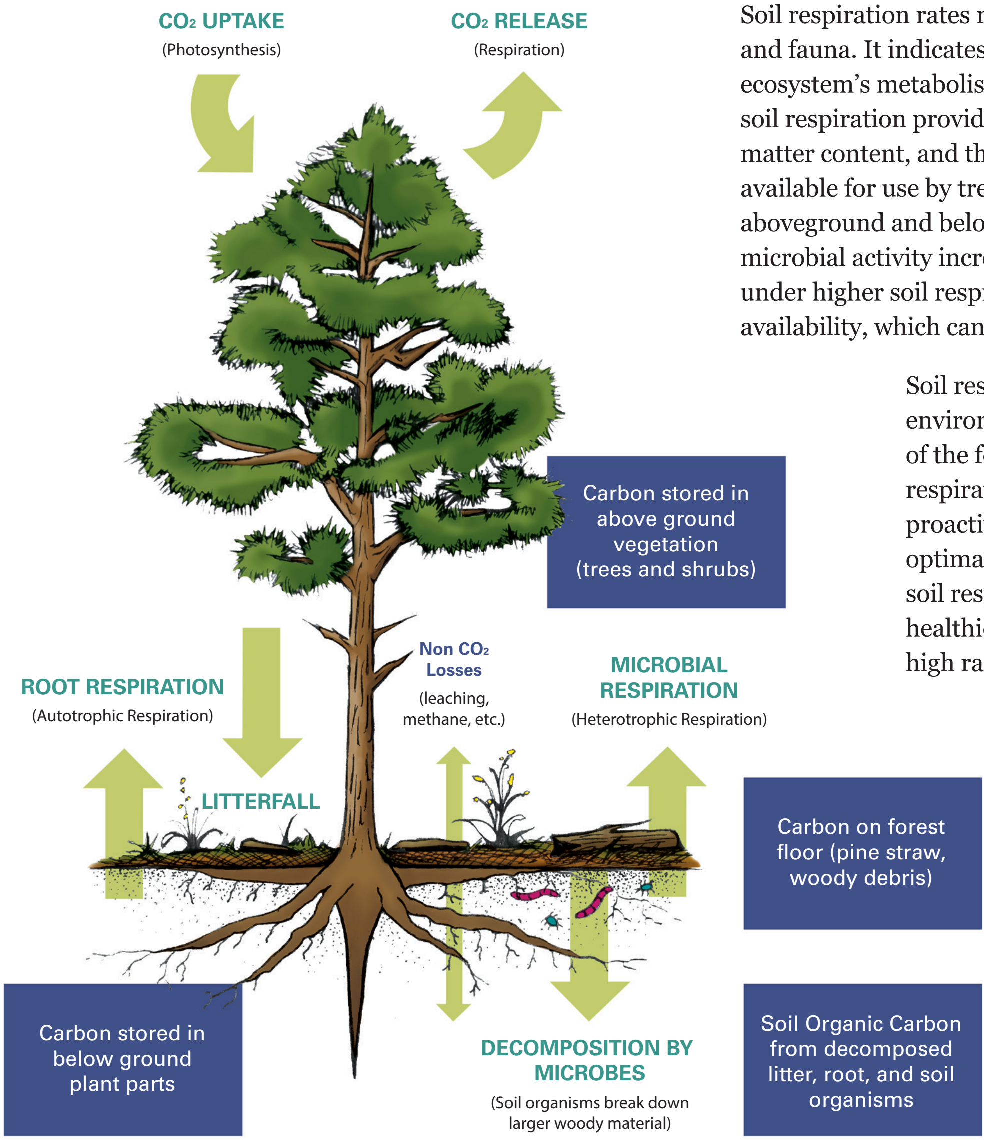
Maintain vital functions *for future generations such as a medium for plant growth to provide stability and support, regulate water flows through infiltration and percolation, cycle and store essential nutrients required for plant growth, filter and buffer pollutants from water, provide sustainable habitat for living things*

