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# Influences of observation method, season, soil depth, land use and management practice on soil dissolvable organic carbon concentrations: A meta-analysis

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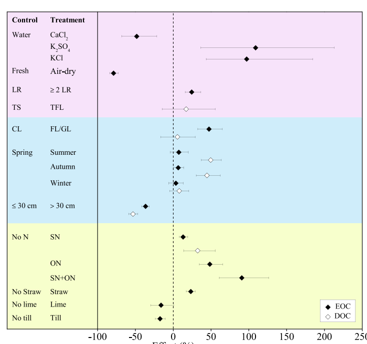
## HIGHLIGHTS

- Extractable organic carbon (EOC) concentrations varied with observation methods.
- Soil EOC levels are higher in non-cultivated lands than in cultivated lands.
- Dissolved organic carbon (DOC) levels differed significantly among seasons.
- Fertilization, straw addition and tillage obviously changed EOC concentrations.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Quantifications of soil dissolvable organic carbon concentrations, together with other relevant variables, are needed to understand the carbon biogeochemistry of terrestrial ecosystems. Soil dissolvable organic carbon can generally be grouped into two incomparable categories. One is soil extractable organic carbon (EOC), which is measured by extracting with an aqueous extractant (distilled water or a salt solution). The other is soil dissolved organic carbon (DOC), which is measured by sampling soil water using tension-free lysimeters or tension samplers. The influences of observation methods, natural factors and management practices on the measured concentrations, which ranged from 2.5−3970 (mean: 69) mg kg$^{-1}$ of EOC and 0.4−200 (mean: 12) mg L$^{-1}$ of DOC, were investigated through a meta-analysis. The observation methods (e.g., extractant, extractant-to-soil ratio and pre-treatment) had significant effects on EOC concentrations. The most significant divergence (approximately 109%) occurred especially at the extractant of potassium sulfate ($K_2SO_4$) solutions compared to distilled water. As EOC concentrations were significantly different (approximately 47%) between non-cultivated and cultivated soils, they were more suitable than DOC concentrations for assessing the influence of land use on soil dissolvable organic carbon levels. While season did not significantly affect EOC concentrations, DOC concentrations showed significant differences (approximately 50%) in summer and autumn compared to spring. For management practices, applications of crop residues and nitrogen fertilizers showed positive effects (approximately 23% to 91%) on soil EOC concentrations, while tillage displayed negative effects (approximately

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−17%), compared to no straw, no nitrogen fertilizer and no tillage. Compared to no nitrogen, applications of synthetic nitrogen also appeared to significantly enhance DOC concentrations (approximately 32%). However, further studies are needed in the future to confirm/investigate the effects of ecosystem management practices using standardized EOC measurement protocols or more DOC cases of field experiments.

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## 1. Introduction

Soil dissolvable organic carbon is referred to the pure carbon in dissolvable organic matter, which is generally defined as the fraction of organic matter that can pass through a filter with a pore size of 0.4−0.6 μm (Bolan et al., 2011; Zsolnay, 2003). It makes up only a small fraction of the total mass of organic carbon in soils (Han et al., 2010). Nevertheless, soil dissolvable organic carbon is ubiquitous in terrestrial ecosystems and influences a myriad of biogeochemical processes that couple carbon with other elements, such as nitrogen, phosphorous and/or sulfur (Bolan et al., 2011). As an inevitable intermediate of carbon biogeochemical transformations, soil dissolvable organic carbon is closely related to a number of pedological processes, such as podsolization. At the same time, environmental problems, such as soil/water (groundwater and surface water) pollution and global warming in association with carbon dioxide emissions from soils, are particularly associated with the dynamics of soil dissolvable organic carbon (e.g., Bolan et al., 2011; Chantigny, 2003; Kalbitz et al., 2000). Therefore, characterizing the concentrations of soil dissolvable organic carbon, among other relevant variables, is necessary to improve the understanding of the carbon biogeochemistry of terrestrial ecosystems.

