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Soil Carbon, Water Management, and Natural Infrastructure: Building Resilient Watersheds in the Northeastern United States

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Introduction

Agriculture in the Northeast faces increasing issues of water management. 2016 was one of the warmest and driest summers on record throughout the Northeast. Farms suffered crop losses ranging from 30-90 percent. Following this experience, many farmers invested in irrigation equipment and water sources. Consequently, estimates suggest seasonal water usage potentially increased by millions of cubic meters, further taxing Northeast water resources.[1]

Climate models also predict increasing frequency of both these short-term droughts and heavy precipitation events, thus exacerbating the region's water management challenges.[2] In response, technical farm adaptations like modernized water monitoring and irrigation scheduling can help increase resilience in the agricultural sector. A more comprehensive approach would involve a holistic policy strategy that works across landscapes to coordinate resources, reduce costs, and generate overall positive environmental impacts. In this policy brief we explore a set of regionally coordinated state-level agricultural policy incentives that could enhance both soil health and water management in the Northeastern United States by harnessing the potential for agriculture to build natural infrastructure.

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The concept of natural infrastructure

Local, national, and global institutions, such as the American Community Garden Association, U.S. Forest Service, and World Resources Institute, have all focused on natural infrastructure, which capitalizes on the broad ecosystem benefits of forests, wetlands, and working lands.[3] This terminology refers to an ecosystem that is designed or managed to provide multifunctional services to the well-being of both humans and the environment.[4]

The concept of natural infrastructure and its holistic management goals serves as an accessible entry point for farmers, scholars, and policymakers, alike. Households and municipalities of all types must bear the costs of flooding, erosion, and water damage and must work together to build rich, healthy ecosystems. For example, Northeast towns and cities depend on upstream watersheds for the storage and gradual release of water into downstream river systems.[5] One natural component of soils which could help facilitate this service is soil organic carbon (SOC).[6] Widely discussed in terms of carbon sequestration, SOC also offers benefits to a wide range of hydrological processes that could help mitigate some environmental costs for municipal governments.

Natural watershed infrastructure can potentially mitigate nutrient-rich runoff, reduce flood peaks, and maintain base flows, among other improvements to soil productivity. Practices supporting these ecosystems include urban measures like green roofs and landscape measures such as targeted afforestation of catchments. But the greatest potential for improving both soils and hydrological management lies in the agricultural sector. We explore to what extent alternative land management methods can improve watersheds by sequestering atmospheric carbon and positively impacting soil-water infiltration, retention, and drainage.

Trends in soil carbon and water management

The appropriation of land for agriculture has long affected SOC balances across diverse landscapes. Conversion of natural ecosystems can deplete soil C pools by 50% in approximately 50 years in temperate regions.[7] Models of historic SOC stocks in the agricultural heartlands of the U.S. estimate large losses—on a magnitude of 50+ Mg C per hectare removed in heavily cropped regions.[8] Recent sequestration analyses, however, propose that management adaptations can recover a majority of lost SOC while maintaining productive land. For example, no-till systems could accumulate an estimated 0.21-0.39 Mg C per hectare per year in cropland.[9]

Principally speaking, a greater percentage of soil C stocks are found in water-stable macroaggregates (>250 μm).[10] These macroaggregates, which are formed by networks of plant roots, fungal hyphae, and fibrous organic matter enmeshing less complex microaggregate soil particles, are important for regulating soil weathering and organic carbon decomposition rates. More aggregation, increased SOC content within water-stable aggregates, and lower proportions of microaggregates—conditions which produce protected, carbon-rich ecosystems—characterize healthy soils. Under conventional systems, uncovered and tilled soils disrupt the formation of aggregates, expose surface soils to more variable conditions of temperature and moisture, and limit biological C-binding activity.[11] In the face of changing climatic conditions, maintaining stable soils through C sequestration means these systems could retain more water from rainfall and for a longer period of time. Even in urban garden settings, improving soil aeration and porosity by incorporating more SOC is critical to holding moisture and building resilience to extreme heat and heavy rain.[12]

Some models predict increases in temperature and atmospheric CO2 will actually improve Northeast yields of forages, corn silage, and wheat grain.[13] But wetter springs will also speed up soil losses, drier summers will enhance erosion, and intensification will further pressure water resources.[14] Threats to soil carbon and soil water are thus ultimately threats to the food resources of the region. In addition, agricultural soil loss and deposition in aquatic ecosystem is a problem which impairs water quality and has cost the U.S. billions of dollars over the past decades to soil and water conservation practices.[15] Most of this soil degradation is connected to intensification rather than with land clearance or predominance of agricultural lands. Consequently, stabilizing soils and slowing water transport from these systems is ever more important as climate change promises to shift production and potentially open up new opportunities for growers.

