

Least limiting water range: A potential indicator of changes in near-surface soil physical quality after the conversion of Brazilian Savanna into pasture

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Abstract

The Brazilian savanna, or “Cerrado”, is an ecosystem that originally covered more than 200 Mha in Brazil. It is estimated that about 49.5 Mha in the Cerrado are now covered with cultivated pastures, which are responsible for half of Brazilian beef production. However, soil and pasture degradation represent a threat to this productive system and to the Cerrado ecosystem itself. Thus, the objective of this research was to evaluate the least limiting water range (LLWR) as an index of near-surface soil physical quality after conversion of Brazilian savanna to continuous and short-duration grazing systems. Three sites were evaluated: native Cerrado (NC), continuous grazing (CG), and short-duration grazing (SG). Thirty soil cores (5 cm height, 5 cm diameter) were collected at each site, and used for soil bulk density, soil water retention curve, and soil penetration resistance curve determinations. The results were used for quantification of LLWR and critical bulk density (D_{bc}), in which LLWR equals zero. The near-surface soil physical quality, as evaluated by the LLWR, was most restrictive for potential root growth in SG. In CG, potential restriction was moderate; however, the entire soil bulk density range was below the D_{bc} . In NC, potential restriction was minimum. The soil structural degradation process was primarily related to the increase in stocking rates in the grazing systems. The LLWR proved to be a useful indicator of Cerrado soil physical quality, being sensitive to alterations in near-surface physical properties.

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1. Introduction

The Brazilian savanna, or Cerrado, is an ecosystem that originally covered an area of more than 200 Mha in the central part of Brazil, corresponding to almost 25% of the country. The core region is concentrated at the Great Plateau of Central Brazil over an approximate area of 150 Mha (São Paulo, 1997).

The Cerrado region is defined based on physiognomic aspects of the vegetation, comprising heterogeneous physio-climatic regions (Ker et al., 1992). The term Cerrado comprises a gradient of physiognomies, from the grassland type known as “Campo limpo” to a sclerophyllous forest, known as “Cerradão”. Between these, there are three intermediate physiognomies, with increasing density of trees: “Campo sujo”, “Campo cerrado”, and “Cerrado *sensu strictu*”, which are the strict savanna forms (Pivello and Coutinho, 1996).

Currently, about 49 Mha of the Cerrado are covered with cultivated pastures, responsible for about half of Brazilian beef production (Macedo, 2001). The expansion of beef production into the Cerrado occurred after the mid 1960s. Financial assistance and the implementation of low-input and much more productive systems based on perennial grasses, such as *Brachiaria decumbens* imported from Africa, promoted a rapid growth of the area covered with cultivated pastures (Costa and Rehman, 1999). However, the sustainability of this productive system has been threatened by soil and pasture degradation. It is estimated that half of the area cultivated with sown pastures in the Cerrado is suffering from degradation (Vieira and Kichel, 1995). The land degradation process after pasture implementation in the Cerrado region is a continuous process, beginning with inadequate pasture/animal management, overgrazing, poor nutrient cycling, weed competition, and finally, soil physical degradation (e.g. compaction, erosion) (Macedo, 2001).

During the 1980s, there was a belief that short-duration grazing (SG) systems could improve soil physical condition by trampling action that theoretically could break soil surface crusts and thus enhance infiltration, porosity and other soil physical properties (Savory, 1983). However, a number of studies indicated detrimental effects of SG on soil bulk density (Dormaar et al., 1989), infiltration rates

(Abdel-Magid et al., 1987), and soil penetration resistance (Bryant et al., 1972; Silva et al., 2003).

