



A remote sensing approach to estimate the load bearing capacity of soil

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ABSTRACT

Preconsolidation pressure (σ_p) of soil can be considered as an indicator of the Load Bearing Capacity (LBC), which is the tolerated surface pressure before compaction, often caused by the traffic of agricultural machinery. In this pioneering study, a remote sensing approach was introduced to estimate LBC through σ_p from soils of the “Rio Preto” Hydrographic Basin, Bahia State, Brazil, in a monthly time lapse from 2016 to 2019. Traditionally, σ_p is measured by a laborious and time demanding laboratory analysis, making it unfeasible to map large areas. The innovative methodology of this work consists of combining active-passive satellite data on soil moisture and pedotransfer functions of clay content and water matric potential to obtain geo-located estimates of σ_p . Estimates were analysed under different classes of soil use, land cover and slope; 95% confidence intervals were built for the time series of mean values of LBC for each class. The overall seasonal variation in LBC estimates is similar in areas with annual crops, grasslands and natural vegetation, and flat areas are less affected by soil moisture variations over the year (between seasons). LBC decreased, in general, at about 0.5% a year in flat areas. Therefore, these areas demand attention, since they occupy 86% of the Basin and are mostly subjected to agricultural soil management and surface pressure by heavy machinery.

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1. Introduction

In the last few decades, Brazil has established itself as a major global agricultural power due to the intensified incorporation of technologies and mechanized operations in the production process, allowing the expansion of the agricultural frontier,

especially in the Cerrado (Savanna) areas [1,2]. The high degree of soil weathering in the Cerrado promotes structural stability, which combined with the smooth topography, greatly favours soil management. On the other hand, incorrect management leads to structural degradation [3,4]. Therefore, it is necessary to have information about the potential for use and risk of damage of soils caused by different management systems, with the help of indicators that make it possible to keep or improve the soil physical quality [5].

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The preconsolidation pressure can be used as a measure of the load bearing capacity (LBC) of soil, that is, the tolerable upper limit of surface pressure that precedes irreversible soil compaction [6,7]. In regions where the applied surface pressure is low, there is low probability of compaction, and the soil undergoes small, elastic or reversible deformations. The LBC reflects the history of pressures that a soil has already suffered. LBC has been used [2,8–10] to predict pressure levels which can be applied to the soil under different water contents without further compaction and to quantify the effects of agricultural operations on soil structure. Furthermore, the propagation of surface pressures through the soil profile can also be predicted [11].

Traditional methods applied to assess physical status of soil are generally laborious, time demanding in the field, costly, and sometimes dependent on laboratory analysis, which is the case when measuring LBC through compression tests. Thus, the development of alternative techniques for assessing the mechanical behaviour and physical attributes of the soils is both technically and economically relevant [12]. Soil physical and structural assessments can be done using modern sensors, through their spectral responses [13–19]. However, there is still a gap regarding the use of remote sensing techniques to estimate LBC. In practice, mapping that soil attribute would increase the performance of soil management procedures and the appropriate land use, but it would rather be feasible only through a remote sensing approach based on sensor data and accurate pedotransfer functions. Some pedotransfer functions were developed for the Brazilian Cerrado soils [2], but with incipient application in remote sensing studies. And, to the best of our knowledge, none using remote sensing data to estimate LBC of Brazilian soils.

Watersheds represent areas of natural resources of remarkable importance in Brazil, but they have been commonly exploited for human activities, especially for farming. This is the case of the “Rio Preto” Hydrographic Basin, located in western Bahia, in the region known as MATOPIBA, an agricultural frontier in the Brazilian Cerrado known to be highly exploited for cultivation of annual crops. Mechanized operations applied to soils with high moisture content must be planned according to the estimated LBC [20] to avoid structural degradation of the soils, especially when the machinery crosses the same area more than once.

The objective of this study was to combine remote sensing techniques and data with pedotransfer functions developed for Brazilian soils to estimate the LBC of the “Rio Preto” Basin under the effects of different classes of soil use, land cover and slope.

The methodological part of the paper was organized in order to: (a) describe the hydrographic basin in terms of geographic and topographic characteristics, and type of vegetation; (b) describe how satellite data were managed to classify the hydrographic basin in classes of land cover and slope; and (c) to show how remotely-driven soil physical data were organized in a spatial grid to estimate LBC. The results were organized into sections that allow one to verify the effect of those classes on the temporal estimates of LBC.

