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Water Extractable Fraction of Soil Organic Carbon as an Indicator of Soil Quality:A Literature Review

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Abstract

Total soil organic matter (SOM) content is a key attribute of soil quality (SQ) since it has far-reaching effects on soil physical, chemical, and biological properties. However, changes in contents of soil organic carbon occur only slowly and do not provide an adequate indication of important short-term changes in SQ. The declining SQ is often potentially the most serious both in the context of farm production and environmental damage. Water extractable organic carbon (WEOC) in the soil represents only a tiny portion of SOM. However, WEOC involves in key soil processes which are either directly or indirectly linked with soil quality. This pool acts as a substrate for microbial activity, a primary source of mineralizable N, S, and P. This review focuses on the importance of WEOC as a sensitive indicator of changing soil quality.

Key words: water extractable organic carbon; soil organic matter; soil qualit

Introduction

Concerns regarding soil degradation and agricultural sustainability have kindled interest in assessment of soil quality. According to Karlen et al., (1997), soil quality (SQ) is "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain biological productivity, maintain or promote air and water quality and support human health and habitation". As a step towards defining sustainable agricultural management practices, Doran et al., (1994) stressed the importance of managing SQ. An assessment usually includes measurements of soil quality indicators that, in some way, influence the function for which the assessment is being made. Such indicators can be divided in to chemical (e.g., pH, extractable nutrients, soil organic matter), physical (e.g., aggregation, bulk density, hydraulic conductivity), and biological (e.g., microbial activity, earth worm numbers, basal respiration).

Long before the introduction of chemical fertilizers, our ancestors had already learned to make use of organic materials for improving growth of their crops

(Hsieh and Hsieh, 1990). Agronomists have long recognised the benefits of maintaining and increasing soil organic matter (SOM), which improves soil fertility and crop production. SOM is intimately linked with many soil quality indicators and, therefore, has gained recognition as a primary indicator of soil quality (Cannel and Hawes, 1994; Robinson et al., 1994). The minimum data set of soil parameters for estimating and monitoring SQ consists of measurable soil properties that influence the capacity of soil to perform crop production or environmental functions (Doran and Parkin, 1996). Many of the soil quality minimum data set indicators have been shown to depend on SOM (Reeves, 1997). Soil quality indicators inextricably linked to SOM include plant available water capacity (Hudson, 1994), infiltration rate (MacRae and Mehuys, 1985; Boyle et al., 1989; Pikul and Zuzel, 1994), aggregate formation and stability (Tisdall and Oades, 1982; Burns and Davies, 1986; Boyle et al., 1989), bulk density (Soane, 1990; Thomas et al., 1995), soil strength (Ekwue and Stone, 1995), cation exchange capacity (Rhoton et al., 1993; Riffaldi et al., 1994), soil enzymes (Dick, 1984) and invertebrate bio-indicators - e.g. earthworms (Hendrix et al., 1992).

The level of our knowledge regarding the significance and applicability of various labile fractions as indicators of soil quality defers greatly. For example, a number of workers have reviewed, in detail, the significance of microbial biomass C and N levels (Sparling, 1997). By contrast, the nature and significance of the non-living, labile organic matter pools are much less well understood. For example, past research on soluble C has concentrated on forest soils, and their significance to the quality of agricultural soils has only recently been recognized. The significance of particulate organic matter has been recognized for some time (Gregorich and Janzen, 1996), but that of the mineralizable and extractable fractions is less well-known.

Water extractable organic matter (WEOM) accounts for only a small proportion of the total SOM in the soil (McGill et al., 1986). Nevertheless, it is now recognized that those molecules influence soil biological activity (Flessa et al., 2000), affect the transport of metals and organic pollutants (Romkens and Dolfing, 1998) and contribute to mineral weathering (Rasmussen et al., 1998) and podzolization (van Hees and Lundstrom, 2000). The WEOM is composed of an array of molecules generally reflecting the composition of total SOM, since the soluble phase tends to be in equilibrium with the solid phase of SOM (Zsolnay, 1996). Numerous biotic and abiotic factors control the temporal and spatial dynamics of WEOM (Murphy et al., 2000). Some of the soil properties such as pH and ionic strength of the water phase determined organic matter solubility, whereas Al and Fe oxides and clay minerals determined the sorption/ desorption equilibrium between the dissolved phase and the solid phase of SOM. The production and the consumption of WEOM are dependent mainly on microbial activities and the equilibrium with the solid phase of SOM.