The least limiting water range (LLWR) has been proposed as an index of soil physical quality for crop growth (Silva et al., 1994), since it integrates the effects of soil aeration, resistance to penetration, and water retention on crop growth into a single parameter. The LLWR has been validated as a soil physical quality indicator for a wide variety of soils, crops, and management systems (Silva et al., 1994; Betz et al., 1998; Tormena et al., 1999; Wu et al., 2003). However, its efficacy as an index of soil physical quality for pasture systems was not evaluated. We hypothesized that the LLWR could be a useful indicator of near-surface soil physical quality in a Cerrado ecosystem. Therefore, the objective of this study was to evaluate the LLWR as an index of soil physical quality after conversion of Brazilian savanna to continuous and short-duration grazing systems.

2. Materials and methods

2.1. Experimental site and sampling

The study was conducted at the National Beef Cattle Research Center of Brazilian Agricultural Research Corporation (Embrapa, 1979), Mato Grosso do Sul State, Brazil (20°26'48"S, 54°43'19"W). According to Köppen's classification, the climate is defined as a transition between Cfa (subtropical humid) and Aw (tropical wet-dry), with a mean annual precipitation of 1500 mm and mean temperature of 22 °C. The soil was classified as a Typic Acrudox with 399 g kg⁻¹ clay, 66 g kg⁻¹ silt, and 535 g kg⁻¹ sand.

Three sampling sites were selected for the study:

- (i) Native Cerrado (NC): an undisturbed site under native sclerophyllous forest “Cerradão”.
- (ii) Continuous grazing (CG): a pasture (0.7 ha) cultivated with *Brachiaria* grass (*Brachiaria decumbens* cv. Basilisk) grazed continuously by two heifers in 1-year cycles. Additional animals were occasionally introduced with the objective of maintaining forage availability at 3.0 Mg ha⁻¹ of total dry matter (TDM). The area was cleared in 1976 and used for continuous grazing until 1993 without any source of liming

or fertilization. When the experiment was initiated the pasture was in a severe state of degradation. The continuous grazing experiment was implemented in November 1993. Seedbed preparation consisted of subsoiling, liming (2.5 Mg ha^{-1}), and fertilization (350 kg ha^{-1} of the formulation 0-20-20). The pasture had not received any additional fertilization since then. Average annual stocking rate was $1.53 \text{ animal units (AU) ha}^{-1}$.

- (iii) Short-duration grazing (SG): a pasture (0.18 ha) cultivated with Tanzania grass (*Panicum maximum* cv. Tanzania) grazed for 7 days followed by resting periods of 35 days. The area was cleared in 1983, and used for continuous grazing from 1983 to 1987 under *P. maximum* cvs. Coloniaio and Tobiaia. The seedbed preparations at that time consisted of liming (1.5 Mg ha^{-1}), and fertilization (400 kg ha^{-1} of superphosphate, and 100 kg ha^{-1} of KCl). In 1988 and 1992, the area received two levels of liming (1.5 and 3.0 Mg ha^{-1}) and two levels of fertilization (400 and 800 kg ha^{-1} of the formulation 0-20-20). Then the area was used for continuous grazing from 1992 to 1998. In November 1998, a subsoiling operation was performed and the area received liming and fertilization for the implementation of the short-duration grazing experiment being evaluated here. The experiment was designed to maintain soil base saturation from 45 to 50%, available P as Mehlich-1 from 4 to 8 g m^{-3} , and K from 60 to 80 g m^{-3} , at the 0–20 cm layer. Nitrogen fertilization rate was $100 \text{ kg N ha}^{-1} \text{ year}^{-1}$. Post-graze residue on this pasture was maintained at $2.0\text{--}2.5 \text{ Mg TDM ha}^{-1}$. Average annual stocking rate was 4.8 AU ha^{-1} and 2.26 AU ha^{-1} for wet and dry seasons, respectively.

2.2. Soil physical properties

The LLWR is a type of pedotransfer function used to estimate optimum soil water content for plant growth based on quantification of bulk density (D_b) for a given soil type under evaluation. However, prior to its computation, it is necessary to parameterize a soil water retention function, $\theta(\psi)$, and a soil penetration resistance function, PR (θ , D_b) (Silva et al., 1994).