I. WHAT IS SOIL RESPIRATION?

All living plants and animals respire, taking in oxygen and releasing carbon dioxide (CO2). In humans, we call this breathing. Respiration literally means breathing (again and again), and is derived from the Latin prefix re- (back, again) and root-word spirare (to breathe). Respiration provides the energy for all living organisms to grow, maintain, and exist. Soil organisms also breathe in oxygen and release carbon dioxide which is referred to as soil respiration. Soil respiration is defined as the combined production of carbon dioxide by all soil organisms and plant components (Figure 1). The extent of which soil respiration occurs affects soil health, soil carbon storage, and nutrient availability, ultimately impacts forest growth. It is a complex relationship among the food web and the physical and chemical environment of the soil. Forest management actions can influence (increase or reduce) the rate of soil respiration, impacting soil health and forest productivity. Therefore, prudent forest management practices can help sustain healthy forest soil conditions and keep forests productive.

Living organisms are composed of organic compounds. As these organisms die and shed parts such as leaves, branches and roots, the matter becomes slowly incorporated into the soil. This soil organic matter is decomposed by soil microorganisms which, in turn, use the energy of decomposition for maintenance and growth. The process of decomposition also converts some of the essential elements needed for plant growth, such as nitrogen and phosphorous, into useable available forms for trees. The soil microbes help to build soil structure, and cycle or store nutrients that might otherwise be washed (leached) away. During decomposition, microbes release complex compounds that help form soil clumps (or aggregates). These soil aggregates act like a sponge in that they increase water absorbance, aeration, nutrient retention, and water infiltration. Forest management activities can alter soil conditions such as soil temperature, moisture, organic matter, chemical elements and soil structure. As soil conditions change, populations of different microbes rise and fall as well. Because the health, vigor, and resiliency of the forest trees depends heavily upon a healthy, active and diverse community of soil organisms, forest management strategies should carefully consider the impact of various treatments on soil health when developing management prescriptions.

Figure 1. Carbon Flows in a Loblolly Pine Forest



II. WHY IS KNOWING YOUR SOIL RESPIRATION RATE IMPORTANT?

Soil respiration rates reflects the soil's capacity to sustain flora and fauna. It indicates soil health and can be thought of as an ecosystem's metabolism or "pulse" because measurements of soil respiration provide information about a forests' soil organic matter content, and the rates that crucial nutrients become available for use by trees. Soil respiration rates increase as aboveground and belowground biomass increases and as microbial activity increases. Increased mineralization rates under higher soil respiration may indicate greater soil nutrient availability, which can result in greater forest productivity.

Soil respiration rates are influenced by environmental conditions and the condition of the forest stand. Landowners can alter soil respiration rates through silviculture and proactive forest management, and aim for an optimal range for a given forest (Table 1). High soil respiration rates do not necessarily mean healthier, more productive forests. Instead, high rates may indicate an unstable system and loss of organic matter due to site disturbance. Other factors that may degrade forest or soil health include a crowded understory, overstocked stand, or residual effects from fertilization. On the other hand, low respiration rates may be indicative of poor soil structure and health or saturated soils.

Soil respiration is a major source of carbon loss from an ecosystem, and influences storage and cycling. Carbon flows through the forest, entering by photosynthesis and exiting to the atmosphere as CO2 via respiration. The balance between carbon inputs (photosynthesis and biomass production) and losses (autotrophic respiration from trees and heterotrophic respiration from soil organisms) is directly related to its ability to function as a C sink for atmospheric CO2. Forest management practices can optimize above-and below-ground productivity and C storage by increasing inputs and controlling losses of C in a forest.

SOIL RESPIRATION INDICATES:

- Nutrient availability for soil community and for tree uptake
- Above- and below-ground plant and root productivity
- Rate at which organisms decompose soil organic matter (Food web metabolism or "pulse")
- Soil aeration and oxygen supply

III. FACTORS INFLUENCING SOIL RESPIRATION

Soil respiration is regulated by many site factors, such as soil organic matter (substrate) supply and quality, temperature, moisture, nutrient availability, soil texture, soil acidity (pH), oxygen availability and soil biology. Many of these regulators vary seasonally as well as annually, and can be directly and indirectly influenced by management practices.

