POTENTIAL USE OF SOLAR RADIATION TO DESINFECT DOMESTIC WASTEWATER IN BRAZIL.

USO POTENCIAL DA DESINFECÇÃO SOLAR DE ÁGUAS RESIDUÁRIAS DE ORIGEM DOMÉSTICA NO BRASIL.

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ABSTRACT:

World's population growth is provoking an increasing demand of energy and clean water. Brazil is, mainly, a tropical country; therefore, it possesses a solar energy potential year round. Solar radiation is a promising energy source option, considering its non-pollutant nature, permanent readiness and cost zero. An alternative use for solar radiation is for disinfection of domestic wastewater (DWW), reducing environmental contamination and increasing water availability for agriculture. Solar radiation values for 202 meteorological stations dispersed in the Brazilian territory were determined. With these data and the model proposed by Sánchez-Román et al. (2007), it was computed the time of exposure necessary to disinfect DWW, to guarantee the World Health Organization's recommendation for agricultural purposes. 48 maps were developed considering four depths of DWW in the solar reactor. These maps showed the time of exposure required, anywhere in Brazil, to disinfect DWW reducing the coliform population from 3.5 x 106 NMP 100 mL^{-1} down to 1.000 NMP 100 mL^{-1}. It could be observed that the solar disinfection technology is applicable in almost all the Brazilian territory during almost all year; and in some specific areas for at least eight months.

KEYWORDS: Time of Exposure, Solar Disinfection, Solar Radiation.

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RESUMO:

O crescimento da população mundial provoca aumento na demanda de energia e água limpa. O Brasil é um País predominantemente tropical; e, portanto, com potencial de energia solar o ano todo. A radiação solar é uma fonte de energia promissora, tendo em vista sua natureza não-poluente, permanente disponibilidade e custo zero. Uma alternativa de uso da radiação solar é na desinfecção das águas residuárias domésticas (ARD), para reduzir a contaminação ambiental e incrementar a disponibilidade de água para a agricultura. Foram determinados os valores de radiação solar para 202 estações meteorológicas espalhadas por todo o Brasil. Com esses dados e a equação proposta por Sánchez-Román et al. (2007), foi determinado o tempo de exposição necessário para desinfetar a ARD, objetivando o seu uso posterior, conforme as recomendações da Organização Mundial da Saúde, na agricultura familiar. Foram desenvolvidos 48 mapas de distribuição dos tempos de exposição para quatro profundidades de ARD a serem tratadas no reator solar. Estes mapas apresentam o tempo de exposição requerido, em qualquer lugar do Brasil, para desinfectar a ARD reduzindo a população de coliformes de 3,5 x 106 NMP 100 mL^{-1} até 1.000 NMP 100 mL^{-1}. Através deles, pôde-se perceber que a tecnologia de desinfecção solar é aplicável em quase todo o território brasileiro, e durante quase todo o ano e em áreas específicas por no mínimo por oito meses.

PALAVRAS-CHAVES: Tempo de Exposição, Desinfecção Solar, Radiação Solar.

INTRODUCTION

Human life and humanity's development are linked to water and energy consumption. World population growth is promoting an increase on energy and clean water demands, which is carrying out environmental consequences for the whole planet.

Solar radiation is the main source for thermal, chemical and dynamic processes in this planet. The radiant energy originated at the Sun that reaches Earth's surface is called solar radiation; its main characteristic is being an electromagnetic field. The solar radiation's magnitude represents the amount of radiant energy in a wavelength interval that crosses a unit of area perpendicular its direction, and per unit time (W m^{-2}). Irradiation refers to radiation arriving at a surface, whether or not the origin is the sun.

Radiance is the radiant flux emitted by a unit area of a source. When radiance is known, it can be determined the radiant flux density; and, if it is integrated in the whole spectrum represents the amount of radiant energy that passes through a plane per unit time and per unit area, this is called irradiance. In other words, irradiance is the radiant flux incident on a receiving surface from all the directions, per unit area of surface, its units are W m^{-2} (Liou, 1980; Iqbal, 1983). Fluence, or dose, refers to the total amount of energy applied per unit area (J m^{-2}); it is the irradiance multiplied by the exposure time.

The solar radiation that reaches the Earth's surface is a function, of astronomical factors, the Sun itself, and factors that deals with the interaction between the solar radiation and our planet atmosphere's constituents. Our atmosphere's physical properties makes solar radiation transmission process difficult to be describe and great complexity (Liou, 1980; Iqbal, 1983).

