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Validation of SMOS L3 and L4 soil moisture products in the REMEDHUS (Spain) and CEMADEN (Brazil) networks

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ABSTRACT

This work analyzes the quality of the soil moisture L3 (25 km) and L4 (1 km) products generated at the Barcelona Expert Center (BEC) in two sites located in distinct semi-arid regions, where measurement networks are installed: “Red de Estaciones de Medición de la Humedad del Suelo” (REMEDHUS), which is located in the central part of the Duero basin (Spain), and National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), at Northeast of the Brazil. REMEDHUS has been used as a calibration/validation site for SMOS and SMAP missions. It is a dense network covering 35 x 35 km² and it has 22 stations. The CEMADEN network provides a database for the development of early warnings for natural disasters that occurs in Brazil, such as droughts and floods. It is a sparse network covering 1000 x 1000 km² with more than 500 station. Results show good correspondence between SMOS L4 data and the in situ soil moisture data for REMEDHUS and CEMADEN networks. Correlations mean range from 0.3 to 0.8, and depend mainly on the station situation, soil type, and land cover on both Spain and Brazil networks. For the average data of both series, the correlation coefficient is higher than 0.6. Results show that the L4 product are better correlated than the L3 product, although L4 and L3 products are quite similar. This indicates that both products are ready for its operational use, with L4 providing a better representation of the soil moisture status at finer scales.

Key-words: soil moisture, SMOS satellite, validation, REMEDHUS, CEMADEN.

Validação de produtos de umidade do solo, SMOS L3 e L4, nas redes REMEDHUS (Espanha) e CEMADEN (Brasil)

RESUMO

Este trabalho analisa a qualidade dos produtos L3 (25 km) e L4 (1 km) de umidade do solo gerados no Barcelona Expert Center (BEC) em dois locais localizados em regiões semi-áridas distintas, onde estão instaladas redes de medição: “Estações de Medição de Umidade do Solo” (REMEDHUS), localizado na parte central da bacia do Douro (Espanha), e Centro Nacional de Monitoramento e Aviso Prévio de Desastres Naturais (CEMADEN), no nordeste do Brasil. O REMEDHUS foi usado como um local de calibração / validação para missões SMOS e SMAP. É uma rede densa cobrindo 35 x 35 km² e possui 22 estações. A rede CEMADEN fornece um banco de dados para o desenvolvimento de alertas precoces de desastres naturais que ocorrem no Brasil, como secas e inundações. É uma rede esparsa cobrindo 1000 x 1000 km² com mais de 500 estações. Os resultados mostram boa correspondência entre os dados SMOS L4 e os dados de umidade do solo in situ para as redes REMEDHUS e CEMADEN. As correlações variam de 0,3 a 0,8 e dependem principalmente da situação da estação, tipo de solo e cobertura do solo nas redes da Espanha e do Brasil. Para os dados médios de ambas as séries, o coeficiente de correlação é superior a 0,6. Os resultados mostram que o produto L4 está melhor correlacionado que o produto L3, embora os produtos L4 e L3 sejam bastante semelhantes. Isso indica que ambos os produtos estão prontos para seu uso operacional, com L4 fornecendo uma melhor representação do status de umidade do solo em escalas mais refinadas.

Palavras-chave: umidade do solo, satélite SMOS, validação, REMEDHUS, CEMADEN.

Introdução

In the last decades, a number of research efforts have focused on the development of remote sensing techniques to characterize soil moisture (SM) over large areas. It has been demonstrated that the protected microwave L-band is very sensitive to the soil moisture present in the land surface (top 5 cm). Nowadays, remote sensing data from satellites gives the opportunity to have soil moisture measurements with enough spatial and temporal resolutions to serve global applications. Consequently, several approaches have been developed to retrieve land surface soil moisture using satellite measurements at different scales. Nevertheless, validation of these soil moisture products is difficult, mainly due to its dynamic nature, the heterogeneity of the land surface, and the scarce number of available in-situ measurements (Schmugge et al., 1974; Jackson et al., 1984; Entekhabi et al., 1994; Reichle et al., 2004; Jackson et al., 2012; Albergel et al., 2012; Piles et al., 2014; González-Zamora et al., 2016; Gumuzzio et al., 2016; Barella-Ortiz et al., 2017; Sabater et al., 2017; Mousa e Shu, 2020; Portal et al., 2020).

SMOS (Soil Moisture and Ocean Salinity) mission, launched on November the 2nd 2009 by the European Space Agency (ESA), obtains frequent soil moisture and ocean salinity global maps using microwave radiometry at L band. This band is not affected by the presence of clouds and is appropriate for monitoring moisture in regions covered by sparse to quite dense vegetation (Kerr et al., 2001).

Soil moisture product is provided by the SMOS Barcelona Expert Center, which algorithm is developed for retrieving high resolution soil moisture maps from low resolution SMOS SM maps.

Thus, the aim of this paper is to validate the SMOS SM L3 (25 km) and L4 (1 km) operational

products produced at Barcelona Expert Center (<http://bec.icm.csic.es/land-datasets/>) over two different semiarid regions, in which in-situ measurements are available, in both sites a measurement network is installed: REMEDHUS (in Spain) and CEMADEN (in Brazil). The two networks are different and complementary: REMEDHUS is a dense network having 25 stations within a SMOS pixel, and CEMADEN is a sparse network covering more than 1000 pixels, having 1 station within a pixel. In this paper, a study of the temporal evolution of the soil moisture at both sites for year 2015 is presented. Even though they are examples of semiarid regions, they are very different sites: REMEDHUS is settled a typical semiarid Mediterranean area meanwhile CEMADEN is installed on Tropical semiarid region. In addition, it is a dense (REMEDHUS) and sparse (CEMADEN) networks. In the study, BEC products are compared to in-situ data from these two networks. A statistical analysis is performed to quantify the accuracy of the SMOS products, doing a matching comparison between the two datasets (satellite and in-situ). A detailed description of the study areas is presented in section 2, relating type of soil, texture, vegetation and probe. Section 3 shows the results obtained from BEC products and in-situ measurements comparison. Finally, the derived conclusions are summarized in section 4.

Material and methods

Study area

The situation of selected areas for this study, is shown in Figure 1. REMEDHUS is on the Iberian Peninsula (red area), while CEMADEN covers a semiarid area in Northeast Brazil (green area).

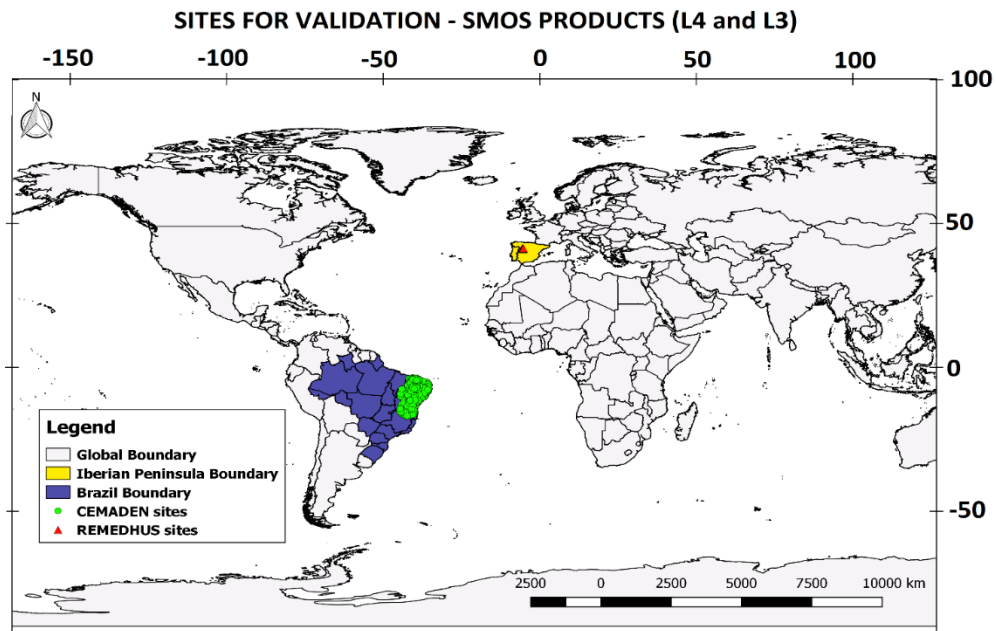


Figure 1: Location of the study area for validation of BEC soil moisture products. CEMADEN network is on the Brazilian semiarid region (in green), and REMEDHUS (in red) covers a semiarid area in the central part of the Duero basin, in Spain.

REMEDHUS Network

The Red de Estaciones de MEDición de la Humedad del Suelo (REMEDHUS) is located in the semiarid region of the central Duero Basin (41.1° to 41.5° N and 5.1° to 5.7° W in Spain)

and covers an area of 1300 km². It has 22 operational soil moisture stations. Figure 2 illustrates the locations of these stations within the Iberian Peninsula.

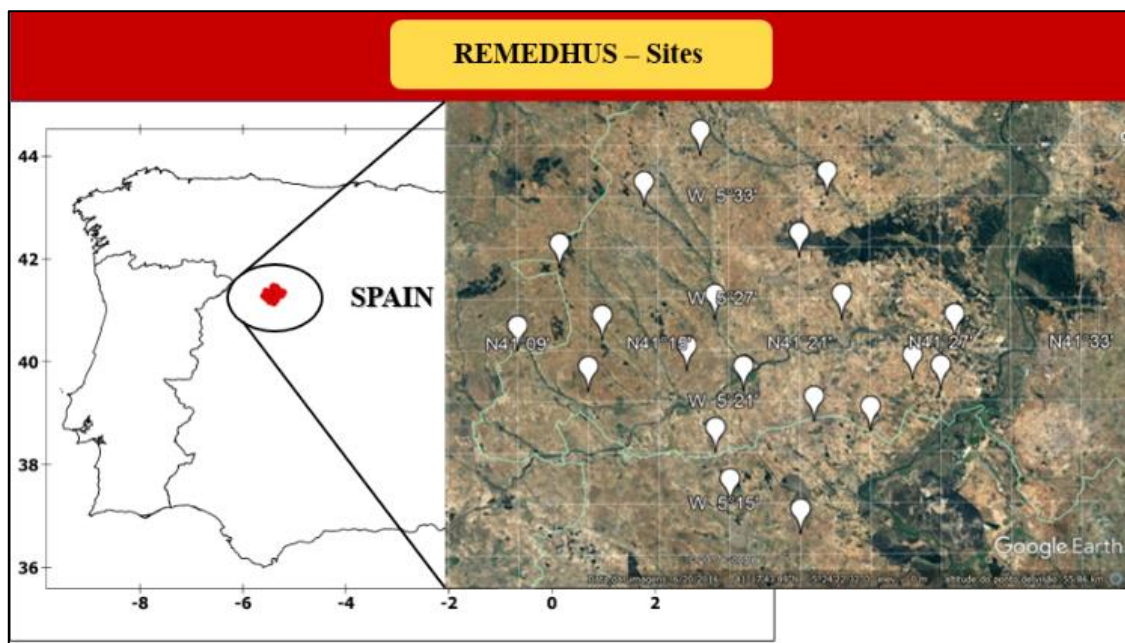


Figure 2: Location of the REMEDHUS (Spain) Network used for validation BEC products (L3, 25 km and L4, 1 km).

