Geoderma 326 (2018) 56–67

Contents lists available at ScienceDirect

Geoderma

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

# An analytic description of field capacity and its application in crop production

W. Daniel Reynolds

*Harrow Research and Development Centre, Agriculture and Agri-Food Canada, 2585 County Road 20, Harrow, ON N0R 1G0, Canada*

A R T I C L E  I N F O

Handling Editor: Morgan Cristine L.S.

*Keywords:*
Field capacity concept
Analytic field capacity expressions
Drainage from saturation
Air and water storage
Nutrient leaching
Seep/W numerical model

A B S T R A C T

It has been established for decades that soil water field capacity (FC) includes four main components: drainage rate or flux (q), drainage time from saturation (t), soil water content in the drained zone (θ), and drainage depth (Z). Despite this, rather little work has been done to incorporate these components into analytic FC expressions, or to determine how such expressions are best used in applications of the FC concept. The primary objectives of this study were: i) develop analytic FC expressions that account for the four components of FC; ii) determine the accuracy of the FC expressions using numerical simulations of soil profile drainage from saturation; and iii) illustrate how analytic FC expressions might be used to optimize air, water and nutrient dynamics in field crop production.

Using a range of representative soil types, the analytic FC expressions predicted q and θ within 36% of numerically determined values for $t \geq 0.01$ days and $Z = 0.3$ m or 1.0 m, which is considered sufficiently accurate for most FC applications. The FC expressions showed that all four FC components are important, and that most FC applications have both agronomic and environmental implications. Static FC definitions based on specified matric head or retention curve shape were frequently inaccurate. It was concluded that the FC concept is most appropriately applied in crop production studies by using integrative FC expressions to optimize air and water storage, drainage flux, drainage time, and potential nutrient leaching rate in the crop root zone.

## 1. Introduction

The concept of field capacity (FC) has existed for about 100 years (e.g. Alway and McDole, 1917), and since then it has become widely used for such diverse activities as:

- crop growth modeling (e.g. Boogaard et al., 2014; Hoogenboom et al., 2017);
- estimating crop root zone gas exchange and plant-available air and water capacities (e.g. Stepniewski et al., 2011; de Jong van Lier, 2017);
- irrigation scheduling (e.g. Sutton and Merit, 1993; George et al., 2000; Rai et al., 2017);
- design of subsurface tile or mole drainage systems (e.g. Childs, 1957; Strock et al., 2011);
- determination of soil trafficability, tillability and susceptibility to compaction (e.g. Earl, 1997; Dexter and Bird, 2001; Rucknagel et al., 2012; Servadio et al., 2016);
- estimating potential for water percolation and nutrient or contaminant leaching below the crop root zone and into subsurface drainage systems or ground water (e.g. de Jong van Lier, 2017; de Jong van Lier and Wendroth, 2016; Meyer and Gee, 1999);
- characterizing soil and crop resilience to water excesses and deficits (e.g. Koide et al., 2014; Reynolds et al., 2015); and
- estimating potential for generation and emission of soil-borne greenhouse gases (e.g. Castellano et al., 2010; Hangs et al., 2013; Rubol et al., 2013).

Despite this, FC has remained rather poorly and loosely defined. Proposed or assumed definitions and concepts for FC include:

- "… amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased, which usually takes place within 2 or 3 days in pervious soils of uniform texture and structure." (Veihmeyer and Hendrickson, 1931).
- "… practical upper limit of soil moisture content found under field conditions in a soil having unobstructed subdrainage." (Colman, 1947).
- "…approximate quantity of water which can be permanently retained in the soil in opposition to the downward pull of gravity" (Dictionary Geotechnical Engineering, 2014).

