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Environmental controls on soil respiration across a southern US climate gradient: a meta-analysis

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ABSTRACT

Carbon (C) cycling in the soil is intimately associated with soil respiration as organic matter is decomposed by microbes. Consequently, soil C stocks and sequestration potential are also intimately associated with soil respiration. Although many soils of the southern and southeastern United States (US) are generally more weathered and contain less C than those of the upper Midwest due to moist, and generally warmer climatic conditions, their soil C sequestration potential may be greater due to their ability to produce biomass year-round, which, in turn, results in greater C inputs. Identifying influential environmental factors that control soil respiration across a large geographic area and climate gradient can improve understanding of soil C sequestration potential in the southern US. The objectives of this study were to evaluate the effects of i) physiographic region (i.e., Arkansas Ozark Highlands, Arkansas Delta, and Florida Flatwoods) and ii) soil moisture regime (i.e., udic and aquic) on the relationship among soil respiration and combined soil moisture and soil temperature related environmental parameters. Despite some expected differences and generally low model predictiveness ($R^2 < 0.4$), results showed numerous similarities among multiple regression model coefficient estimates across widely differing physiographic regions along a southern climate gradient. Results also showed the relationship among soil respiration and soil moisture and soil temperature related environmental parameters differed ($P < 0.05$) between soil moisture regimes within regions. Improving the ability to predict soil respiration from directly measured and/or indirectly calculated environmental parameters will increase the understanding of factors controlling soil C sequestration, and potential agronomic and ecological sustainability, in the weathered soils of the southern and southeastern US.

1. Introduction

Integrating both autotrophic and heterotrophic processes, soil respiration is responsible for the greatest flux of carbon (C) from terrestrial ecosystems to the atmosphere (Bond-Lamberty and Thomson, 2010; Vicca et al., 2014). Consequently, soil respiration is a key component of global C cycling and the characterization of the partitioning of C among the atmosphere, biosphere, and pedosphere is vital to furthering our understanding of the constraints on the global C budget.

It is well-established that climate is a main factor controlling soil organic matter (SOM) decomposition and C cycling; thus climate differences contribute to differences in C stocks and sequestration potential among soils. The primary climatic or environmental factors influencing soil respiration are moisture (Brown et al., 2009; Gaumont-Guay et al., 2006; Davidson et al., 1998; Wagai et al., 1998) and temperature (Reth et al., 2009; Brye et al., 2006b; Fierer et al., 2006; Fang and Moncrieff, 2001; Davidson et al., 1998; Lloyd and Taylor, 1994). Soil moisture often displays a quadratic relationship with soil respiration, whereas soil respiration commonly increases to an optimum soil moisture level, typically around 50 to 60% water-filled pore space, then decreases thereafter as the soil is too wet for optimal microorganism activity due to oxygen limitations (Taggart et al., 2012; Brye and Riley, 2009; Gaumont-Guay et al., 2006; Parton et al., 1993; Linn and Doran, 1984). In contrast, soil respiration typically increases exponentially as soil temperature increases (Wagai et al., 1998; Lloyd and Taylor, 1994; Parton et al., 1993) to a point before the temperature is too warm and microbial enzymatic functions begin to breakdown.

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Despite our general understanding of the effects of environmental factors on soil respiration, relationships among soil respiration and soil moisture and temperature independently have been quite variable and inconsistent (Lloyd and Taylor, 1994). Soil respiration has been reported to be positively correlated (Pingintha et al., 2010; Brown et al., 2009), negatively correlated (Brye et al., 2006b; Jones et al., 2006), and uncorrelated (McMullen et al., 2014; Ding et al., 2010; Brye et al., 2006a; Al-Kaisi and Yin, 2005) to soil moisture. Though soil respiration has generally been reported to be positively correlated to soil temperature (McMullen et al., 2014; Ding et al., 2010; Ruehr et al., 2010; Brown et al., 2009; Brye et al., 2006a; Jones et al., 2006; Fang and Moncrieff, 2001), Davidson et al. (1998) suggested that soil moisture and temperature may act independently or be confounding, interdependent factors controlling soil respiration. In addition, soil respiration and soil temperature have demonstrated diel hysteresis (Gaumont-Guay et al., 2006; Oikawa et al., 2014), which further complicates the relationship between soil respiration and soil temperature. Consequently, the clear variations in field-observed relationships among soil respiration and soil moisture and temperature has led to uncertainty in the prediction of soil respiration beyond site-specific, local scales.

In the southern United States (US), where temperatures are greater and seasonal temperature variations are generally less-pronounced than in the upper Midwest, soil respiration rates are also typically greater and elevated fluxes persist for a longer duration throughout the year (Motschenbacher et al., 2015; McMullen et al., 2014; Smith et al., 2014; Brye and Riley, 2009) compared to the upper Midwest (Brye et al., 2002; Wagai et al., 1998). Consequently, temperature and moisture gradients throughout the US have contributed to southern soils often having lower SOM contents relative to northern soils. Although differences in soil properties, land use, soil management, and climate conditions influence C sequestration and cycling (Guo and Gifford, 2002; VandenBygaart et al., 2002, 2003; Lal, 2004; Bernsten et al., 2006; Davidson and Janssens, 2006; Laganière et al., 2010), VandenBygaart et al. (2002, 2003) suggested that the C sequestration potential was generally greater for soils with low SOM contents than soils containing greater C stocks. Consequently, highly weathered soils, such as the soils that are widespread throughout the southern US (i.e., Ultisols) and those with a long history of cultivated agriculture, particularly those of the Lower Mississippi River Delta region and other areas of intense agriculture throughout the southern US, may have a greater potential for further soil C sequestration than comparatively less weathered, upper-Midwestern soils (i.e., Alfisols and Mollisols) due to generally lower SOM contents.