Figure 2. Forest Soil Profile Represnting Utisol Soil Order

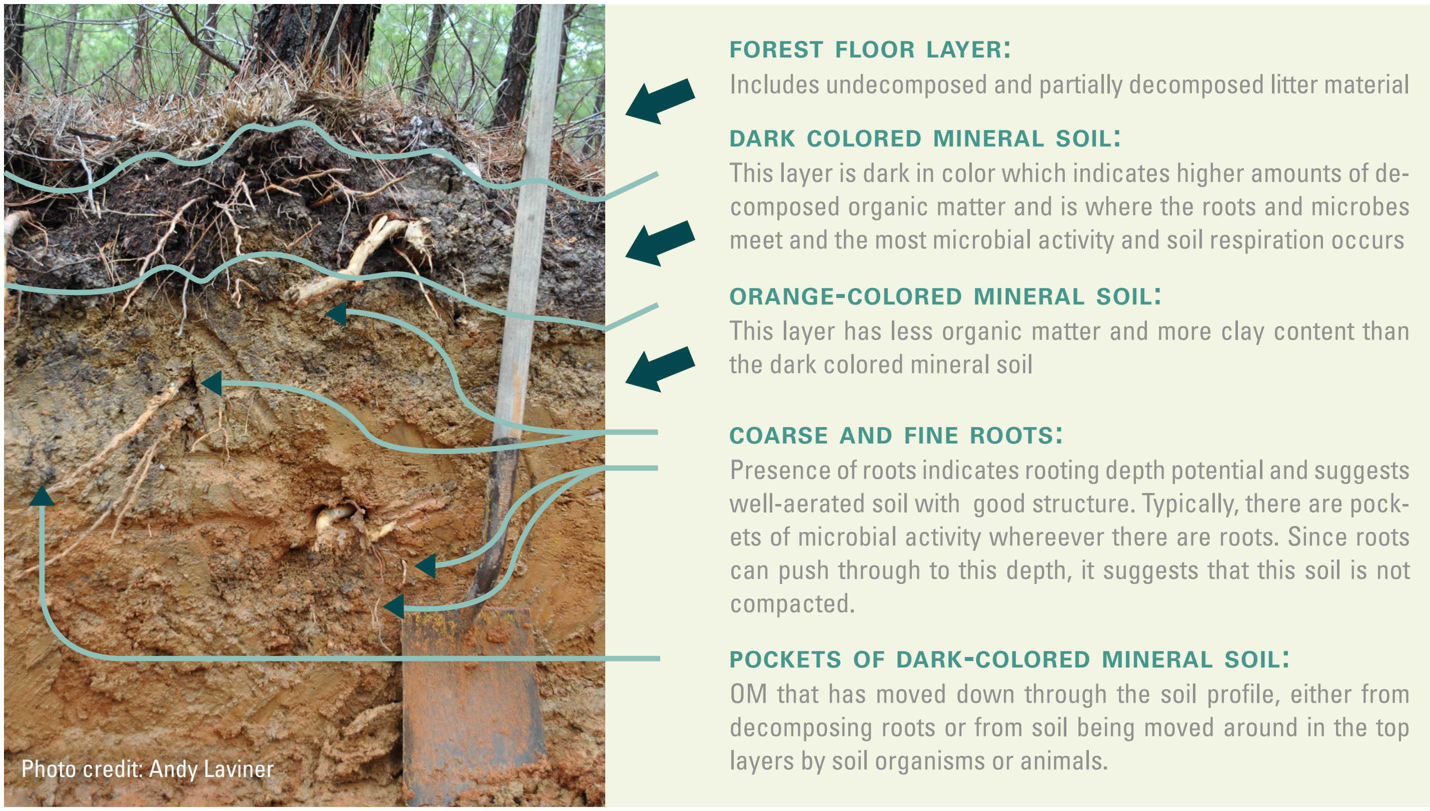


Table 1. What Your Soil Respiration Rates Are Telling You

Low soil respiration rate suggests	Optimal soil respiration rate suggests	High soil respiration rate suggests
• Little organic material or soil microbial activity • Limited biological activity and organic decomposition • Limited nutrient recyling available to feed plants and microorganisms • Reduced root activity • Unhealthy, low vigor, or underperforming forest	• Active microbial communities and productive root systems • Steady cycling of nutrients are available for plant and microbial uptake • Diverse and active microbe community • Improved resistance to pathogens and forest pests = lower risk of tree loss • Longer-term balance between annual litter and carbon inputs and and soil C loss	• Short-term disturbance due to changes in factors affecting respiration • Excess or imbalance of a specific nutrient • Potential for brief depletion of site nutrients, result in leaching losses of nutrients, and reduce overall productivity over the long-term • Rapid loss of soil organic matter