The use of radiometers installed at certain points of interest on the surface of the Earth, is the simplest way to measure solar energy readiness. However, those excellent point measurements instruments are costly and not very practical when great extensions are been evaluated. That it is why a dense actinometrical network in Brazil does not provide enough economical return (Nunes et al., 1979). The efforts done by INPE (Instituto de Pesquisas Espaciais - Space Research Institute) and

LABSOLAR/UFSC (Laboratorio de Energia Solar / Universidade Federal de Santa Catarina - Solar Energy Laboratory / Santa Catarina Federal University) in developing a radioactive transfer model (BRAZIL-SR), justify what was described above for Brazil.

Using the BRASIL-SR model, several data bases and satellites, such as GOES-8 and GOES-12, Martins et al. (2005) found 5 kW h m-2 day-1 (18 MJ m^{-2} day^{-1}) as an average in the Brazilian territory. Considering that the model is not fully calibrated, the use of FAO Irrigation and drainage Paper 56 (Allen et al., 1998) methodologies for the determination of solar radiation is useful to evaluate solar energy availability.

Considering that Brazil is located mainly in the tropical area of our planet, it possesses a solar energy potential during the whole year. Solar radiation is a promissory option, considering its no-pollutant nature, its permanent readiness and its zero cost. An applicability of solar radiation is its use in domestic wastewater (DWW) disinfection, reducing environmental contamination and increasing water and nutrients availability for fertigation.

Sánchez-Román (2006) developed a model to simulate DWW disinfection as a function of fluence (dose) and DWW depth in a reactor developed for this purpose. The author also proved that pre-treated DWW (bar screen and grit channel) and then passed through a concrete septic tank with a residence time of approximately 14 hours could be disinfected with solar radiation. Sánchez-Román et al (2007b) checked the financial viability of solar disinfected DWW with primary treatment for rural Brazilian conditions. The results from that evaluation draw to conclude that the project is viable from a financial point of view. It were obtained positive results for Present Value, Internal Rate of Return, Capital Time of Return and Cost-Benefit relationship.

Considering that solar radiation varies regionally and seasonally, the time of exposure to guarantee the disinfection required also varies accordingly. According to Sánchez-Román (2006), to diminish the E. coli population from 3.5 x 106 MPN/100mL to 1,000 MPN/100mL with a DWW depth of 0.20 m, it is required a dose of 32.59 MJ m^{-2}, which corresponds to less than two days of exposure as an average for Brazil. The objective of this paper is to determine the potential use of solar radiation to disinfect domestic wastewater in Brazil, using the model proposed by Sánchez-Román et al. (2007a) and the methodology to determine the solar radiation proposed by Allen et al. (1998), developing maps that show the exposure time required regionally along the year.

MATERIAL AND METHODS

SOLAR RADIATION COMPUTATION.

The method used is the one recommended by Allen et al. (1998) for the determination of solar radiation when it is known the solar constant, latitude, solar declination, and day of the year. The calculation procedure for daily values is:

a) the extraterrestrial radiation was computed for daily periods (eq. 1), through out the year, knowing the latitude for the specific location, the solar constant, the solar declination, and the day of the year:

$$Ra = \frac{24\,(60)}{\pi} Gsc \quad dr\left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \quad (1)$$

Where Ra is the extraterrestrial radiation (MJ m^{-2} day^{-1}); Gsc is the solar constant (0.0820 MJ m^{-2} day^{-1}); *dr* is the inverse relative distance Earth-Sun (radians); ω_s is the sunset hour angle (radians); δ is the solar declination (angle of the Sun with respect to the Equator, in radians). Latitude (φ) is expressed positive for the Northern Hemisphere, and negative for the Southern Hemisphere.

b) the inverse relative distance Earth-Sun *(dr)* and the solar declination (δ) were computed using eq. 2 and eq. 3, respectively:

$$dr = 1 + 0{,}033\cos\left(\frac{2\pi}{365}J\right) \quad (2)$$

$$\delta = 0{,}409\sin\left(\frac{2\pi}{365}J - 1{,}39\right) \quad (3)$$

Where *J* is the number of the day in the year for which the calculation was made.

