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GREEN WATER FOOTPRINT AND SUSTAINABILITY FOR ESPIRITO SANTO STATE

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ABSTRACT

Water footprint is a relatively new concept of freshwater appropriation that considers its direct and indirect use by a consumer or producer and used as a comprehensive indicator of the appropriation of water resources. The objective of this study was to estimate the green water footprint and evaluate its sustainability in the state of Espírito Santo, using the land use information and indicators of water scarcity. The total green water footprint was estimated by the sum of the green water footprints of pasture, forest, coffee cultivation, forestry, and other agricultural uses. The state's total green footprint estimated was 47.5 billion m³/year, and the pasture class represented 48.5% of this total, followed by forest (29.8%), coffee cultivation (10.1%), forestry (6.4%), and other crops (5.2%). The ratio between the mean annual total volume of precipitated water and the green WF in the state was 80%. The environmental sustainability assessment shows that the green footprint was unsustainable for most of the year, on average, mainly in the May to September.

Palavras-chave:
água doce
evapotranspiração real
escassez hídrica

PEGADA HÍDRICA VERDE E SUSTENTABILIDADE PARA O ESTADO DO ESPÍRITO SANTO

RESUMO

A pegada hídrica (PH) é um conceito relativamente novo de apropriação da água doce que considera o seu uso direto e indireto por um consumidor ou produtor, sendo usada como um indicador abrangente da apropriação de recursos hídricos. O presente estudo teve como objetivo estimar a PH verde e avaliar a sua sustentabilidade no estado do Espírito Santo, utilizando informações de uso da terra e indicadores de escassez de água. A PH verde total foi estimada pelo somatório das PH verdes da pastagem, vegetação nativa, cafeicultura, silvicultura e outros usos agrícolas. A pegada verde total do estado foi estimada em 47,5 bilhões de m³/ano, sendo que a classe pastagem representou 48,5% deste total, seguida pela vegetação nativa (29,8%), cafeicultura (10,1%), silvicultura (6,4%), e outros cultivos agrícolas (5,2%). A relação entre o volume anual médio de água precipitada e a PH verde no estado foi de 80%. A avaliação da sustentabilidade ambiental demonstra que a PH verde apresentou-se insustentável em seis meses do ano, principalmente de maio a setembro.

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INTRODUCTION

Despite being renewable, water is considered a limited natural resource. Because of the limitation on the availability of water, in quantity and quality, especially fresh water, it is necessary to use it rationally, in order to ensure its sustainable supply. The use of tools and indicators allows a better understanding of the functioning of water dynamics in the hydrological cycle, especially in its terrestrial phase, as well as assisting in decision making related to water resources management. In this sense, one indicator that has been used is the water footprint.

The concept of water footprint (WF) encompasses both direct and indirect use of water by a consumer or a product. This is considered a broader indicator of appropriation of water resources, which differs from the traditional and restricted concept of water intake (consumption), as it also allows the quantification of the volume required for the dilution of pollutants. This indicator separates water consumption into three components: blue WF, which refers to the consumption of fresh, surface or groundwater from its direct catchment in springs; green WF represents the evapotranspiration (consumption) of water temporarily stored in soil and vegetation; and gray WF, the volume of water needed to dilute pollutants (HOEKSTRA *et al*., 2011, MEKONNEN & HOEKSTRA, 2011; EMPINOTTI & JACOBI, 2013; SILVA *et al*., 2013; BLENINGER & KOTSUKA, 2015; SCHYNS *et al*., 2015 ; BLENINGER; KOTSUKA, 2015).

In terms of global average values, the total WF of the Earth, from 1996 to 2005, was distributed as follows: 74% green WF; 15% gray WF and 11% Blue WF (MEKONNEN & HOEKSTRA, 2011a). In the state of Espírito Santo, specifically in the Itapemirim river basin (IRB), green WF also had the highest proportion of total WF with 86%, followed by blue and gray WF, with 9% and 5%, respectively, in 2007 to 2012 period (LEAL *et al*., 2018)[1].

In the same periods mentioned above, the WF of agricultural production represented 92% of the total Earth's WF (MEKONNEN & HOEKSTRA, 2011a) and 90% of the total WF of IRB (LEAL *et al*., 2018) 4. The green and blue WFS originated in agricultural production, together represented 85% of the total terrestrial WF (MEKONNEN & HOEKSTRA, 2011a) and 95% of IRBs total WF (LEAL *et al*., 2018)[5].

Regarding agricultural production (excluding livestock), in relation to the sum of green and blue WF, green WF represented, in general 86% on Earth (MEKONNEN & HOEKSTRA, 2011a); 93% in the European Union (VANHAM & BIDOGLIO, 2013); 92% in Brazil and 95% in the Paraná River Basin (MEKONNEN & HOEKSTRA, 2011b); and 91% in IRB (LEAL *et al*., 2018)[4].

According to MEKONNEN & HOEKSTRA (2011b), green water is often the most significant in general consumption, even in regions with irrigated agriculture, with higher consumption of blue water. SCHYNS *et al*. (2015) state that it is necessary to better understand the aspects related to the availability of green water, so that it can be better managed, since, surprisingly, studies and discussions about water scarcity have been mainly focused on blue water.