In an effort to characterize the relationship among soil respiration and combined soil moisture and temperature in broiler-litter-amended, pasture soil in the Ozark Highlands of the southern US, McMullen et al. (2014) used multiple regression techniques to determine broiler litter rate effects on soil respiration using soil moisture and temperature measurements made concurrently with respiration measurements. It was concluded that a single, multiple regression model using combined environmental factors could predict soil respiration regardless of broiler litter rate for a managed grassland on a highly weathered Ultisol in the Ozark Highlands (McMullen et al., 2014). Similar approaches have also been used to evaluate residue and water management effects (Smith, 2013) and different bioenergy crop effects (Helton, 2014) on soil moisture-temperature-respiration relationships in the Lower Mississippi River Delta region of eastern Arkansas.

As long-term sustainability and improving soil health continue to be at the forefront of environmental and agricultural issues, understanding the complex interactions among environmental factors and soil respiration becomes even more important in regions, such as the southern and southeastern US, where SOM contents are generally low due to the combination of moist and warm climatic conditions and historic annual cultivation for crop production. If regional, rather than geographically isolated, relationships among soil respiration, moisture, and temperature exist, or can be developed across broad climatic conditions, then soil management practices can be further refined to minimize C losses to the atmosphere. Furthermore, Vicca et al. (2014), who conducted a meta-analysis on the influence of altered precipitation patterns on soil respiration, recognized the need to evaluate relationships and establish functions across a broad range of soil moisture conditions.

To our knowledge, there have been no meta-analyses conducted evaluating the relationships among soil respiration and combined soil moisture and temperature related environmental parameters over broad geographic/topographic and/or climatic gradients for soils of the southern and southeastern US. Therefore, the objectives of this study were to evaluate the effects of i) physiographic region (i.e., Arkansas Ozarks, Arkansas Delta, and Florida Flatwoods) and ii) soil moisture regime (i.e., udic and aquic) on the relationships among soil respiration and combined soil moisture and soil temperature related environmental parameters across a climate gradient in the southern-southeastern US. It was hypothesized that the relationship among soil respiration and combined soil moisture and temperature differs greatly among physiographic regions representing a climate gradient. It was also hypothesized that the relationship among soil respiration and combined soil moisture and temperature would differ greatly between soil moisture regimes.

2. Materials and methods

Over an approximate 11.5-year period between May 2002 and December 2013, eight independent studies were conducted at a variety of locations, for a variety of durations, and included a variety of land uses and site-specific management practices across a climate gradient from the northwest Arkansas to east-central Arkansas to south-central Florida (Table 1; Fig. 1). All eight field studies generated similar datasets that included simultaneous measurements of soil respiration, soil temperature, and soil moisture periodically over time. A total of 4511 soil respiration-temperature-moisture observations were generated among these eight studies. These observations have been assembled into a single dataset to address and test the above-stated objective and hypotheses using a meta-analysis approach.

2.1. Site descriptions

2.1.1. Arkansas — Ozark Highlands

Data from two field studies conducted in the Ozark Highlands of northwest Arkansas were included in this meta-analysis. One study, providing 326 observations for the meta-analysis, was conducted during the 2006 growing season on loam and silt-loam Alfisols and an Ultisol in a native tallgrass prairie in Rogers, AR and in a chronosequence of four tallgrass prairie restorations, ranging in age at the time from 3- to 26-years old, at the Pea Ridge National Military Park near Garfield, AR (Brye and Riley, 2009). The second study, providing 594 observations, was conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR for three consecutive years between May 2009 and May 2012 in small plots of a managed grassland on a silt-loam Ultisol that received annual application rates of 0, 5.6, or 11.2 Mg ha^{-1} of non-pelletized broiler litter from a local source (McMullen et al., 2014). All three sites included in these two field studies conducted in northwest Arkansas were located in Major Land Resource Area (MLRA) 116 A, the Ozark Highlands (Brye et al., 2013). Of the 920 total observations from northwest Arkansas, 198 measurements were conducted on soils with an aquic soil moisture regime, whereas the remaining 722 measurements were conducted on soils with a udic soil moisture regime. The 30-y (1981–2010) mean annual precipitation and air temperature range from 115.6 to 119.2 cm and from 14.5 to 14.6 °C, respectively, throughout the region encompassing the Ozark Highlands field sites (NOAA, 2015).

2.1.2. Arkansas — Delta

Data from five field studies conducted in east-central Arkansas were included in this meta-analysis. One study, providing 576 observations,