The sunset hour angle (ω_s) was computed using eq. 4:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \quad (4)$$

The maximum possible duration of sunshine or daylight hours, *N*, was computed using eq. 5:

$$N = \frac{24}{\pi}\omega_s \quad (5)$$

c) solar radiation (*Rs*), when not measured can be estimated using the equation proposed by Angstrom (eq. 6).

$$Rs = \left(a_s + b_s \frac{n}{N}\right) Ra \quad (6)$$

Where *Rs* is the short waves solar radiation (MJ m^{-2} day^{-1}); *n* is actual duration of sunshine (hour); *N* are the daylight hours for the day of interest (hour); a_s is a regression constant, expressed as a fraction of the extraterrestrial radiation that reaches Earth in cloudy days *(n=0);* $a_s + b_s$ is a fraction of the extraterrestrial radiation that reaches Earth on clear days (n=N); and Ra is the extraterrestrial radiation (MJ m^{-2} day^{-1}). It can be noticed that *n/N* is the relative relationship of sunlight in any day of interest.

d) Allen et al. (1998) recommended the use of as = 0.25 and bs = 0.50 when real data of solar radiation nor calibration to improve the values of these parameters are available.

In this paper, the values used in the solar radiation computation process are shown in Table 1.

Table 1. Values of as and bs for Angstrom equation used in this paper.

Month	Viçosa*		Rest of Brazil	
	a_s	b_s	a_s	b_s
January	0.233	0.363	0.25	0.50
February	0.256	0.361	0.25	0.50
March	0.275	0.321	0.25	0.50
April	0.235	0.373	0.25	0.50
May	0.220	0.396	0.25	0.50
June	0.239	0.346	0.25	0.50
July	0.251	0.359	0.25	0.50
August	0.220	0.369	0.25	0.50
September	0.203	0.417	0.25	0.50
October	0.186	0.448	0.25	0.50
November	0.202	0.427	0.25	0.50
December	0.236	0.334	0.25	0.50

*Source: Vianello & Alves (1991).

CLIMATOLOGICAL DATA USED.

Data used in this paper have origin in Normais Climatológicas (1992). On that reference, the data of 202 weather stations, spread throughout the Brazilian territory, were available. It was picked out the mean monthly total daylight hours for each station for 30 years series.

FLUENCE REQUIREMENTS COMPUTATION.

The model proposed by Sánchez-Román (2006) (eq. 7) was used to compute the fluence (dose) necessary to guarantee a fecal coliform population reduction from an initial value of 3.5 x 106 NMP/100 mL down to 1,000 NMP/100 mL for DWW as an effluent from a septic tank:

$$\frac{N}{No} = \frac{\exp\left(1.047 - 0.321\,F + 6.304\,d\right)}{\left(1 + \exp\left(1.047 - 0.321\,F + 6.304\,d\right)\right)} \qquad (7)$$

Where *N* represents the *E. coli* population present in DWW after being exposed to solar radiation (NMP/100 mL); No is the initial E. coli population present in DWW before being exposed to solar radiation (NMP/100 mL); F is the dose (fluence) received by DWW (MJ m^{-2}); and d is the depth of DWW in the reactor (m).

MAPS ELABORATION.

Once solar radiation distribution along the year in Brazil was computed, it was necessary to determine the dose required to reduce the fecal coliform population as a function DWW depth to be treated, using eq. 7, and the location of the weather stations reported in Normais Climatológicas (1992). The results were spatialized in a geo-referenciated.

The values of total daylight hours presen-

-ted in the Normais Climatológicas are total monthly values. The results are presented as maps for every 15th day of every month, for each of the four depths studied by Sánchez-Román et al. (2007). As a total, 48 maps were elaborated. On this paper, four maps, representing each season, are presented for each depth of water that was considered (see Fig. 1, Fig. 2, Fig. 3, and Fig. 4). The software ArcMap 8.3 was used to process the information. All maps are available, when requested to the corresponding author.

