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Author(s):

Pat J. Unkefer, Michael H. Ebinger, David D. Breshears, Thomas J. Knight, Christopher L. Kitts, Suellen A. VanOoteghem

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Pat J. Unkefer (punkefer@lanl.gov; 505-665-2554)
Biosciences Division (B-S1), Mail Stop E529
Los Alamos National Laboratory
Los Alamos, NM 87545

Michael H. Ebinger (mhe@lanl.gov; 505-667-3147)
Environmental Dynamics and Spatial Analysis Group (EES-10), Mail Stop J495
Los Alamos National Laboratory
Los Alamos, NM 87545

David D. Breshears (daveb@lanl.gov; 505-665-2803)
Environmental Dynamics and Spatial Analysis Group (EES-10), Mail Stop J495
Los Alamos National Laboratory
Los Alamos, NM 87545

Thomas J. Knight (tknight@usm.maine.edu; 207-780-4577)
Biological Sciences Department, 96 Falmouth Ave.
University of Southern Maine
Portland, ME 04103

Christopher L. Kitts (ckitts@calpoly.edu; 805-756-2949)
Associate Director, Environmental Biotechnology Institute
California Polytechnic State University
San Luis Obispo, CA 93407

Suellen A. VanOoteghem (svanoo@fetc.doe.gov; 304-285-5443)
Environmental Science and Technology, PO Box 880
National Energy Technology Laboratory
Morgantown, WV 26507-0880

Introduction

Carbon emissions and atmospheric concentrations are expected to continue to increase through the next century unless major changes are made in the way carbon is managed. Managing carbon has emerged as a pressing national energy and environmental need that will drive national policies and treaties through the coming decades. Addressing carbon management is now a major priority for DOE and the nation.

One way to manage carbon is to use energy more efficiently to reduce our need for major energy and carbon source-fossil fuel combustion. Another way is to increase our use of low-carbon and carbon free fuels and technologies. A third way, and the focus of this proposal, is carbon sequestration, in which carbon is captured and stored thereby mitigating carbon emissions.

Sequestration of carbon in the terrestrial biosphere has emerged as the principle means by which the US will meet its near-term international and economic requirements for reducing net carbon emissions (DOE Carbon Sequestration: State of the Science. 1999; IGBP 1998). Terrestrial carbon sequestration provides three major advantages. First, terrestrial carbon pools and fluxes are of sufficient magnitude to effectively mitigate national and even global carbon emissions. The terrestrial biosphere stores ~2060 GigaTons of carbon and transfers approximately 120 GigaTons of carbon per year between the atmosphere and the earth's surface, whereas the current global annual emissions are about 6 GigaTons. Second, we can rapidly and readily modify existing management practices to increase carbon sequestration in our extensive forest, range, and croplands. Third, increasing soil carbon is without negative environment consequences and indeed positively impacts land productivity.

The terrestrial carbon cycle is dependent on several interrelationships between plants and soils. Because the soil carbon pool (~1500 Giga Tons) is approximately three times that in terrestrial vegetation (~560 GigaTons), the principal focus of terrestrial sequestration efforts is to increase soil carbon. But soil carbon ultimately derives from vegetation and therefore must be managed indirectly through aboveground management of vegetation and nutrients. Hence, the response of whole ecosystems must be considered in terrestrial carbon sequestration strategies.

Objective

The complex interrelationships between plants and soils in the environment are not well understood. Our current understanding is based on an unsatisfactory combination of incomplete scientific knowledge and sound but often site-specific empirical observations. A better understanding of the basic principles governing the interrelations are needed to support the development of practical field approaches that are less site-specific and more generalizable from one site to another. Several knowledge gaps must be advanced to allow this better scientific understanding: (1) a better understanding of plant growth and associated fluxes of carbon from plants to soils is required and (2) a better understanding of the interrelationships between plant growth and soil quality improvement.