Site Factors:

Soil Organic Matter

Soil Organic Matter (SOM) is made up of various forms of decaying leaf litter, dead and decaying roots and soil organisms, and secretions of compounds from roots. SOM provides food and habitat for soil fauna and microorganisms, thus the quality and quantity of SOM has a direct impact on the rate of decomposition and soil respiration. SOM is central to the functioning of many physical, chemical, and biological processes in the soil, such as nutrient turnover, nutrient retention and availability, resistance to erosion, aeration, and moisture retention and availability.

Forest residues and organic matter inputs may not have market value, but these inputs are important to consider as they represent a large (and free) bank of nutrients. When forest residues are removed, the loss of some nutrients can be replaced with fertilization, but the many functions of SOM cannot. Soil health, long-term soil productivity, and soil respiration improve with increased soil organic matter; therefore, management approaches that retain organic matter uniformly about the site and optimize organic matter inputs to the soil help to maintain long-term soil productivity.

Temperature

Soil respiration generally increases as soil temperature increases until it reaches a maximum temperature of 95-104° F, at which point it begins to decline. On a smaller scale, soil temperature may also influence soil respiration indirectly via its effects on dissolved organic matter and oxygen transport in the soil. This transport and diffusion is important for microbial metabolism and is influenced by water content of the soil. As temperature increases, water content and diffusion may decrease, thereby decreasing soil respiration rates. Management activities that leave some live, non-competitive vegetation (such as goatweed) and/or harvest debris evenly distributed about the site can serve to moderate soil temperature extremes and benefit soil health.

Soil Moisture:

Soil moisture is another important component influencing soil respiration. In general, soil respiration is low under dry conditions, reaches a maximum in intermediate soil moisture levels, and decreases at high soil moisture levels when oxygen becomes limiting and anaerobic conditions dominate. The optimum water content is usually somewhere near field capacity, because the macropore spaces are mostly air-filled, thus facilitating oxygen diffusion, and the micropore spaces are mostly water-filled, enabling diffusion of dissolved organic matter. When soil water content exceeds optimum conditions, soil respiration slows due to oxygen deficits. Site preparation activities such as bedding and subsoiling (ripping) can improve the soil environment for optimum soil respiration and facilitate root development and tree vigor.

Soil Nutrition

Highly fertile soils, soils with high nutrient content, are generally associated with high plant growth rates. High growth rates may result in optimum soil respiration rates. Conversely, low soil nutrient status can slow growth rates and slow soil respiration rates. Management activities such as weed control can decrease respiration and soil C but can still benefit tree growth. Herbicide application or prescribed fire could be used to reduce competition from non-timber species, and thinning of the forest stand would reduce intraspecific competition for soil nutrients.

Soil Texture

Soil texture, the look and feel of a soil, influences soil respiration. Soil texture is determined by the proportions of clay, sand, and silt particle, which also determines soil structure and porosity. Soil porosity can determine the capacity of the soil to store nutrients, hold water, move water, diffuse gas, and ultimately maintain its long-term fertility. Generally, clayey soils or compacted soils limit diffusion of gases such as oxygen and carbon dioxide and have lower respiration rates than other texture classes. If you rub soil between your fingers: sandy soils feel gritty. Silt soils feel smooth or like wheat flour. Clay soils feel slick or sticky.