RESULTS AND DISCUSSION

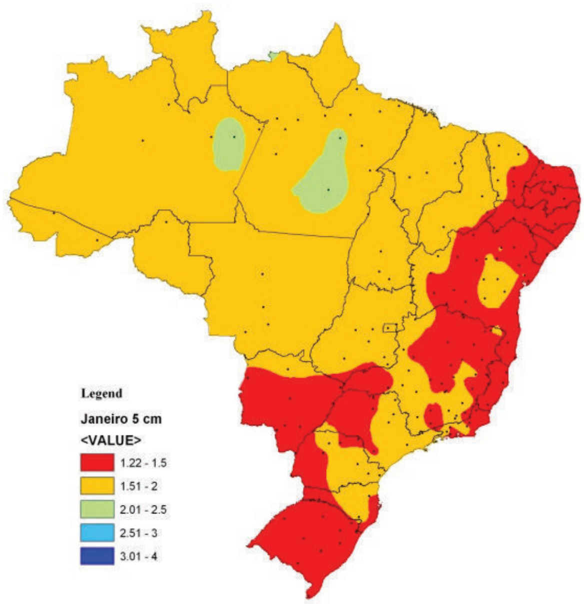
It can be observed on Fig. 1, 2, 3 and 4, that the best conditions to accomplish the DWW disinfection using solar radiation are present in the northeast of Brazil, along all the year. The states of Rio Grande do Norte, Paraíba, Pernambuco, Alagoas and Sergipe present great potential for any depths and any month studied. In the southern part of Brazil (states of Santa Catarina, Paraná and Rio Grande do Sul), during the winter months (May to August), the exposure times increase in up to four days. Therefore, in those states and in that time of the year, the alternative of solar disinfection (SODIS) would turn out to be less practical that in the rest of Brazil.

Summer and spring represented by January and October in figures 1 to 4, show the potential use of the technology in all the country. The northern region of Brazil shows some spots that will require more than two days of exposure, that happen during the rainy season. In almost all the country, the time of exposure is two days or less.

Winter time is represented by July in figures 1 to 4; therefore, the southern part of the country shows values greater than 2.5 days for any of the depths of DWW proposed to be treated. Considering the availability of solar radiation in Brazil during this season, even the south part of the State of Mato Grosso do Sul, the southeast Region, and the coast line of the country from the State of Rio Grande do Sul up to the State of Paraiba require 2.5 days of exposure.

The beginning of fall is represented by March in figures 1 to 4; the conditions during this season are quite similar to the ones presented for summer time. The time required to expose the DWW is also less than two days.

The northern region of Brazil is located mainly at the equatorial region of the planet; this fact creates climatic conditions to apply SODIS in all seasons of the year (Figures 1 to 4). The exposure time is equal to two days; and in southern part of the state of Amapá, the eastern part of the state of Pará, and the northern part of the state of Tocatins de exposure time diminish to 1.5 days. However, values around 2.5 days are present in some areas of the northern region of the country when water depth is increased to 0.20 m probably due to the rainy season; but the exposure time, in a general sense in this region, is equal to or less than two days along all the year.