This network provides intensive observations over a 35 km × 35 km area, which makes it suitable for calibration and validation of instruments on-board of satellites (Sánchez et al.,

2012). The REMEDHUS soil moisture network has been largely selected for SMOS calibration/validation (Cal/Val) studies. It covers an area of approximately a SMOS pixel size (40 x

30 km). The real-time measurements of soil moisture profiles were obtained in 20 stations with Hydra probes, that measure with an accuracy of 0.003 m³/m³ for soil moisture, with depth of 0-5 cm. The instrument used at each station is the Theta Probe, which is able to perform continuous measurements of the volumetric moisture of the soil. General Packet Radio Service (GPRS) modems are used for controlling and managing the network, as well as for remotely transferring the data.

The REMEDHUS soil moisture network has been largely used for calibration and validation in many field campaigns mostly of them related to

SMOS and SMAP missions (Dorigo et al., 2011; Sánchez et al., 2012; Sánchez-Ruiz et al., 2014).

According to Sánchez et al. (2012), the REMEDHUS average annual precipitation is 385 mm and its mean temperature is 12°C, and typical features of the continental semiarid Mediterranean climate are registered. The land use is mainly agricultural, crop fields, and vineyards. There are also patchy areas of forest and pasture. Measurement stations at REMEDHUS are related in Table 1. It encloses information about geographical situation and soil type.

Table 1: Table 1: Description of the 20 REMEDHUS sites selected (complete series), including symbol, geographic coordinate and soil physic properties (percentage of sand, loam and clay).

Names	Symbols	Latitude	Longitude	Sand	Loam	Clay
<i>Canizal</i>	K13	41.20	-5.36	-	-	-
<i>Carretoro</i>	K10	41.27	-5.38	91.16	5.71	3.13
<i>Casa Periles</i>	M5	41.40	-5.32	81.64	8.31	10.05
<i>Consejo del Monte</i>	N9	41.30	-5.25	62.46	16.78	20.76
<i>El Coto</i>	I6	41.38	-5.43	89.81	5.93	4.26
<i>El Tomillar</i>	H7	41.35	-5.49	85.1	9.64	5.26
<i>Granja G</i>	K9	41.31	-5.36	74.36	15	10.64
<i>Guarrati</i>	H9	41.29	-5.43	19.78	44.99	35.23
<i>La Atalaya</i>	J14	41.15	-5.40	66.81	20.98	12.21
<i>La Cruz de Elias</i>	M9	41.29	-5.30	49.83	24.89	25.28
<i>Las Arenas</i>	F6	41.37	-5.55	67.19	13.7	19.11
<i>Las Bodegas</i>	H13	41.18	-5.48	70.36	11.45	18.19
<i>Las Brozas</i>	L3	41.45	-5.36	82.25	6.44	11.31
<i>Las Eritas</i>	J12	41.21	-5.41	60.94	16.85	22.21
<i>Las Tres Rayas</i>	E10	41.28	-5.59	75.11	16.35	8.54
<i>Las Vacas</i>	O7	41.35	-5.22	78.84	13.47	7.69
<i>Las Victorias</i>	K4	41.43	-5.37	87.09	9.27	3.64
<i>Llanos de la Boveda</i>	L7	41.36	-5.33	46.8	20.78	32.42
<i>Paredinas</i>	J3	41.46	-5.41	85.05	11.26	3.69
<i>Zamarrom</i>	F11	41.24	-5.54	81.52	11.97	6.51

Most of its territory is made up of extensive herbaceous crops or natural vegetation. Traditionally, land use databases (Crop and Harvest Map of Spain, Land Use Information System -SIOSE-, Corine Land Cover) have been classified as extensive arable crop areas into homogeneous categories without specifying the crop or species, with a homogeneous land cover (80% crops). It counts with a complete and operational network with sensors for measuring temperature and soil moisture (Piles et al., 2009). The general classification of soil includes crops and natural surfaces and it is shown in Figure 2.

This classification map has been generated for 2011, 2012, 2013 and 2014 and can be downloaded at

<http://www.mcsncyl.itacyl.es/es/descarga>. In this study, the 2014 classification map, presented at Fig. 3, has been used.

Nowadays, these maps are generated using information from images of the Satellites Deimos-1 (2011-2016), Landsat 8 (2013-2016) and Sentinel-2A (2016). According to Medina and García (2015), starting in 2017, the spatial resolution of the product is expected to improve from 20 m to 10 m. Nevertheless, this improvement will depend on the availability of Sentinel-2A images. For the classification, it will be used a computer learning algorithm with different information, such as terrain elevation, slope, annual mean rainfall, and land use.

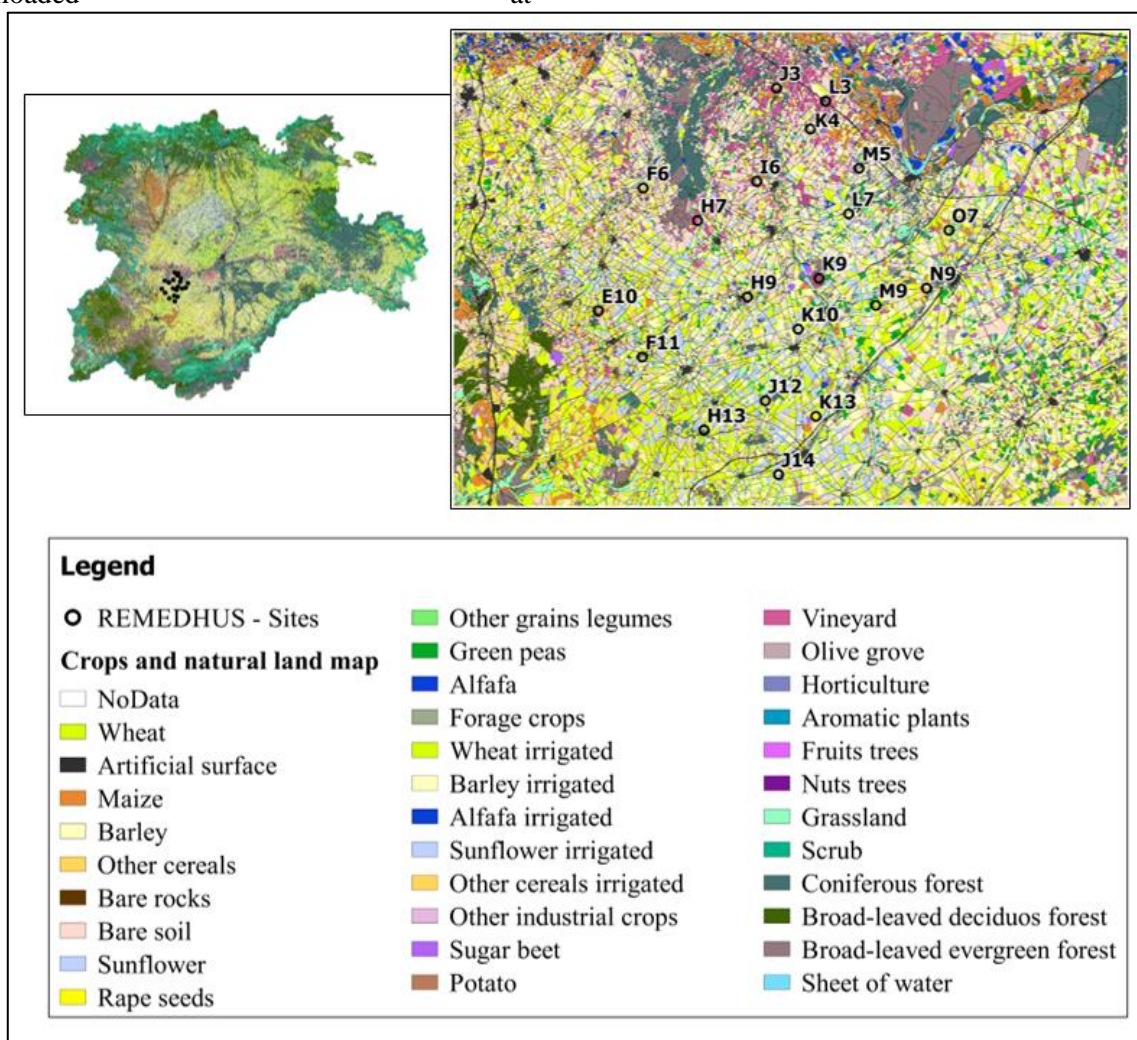


Figure 3: General view of the land cover map (crops and natural surfaces) of Castilla y León in 2015. Scale 1: 5.500.000 (<http://www.mcsncyl.itacyl.es/es/descarga>), with the situation of the stations.

Figures 4 and 5 present soil characteristics: the classic soil typology (Fig.4) and alphanumeric textures map (Fig. 5) of the Institute of Natural

Resources and Agrobiology of Salamanca (IRNASA).

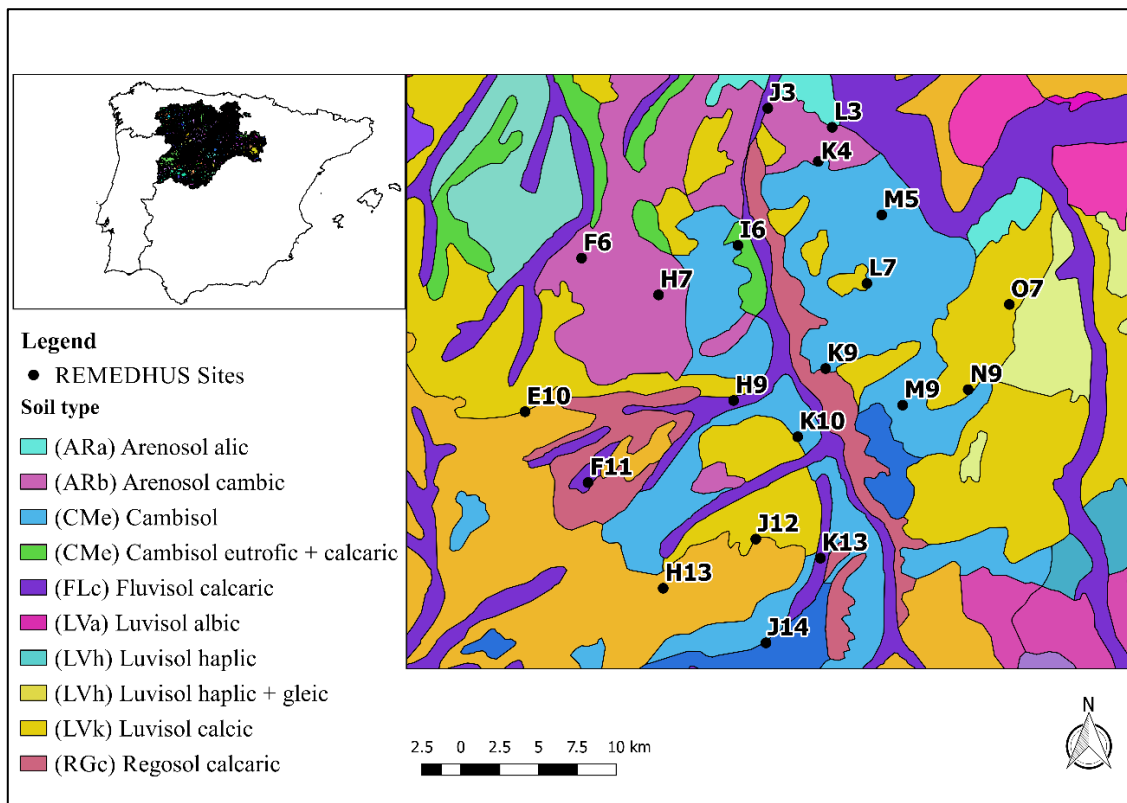


Figure 4: General view of the soil types of Castile and Leon in 2014 for REMEDHUS sites. The symbols of the sites are described in Table 1. Scale 1: 5.500.000.