IV. FOREST MANAGEMENT CONSIDERATIONS

Harvesting

Forest harvesting can have a dramatic impact on soil physical and chemical properties and soil respiration due to tree removal, but also from the harvesting equipment itself which can disturb the site and compact the soil. Harvest methods, forest type, speed of regeneration (or replanting), and climate conditions will influence how much soil respiration is affected. Biomass removal as a result of harvesting generally increases soil temperature and reduces soil water content by increasing water evaporation at the soil surface. A large amount of forest litter and dying tree roots that decompose easily are typically left after a harvest, which can increase soil organic matter content. Proactive organic matter management can result in optimum soil respiration rates and increase soil carbon storage.

Site Preparation

Site preparation techniques can influence respiration rates and sources. For example, heterotrophic respiration (CO2 released from soil microorganisms) may dominate in early stands following site preparation, while autotrophic respiration (CO2 from roots) may become more dominant following canopy closure when root biomass increases. Site preparation techniques like prescribed fire reduces forest floor litter and may temporarily reduce soil respiration rates, while subsoiling (ripping), soil tillage, and bedding increases organic matter incorporation, decomposition and soil respiration.

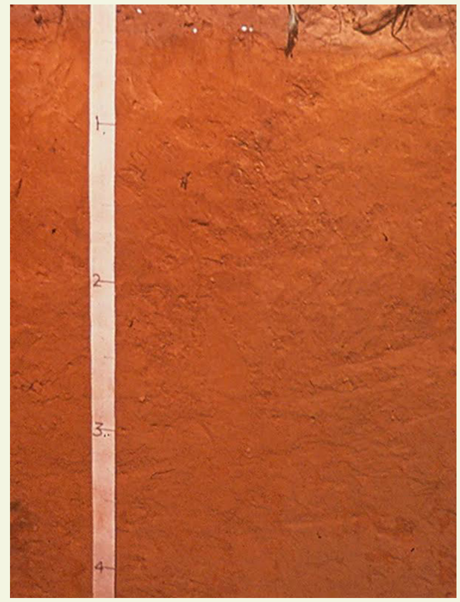
Thinning

Forest thinning alters many different site factors like soil temperature, moisture, and substrate availability, which influences respiration. Thinning partially removes trees

Figure 3. Three Soil Profiles Showing a Range of Soil Organic Matter Content and Soil Structure

This forest soil profile from western Virginia shows the presence of soil development indicated by a change in soil color through the profile. This results from adequate soil drainage, good soil structure and aeration, and presence of roots and organic matter.

This is a poorly drained forest soil from North Carolina. The grey color indicates poor drainage or saturated conditions with low oxygen content, but the upper layer shows the accumulation of organic matter due to slowed decomposition.



This forest soil from Florida has low soil organic matter and high clay content. Soil structure is poor, as indicated be the absence of roots and high clay content.

KEEP YOUR SOIL COVERED!

Keeping your soil covered with organic matter or vegetation throughout all stages of your rotation and following harvests helps to control soil erosion and minimize nutrient losses, protects soil aggregates and soil structure, suppresses weeds, conserves moisture, regulates soil temperature, and provides habitat for soil organisms.

SOIL STRUCTURE refers to how the various particles of sand, silt and clay fit together, creating small and large pore spaces.

SOIL AGGREGATES (or clusters of particles) improve soil structure, and are formed when sand, silt, and clay particles are "glued" together by chemical and biological processes. Mycorrhizae fungi, earthworms, soil microorganisms and plant roots are responsible for creating aggregates.

from a stand to reduce competition, improve crop tree productivity, and reduce wildfire risk. Like forest harvesting, thinning decreases stand density and leaf area, increases light and nutrient availability, and alters soil temperature and moisture regimes. In addition, mechanical thinning may cause soil compaction from machinery, which decreases soil aeration, and restricts root growth and microbial activities. Generally, when implemented under appropriate conditions, forest thinning results in healthier, more productive forests that balance soil nutrient cycling and respiration rates with aboveground productivity.

Chemical Fertilization and Herbicide Treatments

Responses of soil respiration to nitrogen fertilization are extremely variable and depend on fertilizer types, application timing, and site conditions. Fertilization can enhance or slow soil respiration levels by changes to the microbial community and impacts to fine- and coarse-root growth. Heavy treatments of pesticides, chemical fertilizers, soil fungicides or fumigants may impact microbial communities, nutrient cycling, and respiration rates. Fungicides, pesticides, and herbicides can kill beneficial organisms in addition to the target organisms. The balance between the pathogens and beneficial organisms may be upset, allowing opportunists (disease-causing organisms) to become problems, requiring maintained chemical control, which is expensive. Therefore, the need for pest and weed-control treatments should be carefully considered and applied at a minimum to balance the benefits to crop tree productivity with the disadvantages from changing the soil community.