January

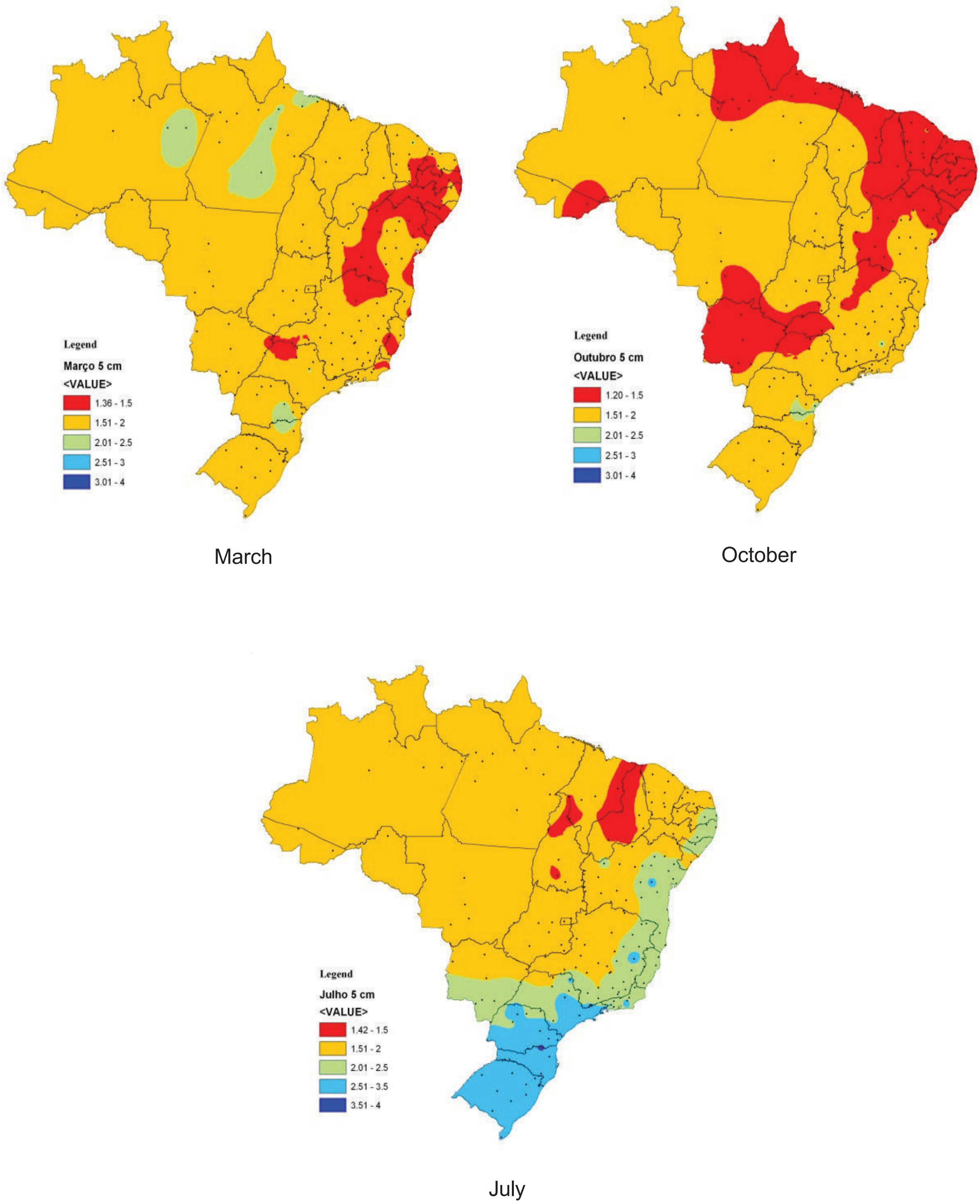


Fig. 1. Required days to expose a water depth of 0.05 m of domestic wastewater to reduce and initial E. coli population from 3.5 x 106 NMP/100 mL to 1,000 NMP/100 mL using direct solar radiation (SODIS).