Soil dissolvable organic carbon can generally be grouped into two incomparable categories, according to the approaches used to collect samples in the field measurements. One category is extractable organic carbon (EOC). EOC is measured by extracting with an aqueous solution as an extractant (e.g., Madou and Haynes, 2006; Rennert et al., 2007). EOC is regarded to represent the total dissolvable organic carbon in the liquid and solid phases of a bulk soil sample. The extraction of soil samples is usually performed ex situ. To date, the extractants that have been widely applied include distilled water and solutions of salts such as calcium chloride ($CaCl_2$), potassium sulfate ($K_2SO_4$), and potassium chloride (KCl) (e.g., Chantigny, 2003). The other category is dissolved organic carbon (DOC). DOC is measured by centrifuging fresh soil samples ex situ (e.g., Giesler et al., 1996; Nambu et al., 2005) or sampling in situ with tension samplers (TS) or tension-free lysimeters (TFL) (e.g., Jones et al., 2014; Yano et al., 2000). DOC is regarded to represent the total organic carbon dissolved in the liquid phase of a bulk soil sample. The fraction of DOC collected by TFL or TS such as suction cups is mostly located in soil macropores while the fraction of EOC extracted with aqueous solutions is regarded to be located in macropores and smaller pores (Chantigny, 2003; Zsolnay, 1996). Therefore, the magnitudes of EOC are generally larger than those of DOC (Zsolnay, 1996). Moreover, the concentrations of EOC and DOC are measured in different dimensions, usually mg $kg^{-1}$ dry soil (d.s.) and mg $L^{-1}$ soil water, respectively. Because of their different meanings, EOC and DOC concentration values cannot be converted. For the same reason, the authors address EOC and DOC separately in this study.

A diverse assortment of laboratory methods have been used to measure EOC concentrations. These methods mainly differ in extractants, extractant-to-soil ratios, extraction temperatures, pre-treatments of soil samples and extract analysis methods (e.g., Chen et al., 2009; Kaiser et al., 2007; Marinari et al., 2010; Michalzik and Matzner, 1999). However, in previous studies, scientists have rarely explained in detail why they chose to use, what were the assumed advantages or limitations of, or what was actually being measured by, each different extractant/extraction technique. At the same time, the comparability of the measured EOC concentrations among these methods still remains unclear. As for DOC concentrations, a few case studies have shown that sampling devices with and without tension may lead to quantitatively variable or sometimes even conflicting results (Buckingham et al., 2008a, 2008b; Toosi et al., 2014). The uncertainty for the comparability in concentrations among applied methods is hindering proper understandings of the variations in EOC or DOC concentrations in response to various ecosystem management practices, land uses and soil conditions. Thus, the comparability of measured EOC or DOC concentrations using different methods clearly needs to be investigated (Avagyan et al., 2014; Bolan et al., 2011).

A number of factors govern the amounts of EOC or DOC in soils, which originate from plant litter, roots, stable organic fractions (humus), microbial decay products and/or the addition of biological waste materials (e.g., Kalbitz et al., 2000; Mcdowell and Likens, 1988; Sanderman et al., 2008). Among them, land use may be the primary factor (Chantigny, 2003). Due to the differing quantity and quality of plant litter, which is the primary source of organic matter, EOC or DOC concentrations in soils may particularly vary among different land use types. This inference has been proven true in some case studies at specific field sites. For instance, some case studies have observed that EOC or DOC levels vary in the order of arable lands < grasslands < forests (Gregorich et al., 2000; Iqbal et al., 2010; Madou and Haynes, 2006; Saviozzi et al., 2001; van den Berg et al., 2012). Some case studies at specific field sites have reported that the levels of EOC or DOC were intensively influenced by management practices such as liming (e.g., Dong et al., 2009; Zhu et al., 2014), organic matter amendments (e.g., Long et al., 2015; Zsolnay and Gorlitz, 1994) and chemical fertilizer applications (e.g., Gong et al., 2009; Sun et al., 2015). Previous case studies have also shown that EOC or DOC concentrations vary with soil depth and season at specific experimental field sites (Dong et al., 2009; Jensen et al., 1997; Jiang and Xu, 2006; Zhong et al., 2015). In fact, however, drawing consistent conclusions among different case studies is difficult because the measured EOC or DOC concentrations usually vary widely among different cases studies, even those conducted under similar natural or management conditions (e.g., Huang and Song, 2010; Ma et al., 2010). These highly variable concentrations are impeding researchers to successfully quantify the effects of the aforementioned factors relying on the traditional statistical methods (e.g., Filep and Rekasi, 2011). Fortunately, a meta-analysis approach, which is a widely adopted method in other areas (e.g., Abalos et al., 2016; Shi et al., 2013), may solve this problem, since this approach uses pair-wise (i.e., treatment against the control at each field site) data from case studies to avoid the impacts of any unconcerned factors (Hedges et al., 1999).

Based upon the above brief review, the authors hypothesized that the measured concentrations of either EOC or DOC were significantly influenced by observation methods and that the responses to land use, management practice, soil depth and season were different between EOC and DOC. To test these hypotheses, the authors performed a comprehensive assessment using a meta-analysis approach (e.g., Hedges et al., 1999). The objectives of this study were to (i) investigate the effects of different but widely adopted observation methods on measured concentrations of EOC and/or DOC; (ii) quantify the responses of EOC and/or DOC concentrations to variations of some natural and/or anthropogenic factors; and (iii) identify future research needs for EOC or DOC concentrations in terrestrial ecosystems.

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