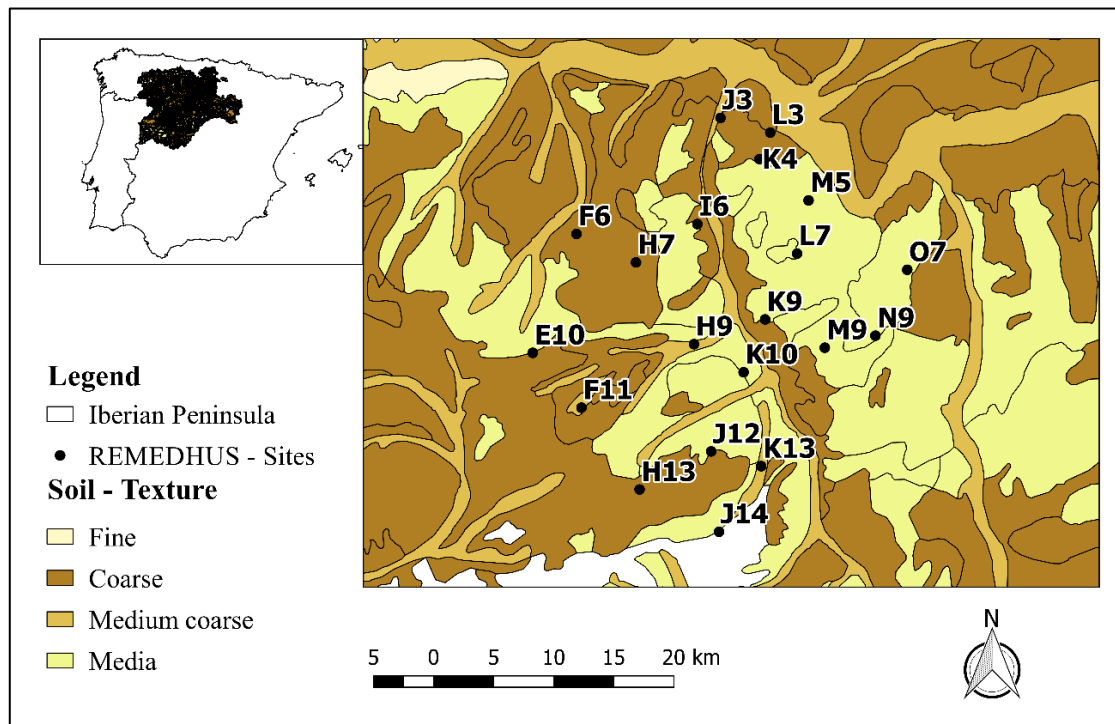


Figure 5: Soil texture map for REMEDHUS sites. The symbols of the sites are described in Table 1. (IRNASA, 2014).

CEMADEN Network

The in situ measurements are obtained from National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), which

is located in Brazil. It has a multidisciplinary team of professionals from different areas, such as meteorologist, hydrologist, engineers, and other

specialists on natural disasters and real time alerts on research and real time alerts.

The CEMADEN in-situ measurements network (Fig. 6) is located in the Northeast Brazilian Semi-arid region. Its information is accessible in real time at <http://www.cemaden.gov.br/mapainterativo/#>.

Each DCP (Data Collection Platform) registers the accumulated precipitation for the last 24 hours and for the accumulated rain during the last seven days. A description of the stations located at the Brazilian Semi-arid region (including code, name and geographic coordinates) is shown in Table 2.

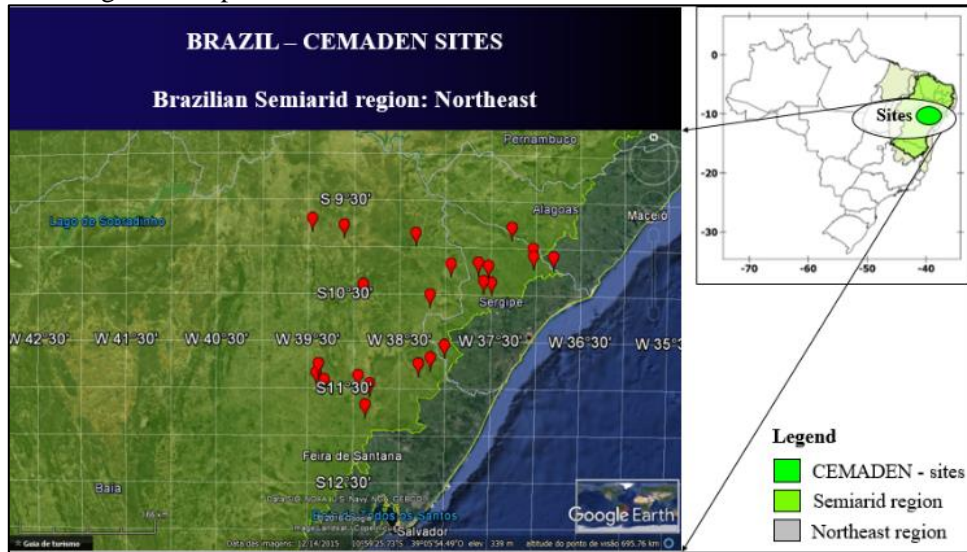


Figure 6: Location of the CEMADEN Network (Brazil) used for validation of SMOS-BEC products. The symbols of the sites are described in Table 2.

Table 2: Location of the 23 CEMADEN sites in Brazilian Semi-arid of the Northeast region, settled at Bahia (BA) and Sergipe (SE) States.

Latitude	Longitude	Stations (CEMADEN)	Symbols	State
-10.23	-37.03	Aquidabã	AQ	Sergipe
-11.59	-38.82	Biritinga	BI	Bahia
-10.14	-37.03	Canhoba	CA	Sergipe
-9.92	-39.11	Canudos	CAN	Bahia
-10.30	-37.64	Carira	CAR	Sergipe
-11.55	-39.32	Conceição do Coité	CON	Bahia
-10.32	-37.94	Coronel João Sá	CO	Bahia
-10.54	-38.90	Euclides da Cunha	EU	Bahia
-10.65	-38.17	Fátima	FA	Bahia
-10.50	-37.58	Frei Paulo	FR	Sergipe
-11.32	-38.16	Itapicuru	IT	Bahia
-10.00	-38.33	Jeremoabo	JE	Bahia
-11.82	-38.87	Lamarão	LA	Bahia
-10.33	-37.53	Nossa Senhora Aparecida	NO	Sergipe
-11.38	-38.29	Olindina	OL	Bahia
-9.92	-37.27	Porto da Folha	PO	Sergipe
-10.23	-36.80	Propriá	PR	Sergipe
-11.48	-39.40	Retirolândia	RE	Bahia
-10.51	-37.49	Ribeirópolis	RI	Sergipe
-11.51	-38.95	Teofilândia	TE	Bahia
-11.18	-38.00	Tobias Barreto	TO	Sergipe
-9.85	-39.46	Uauá	UA	Bahia
-11.38	-39.38	Valente	VA	Bahia

Actually, 500 DCP are operating in the Brazilian Semiarid region. These DCP, called DCP-Aqua, are provided with data logger, Global Position System (GPS), one rain gauge, soil moisture sensors at two depths (10 and 20 cm), besides other instruments for communication and solar power module. Besides there are other 95 DCP-Agro, with one cabinet for the data logger, GPS and temperature and soil moisture sensor at different depths (10, 20, 30 and 40 cm). More detail can be found in Celaschi and Xavier Jr (2016).

The Brazilian semiarid region has more than 1100 municipalities, covering an area of 969,589.4 km², which is distributed over nine states of Brazil: Alagoas, Bahia, Ceará, Minas Gerais, Paraíba, Pernambuco, Piauí, Rio Grande do Norte and Sergipe. Considering the territorial dimension of each State, 92.97% of the territory of Rio Grande do Norte are in the semiarid region, 87.60% of Pernambuco, 86.74% of Ceará, 86.20% of Paraíba, 69.31% of Bahia, 59.41% of Piauí, 50.67% of Sergipe, 45.28% of Alagoas and 17.49% of Minas Gerais. As highlighted by Brazilian Institute of Geography and Statistics (IBGE), there are over 22 million people living in the region. Furthermore, this region has a variety of agricultural systems

with different soil types, topography and rainfall patterns (INSA, 2014).

The availability of water in the soil is crucial for agricultural production in Semiarid northeast, becoming the most limiting factor to achieve high agricultural productivity. Furthermore, the extreme variability of climatic conditions also influences on agricultural productivity, due to water supply to plants. Plants needs enough water to achieve good crop yield production or as in the recent years in the region, extremely low water supply can derive to total crop failure (Antonino et al., 2000).

One of the Brazilian Semiarid landscape features is the vegetation of Caatinga (as shown Figure 7, in dark green), which is a biome with great biodiversity. Because of an inappropriate use of the resources combined with climate change and the specific soil characteristics, these areas may lead to a desertification process and a gradual loss of soil fertility. Consequently, these inappropriate land uses combined with change climatic variations can generate a desertification process. Actually, this region is being influenced by the impact of desertification, as shown in Figure 8 (IBGE, 2016).