SOC ultimately improves soil health and resilience to climate change by retaining more plant-available water and nutrients and promoting the formation of soil structure. The potential for productive rural and urban lands to better manage the turnover of SOC therefore promises to both sequester atmospheric carbon and optimize soil-water management.[16] But by what means? Adopting continuous living cover on agricultural landscapes, as opposed to conventional management, is one way that farmers and landowners can reverse long-term soil degradation, recover lost SOC, and build ecosystems that support both social needs and the natural world. By replacing anthropogenic inputs with diversified plant communities, farms will observe immediate belowground improvements.

Holistic management solutions

Effective soil-water management is positively correlated with soil properties such as aggregate stability, bulk density, and hydraulic conductivity—all of which are impacted by SOC. For example, analysis shows high SOC values are associated with increased soil water holding capacity[17] and retention across a range of soil types.[18] Healthy, carbon-rich soils are clearly able to regulate water resources under varying dry or saturated conditions. Maintaining ground cover and continuous living roots on a landscape can further promote the formation of soil structure, improvement of infiltration rates, and retention of plant-available water. As opposed to increased conventional intensification, such ecological intensification can help close yield gaps while reversing negative externalities such as soil erosion and flood damage.[19]

Top priorities for developing ecologically sound soil management include:

- Establishing baseline soil water measurements to better assess the impact of soil physical changes between annual and perennial systems;
- Shifting agricultural research funds to promote the development of a positive feedback cycle of agroecology research, policy, education, and practice; and,
- Supporting perennially-based land management practices across 25-35% of productive land in major Northeast watersheds.

Perennial forage crops

While a variety of practices can contribute to these goals, we will focus on perennial forage crops as a specific example. Perennial forage crops offer particularly flexible management because they can be used for biomass or forage and the land can be returned to other uses in a season. Farmers are also familiar with their management and have existing capacity to grow, harvest, store, and transport these forages.

In particular, recent research on perennial bioenergy crops has largely focused on switchgrass due to its relatively high productivity under various environmental conditions (including the Northeast), suitability for marginal lands, and considerably low water and nutrient requirements. These characteristics allow for switchgrass production under existing federal programs, such as the Environmental Quality Incentives Program (EQIP) or the Conservation Reserve Program (CRP). Both modeling and experiments further demonstrate these perennially-based systems decrease runoff, increase soil water content during many months of the year, and generally improve water use efficiency.[20] While this set of practices outperforms other cropping systems with regards to improving soil hydrology, more work is needed to expand opportunities for perennial integration.[21]

A farm case study in Pennsylvania almost completely eliminated erosion by maintaining soils that were permanently covered with living vegetation; however, this outcome was achieved with a diverse mix of perennial grasses, legumes, and nonlegumes, in addition to cover cropping, no-till planting, and managed forestry.[22] This mixed system, in conjunction with the assistance and expertise of the USDA Natural Resource Conservation Service, was critical to allowing farm operations to reduce the cost of fertilizers, machinery, and fossil fuel while improving stocking rates and increasing grazing yields. Northeastern farms should thus give similar consideration to practices like cover cropping, which has a demonstrable ability to manage nitrogen[23] and increase soil water management options during droughts or periods of soil saturation.[24] But whether a farmer is seeking to establish perennials or cover crops or a no-till system, numerous structural and field-level barriers to adoption constrain individual actions.

Financing ecosystem services

Who should pay for a comprehensive transition to perennial forage crops? And how? The multiple, disaggregated downstream benefits of a perennial agroecosystem make it difficult for decision makers in each state to assign individual financial responsibility. Lately, however, farm advocates and policymakers have seriously considered payments for ecosystem services (PES) to compensate land managers for environmentally desirable outcomes.[25] This policy can cover transition costs, reward those farmers who achieve the best environmental outcomes, and promote long-term commitment to reinforcing the multifunctional services of our ecosystems.

Soil scientists, agronomists, and farmers though still lack effective ways to measure outcomes, such as stabilized SOC content, reduced flood risk, or increased water storage, across landscapes and watersheds. Nonetheless, the region could initially implement a payment for agricultural practices to begin to convert annual cropland to perennial forages. Then a targeted ecosystem service payment could be developed based on the ability of each farm to establish long-term water holding capacity and retention infrastructure. In effect, states would implement a series of measures, outcomes, and payment rates so that each farm can demonstrate its contribution to a healthy, multifunctional ecosystem and receive fair compensation.