2. Material and methods

2.1. Study area

The data used in this study were driven from the “Rio Preto” Hydrographic Basin, which covers an area of 23 223 km², centred at the coordinates 11° 3′ 37.01″ S and 45° 12′ 8.55″ W, and located in the west of Bahia State (BA), Brazil. It reaches the states of Tocantins (TO) and Piauí (PI), draining the municipalities of Formosa do Rio Preto - BA, Santa Rita de Cássia - BA, Mansidão - BA, Riachão das Neves - BA and Mateiros - TO (Fig. 1).

The climate of the region, according to the Koppen classification system, is Aw (semi-humid tropical with summer rains) with mean annual rainfall ranging from 800 to 1 700 mm [21]. The vegetation consists of the Brazilian Cerrado (savanna) domain with physiognomies ranging from dense trees (*Cerradão*) to grassy-woody plants [22]. Yellow Latosol, Quartzarenic Neosols, Neosols-Litolic, Hydromorphic Planossols, Red-Yellow Argisols, and Haplastic Gleysol [23] are the dominant soil classes.

The landscape varies from flat to smoothly undulating topography, which favours agricultural practices and high yields of crops under intensive conventional agriculture. The topography contributes to the expansion of crop cultivation in the region, mostly soybean, corn, cotton, and common beans.

The next subsections describe the process of sensor data processing and estimation of load bearing capacity of the soils of the Basin, which defines the innovative methodology. Fig. 2 gives a graphical summary of that process. Firstly, LANDSAT 8 products were used to determine three classes of soil use and land cover: Annual crops/Livestock, Forest/Savanna, Grassland/Pasture. Next, elevation data retrieved from the Shuttle Radar Topography Mission (SRTM) were used to classify the soils of the Basin in three classes: Flat and Slightly Wavy Relief, Wavy Relief, Steep Slopes and Cliffs. Afterwards, gridded data on soil moisture were retrieved from SMAP, combined with clay content (from SOILINFO) data and then used in pedotransfer functions to obtain geo-located estimates of LBC.

2.2. Classification of soil use, land cover and slope

The hydrographic basin was classified according to the following classes of soil use and cover: Annual Crops/Livestock, Forest/Savanna Formation, and Grassland/Pasture Formation. The classification was based on images obtained from the LANDSAT 8 Operational Land Imager (OLI) satellite, from the United States Geological Survey [24] Earth Explorer platform, using the following bands: B2 - blue (0.450–0.515 µm), B3 - green (0.525–0.600 µm), B4 - red (0.630–0.680 µm), B5 - near infrared (0.845–0.885 µm), B6 - mid-near infrared (1.560–1.660 µm) and B7 - mid infrared (2.100–2.300 µm) [25] (NASA, 2019). The images were pre-processed by transforming digital numbers into radiance and reflectance using the Dark Object Subtraction (DOS) method. A supervised classifier based on the Maximum Likelihood method was trained by manually annotating pix-

