

The Impacts of Biochar Usage and Covercropping Practices on the Composition and Fertility of Soil in the Shenandoah Valley Region of Virginia

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Abstract

The Shenandoah Valley, Virginia's most fertile natural treasure, is currently facing challenges to its soil fertility and health due to unsustainable farming practices which cause nutrient depletion. This research paper highlights the silty-loam soil, which is the primary soil texture of the valley, and proposes two sustainable soil management practices: cover cropping and biochar application and their ability of soil rejuvenation, enhanced nutrient cycling, and long-term adaptability. Currently, cover cropping (CC) is utilized in 10% of the farms in the Shenandoah Valley. This practice consists of planting crops between cash crops, providing significant improvements to soil composition, increased soil organic matter (SOM), and microbial activity crucial for the carbon (C) and nitrogen (N) cycles supporting the ecosystem. CC has also been credited with carbon sequestration, lifting a heavy dependence on fertilizers, and minimizing pollution. The other practice researched in this paper is biochar (BC), a carbon-rich substance created by pyrolysis, which has promoted similar benefits to CC, including enhancing soil structure, nutrient retention, and boosting microbial populations—specifically applicable in the silty-loam soils of the Shenandoah Valley. This paper thoroughly dissects both practices in terms of environmental benefits, economic feasibility, and analyzes their alignment with the following United Nations Sustainability Goals: Life on Land (15), Climate Action (13), and Zero Hunger (2). Despite the challenges that do remain, specifically with initial investment costs, pest risks, mistrust with farms, and the lack of long-term research with newer innovations such as biochar, both practices provide promising results in reversing soil degradation and enhancing nutrient cycling. With increased education and awareness regarding the economic incentives and benefits of these practices, widespread adoption of cover cropping and biochar could significantly restore the soil health, fertility, and the overall crop productivity of the Shenandoah Valley.

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Introduction

The Shenandoah Valley has been dominated by agricultural industries for centuries, known for its soil's high organic matter and limestone content (King & Marlowe, 2021). Two hundred years ago, its soil provided abundant harvests to the Keyser people, who relied on simple irrigation systems to grow crops (Front Royal, 2023). Today, the valley serves as a vibrant center for diverse agricultural production on industry-leading farms, still reliant on the same nutrient-dense soil. Undeniably, this plentiful land is an essential ground for production in Virginia, and must be preserved through sustainable practice. The main issue facing agroecosystems today is a loss of nutrients due to a decoupling of the nutrient cycles (Jernigan, 2025). This causes leakage of essential nutrients, accelerating climate change and water pollution issues. It is essential to restore these nutrient cycles with sustainable practices in order to restore nutrient balance and fertility within the Shenandoah Valley soil for years to come while providing economic advantages to farmers. Evidently, when deciding the primary factors to preserve soil quality, soil composition and soil organic matter are the two major contributors. This literature review investigates the question of how cover cropping (CC) and biochar (BC) practices restore the nutrient cycles in the soil of the Shenandoah valley region of Virginia. This topic aligns with the Agriculture and Food Research Initiative (AFRI) priority area of Bioenergy, Natural resources, and Environment. Primarily using research databases such as JSTOR and the Virginia Tech library database, we used keywords including "cover cropping," "silty-loam soil," "nutrient cycling," "environmental impacts," and boolean operators in advanced search. We sorted through these results for journals within the past ten years, reviewing the abstracts to determine the sources' relevance to our research question.

Literature Review

Soil Factors

Soil Structure and Texture of the Shenandoah Valley

Over hundreds of years, Virginia's Shenandoah River carved out what is now known as the Shenandoah Valley, breaking down limestone, sandstone, shale, and dolomite rocks along the way and distributing them to create the rich, fertile, floodplains of karst that now host 11% of Virginia's total farmland (USDA, 2022; NPS, 2022). The naturally fertile and limestone-rich soils neutralize soil acidity and supply calcium for plant nutrition. The region experiences an average rainfall of 38 inches per year, leaving farms with an ample supply of water for crops (NPS, 2022b). Farms in the Shenandoah Valley specialize in large-scale corn and soybean production, which combined account for over 12% of total crop production in the Valley (USDA, 2022). The soil in the valley area is classified by the United States Department of Agriculture (USDA) as part of the Groseclose and Frederick Series (USDA, 2002a; USDA, 2002b). These soil series are characterized by deep, well-draining soils perfect for growing row-crops with a silty-loam layer on top of many layers of clay. Such soil creates a beneficial environment for hosting the biotic soil factors that make the Shenandoah Valley the agriculture powerhouse of Virginia.