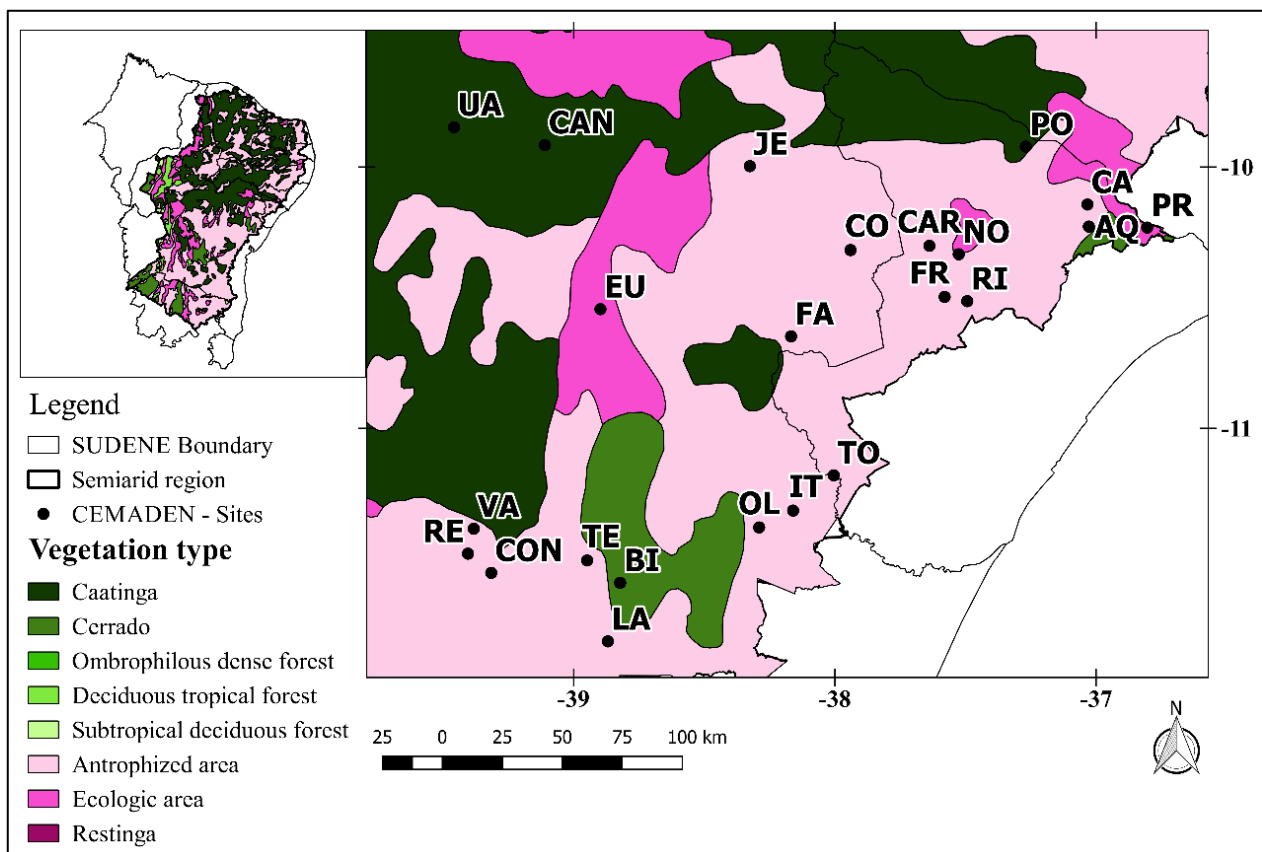


Figure 7: Brazilian Semiarid Biome Map, obtained from Brazilian Institute of Geography and Statistics, for CEMADEN sites (IBGE, 2016). The symbols of the sites are described in Table 2.

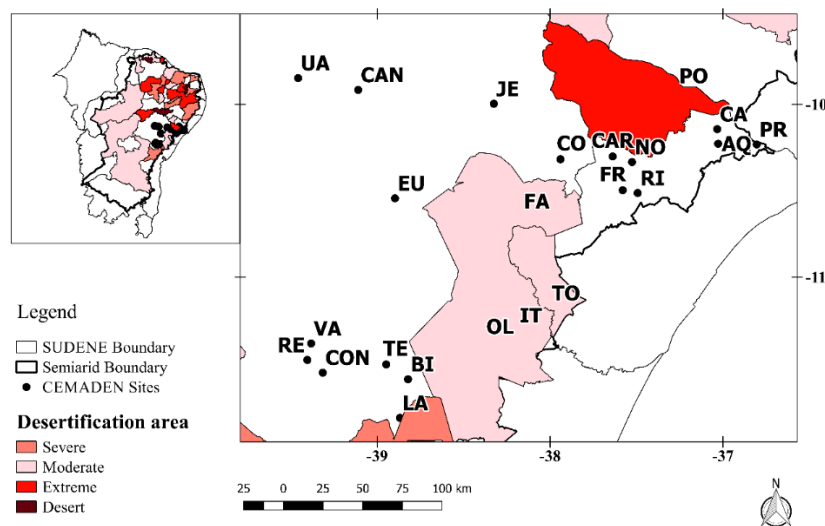


Figure 8: Areas of desertification at the Brazilian Semi-arid for study area (IBGE, 2016). The symbols of the sites are described in Table 2.

As observed in the previous figures, CEMADEN sites are located in areas whose biomes are Caatinga, Cerrado, anthropic, and ecological areas. In this area, changes in land use has been recently observed, which are affected at different desertification levels: moderate, severe and extreme.

Moreover, it is important to know the soil type of the Brazilian Semi-arid for soil moisture analysis. Figure 9 illustrates the main soil type for CEMADEN sites (IBGE, 2016): Haplic Cambisol - CX (1), Red-Yellow Argisol - PVA (6); Yellow Latosol LA (1); Chromic Luvisol - TC (2); Natric Planosol - SN (2); Haplic Planosol - SX (6); Litolic Neosol - RL (5).

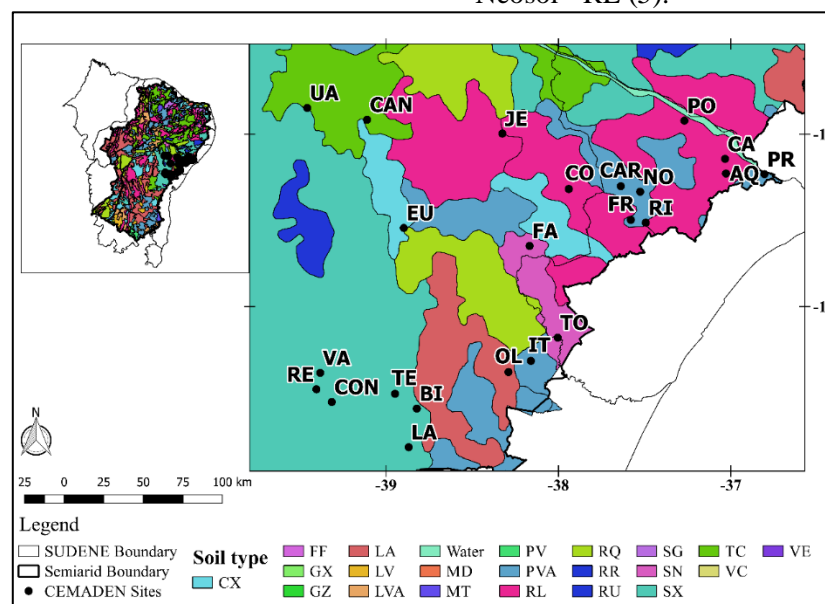


Figure 9: Brazilian Semi-arid Soil Map obtained from Brazilian Institute of Geography and Statistics (IBGE, 2016). Legend: CX – Haplic Cambisol; FF – Petric Plinthosols; GX – Haplic Gleysols; LA – Yellow Latosol; LV – Red Latosol; LVA – Red-Yellow Latosol; MD: Chernosol Rendzico; MT – argiluvic Chernosol; PV – Red Argisol; PVA – Red-Yellow Argisol; RL – Litolic Neosol; RQ – Quartzenic Neosol; RR – Regolitic Neosol; RU – Fluvic Neosol; SG - Hydromorphic Planosol; SN – Natric Planosol; SX – Haplic Planosol; TC – Chromic Luvisol; VC – Chromic Vertisol; VE – Ebanic Vertisol. The symbols of the sites are described in Table 2.

Other characteristic of the Brazilian semiarid region is also the large spatial and temporal variability of rainfall and successive droughts (Moura and Shukla, 1981; Tenorio, 1989; Hastenrath, 2006). The synoptic systems, such as frontal system, cyclone vortices of high levels (UTCv) and the South Atlantic Convergence Zone (SACZ), are responsible by occurrence of heavy rain in this semiarid region. Other atmospheric systems acting in the Northeast of the Brazil (NEB) are Intertropical Convergence Zone and Easterly Waves Disturbances. These phenomena are related with rainfall in a directly or indirectly manner over the NEB region. Also, the positive and negative precipitation anomalies over the south of the Northeast are associated with positive and negative phases of the ENSO phenomena, respectively (Hastenrath, 2012; Marengo et al., 2013, 2016).

An analysis of the variability of the rainfall in Brazilian semiarid region is presented by Molion and Bernardo (2002). They observed that the North Northeast region (includes part of Ceara, Maranhão, Rio Grande do Norte, Paraíba, Piauí, and Pernambuco States) is characterized with maximum rainfall in March. The rainfall extends

from February and May (FMAM), with values of 400 mm/year for the interior and more than 2,000 mm/year for coastal area. On the southern part (which covers the State of Bahia, the north of Minas Gerais, the northwest of Espírito Santo, the southern parts of the Maranhão and Piauí and the extreme southwest of Pernambuco), the rainfall varies from 600 mm/year (interior) to more than 3,000 mm/year (coastal) for the period between the months of November to February. Another area known as the Zona da Mata (since Rio Grande do Norte until south of Bahia) has annual rainfall totals ranging from 600 to 3000 mm. Its wettest period corresponds from April to July, with peak rainfall in May. The variability of rainfall in the Northeast of Brazil has a strong influence on agriculture, as highlighted by Silva et al. (2012).

According to Marengo et al. (2009, 2016), severe droughts caused by climatic variations impair crop growth and, consequently, cause serious social problems (especially for the majority of the population living in the region in extreme economic difficulty). Figure 10 illustrates areas with the percentage of drought index in the Brazilian Semiarid region (IBGE, 2016).