Land use and related management practices affect soil properties, and thereby are likely to influence WEOM. However, their impacts on the amount and composition of WEOM have not been extensively studied, and the information appears fragmented and some times contradictory. In general, WEOM concentration vary in the order forest soils > grassland soils> arable soils mostly due to different vegetation types (Haynes, 2000). However, the size and the composition of this organic matter pool are also influenced by management practices such as liming (Andersson et al., 2000), organic amendment (Chantigny, 2003), mineral fertilization (Chantigny et al., 1999). Many studies report significant fluctuations in WEOM following change in land use or management practices. However, the processes driving the effects are largely unknown. Both short - term and long – term effects of land use and management practices remain poorly understood under field conditions, since many environmental and soil factors interact at the same time. Comparing data from different studies is often delicate since large discrepancies pertaining to the methodological approaches used to characterize WEOM in different ecosystems exist (Zsolnay, 1996). The main objectives of this review are to report on the short - term and long- term effects of land use and management practices on WEOM, and to identify the issues that should be addressed in future studies.

Total soil organic matter

Organic matter can be described as "all organic materials found in soils irrespective of origin or state of decomposition" (Baldock and Skjemstad, 1999). Soil organic matter content is measured as organic C content. Although the organic fraction of soils typically accounts for a small, but variable, proportion (typically 5-10%) of soil mass, it exerts far- reaching affects on soil properties. Soil organic matter has long been recognized as the key indicator of soil productivity (Allison, 1973). An equilibrium soil organic matter content is attained within a mature natural ecosystem that is dependent upon the interaction of soil-forming factors (i.e., climate, topography, parent material, and time) (Baldock and Nelson, 2000). At this equilibrium level, the amount of organic C accumulating in the soil is the same as the amount lost via respiration as CO_2.

Soil organic C is shown in Figure 1 as being composed of two major pools: a labile and a stabilized fraction. This is a convenient division, although, in fact, soil organic matter includes continuum of materials ranging from highly decomposable to very recalcitrant. The labile fraction consists of material in transition between fresh plant residues and stabilized organic matter. It generally is considered to have a short turnover time (less than 10 years) (Janzen et al., 1997). Pools of organic matter that have been identified as part of the labile fraction include particulate organic matter, microbial biomass

C, water extractable organic C (WEOC).