Approach

The effectiveness of terrestrial carbon sequestrated has been demonstrated on each of the continents, usually in the context of improving the land management and particularly by reducing the cultivation of croplands. Less work has addressed the improvement of carbon in a broad class of lands that can be termed grazing lands. This term reflects the end use of a large fraction of the lands slated for re mediation and also reflects the current use of lands being grazed. Collectively these grazing lands are characterized by having the potential for improved carbon sequestration or storage where better management practices or inputs such as fertilizer or improved species can be used.

Many approaches to increasing terrestrial carbon storage are focusing upon the goals of increasing the carbon in the vegetation as well as the carbon in the soil. Accomplishing these goals depends upon fixing and storing greater amounts of atmospheric carbon. Fixing an increased amount of carbon can be most readily accomplished by increasing the biomass produced by increasing the vegetation growing at a site. Examination of the practical requirements for increasing biomass production reveals a positive, self-reinforcing cyclical process between the amount of biomass produced and the soils' capacity to support biomass production. Or re-stated the soils capacity for plant growth (its fertility) is profoundly impacted by the amount and type of plant life growing in the soil. The soil organic matter is derived from the vegetation grown at a site. The soil organic matter is a strong determinant of many of the properties that dictate the amount and type of plant life that can grow in a soil. These include the soil pH, the availability of plant nutrients, the soil's water holding capacity, and the extent to which water can infiltrate.

Re vegetation of reclaimed lands presents an excellent opportunity to optimize the carbon sequestration on these lands. An attractive re vegetation strategy for extreme environments is the use of native vegetation or vegetation that is well adapted for similar environments. The potential of native plant species for land reclamation is being recognized by those attempting to reclaim mine sites in regions with challenging climatic conditions and limiting soil quality. Workers at mine sites in Colorado (Long, 1999), Arizona (Pfannenstiel, 1999) and Utah (Daniels, 1999) all reported successful applications of native species. They reported the need to use an ecosystem approach. Pfannenstiel's (1999) work had spanned the longest period of time and thus had developed a more advanced understanding of successful practices. He noted the importance of including multiple types of plant species, growing sufficient ground cover to increase soil water, using natural associations between native species and matching soil with plant species. Thus he articulated key elements of an initial understanding of re vegetation with native species. The plant survival rates were acceptable but needed improvement to increase practicality and the number of types of plants used was limited.

Project Description (or Technology)

The factors that dictate the degree to which native or adapted species succeed at a site are not well understood; and this lack of understanding hampers our ability to efficiently re vegetate sites while optimizing carbon sequestration. Studies have been initiated to address major key technical issues including (1) key plant growth conditions and (2) influences of soil organic matter on soil quality.

1. Key plant growth conditions: Effectiveness of amendments to native plant survival and establishment in native soils.

Recent work at LANL led to the discovery of a key molecular level nutrient monitoring and management system used by plants to regulate carbon fixation; this system is focused upon the nutrient, nitrogen (Knight and Langston-Unkefer, 1988, Unkefer et. al., 2000). Nitrogen is the growth-limiting nutrient for essentially all well watered plants in their natural environments. Plants have grown and reproduced for eons in an environment with uncertain supply of water and nutrients; survival has dictated a conservative assessment and husbanding of nutrients. Plants must also regulate their acquisition and metabolism of carbon and nitrogen to provide adequate amounts of these nutrients in the proper stoichiometry required to synthesize their various component proteins, carbohydrates, lipids, etc. The discovery of this resource-based regulatory system governing plant metabolic rate, growth rate and overall accumulation of biomass, provides a much greater biochemical understanding of plant growth and is directly related to assessing plant carbon pools and fluxes.

This work has provided a means to increase the nitrogen use efficiency of plants which is a strongly linked with water use efficiency. This relationship will be explored in an attempt to find a practical means of enhancing the effectiveness of establishing greater vegetation on lands.