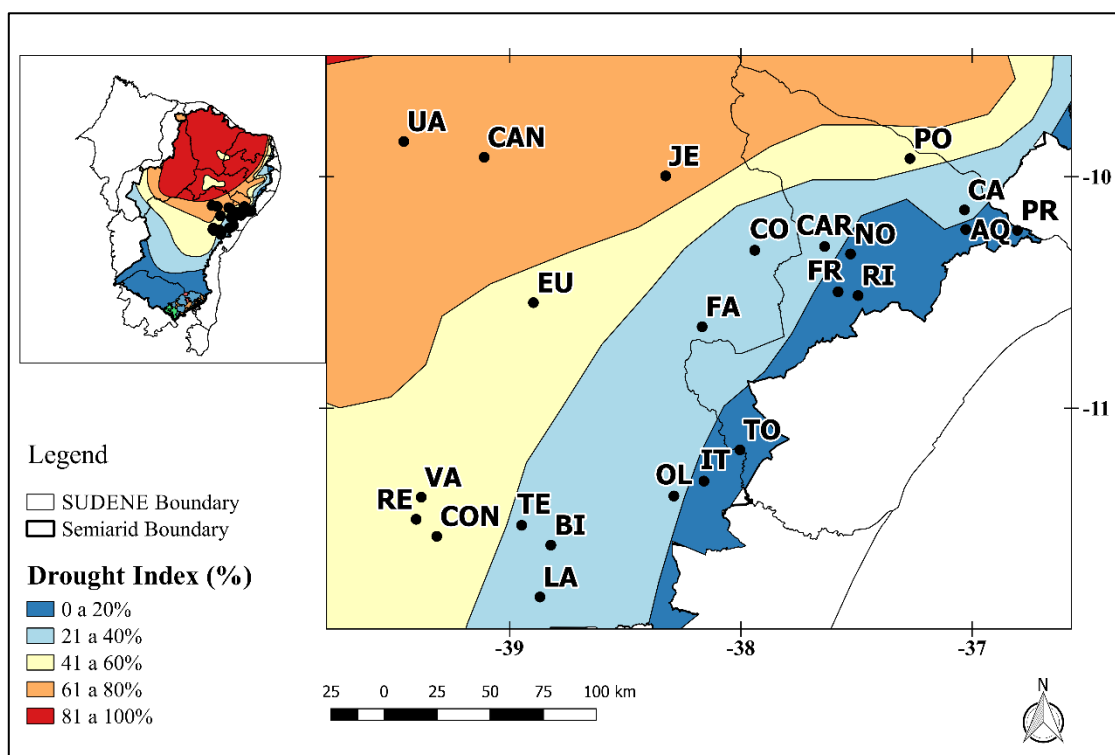


Figure 10: Percentage of drought index for Brazilian Semiarid region (IBGE, 2016). The symbols of the sites are described in Table 2.

Thus, millions of farmers are submitted to the risk of drought, and, consequently with possible loss of food. The semiarid population is conditioned to survive mainly on economic

activities connected to livestock and agriculture in a highly vulnerable environment. It in general seeks the best possible utilization of the adverse natural conditions, although supported in a weak

basic technique using, in most cases, traditional technologies (SUDENE, 2014).

BEC Products

Land surface products obtained from the ESA's SMOS satellite are generated at different levels. Level 0 data are raw data. Level 1A data are calibrated visibilities obtained from correlation between signals measured by antenna receivers before applying image reconstruction in full polarization (pole-to-pole time based segments). Level 1B Brightness Temperature is the output of the image reconstruction, which consists of the Fourier components of brightness temperatures in the antenna polarization. Level 1C Brightness Temperatures are brightness temperatures obtained at the top of the atmosphere from measurements at multi-incidence angle of the same spot and geolocated to a system equal gridded. Datasets are provided for land and sea pixels. Level 1C is a product based on averaged of the brightness temperatures, considering 42.5° of incidence angle. Level 3 and L4 Barcelona Expert Centre (BEC) daily products are maps of soil moisture available at 25 km (global scale) and 1 km (Iberian Peninsula, South Africa and Ghana). The ascending orbits are processed separately from the descending ones and the maps are provided at global scale. 3-days average, 9-days average, monthly and annual maps of soil moisture are constructed using spatial averaging of all available orbits of ESA L2 SMOS data. In this study Soil Moisture Level 3 and cloud-free Level 4 products are compared with in-situ soil moisture measurements.

SM Level 4 product is produced using an algorithm developed at BEC (first proposed in Piles et al. 2011, then upgraded in Piles et al., 2014) for retrieving high resolution soil moisture (HR SM) maps (1km) from low resolution SMOS SM maps (SMOS-BEC L3 at 25km, in this paper). This method is based on the "Universal Triangle" concept, establishing a relationship of Land Surface Temperature and Normalized Difference Vegetation Index parameters to soil moisture status (Dobson et al., 1985; Petropoulos et al., 2009, Piles et al., 2014). The BEC algorithm adds also SMOS

brightness temperature maps at vertical and horizontal polarizations. Consequently, the downscaling algorithm for obtaining high resolution soil moisture maps, uses several variables derived from satellite data at different spatial resolution (LST and NDVI at high resolution and SM and brightness temperature at low resolution) and at different bands. In its cloud-free version, ERA-Interim data from ECMWF is used for gap-filling MODIS LST. For the comparison, daily in-situ soil moisture measurements were compared with satellite-based soil moisture data provided by BEC at 0.25° and 0.01° degree for L3 and L4 products, respectively for year 2015.

A statistical analysis was accomplished, including the correlation coefficient (R), root mean square error (RMSE), BIAS and slope, has been done for each station of the REMEDHUS and CEMADEN sites.

Results and discussion

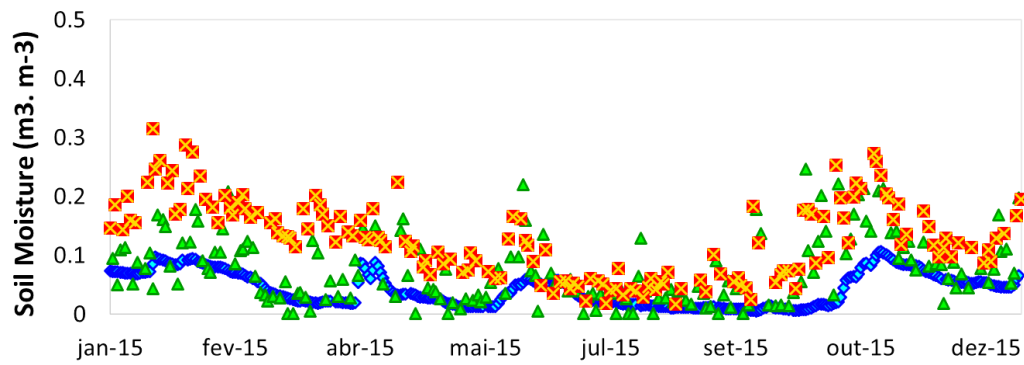
The results are presented in Table 3 for REMEDHUS site and in Table 4 for CEMADEN. The study has been development for both overpasses, ascending and descending separately.

Firstly, results in REMEDHUS are presented. In general, there is a good statistical agreement between in-situ and BEC datasets. When analyzing SM L3 product for ascending the best results are obtained at stations Carretoro, Granja G, La Atalaya, La Cruz de Elias, Las Arenas, Las Bodegas, Las Eritas, Las Vacas, Paredinas and Zamarron stations. L4 products ascending pass, follow similar behavior for almost all the stations, except for El Tomillar, Las Bodegas and Las Tres Rayas, which have correlation coefficient values above 0.5. For the descending pass, we have observed that only 2 station have high correlation with L3 product, La Atalaya and Zamarron (Gonzalez et al., 2015). Then, in REMEDHUS the conclusion is that ascending results are better than descending.

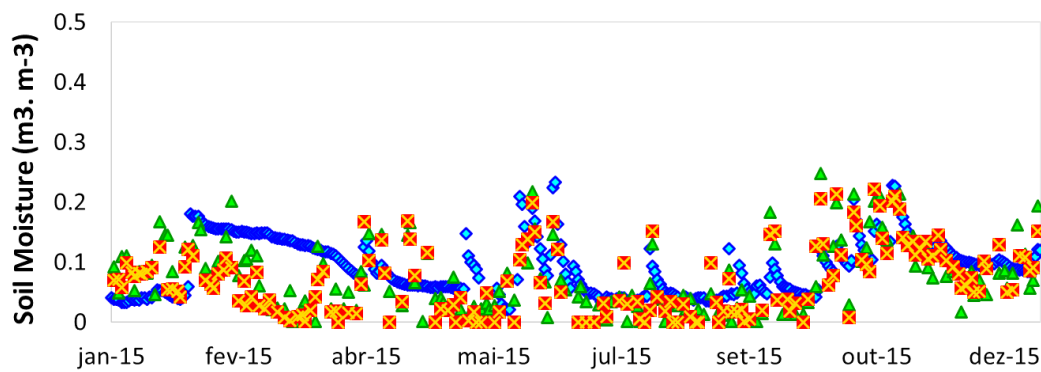
Table 3: Statistical results obtained from in situ measurements (REMEDIHUS sites) and BEC soil moisture dataset (L3 and L4 products) during 2015, ascending and descending pass.

REMEDIHUS - Stations	SMOS-BEC Products: Ascending pass							
	L3				L4			
	Corr. Coef	RMSE	BIAS	SLOPE	Corr. Coef	RMSE	BIAS	SLOPE
Canizal	0.537	0.048	-0.002	0.528	0.527	0.047	0.086	0.554
Carretoro	0.671	0.055	0.040	0.273	0.638	0.056	-0.070	0.306
Casa Periles	0.359	0.040	-0.002	0.407	0.537	0.039	0.030	0.488
Consejo del Monte	0.382	0.083	-0.002	0.175	0.569	0.080	0.034	0.237
El Coto	0.138	0.023	0.006	0.000	0.177	0.059	-0.028	0.000
El Tomillar	0.560	0.013	-0.010	2.255	0.417	0.014	-0.043	1.847
Granja G	0.517	0.043	-0.001	0.583	0.653	0.041	0.024	0.625
Guarrati	0.264	0.028	0.004	0.112	0.396	0.022	0.078	0.172
La Atalaya	0.693	0.033	0.004	0.830	0.544	0.034	0.040	0.805
La Cruz de Elias	0.571	0.040	-0.001	0.658	0.569	0.039	0.028	0.704
Las Arenas	0.593	0.038	-0.009	0.788	0.415	0.040	0.126	0.677
Las Bodegas	0.529	0.070	0.000	0.393	0.424	0.078	0.124	0.297
Las Brozas	0.465	0.022	0.000	1.077	0.410	0.022	0.038	1.043
Las Eritas	0.645	0.045	0.004	0.604	0.624	0.044	0.021	0.631
Las Tres Rayas	0.539	0.036	0.017	0.831	0.283	0.041	-0.037	0.196
Las Vacas	0.519	0.041	0.001	0.640	0.621	0.040	0.023	0.668
Las Victorias	0.014	0.022	-0.002	0.035	-0.299	0.022	-0.010	-0.229
Llanos de la Boveda	0.230	0.062	0.002	0.204	0.535	0.061	0.014	0.240
Paredinas	0.403	0.025	0.007	0.831	0.679	0.024	-0.059	1.089
Zamarrom	0.685	0.028	0.002	1.081	0.635	0.031	-0.002	0.948
SMOS-BEC Products: Descending pass								
Canizal	0.512	0.059	-0.037	0.072	0.072	0.048	0.020	0.554
Carretoro	0.439	0.026	0.012	0.841	0.239	0.028	-0.037	0.490
Casa Periles	0.313	0.041	0.007	0.418	0.142	0.043	-0.034	0.195
Consejo del Monte	0.225	0.081	0.010	0.163	0.122	0.087	-0.038	0.082
El Coto	0.188	0.014	0.016	0.761	-0.210	0.014	-0.040	-0.868
El Tomillar	0.496	0.013	0.013	2.138	0.040	0.016	-0.028	0.150
Granja G	0.356	0.043	0.013	0.443	-0.094	0.051	-0.037	-0.112
Guarrati	0.241	0.034	0.020	0.105	0.258	0.033	-0.048	0.113
La Atalaya	0.591	0.033	0.020	0.855	0.076	0.043	-0.038	0.112
La Cruz de Elias	0.444	0.043	0.009	0.563	0.195	0.048	-0.033	0.234
Las Arenas	0.498	0.040	0.013	0.717	-0.035	0.048	-0.029	-0.047
Las Bodegas	0.456	0.076	-0.003	0.373	0.264	0.057	-0.038	0.284
Las Brozas	0.389	0.022	0.012	0.924	-0.071	0.024	-0.036	-0.225
Las Eritas	0.569	0.059	0.027	0.203	0.197	0.044	-0.070	0.751
Las Tres Rayas	0.554	0.034	-0.010	0.917	0.144	0.037	0.020	0.700
Las Vacas	0.464	0.044	0.009	0.516	0.346	0.046	-0.032	0.440
Las Victorias	-0.033	0.020	0.009	0.002	-0.189	0.022	-0.036	-0.521
Llanos de la Boveda	0.174	0.063	0.009	0.155	0.030	0.066	-0.036	0.001
Paredinas	0.393	0.026	0.018	0.871	0.290	0.027	-0.042	0.618
Zamarrom	0.636	0.033	0.015	0.775	0.343	0.029	-0.041	1.218