Key Concepts in Biotic Soil Factors

Soil organic matter (SOM) is one of the foundational elements of determining soil health, fertility, and ecosystem function. A critical component of SOM is living organisms, such as microorganisms, fungi, and earthworms. In a study authored by Texas A&M professors, it was concluded that SOM and soil organic carbon (SOC) deposition, decomposition, transformation, and stabilization were fully dependent on the structure, abundance, composition, and living or dead biomass production of the soil microbial communities (SMC) (Bhattacharyya et al., 2022, p. 2).

Soil microbes contribute to the production of glomalin, a glycoprotein secreted by mycorrhizal fungi which acts as an organic glue to bond aggregates (Crops and Soils Division Extension, 2025). This binds microaggregates to assemble stronger structures that reduce erosion, slow decomposition, and enhance long-term carbon (C) storage in soil (Bhattacharyya et al., 2022, p. 2). This mycorrhizal fungus also provides more nutrient uptake and stability for plants (Hoorman & Sundermeier, 2017). Much of the C found in soil originates from labile compounds, which are processed by SMC. The leftover material stabilizes and binds to minerals to form organomineral complexes, which are crucial for carbon sequestration (Bhattacharyya et al., 2022, p. 4), an important step towards combating climate change. In her report, Dr. Weijia Liu, affiliated with the Institute of Agricultural Bioenvironment and Energy, claimed that microbes mitigated soil pollution (Liu et al., 2023, p. 6) by breaking down pesticides, pollutants, and heavy metals into tiny pieces using enzymes—a process called biodegradation, in which the microbes get nutrients from to help them grow (Maglione et al., 2024, p. 728). Along with C, microbes also regulate soil organic matter using nitrogen (N)—via fixation, nitrification, and denitrification—and phosphorus (P) for enzyme production in plants (phosphatases) to carry out their biogeochemical cycles (Liu et al., 2023, p. 10).

The carbon to nitrogen (C:N) ratio of organic matter indicates the rate of microbial growth, nutrient cycling, and healthy soil. Ideally, the ratio is 24:1, which indicates a balanced rate at which microbes consume organic matter and convert it to nutrients that plants can use (Natural Resources Conservation Service, USDA, 2011). Overall, microbes are essential to SOM and balancing weaker nutrient cycles. Through decomposition and the release of key nutrients like C and N, microbes actively work to improve soil structure and provide nutrients to crops.

Biochar as a Soil Amendment

Biochar is an organic material that appears similar to charcoal. It is naturally produced in high heat, low oxygen conditions such as forest fires—ensuring that the material does not combust—through a process known as pyrolysis. Pyrolysis creates broken down biomass composed of molecules that convert into both gas and solid biochar. To mimic this natural process that takes decades to centuries, humans have created pyrolysis reactors that can produce over 100 tons of biochar a day (Murray, 2021). Roughly categorized by its ingredients, biochar normally consists of biomass such as pellet-based feedstock, hay, human or animal excrement, or the husks of produce such as rice and peanuts (Jahromi et al., n.d., pg. #1.).

Biochar is a natural carbon sink that typically contains 50-80% carbon (Ciolkosz D, 2023), with 5–10% of carbon in Biochar emitted into the soil within 100 years of application (Nan et al., 2022). This feature allows biochar to be an extremely valuable soil amendment as it improves soil and plant health through providing a stable carbon source. Additionally, biochar is a sustainable soil amendment as it does not emit carbon dioxide (CO₂) into the atmosphere. Instead, it stores stable carbon—with 90% of the carbon in biochar being stable (Singh et al., 2012, p. 11770)—to be used by plants in photosynthesis, actively combatting the greenhouse effect. Additionally, when biochar is used as a soil amendment it enhances soil's physical and chemical properties by increasing the soil's cation exchange capacity, which is the soil's ability to hold and supply nutrients over time. This is influential in decreasing nutrient loss and increasing soil buffering capacity, both vital for improved soil fertility (Crops and Soils Division Extension, 2025).

Additionally, C attracts other key factors of high soil health such as microbes (Rayne & Aula, 2020, pg. 10). Without C, microbes do not receive sufficient energy to conduct organic material breakdown. Therefore, adding biochar to soil boosts organic matter breakdown, enhancing soil structure. This process is key in restoring balance to the C cycle, a foundational component of plant health. Through these benefits, it is expected to see increased crop yields (Sapkota et al., 2025, pg. 715). Specifically, biochar is most efficient in semi-arid regions (Sapkota et al., 2025, p. 703), a characteristic of the Shenandoah Valley, demonstrating its effective use as a soil amendment in this region.

