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Mine waste contamination limits soil respiration rates: a case study using quantile regression

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Abstract

We present an application of a statistical approach, quantile regression (QR), which identifies trends in soil processes otherwise masked by spatial and temporal variability. QR identifies limits on processes and changes in the variance of a response along an environmental gradient. We quantified in situ soil respiration, pH, and heavy metal concentrations across a mine waste contamination gradient that spanned greater than an order of magnitude of metal concentrations. Respiration values were monitored at study sites over 2 years. We used QR to show that soil respiration was limited with respect to both heavy metals and pH, and that both increased metals and increased acidity constrained variation in soil respiration values. Maximum respiration values declined by 48% over the Metals Contamination Index (MCI) range and by 72% over the pH range. The use of QR avoided the necessity of discriminating between multiple sources of variation in a spatially and temporally variable system. It is often unrealistic or too time consuming and expensive to attempt to measure all of the relevant predictor variables in the field. The simpler approach offered by QR is to explore factors that limit a process, recognizing that not all of the factors contributing to a soil function will be measured. An application of this approach to the evaluation of a mine waste remediation procedure is discussed.

Keywords: Quantile regression; Contamination gradient; Heavy metals; pH; Regression; Mine wastes

1. Introduction

The large natural variability of soil processes often makes it difficult or impossible to measure the effects of a soil perturbation (i.e. pollutant) on soil function (Klironomos et al., 1999). This impediment has been identified as a major challenge facing the field of soil ecology (Arnold and Wilding, 1991; Ettema and Wardle, 2002). We have studied the response of soil respiration to mine waste (heavy metal) contamination using a statistical approach that facilitates separating trends in soil processes from natural temporal and spatial variability. Soil respiration (CO_2 efflux), a common measure of soil health (Edwards et al., 1970; Hanson et al., 2000; Illeris et al., 2003), responds to contaminants but also to temporal changes in moisture, temperature, light conditions, and spatial variation in soil fertility (Edwards, 1975; Edwards and Ross-Todd, 1983; Dörr and Münnich, 1987; Buchmann, 2000). In addition to concentration effects, most contaminants interact with the soil physiochemical structure to varying extents to impart additional variability (Dahlin et al., 1997; Vanhala, 1999). For instance, the toxicity of heavy metals depends on soil acidity and organic matter because these factors strongly influence metal/metalloid bioavailability (Lock and Janssen, 2001).

As a result of these complex interactions, bivariate scattergrams of soil respiration values versus contaminant concentrations often display a characteristic 'wedge-shape' pattern that suggests contaminants act to limit maximum respiration values (Terrell et al., 1996). Wedge-shaped data distributions, which are relatively common in ecological studies, occur when the measured factor limits the ultimate ceiling of the data distribution but unmeasured factors are limiting over

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portions of the predictor variable range (Thomson et al., 1996; Cade et al., 1999). The development of quantile regression (QR) has filled a need for a statistical method of analyzing the upper limit of a response variable distribution (Koenker and Bassett, 1978; Koenker and D'Orey, 1987). QR analysis can be used to estimate a rate of change for the upper limit of a response variable distribution instead of the mean (Cade and Noon, 2003). Functions are defined by finding the minimum sum of asymmetrically weighted residual errors (Koenker and Bassett, 1978; Cade et al., 1999). Function lines fit portions of the data set (quantiles (τ)) such that at any point along a predictor variable distribution a given portion of the response variable data falls below the described function. This means that at any given point along an independent axis 90% of the response variable data distribution lies below a line described by $\tau = 0.90$. Applications of QR to analyze limiting ecological relationships have been reviewed (Cade et al., 1999; Cade and Noon, 2003), but to our knowledge, this method has not yet been used in soil ecology.

We measured the response of in situ soil respiration to a wide range of heavy metal concentrations in soils that have been contaminated by fluvial mine waste for about 100 years (Moore and Luoma, 1990). QR was performed on respiration data using metal concentrations as well as pH as predictor variables. Soil pH was measured because soil acidity generated from the oxidation of sulfidic ores in mine wastes affects the bioavailability of heavy metals (Cavallaro and McBride, 1980; Harter, 1983). It has also been reported that metal toxicity in soils changes over time with changes in soil physiochemical characteristics (i.e. pH) further altering metal availability and metal speciation (Lock and Janssen, 2001).

Where heavy metal concentrations and pH are highly correlated, it is not possible to separate the effects of either on soil function (Speir et al., 1999). Our preliminary investigations indicated that pH and metal concentrations were not strongly correlated at our study site, thus allowing the interaction of the separate effects of heavy metals and pH on the suppression of soil function to be studied in a field setting. Below we report separately on the limiting effects of metals and pH. We also present soil organic matter content data for selected sites because cation exchange between organic materials and heavy metals is an important mechanism of metal stabilization and detoxification, and therefore likely plays a role in determining the observed patterns (Doelman and Haanstra, 1984; Temminghoff et al., 1997; Kinniburgh et al., 1999; Ge et al., 2002).

2. Materials and methods

2.1. Study site description

Large-scale floods in the late 1800s and early 1900s near the historic mining and smelting districts of Butte and Anaconda, Montana deposited metal-rich mine wastes over the upper Clark Fork River floodplain (Moore and Luoma, 1990). Wastes were distributed heterogeneously and subsequently re-worked by later floods and channel migration such that contaminant concentrations vary over numerous spatial scales (Helgen and Moore, 1996). These turn of the century floods raised the level of the valley floor by more than a meter, thus all of the soils at the study sites are fluvial in origin and of approximately the same age (about 100 years). Over-bank flooding has been rare since the 1950s when upstream flood control structures were emplaced that have mitigated flooding and prevented the downstream migration of sediments. Subsequently, the channel has degraded through the deposited sediments resulting in an isolated channel (Moore and Luoma, 1990). The area receives an average of 33.7 cm of rain yr^{-1}.

The primary study area was located within the riparian zone of the Grant Kohrs Ranch National Historic Site, an active cattle ranch in Deerlodge, Montana, USA. Much of the riparian zone is fenced to restrict grazing by cattle and vegetation within the fenced area includes grasslands, willow thickets, sand bars, and slickens. All study sites were vegetated with the exception of slickens sites (Table 1).

Slickens, un-vegetated low pH tailings deposits, are visually identified by the presence of surface accumulations of heavy metal salts. Slickens are of special interest because metals washed from them by storms represent a source of acute toxicity to the aquatic ecosystem and dust blown from slickens is of human health concern (Nimick and Moore, 1991). Two of the study sites reported below were located entirely in slickens, while three others were located partially in slickens (see Table 1). Six less contaminated secondary

Table 1
pH, MCI, copper, organic matter content, and respiration (range) values for slicknes sites and two sites with the highest MCI values

Site	pH	MCI	Cu (mg kg^{-1})	OM (%)	Respiration (μmol co_2 m^{-2} s^{-1})
71-slickens	4.23	1.91	1400	1.3	(0.32–1.60)
66-slickens	4.50	2.06	3300	1.7	(0.36–1.96)
35-part slickens	5.09	2.04	2800	2.9	(1.72–2.74)
53-part slickens	5.20	2.02	2700	2.7	(1.66–2.82)
60-part slickens	5.30	1.89	1200	2.2	(2.21–4.75)
56-grassland	6.25	2.29	7100	8.8	(2.41–5.82)
57-grassland	7.32	2.30	6300	4.5	(2.87–6.65)