Carretero



Granja G



Las Eritas

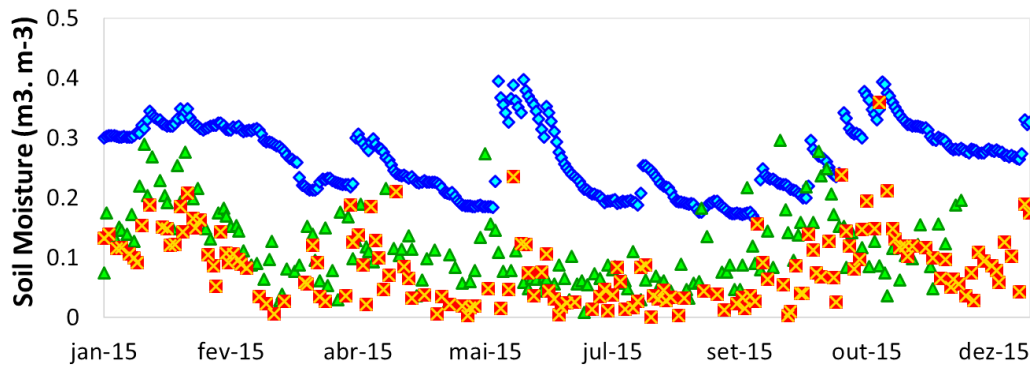
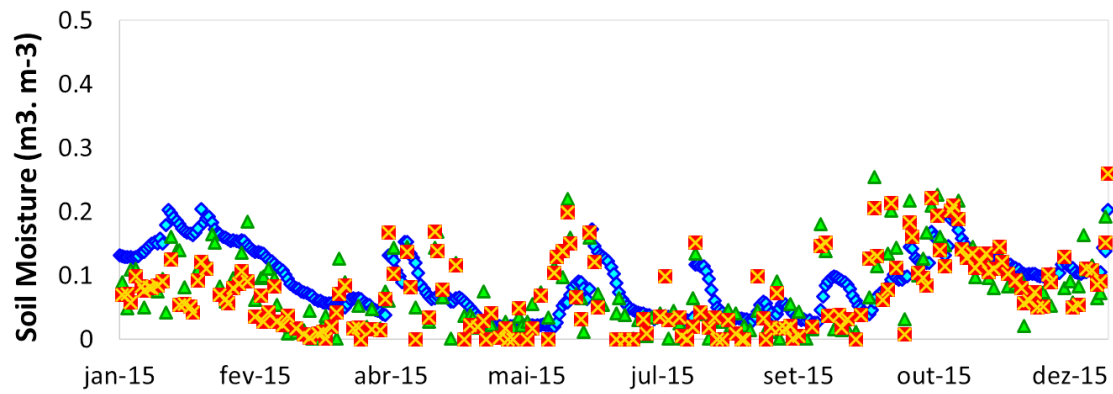
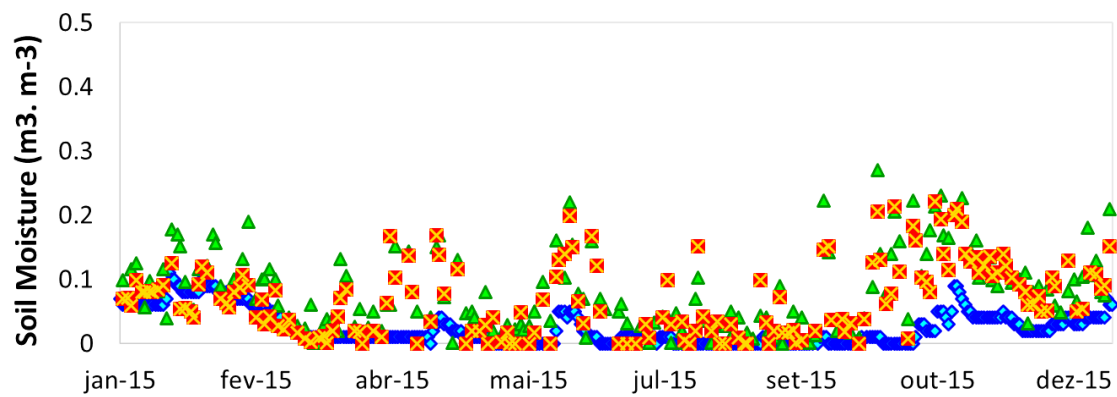


Figure 11: Soil moisture time series of the REMEDHUS sites (Carretero, Granja G, Las Eritas, Las Vacas, Paredinas and Zamarrom) obtained from measurement in situ and BEC products (L3 and L4) for ascending pass during 2015.

Las Vacas



Paredinas



Zamarrom

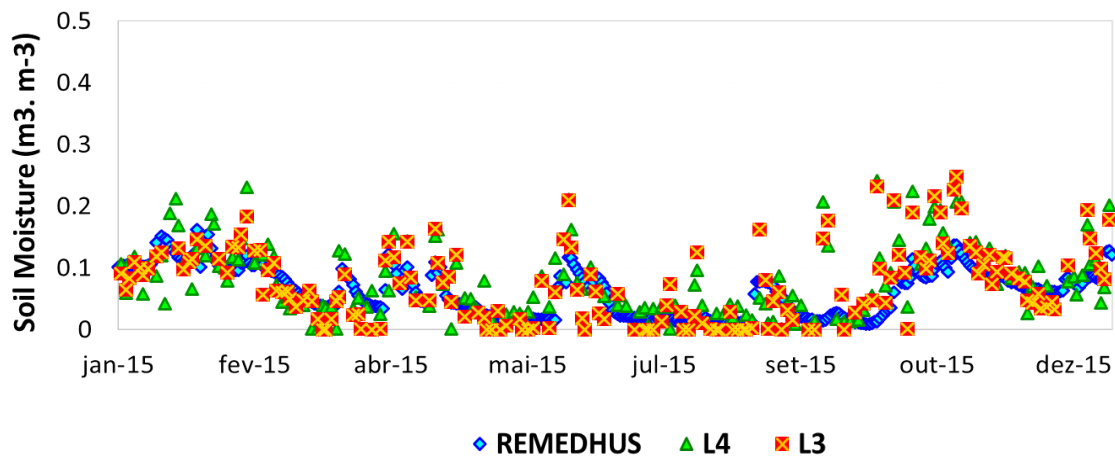


Figure 11 (Continue).: Soil moisture time series of the REMEDHUS sites (Carretoro, Granja G, Las Eritas, Las Vacas, Paredinas and Zamarrom) obtained from measurement in situ and BEC products (L3 and L4) for ascending pass during 2015.

Figure 11 plots the evolution for in-situ measurements with respect to SM L3 and L4 BEC products. In this case only ascending pass is presented because is the one that obtain better results. Moreover, the correlation coefficients values are larger than 0.6 for Carretero, Granja G, Las Eritas, Las Vacas, Paredinas and Zamarrom and errors below 0.05 m³.m⁻³ for both L3 and L4 products, are obtained. These sites have different soil types and textures: Carretero, Granja G, Las Eritas, Las Vacas and Paredinas are located in areas with Cambisol eutrófico (CMe), Regossol (RGc), Luvisol (LvK), Luvisol (LvK), Arenosol (Ara) and Fluvisol (Flc), respectively. And, only Granja G and Paredinas sites are classified as coarse texture soil.

Observing the evolution of the measurements, in general, the BEC soil moisture products underestimate in-situ measurements except for Carretero and Paredinas sites. This result could be explained because of the differences on the soil type among stations; Carretero, for example has more quantity of sand than Paredinas: sandier soils tends to infiltrate the water into the soil faster, due to the porosity.

Besides the characteristics of the soil are distinct, these two sites have different cover crops: Carretero is covered by wheat, while the predominant crop at Paredinas is corn. Others land use cover for REMEDHUS sites are: irrigated cevada (Canizal), bare soil (Casa Periles, Las Arenas and Las Victorias), fodder (Consejo del Monte and Las Vacas), beet (El Coto), vineyard (El Tomilar), artificial surface (Granja G, Las Bodegas, Las Tres Rayas and Llanos de la Boveda), irrigated sunflower (Garrati, La Atalaya), wheat (La Cruz de Elias), others cereals (Las Eritas and Zamarrom). Thus, each site has a special retention characteristic for the soil moisture.

The evaluation of soil moisture series shows the difference between L3 and L4 products, depending on the orbit (ascending and descending) and soil moisture influence in the different periods (dry and wet), seasonal patterns of the Spain (REMEDHUS) during 2015 year. In general, good agreement between SMOS L4 and in situ measurement is appreciated, although the SMOS L3 correlation coefficient values are higher for some stations. The underestimation of SMOS L4 soil moisture is fairly constant. Therefore, it was observed that L3 and L4 products have very similar trends and this behavior is maintained for almost all stations. However, it was verified that some stations respond better from L4 products, considering ascending pass. Results are better for

ascending than descending passes both for L3 and L4 products. It seems that ascending passes respond to values more representatives of the moisture conditions than the descending passes (Banks et al., 2016). Finally, in general, from this comparison it can be stated that SMOS products underestimate the measured soil moisture data.