Thirty undisturbed soil cores (5 cm height, 5 cm diameter) were collected at each sampling site in February 2002. Samples were saturated on tension tables (Topp and Zebchuk, 1979). Soil water retention curve (SWR) was determined following the procedure described by Silva et al. (1994). Cores for each treatment were separated in 10 groups of 3 cores. Each group was subjected to one of the following water suctions (ψ): (i) 20, 40, 60, 80, and 100 hPa on tension tables and (ii) 300, 500, 700, 1000, and 15,000 hPa on pressure plates. After the equilibrium of $\theta(\psi)$, samples were wrapped in plastic film and stored at $5 \pm 1^\circ \text{C}$ for 1 week to ensure equal water distribution throughout the soil cores. This procedure was necessary before determining PR, which is strongly dependent on water content.

Measurement of PR was performed using an electronic cone penetrometer with a semi-angle of 30° and a 0.1167 cm^2 basal area. Penetration rate was 1.0 cm min^{-1} , with values recorded every 0.7 s. Immediately after determining PR, soil cores were oven dried at 105°C for 24 h and volumetric water content (θ) and D_b determined.

The functional relationship between θ and ψ , known as SWR, was established for each treatment using the model employed by Silva et al. (1994) and Betz et al. (1998). This model takes into account the effect of D_b on SWR properties, as shown:

$$\theta = \exp(a + bD_b)\psi^c \quad (1)$$

or the linearized form:

$$\ln \theta = a + bD_b + c \ln \psi \quad (2)$$

where θ is the soil volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$), ψ the soil water suction (hPa), and a , b , and c are the model-fitting parameters.

The functional relationship between PR, θ , and D_b was established for each treatment using the model proposed by Busscher (1990) and employed by Silva et al. (1994) and Betz et al. (1998):

$$\text{PR} = d\theta^e D_b^f \quad (3)$$

or the linearized form:

$$\ln \text{PR} = \ln d + e \ln \theta + f \ln D_b \quad (4)$$

where PR is the soil penetration resistance (MPa), D_b the soil bulk density (g cm^{-3}), and d , e , and f are the model-fitting parameters.

The LLWR was determined for each core following the methodology proposed by Silva et al. (1994). Critical values for pasture growth associated with PR, ψ and air-filled porosity were obtained from the literature. Field capacity was established as θ at 100 hPa (Haise et al., 1955), permanent wilting point as θ at 15,000 hPa (Richards and Weaver, 1944). Root-limiting PR was set at 3.0 MPa (Lipiec and Hakansson, 2000) and air-filled porosity $\geq 10\%$ was assumed to be critical for plant growth (Grable and Siemer, 1968). Water contents at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}) were predicted from Eq. (2), while water content where PR is equal to 3.0 MPa (θ_{PR}) was predicted from Eq. (4). Water content in which air-filled porosity is equal 10% (θ_{AFP}) was calculated as:

$$\theta_{AFP} = \left[\left(1 - \frac{D_b}{D_p} \right) - 0.1 \right] \quad (5)$$

where D_p is the soil particle density, assumed to be 2.65 g cm^{-3} .

As described by Wu et al. (2003) there are four possibilities for calculating the LLWR, depending on the values of the functions θ_{PR} , θ_{FC} , θ_{WP} and θ_{AFP} :

- (a) if ($\theta_{AFP} \geq \theta_{FC}$) and ($\theta_{PR} \leq \theta_{WP}$):

$$\text{LLWR} = \theta_{FC} - \theta_{WP};$$

- (b) if ($\theta_{AFP} \geq \theta_{FC}$) and ($\theta_{PR} \geq \theta_{WP}$):

$$\text{LLWR} = \theta_{FC} - \theta_{PR};$$

- (c) if ($\theta_{AFP} \leq \theta_{FC}$) and ($\theta_{PR} \leq \theta_{WP}$):

$$\text{LLWR} = \theta_{AFP} - \theta_{WP};$$

- (d) if ($\theta_{AFP} \leq \theta_{FC}$) and ($\theta_{PR} \geq \theta_{WP}$):

$$\text{LLWR} = \theta_{AFP} - \theta_{PR}.$$

If LLWR equals zero, then D_b at which this occurs is known as the critical bulk density (D_{bc}). Bulk density above the D_{bc} is an indicator of inadequate physical environment for plant root system development.