*E-mail address:* dan.reynolds@agr.gc.ca.

https://doi.org/10.1016/j.geoderma.2018.04.007
Received 5 February 2018; Received in revised form 15 March 2018; Accepted 8 April 2018

- "… lowest moisture content to which a soil can be brought by drainage alone …" (Childs, 1957).
- "… water content of soil that has been allowed to drain freely for two days from saturation with negligible loss due to evaporation" (Townend et al., 2000).
- "…content of water … remaining in a soil 1, 2 or 3 days after having been wetted with water and after free drainage is negligible (Colman, 1947; Glossary of Soil Science Terms, 2008).
- root zone water content in an initially saturated or field-saturated soil after:
  - rate of change of water content approaches zero (Kutilek and Nielsen, 1994; Lal and Shukla, 2004) or becomes "relatively small" (Ratliff et al., 1983);
  - drainage flux has "materially decreased" (Veihmeyer and Hendrickson, 1931), or "effectively ceased" (Encyclopedia of Soil Science, 2008), or "becomes negligible" (Meyer and Gee, 1999).

All of these definitions and concepts are essentially valid, but they are clearly not precise. What is clear, however, is that the fundamental components of FC include: i) a soil water content; ii) soil water drainage expressed as a drainage flux or a rate of change in water content; iii) drainage time from saturation; and iv) a depth or depth-range in the soil profile.

Youngs (1960), Nachabe (1998), Cong et al. (2014), and Assouline and Or (2014) have proposed approximate analytical expressions for homogeneous soil that combine some or all of the moisture, drainage flux, drainage time, and drainage depth components of FC. These expressions are briefly described below.

Youngs (1960) used step-function hydraulic property relationships to obtain:

$$t_{FC} = \frac{Z(\theta_S - \theta_R)}{K_S}\ln\left(\frac{K_S}{q_{FC}}\right) \quad (1)$$

where $t_{FC}$ [T] is drainage time from soil saturation to FC at depth, Z [L], $K_S$ [LT$^{-1}$] is soil saturated hydraulic conductivity, $q_{FC}$ [LT$^{-1}$] is field capacity drainage flux at depth Z, and $\theta_S$ [L$^3$ L$^{-3}$] and $\theta_R$ [L$^3$ L$^{-3}$] are the saturated and residual (non-drainable) volumetric soil water contents, respectively.

Nachabe (1998) combined the Brooks and Corey (1964) quasi-empirical hydraulic conductivity function, K(θ,h) [LT$^{-1}$] (described in Section 5), with redistribution of an infiltrated square wave pulse of water to obtain:

$$t_{FC} = \frac{I}{\beta K_S}\left[\frac{K_S}{q_{FC}} - 1\right] \quad (2.1)$$

where I [L] is the specific volume of water infiltrated into uniformly unsaturated soil, β [–] is the Brooks and Corey (1964) pore connectivity and size-distribution parameter (see Eq. (10)), and it is assumed that pore water hydraulic head gradient is unity during redistribution. The infiltration rate in Eq. (2.1) is assumed sufficient to produce $\theta_S$ in the infiltrated water pulse, and hence, conservation of soil water mass dictates:

$$I = Z_0(\theta_S - \theta_R) = Z_f(\theta_{FC} - \theta_R) \quad (2.2)$$

where $Z_0$ [L] is the initial depth of the infiltrated pulse, and $\theta_{FC}$ [L$^3$ L$^{-3}$] is the field capacity soil water content of the redistributed water pulse which extends to depth, $Z_f$ ($Z_f > Z_0$), at $t = t_{FC}$.