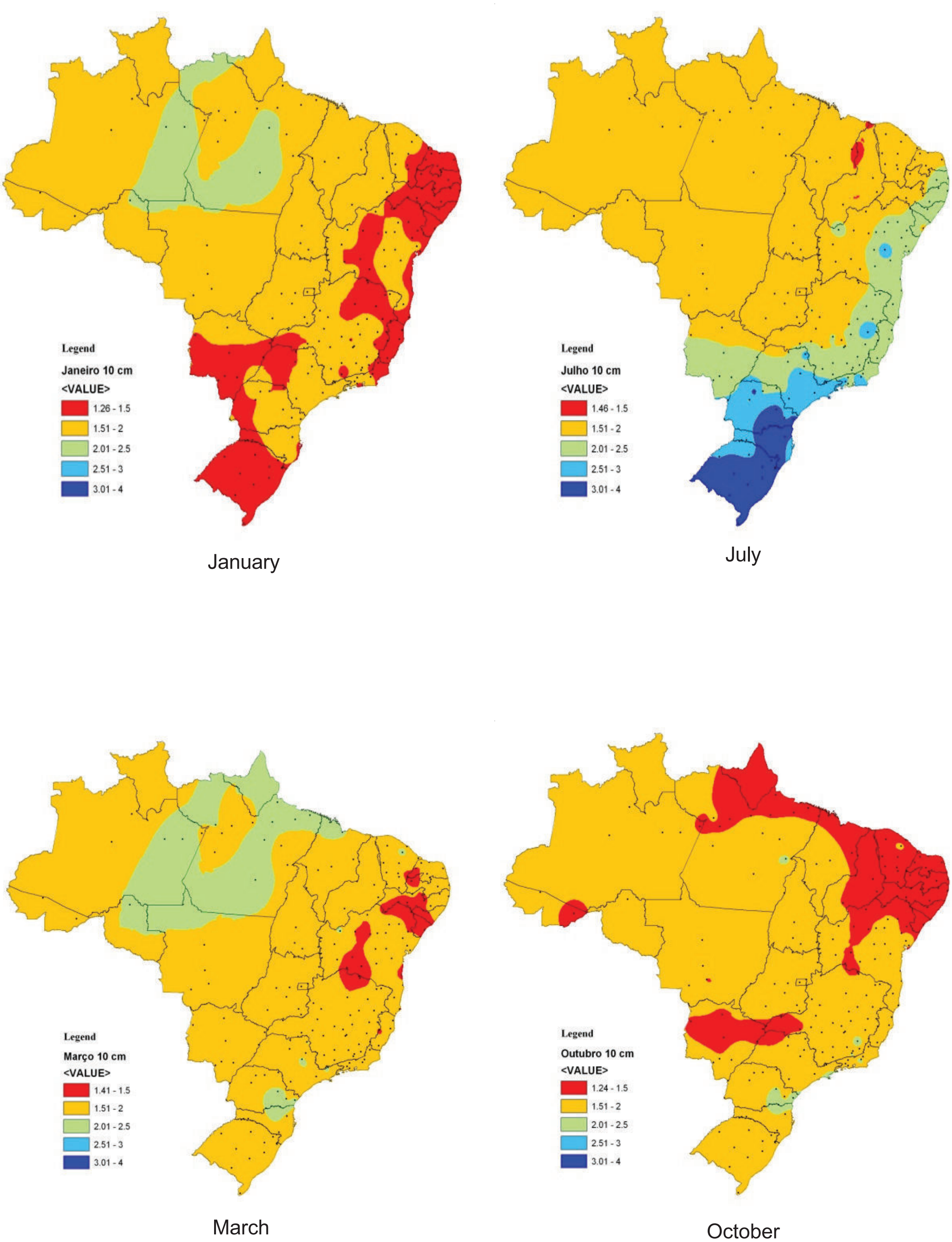


Fig. 2. Required days to expose a water depth of 0.10 m of domestic wastewater to reduce and initial E. coli population from 3.5 x 106 NMP/100 mL to 1,000 NMP/100 mL using direct solar radiation (SODIS).