Statistical analysis was carried out with the REG procedure of SAS/STAT system (SAS Institute, 1999).

3. Results and discussion

Coefficients from the least-squares fit of the SWR curve for each treatment were:

$$\text{NC} : \ln \theta = -1.441 + 0.692D_b - 0.097 \ln \psi, \\ R^2 = 0.84 \quad (6)$$

$$\text{CG} : \ln \theta = -1.783 + 0.972D_b - 0.105 \ln \psi, \\ R^2 = 0.83 \quad (7)$$

$$\text{SG} : \ln \theta = -0.911 + 0.243D_b - 0.101 \ln \psi, \\ R^2 = 0.90 \quad (8)$$

Soil water content varied positively with D_b and negatively with ψ . These results are in agreement with those found by Betz et al. (1998) and Tormena et al. (1999).

Coefficients from the least-squares fit of the soil penetration curve for each treatment were:

$$\text{NC} : \ln \text{PR} = -1.529 - 1.230 \ln \theta + 6.213 \ln D_b, \\ R^2 = 0.90 \quad (9)$$

$$\text{CG} : \ln \text{PR} = -3.024 - 1.709 \ln \theta + 8.026 \ln D_b, \\ R^2 = 0.86 \quad (10)$$

$$\text{SG} : \ln \text{PR} = -2.146 - 1.488 \ln \theta + 4.932 \ln D_b, \\ R^2 = 0.85 \quad (11)$$

Penetration resistance varied positively with D_b and negatively with θ , as also reported in other studies (Silva et al., 1994; Betz et al., 1998; Tormena et al., 1999). The decrease in PR with the increase in θ is associated with the reduction in cohesion and angle of internal friction (Camp and Gill, 1969). The increase in PR with D_b could be attributed to compaction of the soil matrix resulting in an increase in interparticle friction (Vepraskas, 1984).

Soil water content at field capacity increased with D_b in all three treatments (Fig. 1), which was also observed by Silva et al. (1994) in a loamy sand soil, by Betz et al. (1998) in a clay loam soil, and by Tormena et al. (1999) in a clay soil. In Brazilian Oxisols, compaction generally does not affect small size pores inside aggregates, but decreases diameter of larger pores between aggregates. As larger pores decrease in diameter, they become active in water retention at low water suction values (Kertzman, 1996).

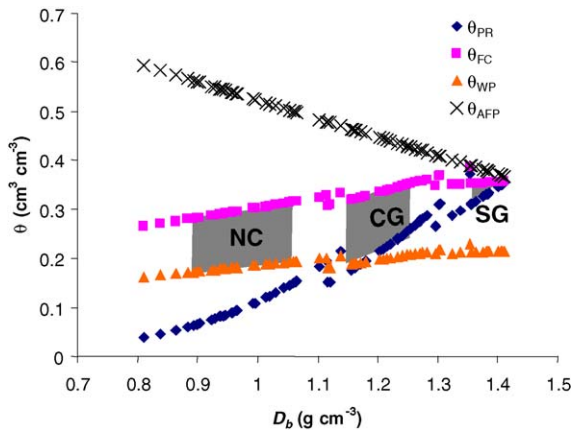


Fig. 1. Soil water content (θ) variation with bulk density (D_b) at critical levels of field capacity (100 hPa, θ_{FC}), at wilting point (15,000 hPa, θ_{WP}), at air-filled porosity of 10% (θ_{AFP}), and at soil penetration resistance of 3.0 MPa (θ_{PR}) in native Cerrado (NC), continuous grazing (CG), and short-duration grazing (SG). Shaded area represents the least limiting water range within mean $D_b \pm$ standard deviation.

