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Deep soil: Quantification, modeling, and significance of subsurface nitrogen

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ABSTRACT

Nitrogen (N) is one of the primary limiting nutrients in Pacific Northwest forests, as well as many other terrestrial ecosystems around the world. Efforts to quantify total soil N and to monitor N cycling have often sampled soils to a depth of 0.2 m, occasionally to 1.0 m depth, or the bottom of the B horizon. However, tree roots often extend many meters into the soil redistributing water to the surface during droughts and contributing to nutrient uptake. This study examined the systematic sampling depth for ecosystem N analyses in the Pacific Northwest, and compared best-fit models of N in deep soil layers with observed quantities. At 22 sites across the Pacific Northwest Douglas-fir zone, O horizon and mineral soil bulk density samples were collected at depths of 0.1 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m. Mineral soil was screened to 4.75 mm and analyzed for total N content. Systematic sampling shallower than 2.0 m produced significantly smaller estimates of total N. On average, only 3% of total soil N was in the O horizon, and 31% was below 1.0 m depth (almost 2700 kg ha^{-1} of N). Over 45% of soil N was below 1.0 m at three sites. A nonlinear mixed effect model using the Langmuir equation predicted total N to 2.5 m with −12.4% mean error given data to 1.0 m, and −7.6% mean error with data to 1.5 m. Shallow sampling of soil N in studies of biogeochemical cycling, forest management impacts, or ecosystem monitoring at best provides a biased estimate and at worst produces misleading conclusions. Research and monitoring efforts seeking to quantify soil N or measure fluxes should sample deep soil to create a more complete picture of soil pools and changes over time.

1. Introduction

Nitrogen (N) is the primary limiting nutrient in many forest ecosystems in the Pacific Northwest (Blake et al., 1990; Chappell et al., 1991; Cole, 1995; Walker and Gessel, 1991). Consequently, the pools, fluxes and transformations of N have been studied in great detail to decipher the complete N cycle and to understand the fate of anthropogenic N inputs. Standard practice for N stock and flow budgets accounts for N either in the top 0.2 m of soil (Amelung et al., 1998; Hart and Sollins, 1998), in the top 1.0 m of soil (Adams et al., 2005), or to the bottom of the B horizon (Van Miegroet and Cole, 1984; Huntington et al., 1988); leaching loss of NO_3^- past this point is considered lost to the system (Van Miegroet and Cole, 1984, 1985). At the landscape scale, the USDA Forest Inventory and Analysis Program monitors soils to a depth of 0.2 m (O'Neill et al., 2005), despite evidence that substantial amounts of carbon (C) and N across all soil orders are stored in subsurface layers, even below 1.0 m (Whitney and Zabowski, 2004; Zabowski et al., 2011; James et al., 2014).

Whitney and Zabowski (2004) found that between 7% and 35% of total soil N could be found below 1 m across sites from all twelve soil orders while sampling to between 1 and 2 m. N in deep horizons of the soil profile is very likely to be actively cycled in forest ecosystems. Tree roots have been documented to reach many meters in depth across ecosystems and plant species (Canadell et al., 1996). Stone and Kalisz (1991) documented Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) rooting to greater than 3 m depth in numerous studies and noted that across over 200 tree species roots deeper than 1.0 m were often found in young stands (1–4 years). In temperate coniferous forests such as those commonly found in the Pacific Northwest, maximum rooting depth has been observed to be 3.9 ± 0.4 m (Canadell et al., 1996). C horizons are strongly affected by soil genesis and biological activity (Richter and Markewitz, 1995); sampling only surface horizons (<0.5 m) ignores all deeper N that is biologically available, and can substantially bias N pool estimates (Whitney and Zabowski,

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2004). While deep roots represent a relatively small proportion of total root biomass, they have been consistently shown to be important for maintaining productivity during dry seasons and droughts through the passive movement of water from depth to the surface (called hydraulic redistribution) (Brooks et al., 2002; Brooks et al., 2006; Sardans and Penuelas, 2014). These same roots facilitate N cycling in deep soil not only by direct uptake, but also by increasing rates of decomposition of organic matter and mineralization of N (Manzoni and Porporato, 2009; Armas et al., 2012). Despite low relative root activity in subsoil compared to topsoil (by soil volume), the relative contribution of subsoil to nutrient uptake can be substantial because of its greater volume (Lehmann, 2003). Considering the substantial land area occupied by soils deeper than 1.0 m in the Pacific Northwest and globally, accurately quantifying subsurface N is important to make the depth of N budgets compatible with the maximum extent of tree rooting zones.

Soils can be expected to differ in the vertical distribution of N due to a variety of factors, including depth to bedrock, degree of development, clay mineralogy, and mineral surface charge. N is generally accepted to be a highly mobile nutrient in its nitrate mineral form, and consequently leaching is the primary mechanism for transport from the soil surface to depth. However, movement of N and organic matter through soil may be slowed or arrested depending upon the distribution and mineralogy of silts, clays, and short-range-order structures, as well as soil pH. Strahm and Harrison (2007) showed nitrate and other N forms could be held in the soil due to the development of variable charge on mineral surfaces, which adsorbs both organic and inorganic forms of N. As pH increases with depth, mineral surface charge equilibria begin to favor positive charges (anion exchange capacity), providing sites for NO_3^- adsorption in addition to NH_4^+ and DON. N adsorption is an interchangeable process, meaning that N stored in deep soil (as NO_3^-, NH_4^+, or DON) is a fungible resource for plant roots.