Each state will need to determine its own willingness to pay for this land-use conversion and the likely contribution of perennialization to improved watersheds and other natural infrastructure functions. One research study estimate indicates that public subsidies would need to range from $50-125 per hectare to compensate farms for the conversion of row crops to switchgrass.[26] Therefore, payments for up to a 50 percent switchgrass conversion across an entire watershed could reach well into the millions and would need to be placed in the context of potential costs from floods, droughts, and additional water management concerns. A payment standard could be developed based on current land use and modeled weather patterns and modified relative to future climatic changes and practical experience.

Policy implications

A few long-term, replicated studies of perennial grasses have targeted the Northeast, demonstrating the economic and environmental potential for perennial forages and associated policy incentives. Some evidence suggests that expanded perennial cover in dairy farming systems could have positive implications for both milk production and phosphorous pollution in Northeast watersheds.[27] Another regional study considered the conversion of some conservation reserve lands to managed perennial energy crops, which would have a nearly negligible disrupting effect on nutrient and sediment storage in subsoils.[28] There seems to exist an untapped potential for perennial grasses to be grown on marginal lands in the Northeast, but the greatest impact on carbon sequestration and soil building will occur when land in annual crop production is converted.[29] Research in the Northeast must thus continue to support policymaking at local, state, and federal levels, as stakeholders should avoid misestimating the production and ecological potential of these practices.

Experiments and assessments in other vulnerable ecosystems additionally show that conversion to perennials from annuals can reliably improve infiltration rates and storage within a few years of establishment.[30] Most current research on perennial grasses has been conducted in the Corn Belt, where land-use change, intensification, and mechanization have left ecosystem services like clean water and flood control distinctly undervalued. These studies have focused on mixed perennial-annual cropping, which has been able to reduce sediment and nutrient flows by as much as 35-fold in extreme rainfall years, but only to the extent that these practices do not impact profits.[31] While crops like switchgrass are considered a central feedstock for a growing bio-economy, farmers are unlikely to commit to a wholesale transition without guaranteed annual payments.[32]

Payment for Ecosystem Services implementation

Some studies have also targeted the Chesapeake Bay Watershed and the potential of a payment for ecosystem services (PES) system to reduce nitrogen runoff.[33] One estimate sets the transition cost in Maryland at $148 per hectare.[34] In other words, if the state paid farmers $148 per hectare to transition maize to fertilized switchgrass, then farmers could theoretically preserve their average profitability and Maryland could meet up to 30% of its nitrogen loading target. While not directly related to the SOC turnover and climate change mitigation strategies discussed above, this policy demonstrates the real possibility for a PES to enhance Northeast watersheds. Within the Chesapeake Bay Watershed, a variety of stakeholders could also take advantage of this proposed water quality incentive program and stimulate new ecological activities. For example, shellfish aquaculture could receive credits under the same PES policy for removing nutrients from the system and eliminating the need for additional water treatment.[35] Thus, while soil building and carbon sequestration are the foundation for implementing natural watershed infrastructure, the structure of a policy like PES forms a big tent which encompasses many activities and practices so long as they achieve the same resilience outcomes.

Although more research is needed on the application of perennial grasses to the Northeast, indications are that a well-designed and implemented PES that enrolls farms across Northeast landscapes could allow the region's soils to hold considerably more plant-available water and reduce the frequency of downstream flooding events. In addition to developing payment systems for rural areas, urban agriculture can also contribute to improving carbon and water cycling.[36] Given that the large proportion of sealed surfaces covering the towns and cities of the region will continue grow with urbanization and create more water management challenges, a diversity of municipalities could benefit from a payment for ecosystem services that promotes continuous living cover and perennial ecosystems. Ultimately, greater buy-in will lower the individual economic burden.

Conclusion

Soil management has significant potential both to reduce climate risks and improve hydrological systems. Fair compensation for natural watershed infrastructure is a great place to start toward this goal. Land management changes come at a cost, and it is important to determine which soil physical changes and systems are eligible for payment. Currently the institutional arrangements of the Northeast and elsewhere in the country seem to be missing a link between the willingness to pay for these services and the potential contribution of these services to improve and maintain the condition of productive lands and watersheds. Governments need to create policies to close this gap and provide appropriate incentives for ecologically sound agricultural development, within which perennial forage crops can play an important role. These policy changes will inevitably reinforce the responsibility of consumers, producers, and policymakers to protect soil health and accurately value the benefits agricultural lands provide to our natural and built environments.

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