Prescribed Fire

Frequent, low intensity fires are a natural part of the forest landscape. Fire can result in rapid changes in soil respiration and soil organic matter, but can have beneficial long-term effects depending on fire frequency and intensity. Burning aboveground biomass creates charcoal. Charcoal is essentially SOM that is resistant to decomposition and persists in soils for decades to millennia, thus contributing to long-term soil C stores. Charcoal can favor microbial communities, and can

Table 2: Management considerations to maintain soil health and productivity.

Forest Management Action	Considerations
Harvesting	Mow non-merchantable trees and shrubs during harvest operations. Delimb and top (buck) the trees in the woods and not in a centralized area. If bucked at centralized location (landing), scatter debris about the harvest site during the harvest. Strictly follow your states' Best Management Practices (BMPs) for forest harvesting to minimize negative soil and water quality impacts. Use skid trails to reduce compaction. Leave some biomass on the forest floor/keep the soil covered. Replant quickly after harvest. Use bole only harvest when appropriate. Redistribute residues on site.
Site Preparation	Avoid concentrating residues in windrows or slash piles. Consider more appropriate options for sites with heavy debris: skip row shearing, between row windrow, mulching. Ameliorate soil problems: subsoiling, bedding, disking. Test soil nutrient limitations and apply fertilizers. Control unwanted plants with herbicide and/or prescribed fire.
Thinning	Strictly follow your states' BMPs. Use thinning methods that limit soil disturbance. Leave some tree boles on the ground to decompose. Remove the appropriate number of trees required for optimal tree vigor. Thin when biological needs of the trees require it. Do not delay due to economic consideration. Avoid 3rd or 4th row thins. Try 5th or 6th row thin. Selectively remove undesirable trees between thinned rows.
Chemical Fertilizer and Herbicide Treatments	Consult research and industry professionals with regard to location specific management strategies. Test your soil before using fertilizers, as they may not be necessary. Use fertilizers at the right stage of growth, and never apply them during drought conditions. Herbicides should be used cautiously for competition control. Follow integrated pest management strategies when using insecticides.
Prescribe Fire	Low intensity, frequent prescribed fire are optimal. Follow historical fire disturbance patterns if feasible. Leave debris evenly distributed; avoid slash pile and windrow burns that unevenly concentrate site nutrients.

improve soil structure thereby enhancing or maintaining healthy respiration rates. Avoid intense fires as they rapidly consume soil organic matter which then affects soil nutrition, soil moisture holding capacity, and soil temperature.

V. MEASURING SOIL RESPIRATION RATES

Many methods are used to measure the rate of soil respiration and range from simple to complex. However, directly measuring soil respiration rates in the field is not a common management practice, as most methods require technical and expensive equipment, and may not provide enough information for a forest manager (Figure 4). However, healthy soil and soil structure is a proxy for optimal soil respiration rates, and can be easily assessed in the field. For information on more affordable methods for measuring soil respiration directly, go to **https://solvita.com/soil.**

Figure 5. Scientists measure soil respiration, soil temperature, and soil moisture in the field using a LI-COR CO_2 gas analyzer chamber and soil temperature and moisture probes. At a steady state, the CO_2 efflux rate at the soil surface equals the rate of CO_2 production in soil (i.e. soil respiration).