Cong et al. (2014) combined the Brooks and Corey (1964) K(θ,h) function with soil water storage at FC to obtain the equivalent of:

$$t_{FC} = \frac{Z(\theta_S - \theta_R)}{(\beta - 1)K_S}\left[\left(\frac{K_S}{q_{FC}}\right)^{\left(\frac{\beta-1}{\beta}\right)} - 1\right] \quad (3.1)$$

where $\theta_{FC}$ is determined by iterative solution of:

$$\theta_{FC} = \frac{K_S}{\delta Z}\left(\frac{\theta_{FC} - \theta_R}{\theta_S - \theta_R}\right)^{\beta} \quad (3.2)$$

with $\delta$ [T$^{-1}$] specified, and unit hydraulic head gradient assumed. Eqs. (3.1) and (3.2) assume an initially saturated soil profile where the FC drainage flux ($q_{FC}$) at depth Z is a fixed percentage (e.g. $\delta = 3\%\ \text{day}^{-1}$) of total soil water storage at FC (i.e. $q_{FC} = \delta Z\theta_{FC}$).

Assouline and Or (2014) modified the Youngs (1960) analysis to produce:

$$t_{FC} = \frac{Z(\theta_S - \theta_{FC})}{q_{FC}}\left[\frac{K_{FC}}{K_M}\ln\left(\frac{K_M}{K_{FC}}\right)\right] \quad (4.1)$$

where

$$K_M = \int_0^1 \Theta K(\Theta)d\Theta \Big/ \int_0^1 \Theta d\Theta \quad (4.2)$$

is a "Θ-weighted" mean hydraulic conductivity in the drained zone, $K_{FC}$ [LT$^{-1}$] is soil hydraulic conductivity at FC, and Θ [–] is defined by:

$$\Theta = \left(\frac{\theta - \theta_R}{\theta_S - \theta_R}\right) \quad (4.3)$$

So far, rather little has been done to develop and test integrative analytical expressions for FC, or to explore how such expressions might be used in the diverse applications mentioned earlier. In addition, the above relationships (Eqs. (1)–(4.3)) have assumptions or limitations that can make them difficult to apply; e.g. the step-function hydraulic property relationships in the Youngs (1960) analysis (Eq. (1)) can be of low accuracy at large times (Youngs, 1960; Youngs and Aggelides, 1976); soil depth (Z) is not explicit in the Nachabe (1998) analysis (Eq. (2.1)); $\theta_{FC}$ must be solved iteratively using an assumed $\delta$ value in the Cong et al. (2014) analysis (Eq. (3.2)); and the $K_M$ value in the Assouline and Or (2014) analysis (Eq. (4.2)) can be difficult to evaluate. The objectives of this study were consequently to: i) derive simple and explicit analytical FC expressions that account for the four FC components; ii) determine the accuracy of the FC expressions using numerical simulations of soil profile drainage from saturation; iii) show how the FC expressions relate to some traditional approaches for determining or estimating FC; and iv) use the analytic FC expressions to illustrate how the FC concept might be applied to optimize air and water storage, water drainage, and nutrient leaching in field crop production. Before proceeding, however, we will briefly review some traditional techniques for estimating FC (Section 2).

## 2. Traditional techniques for estimating field capacity

Field capacity has traditionally been estimated using a range of so-called "static" and "dynamic" approaches (e.g. Assouline and Or, 2014). Static approaches assume pore water matric head and water content have "gravity-equilibrated" to constant values, and include: i) specification of a field capacity pore water matric head, $h_{FC}$ [L]; and ii) estimation of $h_{FC}$ and the corresponding field capacity volumetric water content, $\theta_{FC}$, using the shape of the equilibrium soil water retention curve, θ(h). Dynamic approaches for determining FC assume water or solute movement at a particular depth becomes unimportant or negligible at a specific drainage rate or drainage time, and include: i) specified rate of change in soil water content, $(d\theta/dt)_{FC}$ [T$^{-1}$]; ii) specified drainage flux, $q_{FC}$, or hydraulic conductivity, $K_{FC}$; and iii) specified drainage time from saturation, $t_{FC}$.

### 2.1. Static approaches for estimating field capacity

Specifying an equilibrated $h_{FC}$ stems primarily from the need to obtain $\theta_{FC}$ using laboratory procedures, which are often more practical and better controlled than field methods (Colman, 1947). This approach usually involves placing a saturated soil sample (e.g. intact or