Soil & Tillage Research 146 (2015) 4–9

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Quantifying soil physical condition based on soil solid, liquid and gaseous phases

Enheng Wang [a,*], Richard M. Cruse [b], Yusen Zhao [a], Xiangwei Chen [a]

[a] Northeast Forestry University, School of Forestry, 26 Hexing Road , Harbin 150040, China
[b] Iowa State University, Department of Agronomy, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Received 26 November 2013
Received in revised form 11 September 2014
Accepted 18 September 2014

Keywords:
Three soil phases
Cobb–Douglas (C–D) production function
Soil structure
Soil compaction
Crop yield

ABSTRACT

Soil is a three-component system comprised of solid, liquid, and gas phases distributed in a complex geometry that creates large solid–liquid, liquid–gas, and gas–solid interfacial areas. Three soil phase index (TSPI) was developed to characterize the physical condition of a medium-textured soil based on solid, liquid, and gaseous phases by utilizing the concept of diminishing marginal productivity expressed in the Cobb–Douglas (C–D) production function. The index was defined as $\mathrm{TSPI} = [(X_s - C)X_l X_g]^N$. Where C and N are the constants for a given soil, X is volumetric proportion of the soil phases, the subscripts S, L, and G denote solid, liquid and gaseous phases, respectively. The use of TSPI is exemplified with soils under a series of tillage and traffic practices. To evaluate this new concept, the effects of machinery compaction on TSPI values were compared to selected credible methods for characterizing compaction effects on soil structure. A strong positive relationship was observed. TSPI had a significant relationship with selected soil properties, such as bulk density, oxygen diffusion rate, redox potential, and grain yield which were measured in a field experiment reported in the literature. Furthermore, the correlation of TSPI and the soil physical parameter S which is defined as the slope of the soil water retention curve at its inflection point was investigated and a significant linear relationship was also found for soil with given water contents. Overall, the primary advantage of TSPI is that it allows characterizing and evaluating the effects of management practices (e.g., tillage and/or traffic) on the three soil phase condition. Additional testing is needed to evaluate the utility of the index for predicting soil productivity under a wide range of conditions.

1. Introduction

Soil structure can be defined as the arrangement of soil particles and voids (Hillel, 1971; Kay 1990). Based on a scientific-agronomic explanation of soil structure's importance given in the latter half of the 19th century by Wollny (Vershinin, 1971), most soil scientists characterized and continue to characterize soil structure by quantitatively measuring primary and secondary aggregate size distribution, or qualitatively describing aggregate shape rather than characterizing all three soil phases (solid, liquid, and gas) (Bronick and Lal, 2005). Aggregate characterizations are relevant only to the solid phase; however, and do not provide information for architecture characterized by connection, distortion and heterogeneity of pores between aggregates (Young et al., 2001).

Soil is a multiphase disturbed system of solid, liquid, and gaseous components (Nerpin and Chudnovskii, 1970). Integration of the three phase configuration controls internal movement and storage of heat and fluids, impacts plant root growth, affects the soil environment critical to soil biology, and interacts with precipitation affecting water runoff, infiltration, and water quality (Connolly, 1998; Bachmair et al., 2009; Tokumoto et al., 2010). The three soil phases are dynamic and typically change temporally over relatively short periods, e.g., one week and spatially in response to changes in natural condition and contrived events (Hillel, 1971). In relation to processes or functional properties soil structure is better considered as a three-phase dynamic system, especially in agronomic applications because soil–water and gas components are critical and are arguably the most dynamic soil factors affecting crop growth and yield (Condon et al., 2002; Green and Erskine, 2004).

The definition of soil structure has been evolving through centuries, beginning with the initial concept of "soil tilth", stirring the soil to prepare a good physical condition for plants (Isgur and Thayer, 1938; Warkentin, 2006). Quantifying soil structure, in a sense is characterizing the soil physical condition, or relationships

---

[*] Corresponding author. Tel.: +86 0451 82191813; fax: +86 0451 82191813.
E-mail addresses: chenxwnefu@163.com, erxin222@163.com (E. Wang).

http://dx.doi.org/10.1016/j.still.2014.09.018
0167-1987/

of an integrated soil solid–liquid–gas system. Quantitative relationships of soil three phases can be characterized in various ways but fundamentally must begin by considering their mass or volume ratios (Kay, 1990). For agronomic purposes (excluding paddy and other hygrophyte crops), the optimum volumetric proportion of solids, liquid, and gas for a medium-textured, none swelling soil in general is hypothetically identified as 50%, 25% and 25%, respectively (Hillel, 1971; Brandy and Weil, 2002). However, the ratio of these three soil phases is limited in that it provides only an independent phase composition, rather than collectively giving a quantitative index permitting relative comparison of functionality between different soils or a common soil with different ratios of the three phases.