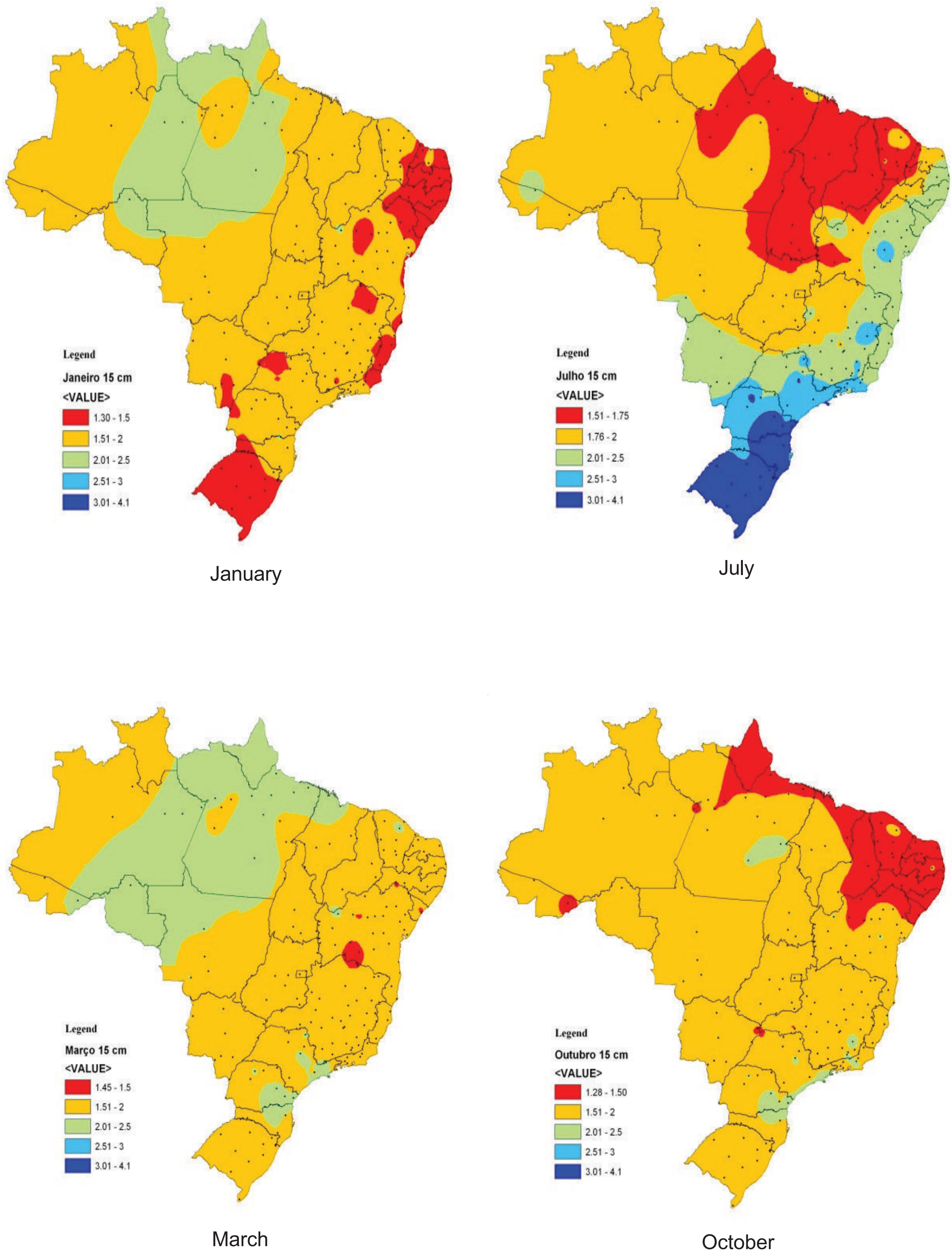


Fig. 3. Required days to expose a water depth of 0.15 m of domestic wastewater to reduce and initial E. coli population from 3.5 x 106 NMP/100 mL to 1,000 NMP/100 mL using direct solar radiation (SODIS).