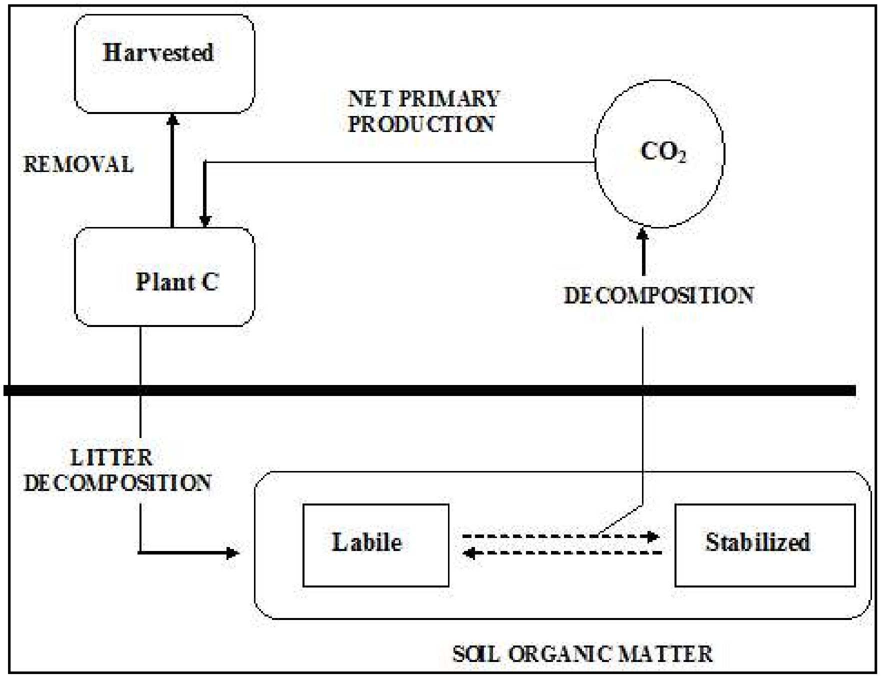

Figure 1: A schematic diagram of the C cycle in agricultural soils. Redrawn from Janzen et al. (1997).

Stabilized organic C is composed of organic materials that are highly resistant to microbial decomposition because of their chemical structure and/ or their association with soil minerals. This fraction consists mainly of humic substances, which are complex systems of high- molecular- weight organic molecules made up of phenolic polymers produced from the products of biological degradation of plants and animal residues (Baldock and Nelson, 2000).

Dissolved soil organic C vs. water extractable soil organic C

The organic matter present in soil solution and passing a filter pore size of 0.4- 0.6 µm is defined as dissolved organic C (DOC) (Zsolnay, 1996). However, this material is distributed among different pore sizes in soil, and the fraction present in meso-pores and micro-pores might not be collectable without disturbing the soil structure. The fraction of DOC collected by lysimeters or suction cups is mostly located in soil macro pores (Zsolnay, 1996). The organic C extracted by agitating soil samples with aqueous solutions is considered WEOC. The magnitude of WEOC is thus generally larger than DOC (Zsolnay, 1996). Many different chemical extractants have been used in attempts to extract a labile portion of organic matter from soils. These can be divided into three broad groups: (i) weak (hot water, hot 0.01M $CaCl_2$), (ii) intermediate (alkaline permanganate, 1M NaOH), or (iii) strong (6N H_2SO_4, $K_2Cr_2O_7 - H_2SO_4$) extractants (Goh and Haynes, 1986). In this review land use is considered as the factor with the greatest influence on WEOC in the soil, since it determines the type of vegetation grown on the soil, and since plant litter is the primary source of organic matter in the ecosystem. Characteristics of WEOC and the short-term and long-term impacts of a change in land use are reviewed. Land management practices are envisioned as secondary factors affecting WEOC in the soil since they are determined by the type of land use. Both the short-term and long-term effects of plant species, liming, mineral fertilization, organic amendments, and tillage are considered here. Environmental factors such as climate, landscape, and soil hydrology and texture represent a tertiary level of influence on WEOC, since they influence the dynamics of soil organic matter at the local and global scales.

Although the figures in the literature range widely WEOC concentration tends to be larger in natural forest than in agricultural soils (Zsolnay, 1996). He reported that in forest flow, WEOC content ranges from 1000-3000 mgL^{-1}. In agricultural soils, he reported a value varying from 5-900 mgL^{-1}. Some other studies have also indicated higher WEOC concentrations in grassland than in agricultural soils (Haynes, 2000). The mechanisms responsible for those differences between forest and agricultural soils have not been clearly identified.

Water extractable organic C may originate from leaching from above or below-ground plant litter and /or the synthetic activity of soil micro flora involved in decomposition of the litter and/or native soil organic matter. Fungi are thought to play a significant role in the production of WEOC (Moller et al., 1999). The greater fungal biomass present in forest floor compared to agricultural soils (Alexander, 1977) could partly explain higher WEOC content in the forest soils. Nevertheless, in the long-term, WEOC content tends to be proportional to the whole soil organic matter content (Delprat et al., 1997), suggesting that WEOC production and concentration should be determined primarily by the amount of organic matter present in soil (Kalbitz et al., 2000).