The Cobb–Douglas production function (C–D production function), which describes an empirical relationship between a specified output and various inputs is one of the widely used multiple production functions in economics (Mas-Colell et al., 1995). Diminishing marginal returns and diminishing marginal rate of technical input substitution are the most important properties for the C–D production function. This function states that for additional production inputs, the additional output(s) will be incrementally smaller while holding all other inputs at fixed quantities. This also may be applicable to the three-phase soil system that is as the components of this system diverge from the optimum volumetric proportion, marginal loss of potential soil productivity is hypothesized. The marginal rate of technical input substitution is defined as the rate at which one input may be substituted for another while maintaining the same level of output, or conversely, as with a soil system, can be viewed as the non-linear change in production of physical condition associated with altering the balance of critical input components (solids, liquids, and gas). In economics the rate of substitution of one product for another is described by a non-linear decreasing function due to the existence of diminishing marginal returns, which is called the diminishing convex marginal rate of technical input substitution. This concept seems applicable to an integrated soil system, as diverging from the optimum volumetric ratio of the three phases will result in a less favorable soil physical condition. The two characteristics of C–D production function expound the internal – interdependent relationship among soil phases.

There is an optimum combination of different inputs for one output level under a certain technical input substitution condition. The optimum composition of the three soil phases should correspond to the most favorable soil structure in a generalized sense. We can assume for this test of concept that the optimum structure for a medium-textured soil occurs if, and only if, the volume of solid, liquid, and gas phases is 50%, 25% and 25%, respectively (Hillel, 1971; Brandy and Weil, 2002).

The objectives of this paper are: (1) to develop the concept of marginal return for soil systems based on departure of solid, liquid, and gaseous phases from an ideal condition and (2) test this concept against another proven soil structure concept the ‘S’ factor and against data from other published studies.

2. Theory

The C–D production function was proposed by Knut Wicksell and tested against statistical data by Charles Cobb and Paul Douglas in 1900–1928 (Mas-Colell et al., 1995). The initial function form was $Y = AL^{\alpha}K^{\beta}$. Where Y is total production, L is labor input, K is capital input, and A is the total productivity factor. Parameters α and β are the output elasticity of labor and capital, respectively. The parameters show how one input substitutes to the other, and they are constants and determined by available technology. There are three requirements for the C–D production function: (1) all inputs are positive, (2) output is positive, and (3) the first derivative exists.

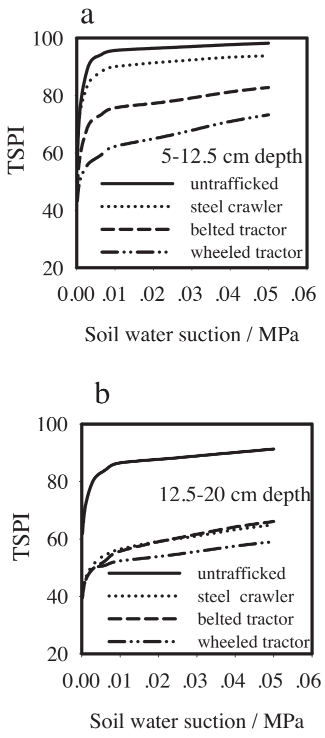

Fig. 1. Three soil phases index (TSPI) under different trafficked soil management (Brown, 1989).

C–D production functions are divided into short-run and long-run analysis depending on the variability of inputs. The short-run function is defined as the time period during which some selected inputs are fixed while others are allowed to vary. If all inputs are variable, the C–D production function is considered long-run. With the development of science and technology, the elements which could determine total production are no longer only labor input and capital input. Increasing the number of inputs the generalized form of the long-run production function can be expressed as:

$$Y = \prod_{i=1}^{n} X_i^{\alpha_i} \tag{1}$$

Here A is the total productivity factor >0, x_i is the input >0, parameters α_i is the output elasticity of each input, $0 < \alpha_i < 1 (i = 1, 2 \ldots, n)$, n is the number of inputs.

For soil, the liquid or gas phase proportion potentially could be “0” under extremely compacted, and/or when the soil is completely saturated or in very dry conditions; however, never becomes negative. The changes (substitution) among soil three phases are continuous thus, constructing the soil three phases as “inputs” and soil structure as “output” meets the requirements of this function.

All three soil components (solid, liquid, and gas) could change concurrently from time to time under soil and crop management practices, especially when a load is applied to the soil, such as done with tillage and/or trafficking. Thus, we selected the long-run C–D production function to build the soil physical condition function. Soil solid, liquid, and gas components are considered as three different separate “inputs” for the soil condition “output”. And because the fractional volume of the three components is interdependent we set “A” in Eq. (1) equal to 1. Thus, we get:

$$\mathrm{TSPI} = x_s^{\alpha_s} x_l^{\alpha_l} x_g^{\alpha_g} \tag{2}$$

where TSPI is the three soil phases index (value ranges from 0 to 100), x_s is the volumetric solid content ($\mathrm{m}^3\ (100\,\mathrm{m}^3)^{-1}$ or %), x_l is