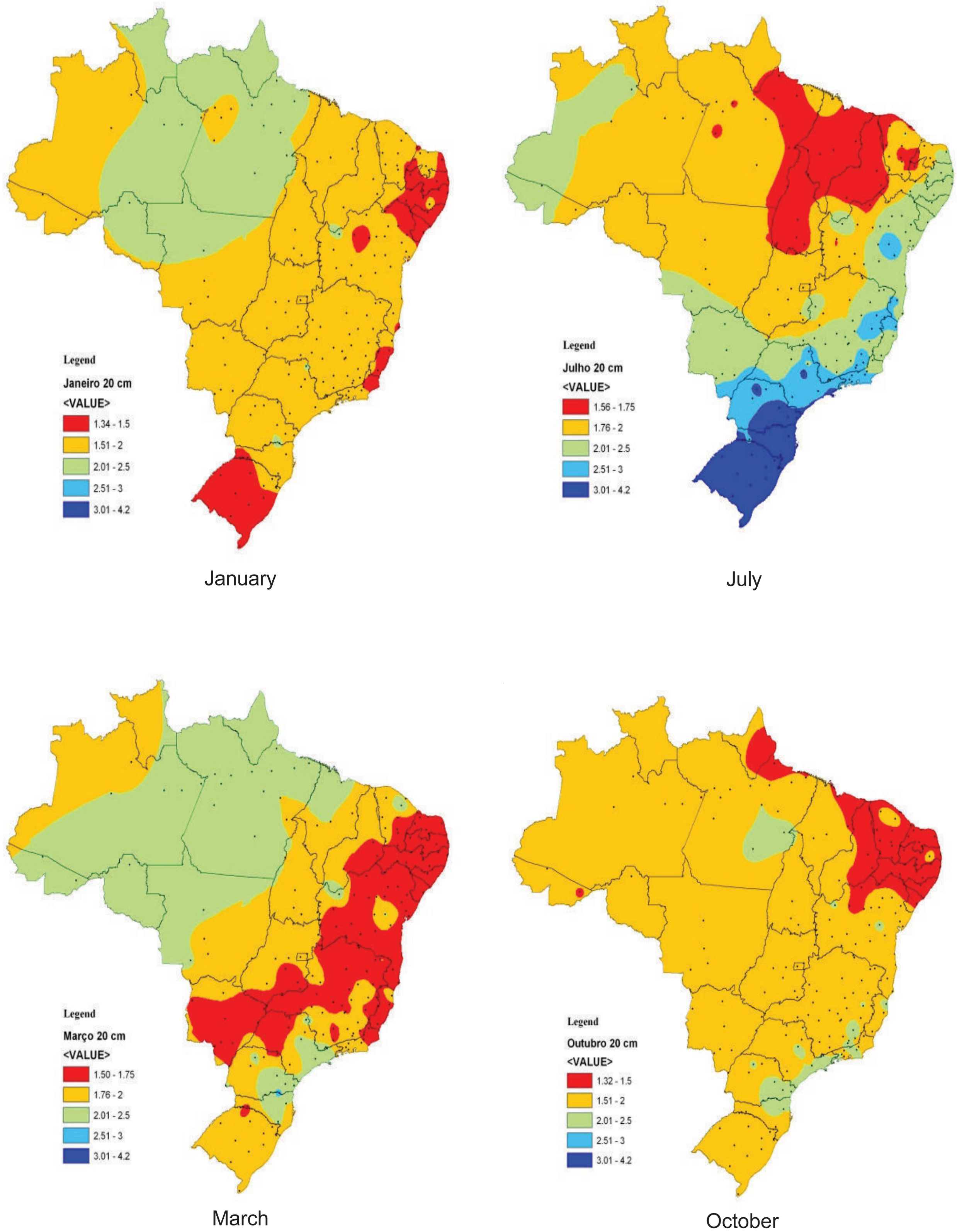


Fig. 4. Required days to expose a water depth of 0.20 m of domestic wastewater to reduce and initial E. coli population from 3.5 x 106 NMP/100 mL to 1,000 NMP/100 mL using direct solar radiation (SODIS).

The Northeastern region of Brazil is a promising region for the application of this technology. For the states of Piauí and Maranhão, only two days of exposure are required independently of the studied DWW depth to be treated along all the year. However, during winter time, represented by the month of July on Figures 1 to 4, the area along the coast line of this region requires 2.5 days of exposure.

In the case of the Southeast and Central Western Regions during winter, the southern part of them (states of Mato Grosso do Sul, São Paulo, Rio de Janeiro, Espírito Santo, and southern part of Minas Gerais), that are part of the Southeastern and the Western Central regions of Brazil, the time of exposure required is of at least 2.5 days; and for Triângulo Mineiro and the state of Goiás two days exposure are required. The rest of the year, from October to March in the states of Mato Grosso do Sul and Triângulo Mineiro, exposure time is only 1.5 days.

The Southern region of Brazil is the least favorable region for the use of this technology. During winter time, at least 3.5 days of exposure will be required even with a depth of 0.05 m, and up to four days for 0.20 m water depth. The summer (January), on figures 1 to 4, shows that solar disinfection can be used in the southern state of Rio Grande do Sul, and guarantee the desired levels of disinfection with 1.5 days of exposure. From October to March, the region has a promising potential solar disinfection technology use, showing two days of exposure requirement. There is a micro climate region, between the states of Paraná and Santa Catarina, where the least time required is 2.5 days any time of the year.

CONCLUSIONS

The study presented here demonstrated that SODIS can be used to disinfect DWW in Brazil to levels recommended by the World Health Organization (WHO) for unrestricted irrigation (<1.000 NMP per 100 mL) during almost all the year with two or less than two days of exposure of the domestic wastewater.

In general, in Brazil the time of exposure is between 1.5 and 2.5 days, along the year except during winter time as it can be noticed on Figures 1 to 4. This figures show the relationship between time of exposure, depth of DWW and solar energy available to produce disinfection. To define time of exposure it has to be considered the depth of DWW that it is being disinfected as an important input data, as well as contamination load. In those figures, the values are fixed initially at 3.5 x 106 NMP 100 mL-1 and finishing with <1000 NMP 100 mL^{-1}.

During winter, the Southern Region has exposure values between 2.5 and 4.2 days of exposure; for the Southeastern Region the exposure time is between 1.4 and 3 days; and for the rest of the country the exposure time goes to less than 2.5 days.

The Southern Region has to be particularly analyzed, technically as well as economically, to be sure that the technology proposed by Sánchez-Román et al. (2007) is viable. The Northeastern Region of Brazil presents exposure values, year round, less or equal to two days, and during winter equal to 2.5 days. Showing its great potential to be implemented as a solution for domestic wastewater treatment, diminishing contamination of surface water bodies, and becoming an irrigation water source.

RECOMMENDATIONS

It is recommended: a) Install domestic wastewater treatment solar disinfection pilot units through the different Brazilian regions, not only as it has been done by the company STAR (www.intecambiental.com.br/star) but also by research teams to validate this technology; b) Along with this, it should be recommended cultures to be risen with this methodology that have a better capacity to absorb the nutrients present in DWW, in way to not provoke damages to the soil; c) Economic viability as shown by Sánchez-Román et al. (2007b) should be performed for the Southern Region with actual in situ data.

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