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Soil biological responses to C, N and P fertilization in a polar desert of Antarctica

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ABSTRACT

In the polar desert ecosystem of the McMurdo Dry Valleys of Antarctica, biology is constrained by available liquid water, low temperatures, as well as the availability of organic matter and nutrient elements. These soil ecosystems are climate-sensitive, where projected future warming may have profound effects on biological communities and biogeochemical cycling. Warmer temperatures will mobilize meltwater from permafrost and glaciers, may increase precipitation and may be accompanied by pulses of nutrient availability. Enhanced water and nutrient availability have the potential to greatly influence desert soil biology and ecosystem processes. The objectives of this 5-year study were to determine which nutrient elements (C, N, P) are most limiting to dry valley soil communities and whether landscape history (i.e., *in situ* soil type and stoichiometry) influences soil community response to nutrient additions. After 3 years of no noticeable response, soil CO_2 flux was significantly higher under addition of C+ N than the other treatments, regardless of *in situ* soil stoichiometry, but microbial biomass and invertebrate abundance were variable and not influenced in the same manner. A stable isotope incubation suggests that fertilization increases C and N mineralization from organic matter via stimulating microbial activity, with loss of both the applied treatments as well *in situ* C and N. However, these responses are relatively short-lived, suggesting long-term impacts on C and N cycling would only occur if meltwater and nutrient pulses are sustained over time, a scenario that is increasingly likely for the dry valleys.

1. Introduction

Desert ecosystems are close to the physical limitations of life. Biology is constrained by available liquid water, as well as the availability of organic matter and nutrient elements that are often at limiting concentrations or in proportions outside the necessary stoichiometric ratios for balanced growth (Virginia et al., 1982; Fountain et al., 1999; Neff et al., 2000). This is especially true for polar deserts (Convey, 1996; Barrett et al., 2007), where low annual temperatures pose an additional constraint (Fountain et al., 1999). The McMurdo Dry Valleys, a polar desert region in South Victoria Land, Antarctica, is one of the coldest and driest deserts on Earth, with annual average temperatures of −20 °C and only 3–50 mm precipitation per year, water equivalent (Fountain et al., 1999, 2010). Despite the physical constraints on biological and ecosystem processes, biological activity occurs during the summer when air temperatures are at or near the freezing point, given that soil temperatures during summer are often several degrees warmer than air temperature (Simmons et al., 2009; Lacelle et al., 2016) to maintain temperatures at which these cold-adapted taxa are capable of functioning (e.g., Hopkins et al., 2006; Ball and Virginia, 2015). Because small fluctuations in temperature can therefore influence the amount of meltwater generation (Ebnet et al., 2005), the McMurdo Dry Valleys are a climate-sensitive system, where small changes in temperature can greatly alter the hydrologic regime and therefore biological and ecosystem processes (Fountain et al., 1999; Lyons et al., 2005; Barrett et al., 2008a; Ball and Virginia, 2012). The McMurdo Dry Valleys may therefore be near a tipping point (Wall, 2007), where the projected changes in climate (Chapman and Walsh, 2007; Steig et al., 2009; Walsh, 2009) could have profound effects on biological communities and biogeochemical cycling, especially if stored sources of water as ice or permafrost thaw (Fountain et al., 2016).

In high-latitude deserts, meltwater pulses may be accompanied by increases in nutrient availability (Robinson et al., 1998; Barrett et al., 2008b; Ball and Virginia, 2012). The resulting release from nutrient

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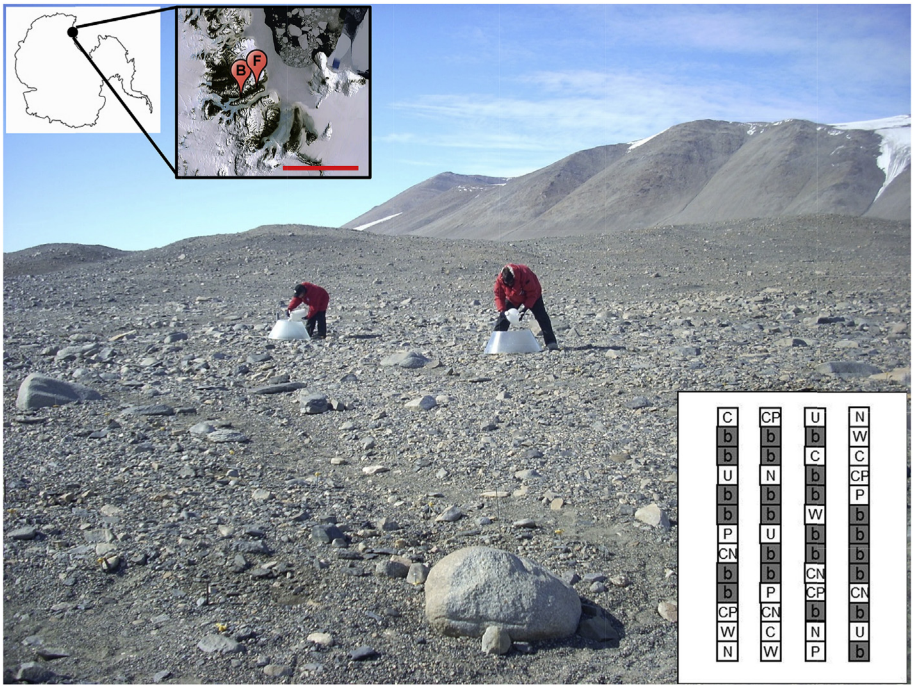