Table 3. In-field soil health assessment

Sight	Smell	Touch
Look for the presence of organic matter residues on the soil surface, and dig into the soil profile to look at changes in soil color and for the presence of organisms and plant roots. Activity and life: the presence of soil organisms (worms, mites, beetles, springtails, termites, ants) and fungal hyphae indicate healthy, active soil. The more activity in your soil the better. Color: if the topsoil color is distinctly different from and darker than the subsoil, OM is accumulating and your soil is likely healthy. If the topsoil is the same color as the subsurface horizons it suggests you are not building OM and soil health may be poor. Darker soil color generally indicates more organic matter and healthier soil. Roots: healthy roots show uninhibited root growth, the presence of many fine roots, and roots white in color indicating absence of pathogens. Unhealthy roots show restricted root growth or lateral growth in compacted soil, few fine roots, and discolorations and lesions indicative of pathogens.	An earthy sweet smell indicates healthy soil, decomposed residues, recycled nutrients, and an active soil food web. A metallic, ammonia or sulfur smell may indicate unhealthy soil dominated by anaerobic condition (low O_2 levels) and anaerobic bacteria with low rates of nutrient cycling. No smell could indicate an inactive soil food web and poor soil habitat. Soil conditions may be too extreme to support and build a healthy, active soil community.	A handful of soil can inform you about soil structure, moisture content, and degree of aeration, referred to as soil tilth. If you rub soil between your fingers: sandy soils feel gritty. Silt soils feel smooth or floury. Clay soils feel slick or sticky. Soil that crumbles easily under finger indicates healthy soil structur. Soil that requires excessive force or a hammer to crush is indicative of poor soil structure, and may limit nutrient cycling, water infiltration and storage, and root growth. A tool called a penetrometer measures pressure required to penetrate soil and is used to identify compacted subsoil layers, poor germination, reduced infiltration, poor root development, and poor aeration. For more information on the use of penetrometers, see http://extension.psu.edu/plants/crops/soil-management/soil-compaction/diagnosing-soil-compaction-using-a-penetrometer.

VI. HOW CAN I TELL IF MY SOIL IS HEALTHY? IN-FIELD SOIL ASSESSMENT

Dig in it! Use your sense of sight, smell, and touch.

Analyze it! Take a sample and send to your local extension office for an affordable soil fertility analysis. Your soil fertility report will provide values of micronutrient and macronutrient concentrations, as well as provide values of your soils pH and organic matter content percentage that can be used to guide management plans. Table 3 lists some characteristics that can be seen, smelled, and touched for a better sense of soil health. For more information on soil testing, contact your local extension office and soil testing lab: **http://www.soiltest.vt.edu/ ; http://www.ext.vt.edu/**

Table 4. Management practices for healthy soils

Increase Carbon Inputs	Regulate Decomposition rates
• Leave slash unburned or broadcast burned in moist cool conditions • Retain some standing trees onsite • Enhance aboveground biomass growth rate • Leaving more residual biomass to decompose in place after thinning and harvesting • Increasing belowground productivity in the form of root growth and microbial and faunal communities • Adding harvest residues or municipal waste	• Reducing soil disturbance. Set up skid trails to minimize litter-layer disturbance • Insulating soil to minimize rapid changes in soil temperature and moisture and thus C loss • Keep soil covered to minimize erosion • Diversifying organic matter inputs (charcoal, CWD, tops) • Limit excessive fertilization inputs • Limit compaction and rutting from equipment to keep soil well-aerated • Minimize flooding for extended periods

VII. MANGE YOUR FOREST BY MANAGING YOUR SOIL: TAKE HOME POINTS

Healthy soils are the foundation for healthy, productive, and resilient forests. Soil respiration respiration represents yet another important indicator of forest and soil health. Management practices that optimize soil health are those that contribute biomass and organic matter to the soil, cause minimal soil disturbance, minimize soil erosion, conserve water, improve soil structure, enhance activity and species diversity of soil fauna, and improve nutrient cycling. Increasing plant carbon inputs and minimizing soil disturbances in order to regulate decomposition rates is the key to optimal soil respiration rates (Table 4). Ultimately, soil health and ideal respiration rates can be achieved and soil carbon can be built through adjustments to forest management practices.

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PREPARED BY

Kristin McElligott, Graduate Research Assistant, Virginia Tech

Marco Minor, Graduate Research Assistant, Texas A&M University

Leslie Boby, Extension Associate, Southern Regional Extension Forestry

Chris Maier, Research Biological Scientist, United States Forest Service

Eric Taylor, Extension Forester, Texas A&M Forest Service

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