



Review

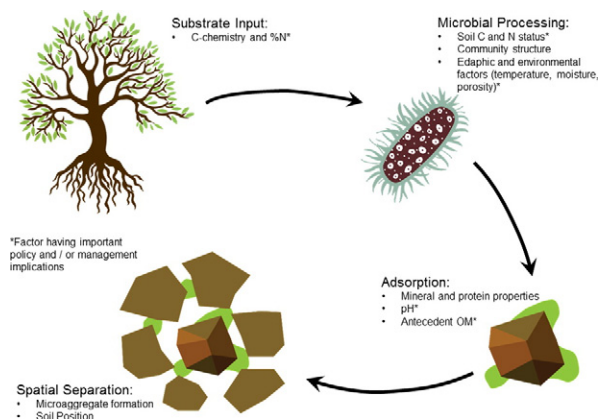
Organic nitrogen storage in mineral soil: Implications for policy and management

Andrew H. Bingham^{a,*}, M. Francesca Cotrufo^b^a Air Resources Division, National Park Service, P.O. Box 25287, Denver, CO 80225, USA^b Department of Soil and Crop Sciences and Natural Resources Ecology Laboratory, Colorado State University, 200 West Lake Street, Fort Collins, CO 80523, USA

HIGHLIGHTS

- We review the current framework for long-term nitrogen stabilization in soils.
- We highlight the most important factors according to this framework.
- We discuss how these factors may influence management and policy decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Nitrogen is one of the most important ecosystem nutrients and often its availability limits net primary production as well as stabilization of soil organic matter. The long-term storage of nitrogen-containing organic matter in soils was classically attributed to chemical complexity of plant and microbial residues that retarded microbial degradation. Recent advances have revised this framework, with the understanding that persistent soil organic matter consists largely of chemically labile, microbially processed organic compounds. Chemical bonding to minerals and physical protection in aggregates are more important to long-term (i.e., centuries to millennia) preservation of these organic compounds that contain the bulk of soil nitrogen rather than molecular complexity, with the exception of nitrogen in pyrogenic organic matter. This review examines for the first time the factors and mechanisms at each stage of movement into long-term storage that influence the sequestration of organic nitrogen in the mineral soil of natural temperate ecosystems. Because the factors which govern persistence are different under this newly accepted paradigm we examine the policy and management implications that are altered, such as critical load considerations, nitrogen saturation and mitigation consequences. Finally, it emphasizes how essential it is for this important but underappreciated pool to be better quantified and incorporated into policy and management decisions, especially given the lack of evidence for many soils having a finite capacity to sequester nitrogen.

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* Corresponding author.

E-mail address: drew_bingham@nps.gov (A.H. Bingham).

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1. Introduction

Nitrogen (N) is an essential nutrient which limits productivity in most terrestrial ecosystems (Chapin et al., 2012; LeBauer and Treseder, 2008). Anthropogenic activity has doubled the rate of terrestrial N fixation and has caused many regions to experience significant impacts from N enrichment such as eutrophication, acidification and loss of biodiversity (Canfield et al., 2010). Soil is the largest pool of fixed and biologically available N; decades of research have improved our understanding of the pathways N moves through in the soil environment, the nature of soil organic N (SON) and its implication for carbon (C) sequestration, work that has been synthesized in important reviews (Knicker, 2011; van Groenigen et al., 2015). Because most anthropogenic N additions end up in the soil (Johnson and Turner, 2014), a thorough understanding of the processes and factors governing its removal from cycling and sequestration is crucial for informing policy and management decisions, yet this information remains scattered throughout the literature.

Despite the fact that mineral N fixed on clays can make a significant contribution to sub-surface soils N stocks (Stevenson, 1986), the bulk of the soil N stock is in organic matter (OM) forms (Schulten and Schnitzer, 1998). Analytical advances in the past few decades have altered our understanding of soil organic matter (SOM) chemistry and resulted in a paradigm shift of the mechanisms explaining its long-term persistence (Lehmann and Kleber, 2015; Schmidt et al., 2011b). For many years it was believed that chemical recalcitrance, i.e., the inherent resistance to degradation, was responsible for the longevity of organic matter in soils. Classically, two mechanisms were thought to foster SOM persistence: 1) selective preservation of structurally complex compounds, such as lignin, suberin and cutin, due to their resistance to microbial breakdown, and 2) condensation reactions forming intricate, irregular organic compounds generally referred to as humus (Kögel-Knaber, 1993; Sollins et al., 1996; Stevenson, 1994). However, empirical evidence of humification has never been found, and advanced chemical analyses of the persistent organic matter pool in soil demonstrated that it is primarily made of chemically labile structures that are easily degraded, with low relative abundance of aromatic groups (Kleber et al., 2011 and references therein). Thus, currently the persistence of organic matter in soil is believed to be an ecosystem property (Schmidt et al., 2011b), controlled by microbial inhibition, physical protection and/or chemical stabilization (Von Lützow et al., 2006).

Many excellent reviews are available outlining the changed understanding of the persistence of SOM (Deb and Shukla, 2011; Kögel-Knabner et al., 2008; Lehmann and Kleber, 2015; Marschner et al., 2008; Nannipieri and Paul, 2009; Sollins et al., 2007; Von Lützow et al., 2006). To date though, there has not been a comprehensive examination of the implications of this new SOM stabilization

paradigm for long-term N sequestration in naturally functioning ecosystems. Because of the importance of N sequestration to ecosystem functioning, as well as to policy considerations such as critical loads and N-saturation, an examination of the factors controlling N sequestration within this revised SOM paradigm is crucial. In this review we will first synthesize the current understanding of the nature of the soil N pool and of the factors controlling its long-term storage in temperate region soils. We will then outline the most important factors (Table 1) such as substrate quality and quantity, mineral composition, and aggregate stability that govern the currently understood mechanisms of N persistence: microbial processing, chemical protection and physical protection from microbial degraders (Fig. 1). Finally, we will examine how recent changes in paradigm may affect policy and management actions undertaken to protect and remediate natural areas experiencing increased N deposition. We will examine consequences for N-saturation under the framework put forward by Lovett and Goodale where the capacity of the soil to process N is seen as the bottleneck leading to saturation and we will address implications for critical loads, mitigation, and restoration policy. We will also elucidate how this new understanding could alter land manager actions and considerations when faced with excess soil N.

Table 1
Factors important to long-term stabilization of N in soils.

Factor	Importance
Substrate C and N chemistry	Affects efficiency and quantity of microbial processing and provides energy for microbial activity
Microbial processing Soil C and N status	Affects efficiency and quantity of microbial processing as well as type of output (NH ₄ vs. microbial residues)
Community structure	Affects efficiency and quantity of microbial processing and production of sequesterable OM
Edaphic and environmental	Conditions that favor greater microbial activity will allow greater production of microbially processed OM
Adsorption Mineral and protein properties	Affects charge and number of adsorption sites
pH	Lower pH favors stronger bond types
Antecedent OM	Affects number of available adsorption sites, strength of bond
Spatial separation Microaggregate formation	Creation of small pore spaces excludes microbes and limits diffusion of water and nutrients
Soil position	Reduced diffusion of water and nutrients at depth limits microbial activity

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