Fig. 1. Diagram of the study site, including the location of Taylor Valley, Antarctica (inset at upper left), application of annual treatments at one of the field sites (photo), and an example of four of the 8 replicate blocks at each site (inset at lower right). Satellite imagery in the inset is courtesy of NASA, available through Google Earth; the red bar represents approx. 100 km. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

limitations has the potential to greatly influence desert soil biology and the ecosystem processes in which they participate (Gebauer and Ehleringer, 2000; Austin et al., 2004; Barrett et al., 2008b). The limitation (and frequently co-limitation) of primary production by N and P is widespread (Elser et al., 2007; Harpole et al., 2011). Studies also show that nutrient additions can influence heterotrophic soil communities and processes, but results are inconsistent across studies, with some studies showing implications for belowground communities and processes and others showing no response (Ramirez et al., 2010; Lamb et al., 2011; Chen et al., 2015; Yang et al., 2017). However, while research has addressed consequences of increased nutrient availability for arid, temperate ecosystems (e.g., Liu and Crowley, 2009; Rao et al., 2009; Hall et al., 2011), as well as other polar ecosystems in the Arctic tundra (e.g., Churchland et al., 2010; Lamb et al., 2011; Wardle et al., 2013), very few studies have investigated multi-year impacts of altered water and nutrient availability in polar deserts such as the McMurdo Dry Valleys of Antarctica (with one known field manipulation in this region described by Hopkins et al., 2008). The low primary production in this region limits contemporary carbon (C) fixation into terrestrial biogeochemical cycles, and as a result these soil ecosystems are thought to be primarily C-limited (Hopkins et al., 2008; Dennis et al., 2012), with at least a portion of the C utilized by soil communities coming from 'legacy carbon' originating from ancient lake sediments rather than contemporary C-fixation (Burkins et al., 2000; Hopkins et al., 2006). It is possible that an increase in N or P mineralization with water pulses will not initially influence biological communities as noticeably as other ecosystems, without first an increase in organic matter production that could result from the stimulation of net primary production. As such, water and nutrient pulses could stimulate overall biogeochemical cycling of C, N, and P in the dry valleys.

In the McMurdo Dry Valleys, soil stoichiometry is determined by abiotic factors such as geologic legacies [e.g. eolian inputs (Lancaster, 2002), glacial till provenance (Heindel et al., 2017), surface chemistry (Heindel et al., 2018), and atmospheric deposition] and hydrologic linkages (transport of nutrients), which then influence the biological communities and ecosystem processes across the landscape (Moorhead et al., 1999; Barrett et al., 2007). For example, species distribution in soil are related to water availability, temperature, and soil chemistry, particularly salinity, where high levels of salt-forming ions such as NO_3^- [a noted legacy result of geology and age that differentiates basins (Magalhães et al., 2012; Czechowski et al., 2016; Lyons et al., 2016)], negatively influence dry valley biota via osmotic imbalance and therefore toxicity (Courtright et al., 2001; Nkem et al., 2006; Poage et al., 2008). Climate variability plays a role in landscape development that determine these geologic legacies, suggesting that future climate warming will play a role in dry valley biogeochemistry. Such chemical and biological differences among locations may influence how the ecosystems respond to changes in nutrient availability that are predicted to accompany climate change.

The objectives of this study were to determine whether the elements most limiting to Antarctic Dry Valley heterotrophic soil communities differ in contemporary edaphic properties such as native N and P content, likely as a result of their different landscape histories (largely N deposition, P weathering). We studied two different locations within one valley that naturally differ in biogeochemical properties, geologic legacies, and biotic potential, allowing us to examine how soils differing in these properties respond to annual water pulses and resource availability. We hypothesized that C will be most limiting, thus C additions will increase soil CO_2 flux (a proxy for soil respiration) and biomass of soil communities, while nutrient elements (N and P) alone will not stimulate biotic activity. However based on previous experiments (Nkem et al., 2006; Poage et al., 2008), we predicted that elevated levels of NO_3^- will increase nematode mortality. We further hypothesized that biogeochemical differences resulting from landscape history influence the response of soil communities to nutrient additions. Soils high in native N, but low in native C and P content will respond to C and CP additions, but not to N additions, and soils high in native soil P content will respond to C and possibly CN additions, but not to CP additions.

2. Methods

2.1. Study site

The study was conducted in two lake basins in Taylor Valley in the McMurdo Dry Valleys, Victoria Land, Antarctica (Fig. 1). Fryxell basin (77°36.5′S, 163°14.9′E) soils are Typic Haplorturbels occurring on Ross Sea drift (late-Quaternary) that contain ice-cemented permafrost and