Sustainable Farming Practices

Cover Cropping

Cover cropping (CC) is a sustainable agricultural practice utilized around the world, including in 10% of the farms in the Shenandoah Valley (USDA, 2022). This method consists of planting crops such as grasses or legumes between cash crops to reduce erosion, increase soil organic matter (SOM), and improve soil fertility (Wolters, 2019, p. 2). This research paper focuses on CCs influence on the abiotic and biotic soil factors of C, N, SOM, and the soil microbes that make these nutrients available for plants to use.

According to Ohio State University, CC residue—the plant material left on the surface after cover crop termination—increases soil organic carbon (SOC) which is beneficial for carbon sequestration (Hoorman & Sundermeier, 2017). The type of cover crop planted influences the amount of C and N fixed into the soil and released from the residue for plant usage. Grasses have a higher C:N ratio, which means they help to soak up N, while soybeans, clover, and other legumes help to fix N into the soil (Hoorman & Sundermeier, 2017). CC increases SOM because there is more plant biomass available for microbes to break down. Stable SOM components contribute to carbon sequestration which reduces greenhouse gas emissions (Dhakal et al., 2024, p. 16-17), vital in combating climate change. CCs influence on SOC and SOM demonstrates its direct support of the United Nations (UN) Goal 13 of Climate Action (United Nations, 2023). If utilized more prolifically throughout the world, CC practices can mitigate the rising CO₂ emissions caused by conventional agriculture practices.

A CC study was conducted across multiple farms throughout Virginia, including Kentland Farm in Blacksburg which is composed of silty-loam soil. This study investigated CC effects on CO₂ burst, N release, and crop yield. It found that over long-term CC use, CO₂ bursts increased more than 50% with a 9-species mixture compared to the control (Pokhrel, 2023, p. 36). CO₂ burst is the measure of CO₂ released by soil microbes. An increase in CO₂ burst indicated an increase in microbial activity which improved soil nutrient cycling (Pokhrel, 2023, p. 36). From an agro-economic perspective, this study found that both short and long-term CC usage did not have an effect on corn yield except for one site (Pokhrel, 2023, p. 37), suggesting that CC usage does not harm yields while also providing ecological benefits that improve crop health.

This study also found that the type of CC used can influence N release, an essential nutrient for crop health. Specifically, the rye, vetch, and cereal rye CC mix produced slower N release whereas hairy vetch released a large amount of N within a month of incubation (Pokhrel, 2023, p. 104). Farmers should consider the N release of their CC plants so that their CC termination can be synchronized with crop planting (Pokhrel, 2023, p. 104). This could significantly lower the amount of N sidedressing needed to amend the soil, reducing expenses on fertilizer. Lawson et al. supports this thought with research finding that the timing of CC termination influences N release and can impact corn yield (Pokhrel, 2023, p. 37). Excessive N fertilizer usage due to its high mobility causes difficulty in matching soil N supply and crop N need, which has contributed greatly to water body pollution globally (Pokhrel, 2023, p. 25). The United Nations (UN) Goal 15, Life on Land, aims to preserve and restore terrestrial ecosystems and promote the sustainable management of forests and farms (United Nations, 2023). By timing crop planting with CC termination to optimize N release, farmers can help to mitigate this pollution as less N fertilizers are needed, improving soil nutrient fixation.

Though CC provides many environmental benefits and potential economic benefits in increased crop yields over the long-term, it is an expensive initial investment. The added seed cost and the potential for reduced yields in the first few years can be a significant barrier for most farmers (Hoorman & Sundermeier, 2017). Nevertheless, there are cost-share and subsidy programs that help farmers bridge that economic barrier when adopting CC mixtures (Wolters, 2019, p. 41). Second, CC can increase insect damage to crops, in some cases, causing crops such as corn to develop stunting and deformities (Wolters, 2019, p. 69-71). Cover crops attract higher numbers of pests that can reduce crop yields. These economic concerns regarding crop yields hold validity, yet diverse CC mixtures increase predator populations to these pests, creating resiliency and reduced need for chemical inputs of pesticides (Rowan et al., 2022, p. 9). Overall, CC repairs the nutrient cycles that conventional practices have made vulnerable, essential to improving soil resilience and fertility.

Biochar

Stimulating the usage of carbon-dense biochar (BC) within the Shenandoah Valley is essential for maintaining the soil fertilization and nutrient quality in the region. Not only is biochar incredibly effective for increasing the carbon content of soil, it is produced from biomass and other agricultural residues (Jahromi, 2023, pg. 1).

Not only is biochar an effective usage of naturally-occurring remnants, but it fills the gap still present regarding soil depletion of the Shenandoah valley over time despite crop rotation and CC (Virginia and West Virginia Water Science Center, 2024, p. 1-2). This soil depletion is shown by the significant decrease of N in the ground, an element essential for the flourishing of microbes and other bacteria that help maintain a stable nutrient content (Liu et al. 2023, p. 1). BC has been proven to effectively decrease nitrous leaking in silty-loamy soil, which is prevalent in the Shenandoah Valley, up to 37%. Such a significant change in nitrogen loss would serve to increase the soil fertility, as well as promote an increase in essential microbes and bacteria (Kabir et al. 2023, p. 4).