Least limiting water range varied from 0.102 to $0.126 \text{ cm}^3 \text{ cm}^{-3}$ in NC, from 0.014 to $0.132 \text{ cm}^3 \text{ cm}^{-3}$ in CG, and from 0 to $0.080 \text{ cm}^3 \text{ cm}^{-3}$ in SG (Fig. 1). When $D_b \geq D_{bc}$, soil structural degradation has occurred, causing restrictions to plant growth. The impact of the $LLWR = 0$ in SG on pasture growth is difficult to predict, since plant growth is a dynamic process, and physiological and/or morphological adaptations are commonly found in plant species growing in stressful environments. However, Silva and Kay (1996) found that corn (*Zea mays*) shoot growth rates declined as soil water content fell outside of the LLWR.

Physical constraints to root growth were minimum in NC, where all D_b values were $< D_{bc}$, and LLWR was equal to available water content (AWC) in 96% of the D_b range (Fig. 1). In CG, all D_b values were $< D_{bc}$. However, θ_{PR} was the lower limit of LLWR in 70% of the D_b range, indicating restrictions to root growth by soil PR at low soil water content (Fig. 1). In SG, θ_{PR} was the lower LLWR limit for all D_b values, and 40% of the D_b range was located above $D_{bc} = 1.41 \text{ g cm}^{-3}$. The LLWR was narrower in SG indicating a poor physical environment for plant growth (Fig. 1).

The LLWR plotted as a function of D_b for each treatment is shown in Fig. 2. The LLWR increased up to $D_b = 1.18 \text{ g cm}^{-3}$ and declined with further increases in

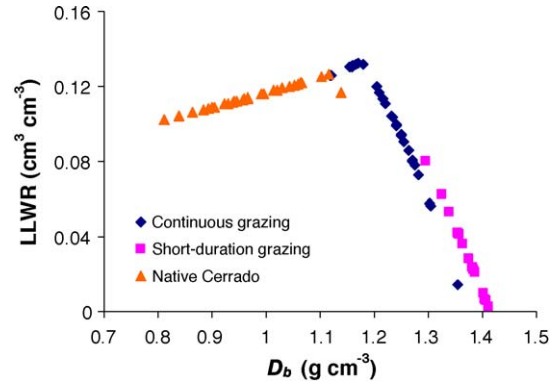


Fig. 2. Variation of the least limiting water range (LLWR) with bulk density (D_b) in native Cerrado, continuous grazing and short-duration grazing treatments.

D_b . Bulk density increased with increasing stocking rate, according to the three treatments. Mean LLWR was $0.114 \text{ cm}^3 \text{ cm}^{-3}$ in NC, $0.102 \text{ cm}^3 \text{ cm}^{-3}$ in CG, and $0.031 \text{ cm}^3 \text{ cm}^{-3}$ in SG.

The D_b values were lower in NC than in CG and SG, in agreement with the increase in the stocking rates. Therefore, soil compaction increased with increasing stocking rate following the sequence $NC < CG < SG$. θ_{PR} increased sharply with an increase in D_b in CG and SG, leading to LLWR reduction. θ_{PR} and θ_{AFP} were more severely affected by structural degradation (i.e. steeper slopes) than either θ_{FC} or θ_{WP} , as also reported by Silva et al. (1994) and Tormena et al. (1999).

The increase in D_b with stocking rate is a well documented process, and has been normally used as a diagnosis of soil compaction in pasture systems (Willatt and Pullar, 1983; Warren et al., 1986). Dormaar et al. (1989) observed increases in D_b and reduction in hydraulic conductivity in soils under SG in comparison with ungrazed exclosures, rejecting the hypothesis that cattle trampling could improve soil physical condition. Despite the different methodological approaches, our results corroborate those found by Dormaar et al. (1989), since we also found an increase in soil PR, and a decrease in air-filled porosity with increasing D_b due to heavy stocking in SG (Fig. 1).