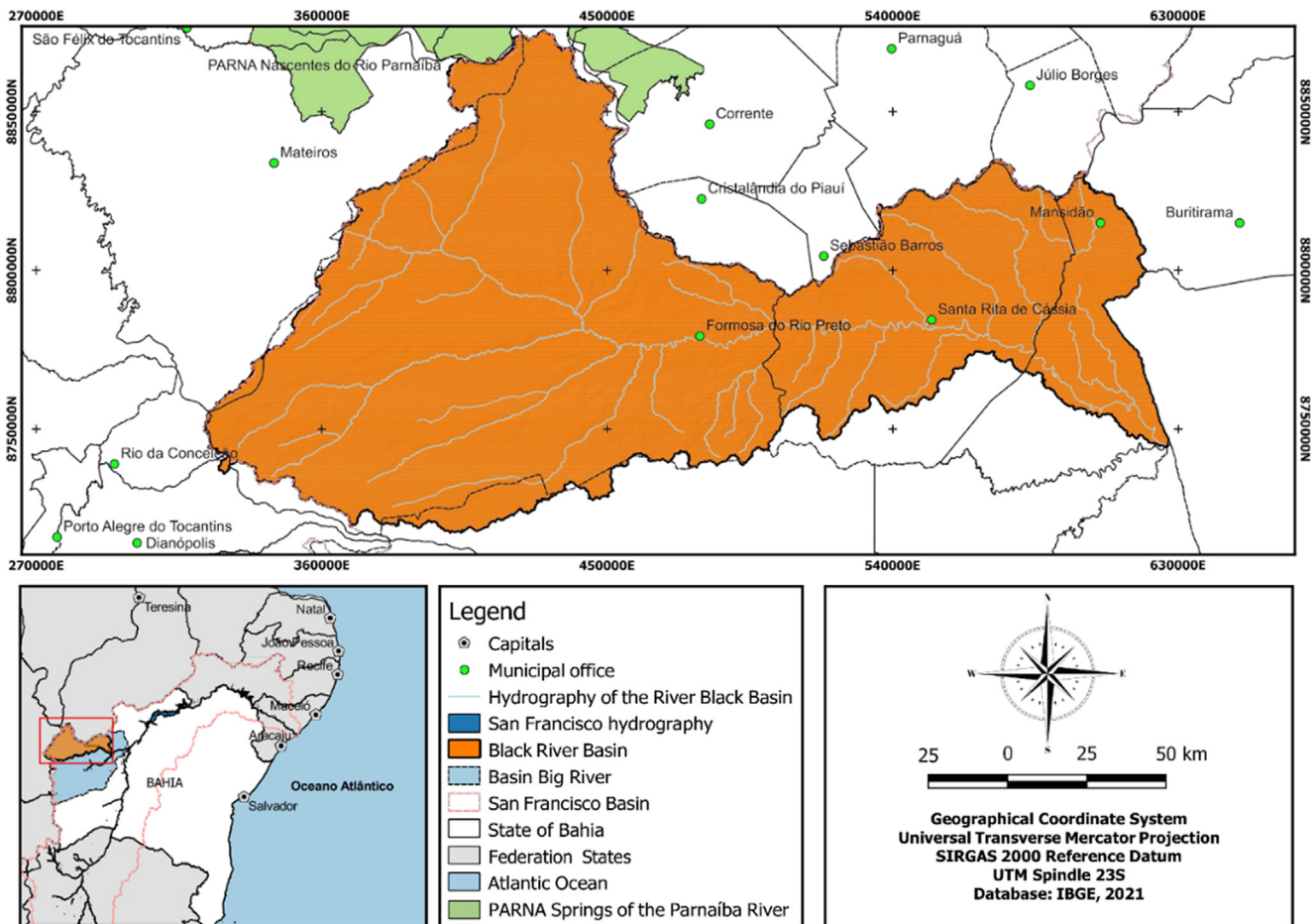


Fig. 1 – Location of the ‘Rio Preto’ Hydrographic Basin, western Bahia, Brazil.