2. Influences of soil organic matter on soil quality

A major step in modernizing land management has been the recognition that the soil carbon content is an integral component of productive soils (a general reference, Lal et. al., 1998b). Soil carbon content is directly and positively correlated with such recognized characteristics of soil quality as bulk density, cation exchange capacity, pH, aggregate size, moisture holding capacity, the soil macrobes (earthworms, etc.) and the availability of plant nutrients because it increases the microbial activities mobilizing these nutrients. Previous investigations of these effects have been hampered by the limitations generated by the complexity of the processes and often by a lack of suitable experimental framework in which these processes can be addressed (Lal et. al., 1998b). We have found a way to overcome at least partially, these limitations.

A more suitable experimental framework is now available to us. Recent advancements in our understanding of ecosystems have provided a longer term conceptual model of the changes in these ecosystems as characterized by changes in their vegetation. Researchers such as Archer and Stokes (2000) have articulated four states of ecosystems and have begun to assess the potential for the effects of chronic and episodic stresses and disturbance to cause transitions from one state to another. These four states are as follows: Steady-state fluctuations; Suppressed re generation; Accentuated degeneration; and Recovery. Work at Los Alamos by Breshears and coworkers has complimented and extended this work and as such provides additional sites for study (see ref's in Breshears et. al this volume). The recognition of these four states of ecosystem health or status and the existence of well characterized study sites provides the opportunity to examine the changes in the soil quality that accompany these changes in ecosystem vegetation. The changes in vegetation are linked to the changes in the soil.

Thus to study soil quality we will choose sites that represent these ecosystem states. Others have recognized the existence of and experimental utility of such states in soil status (Tongway and Hindley, 2000). Thus we will use sets of research sites that represent these four ecosystem states at various locations (mesic and semi arid) with different climates (colder and warmer) and will different soils. We can use gradients of climate (elevation) to provide transitions that can be studied. Such gradients exist within the Los Alamos Ecological Research Park and for which extensive data sets are available on climate, carbon inventory and vegetation (see refs in Breshears et. al., this volume). Basic site and soil characterization has either been done or will be done as a part of this work. This characterization includes such parameters as site plant biomass and plant community and soil carbon, pH, moisture, plant nutrients, and fundamental soil physical properties.

All of this work will be done within the larger scientific context of broader ecological investigations currently underway at these (Breshears et. al., 2001; Ebinger et. al., 2001) and other sites to be selected using these same criteria.

2A Microbial capability for decomposition of biomass: the fuel source for soil microbes and their soil building functions.

The decomposition of biomass is a vital component of healthy and fertile soil. This decomposition of biomass fuels the various microbial activities in the soil, including the essential microbial mobilization of nutrients. This microbial activity is a key determining factor in the availability of the plant nutrients nitrogen and phosphorous. Decomposition of biomass can also be expected to fuel other microbial activities as the deposition of carbonates. Thus understanding better the microbial decomposition of biomass is a key to a better understanding of soil quality and its management.

At sites where the decomposition rates for woody and herbaceous biomass have been determined, we will examine the microbial potential for this decomposition. Sites will be selected from the above mentioned gradients to allow us to examine the development of soil quality over timeframes extending far beyond the length of the study. The woody biomass has much greater proportion of lignin relative to cellulose while grassy biomass is more cellulosic in composition. Different microbial capabilities are needed to decompose these two general types of materials. Expect to be able to monitor he changes in the microbial capability as the vegetation changes at a site. For example as the soils microbial population changes to adapt to the decomposition of woody biomass in soils previously growing grass and then invaded by woody species. This information will tell us at what rate the soils are adapting.

2B Microbial capability for improving available N: a growth-limiting plant nutrient.

The microbial conversion of plant liter to energy and other nutrients feeds the microbial mobilization of plant nutrients from the soil. Thus the release of some carbon from the soil is necessary in order to improve a soil's capability to grow more biomass. These are cycles that must be enhanced together.