In conjunction with nitrous properties, C is also essential to guarantee a sound soil structure and effective water absorption (Easton, 2021, p. 16). An effective method to combat the lack of C within some soil substrates is the usage of human fecal biochar (HFBC) (Krueger et al. 2020, p. 4-6). Formed with virtually the same method as other biomass-based biochars, HFBC is heated in an oxygen-deprived environment, then compressed into a more manageable form (Krueger et al. 2020, p. 2-3). The appeal of utilizing this particular substrate for biochar creation is the potential for carbon sequestration (Xu et al. 2023), which is incredibly viable for combatting climate change, which is explicitly noted as the UN's 13th Development Goal (United Nations, 2025). Though the increase in temperature during BC does emit C, when implemented in soil through HFBC, its stable C content can help to maintain structural soundness, thus preventing the release of CO₂ into the atmosphere (Xu et al. 2023). This sequestration aid is essential for ensuring the high yields the Shenandoah Valley is known for. In addition to human fecal biochar, other subvarieties such as corn husk biochar and biomass pellets are also effective for C and N regulation (International Biochar Initiative, 2025, p. 3-5).

In regards to implementation in the Shenandoah Valley region, it is reflected that BC would likely be most viable in larger quantities, roughly 25 tonnes per hectare (Drew, 2022, pg. 14). Farmers and property owners are also encouraged to continue routine usage of pesticides, though it is vital to note that in soil testing conducted in Minnesota, a minor change in pH was noted after the introduction of BC substrate layers onto the ground (Drew, 2022, pg. 15, 19). This data proved to be a potential concern, but was hypothesized to be related to other natural occurrences rather than the ongoing biochar additions. When utilized on the same silty, loamy soil found in the Shenandoah Valley, the nutrient-housing, carbon sequestering properties of BC are clear (Bhattacharyya et al. 2022, p. 1).

The substrate is viewed by many industry professionals as not only promisingly effective, but also a product with potential for major economic investment in the future (IMARC, 2025, p. 3). In adjacency, farmers remark on being relatively hopeful for the practice's mitigation of C imbalance and climate change, yet weary of the monetary requirements to acquire BC. Since the practice was only formally proposed relatively recently, many agricultural workers remain unaware of its long term cost to benefit ratio. Thus, there is a level of distrust that is hard to combat until a significant amount of time has passed (Drew, 2022, pg. 39-41). In conjunction, though the USDA also thoroughly endorses BC, the organization has publicly released statements warning agricultural workers to avoid utilizing BC on already highly productive soils, as it may have the

opposite of its intended effect (USDA, 2025, pg. 1). Specifically, BC can trigger humus to decompose, compromising a vital soil component (Kabir et al. 2023, p. 1-3). This proves to be a notable discontinuity in research regarding the substrate, as these potential negative effects have not been widely tested, but are largely speculated by professionals (Grumke, 2024, pg. 4-10), which proves to be a major limitation in biochar observation.

Despite these setbacks, BC is a rising star in the world of nutrient replenishment, and a potential keystone in decreasing food insecurity by raising the productivity and yields of soil. In conjunction, the carbon-sequestering properties of this temperature-treated biomass can effectively help to combat the climate crisis (United Nations, 2024). BC usage is essential for restoring sound structure and essential microbes to the soil of the Shenandoah Valley.

Conclusion

Sustainability takes time. Often, major economic and environmental benefits of these agricultural practices are seen in the long-term but not in a short-term context. Conjunctively, CC and BC amendments are often less trustworthy due to their potential for yield reduction in the short-term (Sapkota et al. 2025). This proves to be a major barrier for farmers that rely on an annual profit for stability. However, a few years of lesser productivity may be necessary in order to create sustainable systems that will ultimately outlast current conventional practices that tend to degrade soils beyond repair. Currently, there are gaps in research regarding long-term BC uses and mixed species CC in silty-loam soils. These are important initiatives to consider to protect the agricultural future of the Shenandoah Valley, and future studies should be done to monitor positive effects and document potential complications. It is vital to continue observing the C output of BC creation to ensure the environment is not negatively impacted. Educating farmers on the effectiveness of these new-age practices needs to be established as a priority. If these regenerative ideas are implemented globally, they will help to improve leaks in the nutrient cycles that serve as the foundation of crop health. This will ensure steady food production and security and promote environmental health on a worldwide scale, working to achieve the UN goals of Zero Hunger (2), Life on Land (15), and Climate Action (13).

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