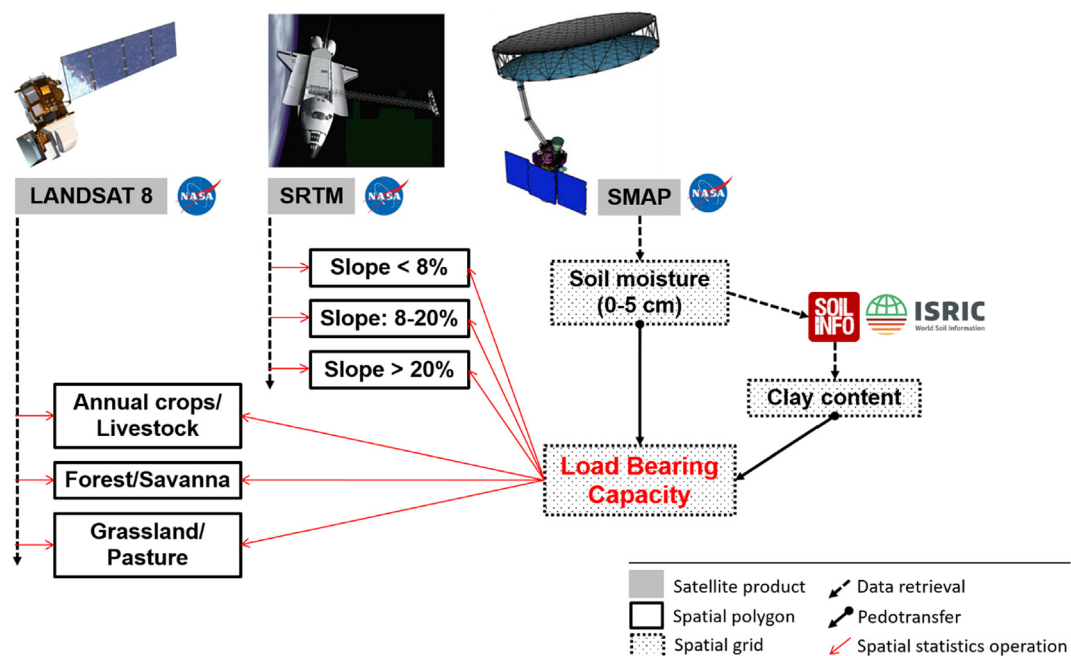


Fig. 2 – Flowchart of data processing for estimation of load bearing capacity of soil.