According to Sánchez et al. (2016), the comparison of the REMEDHUS stations with BEC products does not result in an improvement of the matching results, and it was shown that the simple average of the stations was sufficiently useful. However, in this study, the comparison of the stations with SMOS L4 soil moisture series has shown a small improvement of the L3 product in relation to the performance measurement dataset for REMEDHUS sites. Another study performed by Zamorra et al. (2016) had presented a study of validation of SMOS L3 product over REMEDHUS, comparing with in situ data at different scale. The results had demonstrated that the difference between the statistical scores obtained with L2 and L3 data was not a significant. However, in general, SMOS L2 and L3 products has been showed dry bias. This effect appears to be larger for the shorter time series and for the ascending overpasses. The areal-averaged results were confirmed comparing with in-situ data, except for very sandy soil and irrigated plots. These characteristics presented by Zamora et al. (2016) are in agreement with the results obtained in this study, where the regions shown in Fig. 11 are not in these particular conditions.

In other study, Gumuzzio et al. (2016) evaluate the capability of modelled vs in situ soil moisture observations for a set of representative stations of the REMEDHUS network for a period of four years (2010–2013). Some underestimation or overestimation of the SMOS series, related to the soil characteristics, was observed with respect to both the in situ and the modelled series.

Portal et al. (2020) have been developed a study using several space-borne SSM products (SMAP and SMOS) for comparison in REMEDHUS network. Moreover, over the Iberian Peninsula, they showed that all products generally agree in their temporal dynamics, with lowest performances in summer, and SMAP-derived products being wetter than SMOS ones. Yet some differences in spatial patterns are observed in the high-resolution products, linked to the fine-scale information they use and the multi-sensor synergies employed, especially in forested areas.

The same statistical analysis was applied at CEMADEN (Table 4). This site has been selected because, even though it is also settled in a semiarid region has very different characteristics from REMEDHUS.

Again the ascending overpasses obtain better correlations than the descending. The correlation coefficient between CEMADEN soil moisture measurements and BEC products have presented lower values for descending pass. Banks et al. (2016) have been highlighted small differences between SMOS passes. Almost all CEMADEN stations have high correlation coefficient values (> 0.5) for the L3 products, except Porto da Folha and Uauã. Nevertheless, correlation coefficients when using L4 soil

Table 4: Statistical analysis obtained from in situ measurements (CEMADEN sites) and SMOS-BEC soil moisture dataset (L3 and L4 products) during 2015 year, ascending and descending pass.

CEMADEN - Stations	Ascending							
	L3				L4			
	Corr. Coef	RMSE	BIAS	SLOPE	Corr. Coef	RMSE	BIAS	SLOPE
Aquidabã	0.834	0.018	-0.090	2.447	0.780	0.019	-0.020	1.918
Biritinga	0.787	0.029	-0.033	1.275	0.670	0.035	-0.030	1.060
Canhoba	0.856	0.037	-0.068	1.126	0.770	0.047	-0.017	0.882
Canudos	0.584	0.026	0.019	0.896	0.540	0.028	0.037	0.848
Carira	0.507	0.040	0.010	0.846	0.320	0.042	0.000	0.483
Conceição do Coité	0.830	0.021	-0.054	1.505	0.750	0.025	-0.025	1.442
Coronel João de Sá	0.681	0.023	-0.899	1.568	0.598	0.025	0.882	1.193
Euclides da Cunha	0.594	0.034	-0.006	0.966	0.470	0.038	-0.012	0.587
Fátima	0.564	0.034	-0.065	0.964	0.450	0.036	0.006	0.656
Frei Paulo	0.786	0.045	0.013	0.926	0.650	0.056	-0.009	0.658
Itapicuru	0.714	0.020	-0.085	1.519	0.680	0.021	-0.010	1.446
Jeremoabo	0.521	0.025	-0.037	1.216	0.440	0.025	-0.034	0.838
Lamarão	0.682	0.031	-0.050	1.318	0.530	0.041	0.030	0.746
Nossa Senhora Aparecida	0.783	0.032	0.035	1.213	0.670	0.039	-0.020	0.938
Olindina	0.550	0.033	-0.024	0.894	0.410	0.035	-0.019	0.565
Porto da Folha	0.417	0.044	-0.026	0.607	0.450	0.045	-0.048	0.607
Propriá	0.650	0.025	-0.121	2.447	0.650	0.025	0.018	1.918
Retirolândia	0.841	0.065	0.153	0.393	0.734	0.076	0.015	0.555
Ribeirópolis	0.500	0.018	-0.038	1.728	0.249	0.023	-0.007	1.120
Teofilândia	0.670	0.018	-0.040	1.734	0.550	0.020	-0.010	1.280
Tobias Barreto	0.782	0.032	-0.080	1.530	0.834	0.030	0.030	1.173
Uauã	0.426	0.074	0.153	0.409	0.450	0.083	-0.005	33.416
Valente	0.780	0.021	-0.059	1.648	0.770	0.025	-0.036	1.418
CEMADEN - Stations	Descending							
	L3				L4			
	Corr. Coef	RMSE	BIAS	SLOPE	Corr. Coef	RMSE	BIAS	SLOPE
Aquidabã	0.750	0.016	0.020	2.515	0.580	0.019	-0.040	1.643
Biritinga	0.830	0.027	0.030	1.106	0.640	0.036	-0.051	0.753
Canhoba	0.760	0.051	0.014	0.892	0.570	0.062	-0.026	0.630
Canudos	0.330	0.026	-0.026	1.080	0.440	0.025	0.001	0.684
Carira	0.460	0.039	0.020	0.811	0.250	0.043	-0.030	0.345
Conceição do Coité	0.780	0.023	0.018	1.493	0.650	0.028	-0.032	1.014
Coronel João de Sá	0.479	0.025	0.089	0.692	0.342	0.024	0.080	1.055
Euclides da Cunha	0.460	0.036	0.000	0.606	0.400	0.037	-0.016	0.398
Fátima	0.610	0.040	0.003	0.724	0.550	0.043	-0.009	0.524
Frei Paulo	0.680	0.056	0.012	0.792	0.500	0.066	-0.023	0.433
Itapicuru	0.690	0.022	0.043	1.443	0.490	0.023	-0.059	0.852
Jeremoabo	0.340	0.027	0.010	0.669	0.170	0.027	-0.029	0.244
Lamarão	0.550	0.050	-0.040	0.968	0.540	0.051	0.010	0.549
Nossa Senhora Aparecida	0.630	0.035	0.025	1.106	0.550	0.039	-0.040	0.837
Olindina	0.370	0.040	0.011	0.554	0.200	0.042	-0.025	0.231
Porto da Folha	0.410	0.039	0.047	0.628	0.470	0.034	-0.058	0.681
Propriá	0.590	0.027	-0.014	2.515	0.550	0.027	-0.002	1.643
Retirolândia	0.559	0.076	-0.013	0.203	0.601	0.085	-0.007	0.012
Ribeirópolis	0.392	0.022	0.003	1.539	0.286	0.025	-0.018	0.686
Teofilândia	0.550	0.022	0.010	1.534	0.340	0.023	-0.020	1.000
Tobias Barreto	0.778	0.035	-0.010	1.305	0.702	0.043	0.010	0.709
Uauã	0.390	0.074	0.007	0.409	0.300	0.077	-0.019	0.229
Valente	0.677	0.022	0.033	1.657	0.633	0.027	-0.051	1.023

moisture product, are generally lower. Due to the level of detail of the surface, 8 stations (Carira, Euclides da Cunha, Fátima, Jeremoabo, Olindina, Porto da Folha, Ribeirópolis and Uauã) do not obtain satisfactory statistical results. It's important to highlighted that each station is located in sandy soil region, which may be affecting the results. s Paredes et al. (2017) have also observed a poor performance for SMOS L3 products.

In order to evaluate the soil moisture derived from satellite and the in-situ values and the temporal trend in the semiarid region, temporal series for 2015 at six CEMADEN stations are shown in Figure 12 (Aquidabã, Canhoba, Conceição do Coité, Retirolândia, Tobias Barreto and Valente).

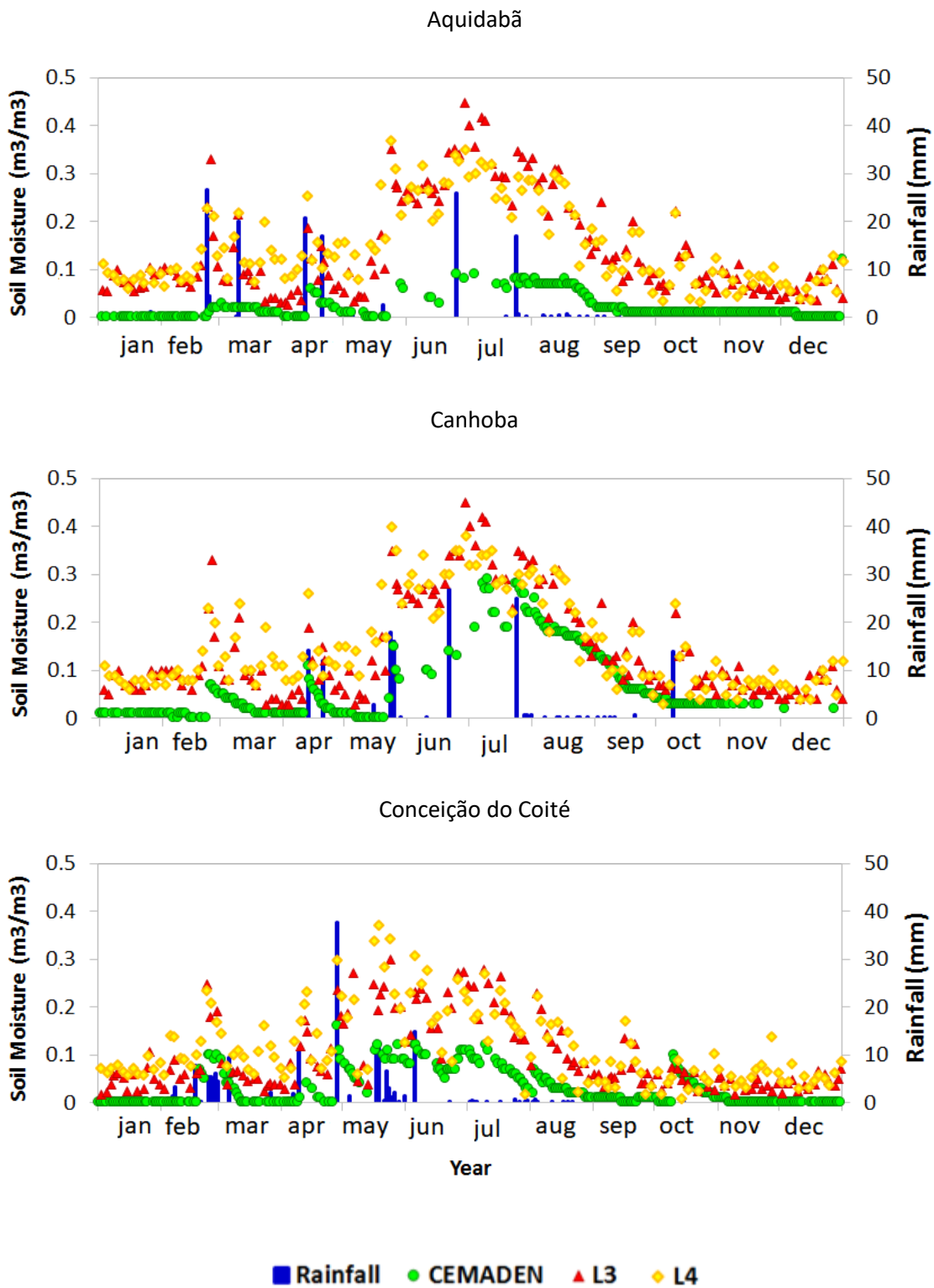


Figure 12: Soil moisture time series of the CEMADEN six stations: Aquidabã, Canhoba, Conceição do Coité, Retirolândia, Tobias Barreto and Valente. Comparison of in-situ measurement with SMOS-BEC products (L3 and L4) for ascending pass during 2015. The descending passes are not showed because the series are very similar to the ascending pass.