Ecosystem nutrient budgets rarely account for deep soil N, despite its abundance and potential importance for sustained productivity of forests. The difficulty of excavating subsurface horizons make mathematical estimates of N in deep soil based upon shallow sampling a useful tool, especially for informing management decisions (such as fertilization) and spatial mapping applications. This study addresses four objectives within industrially managed coastal Douglas-fir forests of the Pacific Northwest: (1) to quantify the total amount and relative distribution of N in deep soil; (2) to determine the effect of sampling depth on estimates of soil N; (3) to evaluate the ability of mathematical models to accurately predict total N to 2.5 m based upon shallower sampling to 1.0 m or 1.5 m; and (4) to assess which soils are most important to sample deeply for N.

2. Materials and methods

Twenty-two sites were selected within similar-age (20–24 years) intensively managed Douglas-fir plantations within the region bounded by the Pacific Ocean and the Cascade Range (Fig. 1). Site selection was based upon maximizing coverage of soil properties (C, N, and degree of soil development), land area (Latitude, Longitude), and site accessibility. The selection of sites under similar vegetation and management allowed us to isolate the effects of parent materials, climate, and topography on soil development. Douglas-fir is the dominant overstory tree species in the region, and a wide range of soil types can be found within this ecoregion (Table 1). The coastal Pacific Northwest is a maritime-influenced climate generally characterized by warm, dry summers and mild, wet winters. Mean annual temperature across all sites was 9.0 °C, ranging from 6.1 °C at the Vailton site in the Cascade foothills to 11.6 °C at the Jory site on the margins of the Willamette Valley. Generally, lower temperatures were found at the northerly and high elevation sites, while higher temperatures were found in southerly and lower elevation sites. The lowest mean January temperature was 0.5 °C at the Tokul site in the northern end of the Puget Trough, and the highest mean July temperature was 19.8 °C at the Honeygrove site in the Willamette Valley. Mean annual precipitation across all sites was 1780 mm, ranging from 813 mm at the Olete site on the east side of the Olympic Mountains to 3302 mm at the Hoko site near sea level on the western edge of the Olympic Range.

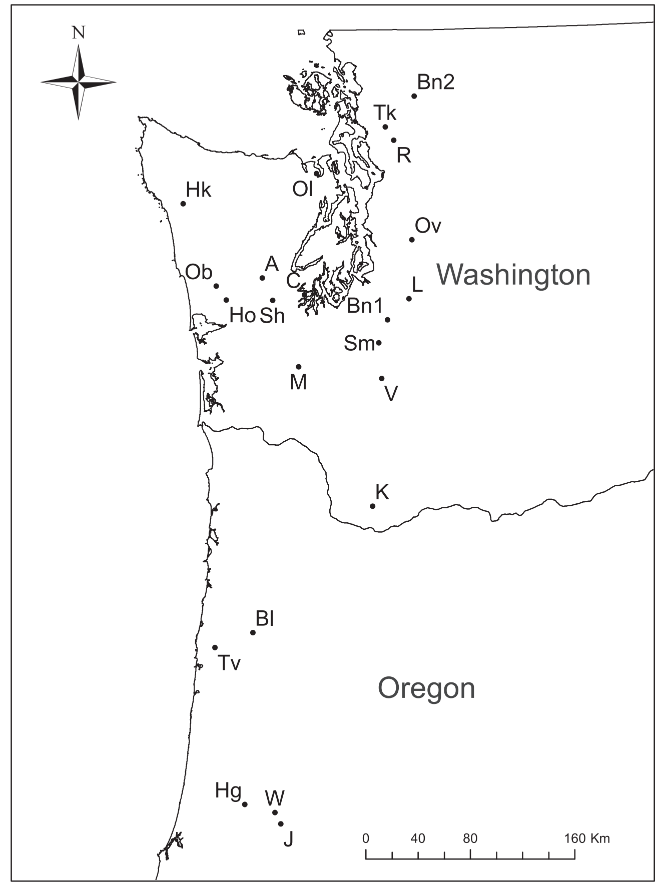

Fig. 1. Locations of 22 soil series sampled in the Pacific Northwest Douglas-fir zone of Washington and Oregon. One soil profile was excavated at each site. Map units for each series are listed in Table 1.

Using an excavator, one soil pit per site was dug to 2.5 or 3.0 m. Profiles were classified by comparison between samples and NRCS Web Soil Survey data (Soil Survey Staff, 2013). Bulk density samples were taken in the middle of succeeding soil layers bounded by the mineral soil surface and depth intervals of 0.1, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m using a soil corer of known volume. Excavation was halted at 1.0 m bedrock at the Kinney site and at 2.0 m hardpan at the O'Brien site. Soil pits extended into the C horizon at all sites (Fig. 2). An O horizon sample was taken at each site using a randomly placed 0.3 m × 0.3 m quadrat. Both bulk density samples and O horizon samples were sealed in plastic bags and immediately returned to the lab, where they were stored at 3.0 °C until analysis.

O horizon samples were weighed, dried at 60 °C to a constant weight, and reweighed. The samples were ground to <0.5 mm using a Wiley Mill. Soil subsamples used in elemental analysis were taken from the bulk density samples to avoid potential biases as recommended by Hamburg (2000). The bulk density soil