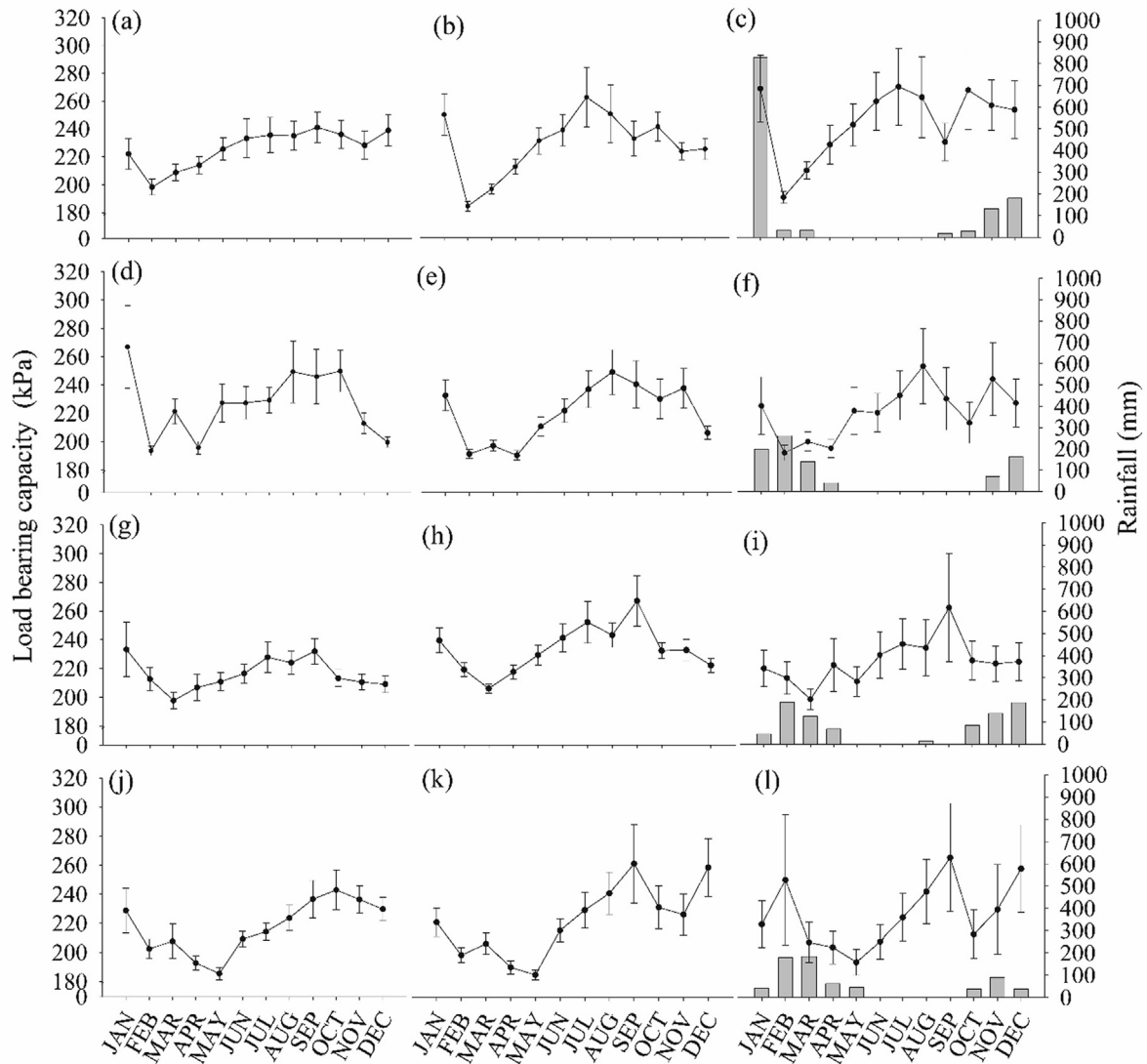


Fig. 3 – Predicted average load bearing capacity (kPa) of the soil classes of soil use and land cover. (a) Annual Crops/Livestock, (b) Forest/Savanna Formation, (c) Grassland/Pasture Formation in 2016; (d) to (f) the same soil classes in 2017, (g) to (i) in 2018; and (j) to (l) in 2019. Vertical lines indicate the 95% confidence interval for the mean. The same rainfall data were considered for all classes in a given year.

consequently contributes to the formation of compacted surface and subsurface layers.

Especially in the dry period (from August to September) of the last two years (2018–2019), soils cultivated with annual crops presented lower LBC than grasslands and natural vegetation. This is probably associated with the amounts of organic carbon (OC) and tillage practices at the surface layer, which reflects a greater potential for water retention and soil breakdown. Higher OC contents in the 0–3 cm soil layer provide greater potential for soil elasticity, contributing to the release of tensions [36]. Soils with high OC contents tend to be more resilient and have better structural recovery, which reflects lower mechanical strengths and low bulk density. Iori et al. found that soils under native forest presented higher values of LBC than soils cultivated with pasture, mainly due

to the higher clay contents of soils under native vegetation, as a consequence of greater cohesion between particles [10].

Animal trampling, inadequate stocking rates and animal overload, depending on the availability of forage and/or semi-intensive or intensive livestock practices, can be factors that cause structural change if soils are at higher limits of surface pressure [37]. In a medium term, they can exert pressures that can cause compaction in the rainy season and breakdown in the dry period. In a long term, they contribute to the irreversible degradation of soils and vegetation.

3.2. Land slope

Fig. 4 shows the mean estimates of LBC for three classes of land slope (<8%, 8%–20%, and > 20%), assessed monthly from