Land use and management practices influence WEOC content in the soil. However, the extent of fluctuations in WEOC as influenced by land use and management practices is not well-known. Figure 2 shows the influence of land use, management practices and climatic and soil factors on WEOC/ DOC level.

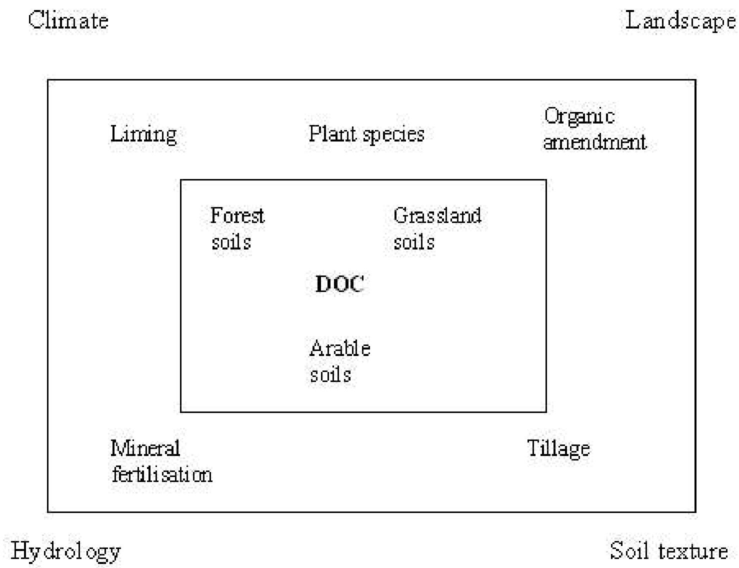

Figure 2: Schematic of the influence of land use, management practices, and climatic and soil factors on DOC/ WEOC. The level of influence increases as factors are closer to the centre.

Conversion of natural forest to agriculture.

Declines in the level of SOM together with WEOC in the world during the last hundred years have been substantial, and have been associated with changing patterns of land use that are driven by population increases (Rees et al., 2001). The most dramatic affect of agricultural practice occurs when soil under native vegetation is converted to arable agriculture typically, SOM levels decline rapidly in the first 10-20 years and then stabilized at a new equilibrium level after 30-100 years (Fenton et al., 1999). A number of factors contribute to the losses of SOM, including (i) a much lower allocation of carbonaceous residues to the soil (due to the relatively wide spacing of crop plants, removal of harvested products, and burning or removal of crop residues); (ii) tillage – induced aggregate disruption and exposure of physically protested organic material to microbial action, thus hastening decomposition rates; (iii) more favourable conditions for decomposition (e.g. tillage - induced aeration); and (iv) greater losses of surface soil.

Conversion of natural forest to agriculture implies clear-cutting and often tillage to incorporate the organic horizon in to the mineral soil. Some studies have reported an initial mobilization of WEOC ranging from 10 to 150mgL $^{-1}$(Delprat et al., 1997). The increase of WEOC content is attributed either to soil disturbance, increase water flux, accumulation of decaying plant debris on the soil, or stimulation of microbial activity. This initial increase in WEOC has been found to last from less than two years and up to ten years (Meyer and Tate, 1983; Moore, 1989). A progressive but rapid decline in the amount of WEOC could be observed a few years after clear-cutting. This decline is primarily attributed to the stabilization of the remaining organic matter and to a lower organic matter net input to the soil (Qualls et al., 2000).

The water extractable organic material mobilized by clear-cutting is mostly composed of medium to large humic acids, organic colloids and organo-metal complexes (Hughes et al., 1990).

As opposed to the conversion of natural forest to agriculture, afforestation of agricultural soils induces a significant increase in WEOC content in the soil (Hughes et al., 1990). Literature also indicates that when grassland soils are switched to arable soils, their WEOC content decreases rapidly. Moreover, the extent of declining WEOC is more evident as the number of years under arable cropping increases, apparently due to a gradual depletion in the SOM (Haynes, 2000).