Several basic elements of microbial community structure and diversity are important in soil quality and ecosystem stability. Robust ecosystems with abundant nutrients are contrasted with stressed ecosystems with shortages of nutrients by the relative degrees of microbial diversity (Atlas and Bartha, 1997). More diverse microbial communities are often characterized by very efficient energy usage which to say that they are expected to use less energy per unit of microbial biomass. This difference in efficiency and diversity may also be expected to be manifested when comparing the improved vs. degraded soils. Relatively diverse microbial communities provide redundancy in functional capability and thus may well provide a degree of resiliency for community to be able to sustain itself when subjected to changes in environmental conditions or stresses. Because the availability of the key plant nutrient, nitrogen, is dependent upon microbial components of the soil we are examining the microbial function diversity with respect to its function of sustaining availability of nitrogen.

2C A new and simplified approach to soil microbial functions:

Existing methodologies for examining the soil microbes are inadequate to address such a complex system. The thousands of different types of microbes present in the soil present more complexity than can be addressed with existing tools. We will develop a simple method of assessing the microbial potential for carrying out specific functions. Specially we will develop tools for examining the key activities of biomass decomposition and mobilization of nitrogen using modern molecular biology techniques whose effectiveness was demonstrated in soil bioremediation studies (Clement et. al., 1998).

Several microbial activities carry out the decomposition of lignin and cellulose. These are distinguished as ligninase and cellulase activities. Several bacterial activities are involved in controlling the availability of nitrogen to plants. These activities are nitrogen fixation which increases available nitrogen and denitrification, which converts nitrogen from forms useful to the plant to nitrogen gas which is not useful to plants and which escapes to the atmosphere.

We will use the PCR-based DNA techniques with a different set of DNA probes to examine the functionalities of decomposition and nitrogen cycling in these soils. The laboratory at California Polytechnic State University is very experienced and expert in these studies, having pioneered the development of some of these techniques. The TRF patterns will be analyzed using three different pattern search/data display methods: hierarchical cluster analysis, principal component analysis and canonical correlation analysis.

Application (or Benefits)

Improving our science-based methods for increasing the vegetation on lands can be expected to have net positive benefit on over terrestrial carbon sequestration. Lal and co authors (1998) estimated that a strong net gain in carbon sequestration is possible with improved soil management practices in the U. S. croplands. This group has more recently (Follett, et.al. 2001) estimated a similar strong net gain in carbon sequestration in the privately owned US grazing lands. They estimated that improved management practices for these lands would result in an increase of 70-205 MMT of carbon sequestered annually. They limited their estimates to the 212 Mha of privately owned grazing land and, as such, did not include the 124 Mha of publicly owned grazing lands. Furthermore they assumed only modest improvements in land management practices and assumed these improvements would actually be implemented on only a fraction of the lands. Thus their estimate was quite conservative.

Developing better science-based methods for establishing and increasing biomass production (or vegetation) on lands being reclaimed or improved will improve the carbon sequestration at these sites. Science-based methods can help practitioners to generalize and interpret results obtained at different sites, in different regions, climates, soils etc. This work will help to develop technologies is such a fashion that they can be more readily implemented. In order to a technology to be useful it must be implemented. If a technical approach is to be implemented it must meet certain criteria: it must be effective; it must be developed to such an extent that it can be practiced by those in the field; and it must be attractive to the practitioner by providing a valuable set of benefits. Other workers have demonstrated the effectiveness of re vegetating sites with native plants. This work will help to develop it for practical implementation and will help to document its expected benefits; the principle of which will be increased carbon sequestration and the consequential improvement of soil productivity.

The Department of Energy has established aggressive targets for low cost carbon sequestration (<$10 / T of C) technical approaches to avoid catastrophic increases in the nation's energy costs. Meeting this target cost range requires a technology that can be implemented inside an existing industry and thus gain cost leverage. The emerging carbon credits market in the US and Canada has established bio sequestered carbon values well within this range. Thus the DOE target cost range can be met using terrestrial bio sequestration of carbon.

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