Holechek et al. (1999) concluded that conservative stocking rates would increase grazing capacity, reduce risk, increase financial return and decrease soil degradation. At least from the soil physical quality standpoint, the results presented here are in agreement

with those of Holechek et al. (1999), since CG with lower stocking rate was less detrimental than SG.

The different growth habits of the grass species in the CG and SG treatments should also be taken into account to evaluate the effects of grazing systems on soil physical quality. Goodloe (1969) stated that grazing episodes in SG improved soil physical condition by converting the top organic matter to litter and chipping, but not compacting the soil surface. Tanzania grass in the SG treatment has a cespitose growth habit, forming bunches that are elevated from ground level, leaving the soil between-bunches almost completely uncovered. Therefore, any benefits of cattle trampling on litter incorporation, nutrient cycling, and physical property improvement in the SG treatment were probably minimum.

Balph and Malechek (1985) observed that cattle were more likely to step in the interstices between-bunches, as they become elevated from the ground, because the bunches provided an uneven surface upon which to walk. This behavior tends to aggravate soil compaction between-bunches, since animal trampling is concentrated in a small area, which means that the stocking rate is virtually greater in between-bunches interstices than that initially stated for the whole area. Critical D_b and LLWR also indicated severe compaction in SG in comparison with CG and NC, in contradiction with the claimed benefits of SG (Goodloe, 1969; Savory, 1983).

Vegetative coverage provided by *Brachiaria* grass in the CG treatment may have protected the soil from the direct action of animal trampling. Wheeler et al. (2002) hypothesized that an organic top layer may dissipate the force of cattle hooves on the soil surface, resulting in less compaction of the soil underneath. Although their research was performed in a distinct ecosystem, it is probable that the prostrate growth habit of *Brachiaria* grass established in the CG may be promoting a similar protection to the soil surface.

The structural degradation of Cerrado soils converted to grazing systems could be related to stocking rate. These results agree with those reported by Silva et al. (2003) in a study conducted on an irrigated rotational grazing system. They found that stocking rates $> 4.4 \text{ AU ha}^{-1}$ caused a significant increase in PR. In the present study, the increase in θ_{PR} was detected as the major cause for decreasing LLWR with grazing systems. The high total porosity of Cerrado

Oxisols and low D_b values (under natural conditions) make them very susceptible to compaction under inadequate management practices.

Even though these results confirmed the potential of the LLWR on assessing soil degradation of Brazilian Savanna after conversion to pasture, additional research is needed before generalizing the use of the LLWR index. Critical values for PR, aeration, θ_{FC} , and θ_{WP} for pasture growth used in the present study should not be taken as definitive. Abdel-Magid et al. (1987) observed that under severe stress of 20,000 hPa soil water suction (well beyond the nominal wilting point of 15,000 hPa), blue grama (*Bouteloua gracilis* (H.B.K.) Lag.) and western wheatgrass (*Agropyron smithii* Rydb.) produced aboveground biomass after a drying cycle. Gilker et al. (2002) found that root growth of Eastern Gamagrass (*Tripsacum dactyloides*) was not inhibited by high soil strength, being restricted by an air-filled porosity value $< 10\%$.

4. Conclusions

The LLWR was affected by grazing systems, being sensitive to the alteration in soil physical properties, and therefore, proving to be useful as an indicator of near-surface soil physical quality in Cerrado ecosystem. The short-duration grazing system on Tanzania grass had the most detrimental effect on soil physical quality while the continuous grazing was intermediate in effect. The soil structural degradation process could be related to the increase in stocking rates of the grazing systems. The increase in stocking rate increased bulk density, which increased the critical soil water content to reach soil penetration resistance of 3.0 MPa. This process was identified as the major cause of LLWR reduction. Thus, it is necessary to select correct stocking rates for rotational grazing systems in the Cerrado region in order to maintain the sustainability of these productive systems, preventing the necessity of new land clearings, and preserving the remaining Cerrado ecosystem.

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