Land use effect on WEOC is partly determined by vegetation type (e.g., tree vs. herbaceous plants). However, plant canopies may be composed of various species present at the same time or in rotation. Natural forests may contain mixed tree species, and the quality of forest floor and WEOM is determined by the dominant plant species (Kuiters, 1993).

Since the amount and the type of carbon input to the soil are dependent on plant species (Zsolnay, 1996), crop rotations in agricultural soil may influence WEOC concentration from year to year. Plant roots exude easily metabolizable material (Barber and Martin, 1976) and that the nature and the amount of the released material may vary among crop species and cultivars (Xu and Juma, 1993). Generally, WEOC concentration is higher under legumes than under gramineae species (Table 1). This difference could reflect different root exudation patterns among crop species. Legumes usually exude more soluble molecules than gramineae to signal their presence to Rhizobia and to rapidly initiate the formation of root nodules (Chantigny, 2003).

Table 1: Average WEOC content (mg kg-1) in the rooting zone of various gramineae and legume species grown in a silty clay loam and a clay loam.

	1990	
	SCL[a]	CL
Gramineae	62 ± 1^{b}	69 ± 4^{b}
Legumes	71 ± 4^{a}	75 ± 1^{a}

Some of the important agronomic practices such as liming influence WEOC in agricultural soils (Karlik, 1995). Various mechanisms such as increase SOM solubility (Erich and Trusty, 1997), increased microbial activities and production of soluble molecules (Guggenberger et al., 1994) could explain this phenomenon to some extent. liming also affect the composition of WEOC by increasing the proportion of humic acid (Cronan et al., 1999).

Inorganic fertilizers also influence WEOC content. Urea based fertilizers temporarily solubalized SOM and increase WEOC content due to an increase in soil pH (Myers and Thien, 1988). However, this effect is short-lived (Clay et al., 1995), suggesting that WEOC is readily biodegradable and rapidly consumed by soil micro organisms (Yano et al., 2000). Undoubtedly, application of organic manure or any other forms of organic materials increases the WEOC content in the soil (Jensen et al., 1997). This immediate increase of WEOC after organic amendments is generally attributed to the presence of soluble material in the amendments (Paul and Beauchamp 1989). The composition of WEOC is also influenced by the type of amendments. Water extractable organic carbon content in plant residues mostly has molecular weight ranging from 710-850, whereas, it varies from 2000-2800 for animal manure (Ohno and Crannell, 1996).

Land use and water extractable organic carbon

Knowledge of the short-term (i.e. less than 5 years) effects of crops and their management on soil organic matter status is essential when considering conservation strategies based on cropping rotation and other forms of establishment of vegetation. Nonetheless, short-term changes in total soil organic C content caused by changes in land management are often difficult to identify or quantify because of the large background organic C pool. Measurement of smaller, more active (labile) fractions of soil organic matter have, however, been used successfully to identify early changes in soil organic matter as influenced by changes in land management practice (Haynes and Beare, 1996). Such labile organic matter fractions include WEOC (Gregorich et al., 1994). The sensitivity of the levels of WEOC to the disturbance on the soil by the continuous practice of conventional agriculture has been identified by several researches (Ghani et al., 2000; Yapa, 2003).

It may take a relatively longer period of time (e.g., a decade or more) to observe a clear reduction of SOM with continuous conventional cultivation, whereas, WEOC tend to exhibit a clear drop within a relatively short period of time – for example, within one or two years after conversion of the natural vegetation in to intensive agriculture (Yapa, 2003) .

Conclusion

It is obvious that changing land uses significantly influence the level of WEOC in soil. Temporary increases of WEOC after the conversion of natural forest to agriculture have been reported though, it is clearly evident that the hastening decline in WEOC in the soil could practically be traced as well as quantified. Long before the evidence of the depletion of total SOM, the drop in WEOC becomes evident. Therefore, the deterioration of overall SQ as a result of the conversion of natural vegetation to agriculture could be traced at much earlier stage using WEOC level in the soil as an indicator than using total SOM level. The level of WEOC could also be used as an indicator to assess the rate of success during the conversion of a degraded land to productive agricultural land.

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