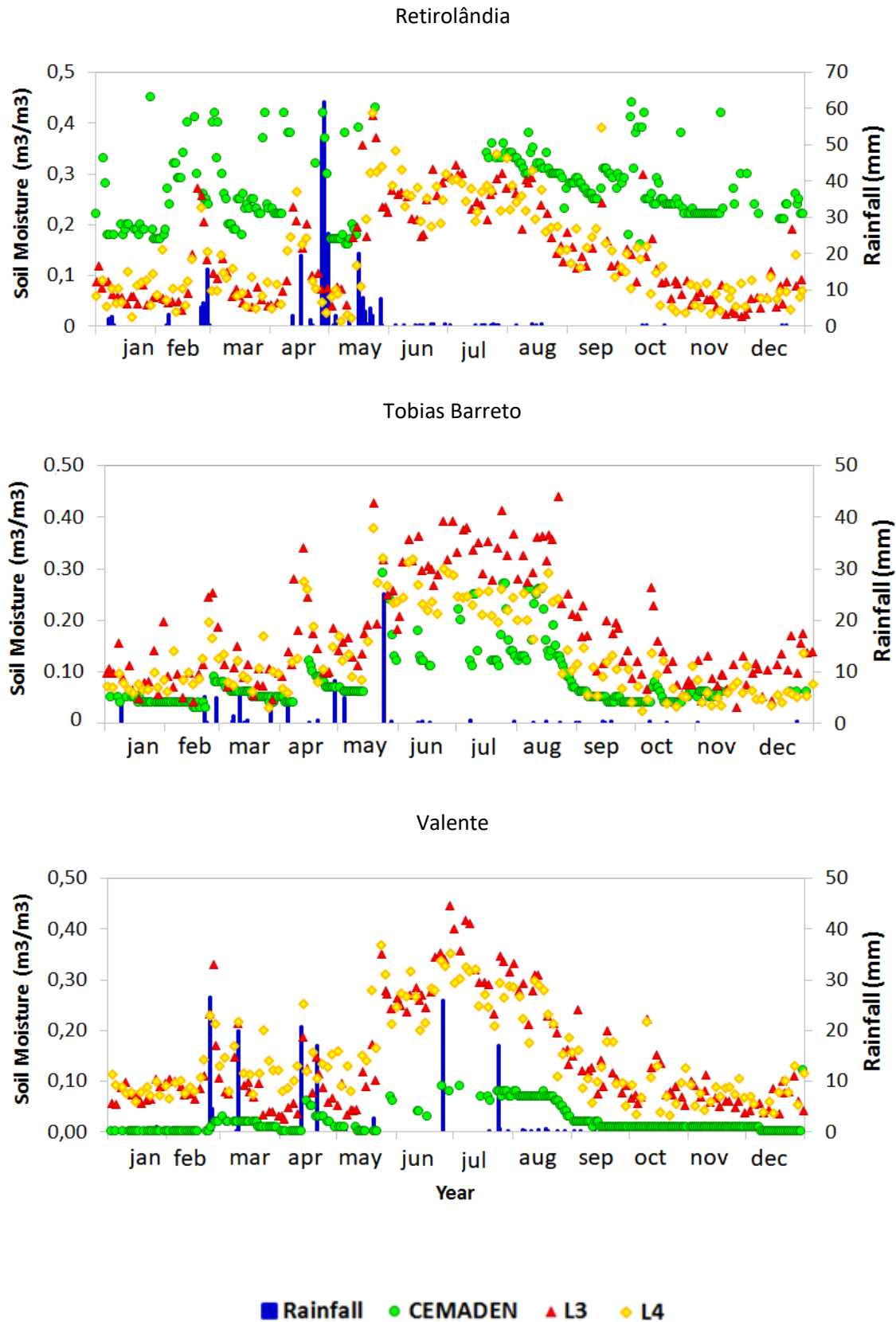


Figure 12 (Continue): Soil moisture time series of the CEMADEN six stations: Aquidabã, Canhoba, Conceição do Coité, Retirolândia, Tobias Barreto and Valente. Comparison of in-situ measurement with SMOS-BEC products (L3 and L4) for ascending pass during 2015. The descending passes are not showed because the series are very similar to the ascending pass.

The results show that satellite products are closer to the in-situ measurements for Canhoba and Conceição do Coité, which present a good statistical analysis. Aquidabã and Retirolândia have a high correlation coefficient, but the performances on the temporal series are not similar to the in-situ measurements. Both stations are located in different regions: Aquidabã is the nearest of the coastline and Retirolândia is within of a Semiarid region. Retirolândia is located on a drier region, with drought about 60%, Haplic Planosol soil type and anthropized area (as shown Figures 8, 5 and 7, respectively). Valente station is located near to the Retirolândia, with the same soil conditions, but they have different rainfall distribution: higher rainfall values registered in May for Retirolândia. The main feature of the semiarid of northeast are the frequent rainfall, which is concentrated from December to April in the northern sector and from November to March in the southern (Marengo et al., 2013). Tobias Barretos station has the best statistical results (correlation coefficient of 0.83 and RMSE of 0.03 m3.m-3).

NEB is a region affected by drought during decades, causing famine, migration and other derived social problems (Marengo et al 2016). In 2012, started a persistent drought on this region that shows an extreme scenario, because it lasted until 2016 in several areas (Marengo et al., 2017). It is the worst drought that has happened in the last 30 years. From 2012 to 2015, Bahia (BA) is the most affected state of the NEB. In this state, about 230 municipalities were affected. The drought has brought much damage to the main sources of income in the region: livestock, and agricultural cultivation of corn and bean. According statistics, around 1,400 municipalities of the all NEB has been affected (Marengo et al, 2013, 2016, Gutierrez et al., 2014). In 2015, the drought that had been already present since 2012 was intensified by El Nino episode. According to the study by Gutierrez et al. (2014), the drought happens because of two atmospheric phenomena: (1) a small increment in the sea temperature at the surface level between 0.5°C and 1.5°C in the central region and the eastern equatorial Pacific Ocean, indicating the presence of ENSO phenomenon; and, (2) the conditions in the Atlantic also were not favorable to rain in this region.

Discussions at the state and federal levels have been started with the objective of improving policy and management of droughts. Thus, Gutierrez et al. (2014) presented a Brazilian study

case, based on studies made by experts. From an analysis of the literature, they found that although there is a high drought management in Brazil, there are still some actions at short and long-term that decision-makers may consider, focusing on improvement in monitoring and forecasting with enhancement of warning systems.

The data from REMEDHUS and CEMADEN stations compared with SMOS products (L3 and L4) has showed that correlation coefficient, RMSE, bias and slope values were in good agreement. As, the statistical values were better for the ascending passes, temporal inter-comparison are presented only for ascending orbits.

Conclusion

In this study, a validation of SMOS-derived BEC L3 and L4 remotely sensed soil moisture using in-situ observations from REMEDHUS and CEMADEN networks has been performed. The in-situ soil moisture series and BEC products (L3 and L4) data have been compared to the REMEDHUS and CEMADEN networks located in the semiarid central part of the Duero basin (Spain), and semiarid northeast part of the Brazilian territory (Brazil). Results show a quite good correlation between SMOS L4 data and the observed in situ soil moisture for REMEDHUS (Carretoro, Granja G, Las Eritas, Las Vacas, Paredinas and Zamarrom) and CEMADEN (Aquidabã, Canhoba, Conceição do Coité, Retirolândia, Tobias Barreto and Valente) networks. For the average data of these series, the correlation coefficient is higher than 0.6. Similar results have been obtained when compared SMOS L3 products for ascending and descending pass. No differences were found for the results of the descending orbits. Thus, we can conclude that SMOS SM products show good correlations between SMOS L3 and L4 data and the observed in situ soil moisture for REMEDHUS and CEMADEN networks. Ascending orbit generally shows better correlations with respect to ground-truth data than descending ones, in agreement that Banks et (2016) highlighted.

In Brazil, the region of the CEMADEN sites has experienced long periods of droughts in the last decades, with large losses on rainfed agriculture. For this reason, the SMOS SM product had been used for calculate the Soil Water Deficit Index (SWDI) in the Northeast Brazil (NEB), showing a reasonably good correlation with the soil moisture at the top (Paredes and Barbosa, 2017). According to Marengo et al. (2017), the drought affecting the

Northeast region of Brazil from 2012 until now has the highest negative impact to the regional economy and society ever seen from decades. They assess the climatic characteristics of the current drought since 2010, using a combination of global reanalyses and sea surface temperature in the tropical Pacific and Atlantic to identify the large-scale circulation features for the February-May peak rainy season in Northeast Brazil. Also, they assess regional rainfall and water deficit patterns to assess the rainfall and water balance characteristics in the region since the beginning of the drought, and satellite derived vegetation products to show the possible effects of the water deficit on the robustness of the vegetation. The results showed that since the middle 1990s to 2016, the rainfall was below normal.

Finally, we can conclude that in situ soil moisture data are necessary to validate the products obtained from SMOS satellite. Moreover, this study provides a validation of SMOS L3 and L4 products in support of its operational use in semi-arid regions. SMOS SM products make available new key information to different studies such as productivity of agricultural crops, implementation of irrigation and water resources. The SM product at high resolution can be used for application of new technologies for diversification of crops, training of rural producers, socio-economic and environmental studies, among other actions.

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