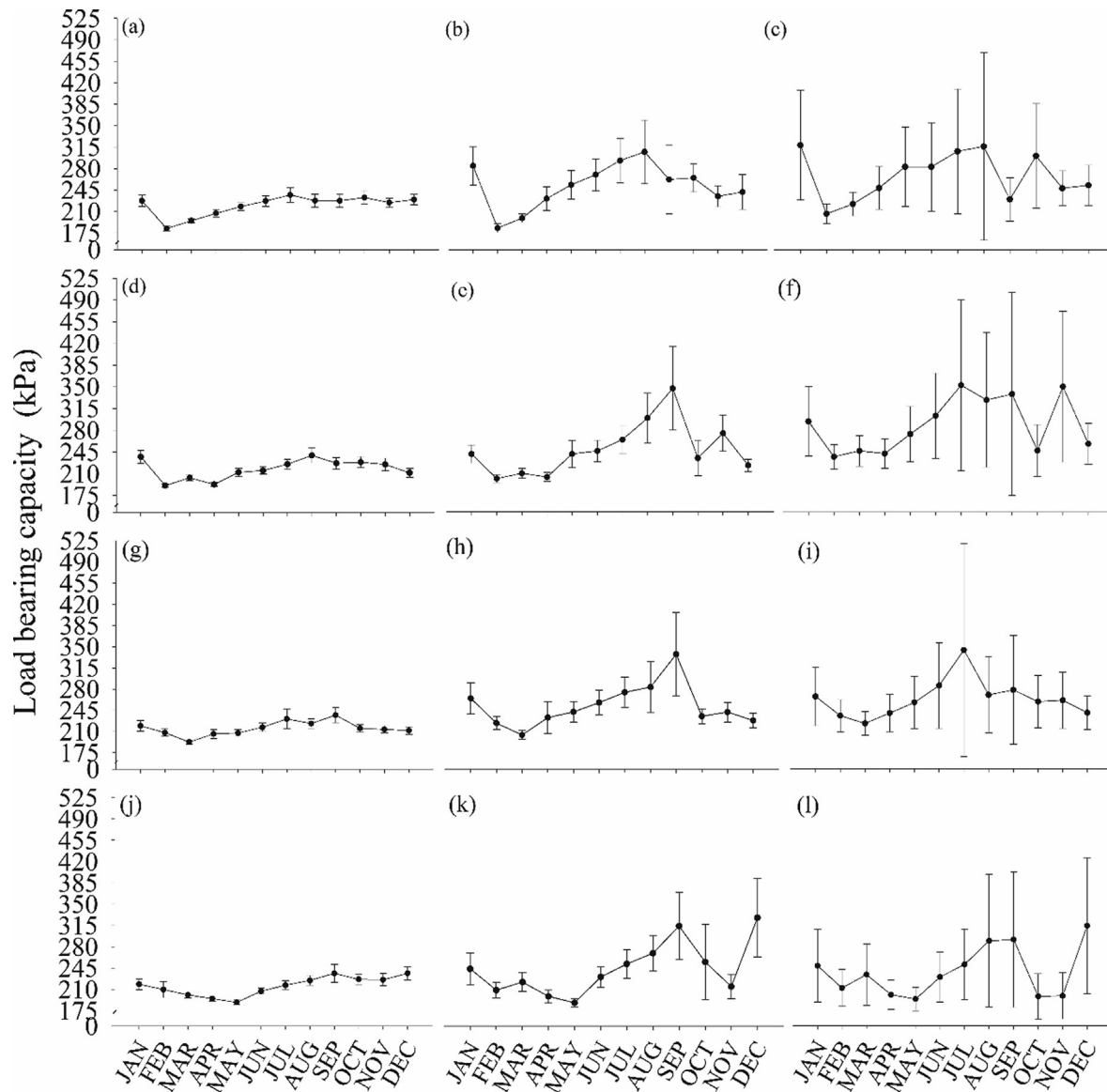


Fig. 4 – Predicted average load bearing capacity (kPa) of the soil classes of land slope. (a) < 8%, (b) 8%–20%, (c) > 20% in 2016; (d) to (f) the same classes in 2017; (g) to (i) in 2018; (j) to (l) in 2019. Vertical lines indicate the 95% confidence interval for the mean. The same rainfall data were considered for all classes in a given year.

2016 (top) through 2019 (bottom). Especially in the dry period, from May to September, significantly ($p < 0.05$) lower values were observed in areas with smooth topography (slope < 8%). On the other hand, areas with slope higher than 8% are more susceptible to water runoff, causing a reduction in the rate of water infiltration into the soil [38]. In addition, slope conditions the accumulation of soil carbon content, as observed by [39] in coffee plantations in flat areas (0%–3% slope).

About 86% of the Basin is flat to smoothly wavy, that is, slope < 8%. Nonetheless, the LBC estimates presented the lowest variability, based on confidence interval length. From July to September, areas with slope higher than 8% showed high variability of LBC.

In general, a temporal (2016–2019) reduction in LBC was observed for all classes of slope, in the following proportions: flat and smooth wavy reliefs (4 kPa or 1.8%); wavy reliefs

(3.32 kPa or 1.2%); and rugged, mountainous reliefs (0.74 kPa or 0.31%).

4. Conclusion

In this study, the load bearing capacity of the soils from the “Rio Preto” Hydrographic Basin, Brazil was estimated using active–passive satellite data on soil moisture and validated pedotransfer functions based on clay content and water matric potential. Estimates were analysed under different classes of soil use, land cover and slope from 2016 to 2019. The estimation is governed by soil moisture at the superficial layer (5 cm depth), and is more affected by land slope than soil use and land cover. The overall seasonal variation in LBC estimates is similar in areas with annual crops, grasslands and native vegetation of the Brazilian Cerrado. LBC esti-

mates in areas with slope < 8% are less affected by soil moisture variations over the seasons. In a four-year lapse, LBC decreased at about 1.8% in areas with slope < 8%. Therefore, these areas demand attention, since they are predominant in the Basin (86%) and mostly subjected to agricultural soil management and heavy machinery.

The approach presented in this work is pioneer and allows to map the dynamics of soil preconsolidation stress by combining validated predotransfer functions and satellite-driven data of physical properties. Future works shall be carried out to increase spatial resolution of soil moisture estimates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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