There are several studies on WF on a global scale, but few on a regional and local scale. In addition, considering the importance of green water in terrestrial water availability, this study was carried out with the objective of estimating green WF and evaluating its sustainability in the state of Espírito Santo.

MATERIAL AND METHODS

The study area comprises the state of Espírito Santo, in the southeastern region of Brazil, with a territory of 46,052.64 km². The state covers 78 municipalities, with a population of approximately four million inhabitants (IBGE, 2018). According to the Köppen classification, the state has four predominant climates: 53.3% Aw and 14.3% Am (humid tropical); 14.9% Cfa and 10.4% Cfb (hot temperate) (ALVARES et al., 2013).

Land use survey

The land use survey conducted in this study was based on the orthophoto mosaic with 1-m spatial resolution, generated from the aerophotogrammetric

1-Disregarding water footprint of native and cropped forests for comparison with other studies.

survey conducted in the state of Espírito Santo in 2007/2008 by the STATE INSTITUTE FOR ENVIRONMENT AND WATER RESOURCES (2008). This represents the last available complete survey of the vegetation of the state, containing 25 classes (Figure 1). Based on this delimitation, combined with the official map of the state political division (Figure 2), the corresponding types and areas of each type of existing land use were computed for each municipality.

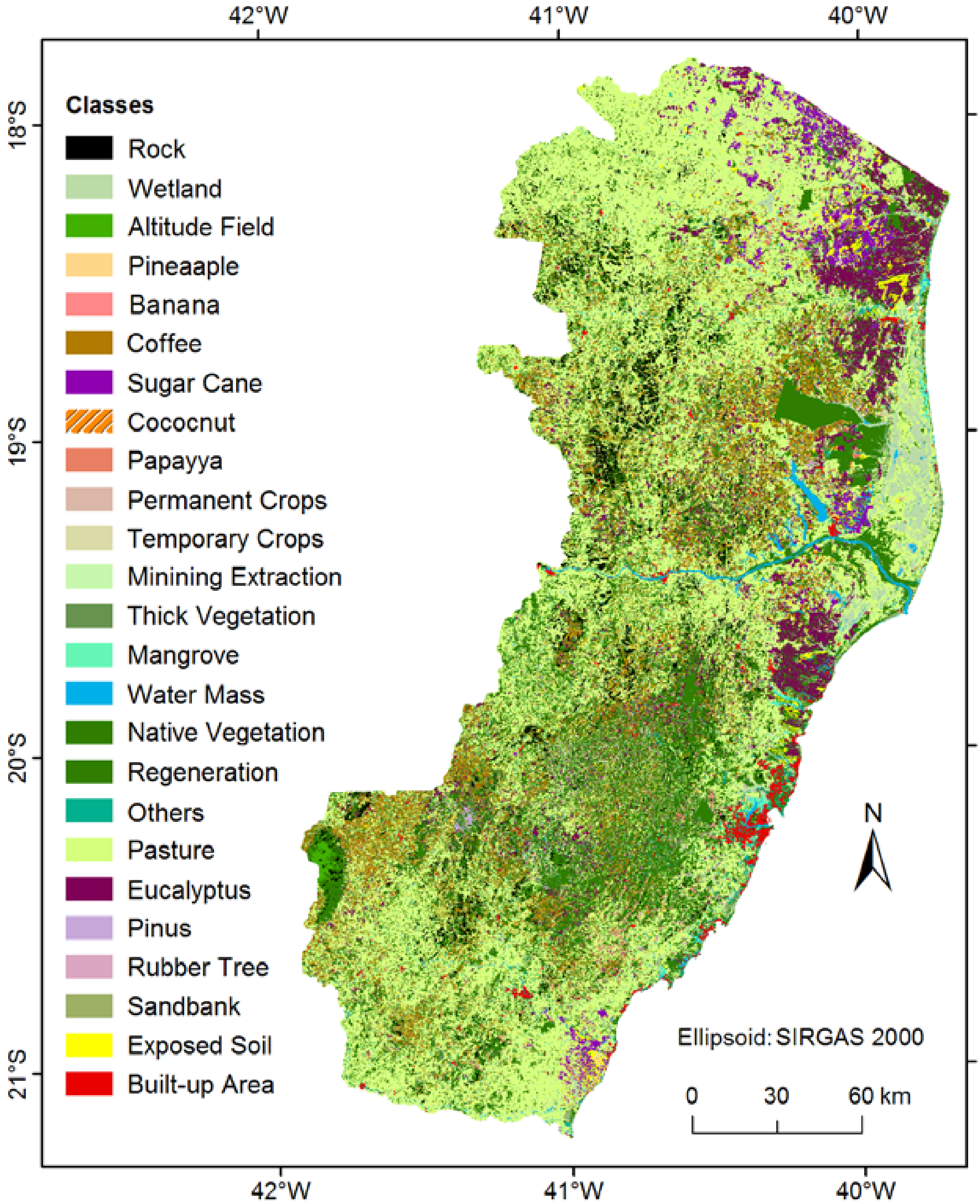


Figure 1. Land use in Espírito Santo in 2007/2008. Source: Adapted from State Institute of Environment and Water Resources (In Portuguese, INSTITUTO ESTADUAL DE MEIO AMBIENTE E RECURSOS HÍDRICOS) (2008).

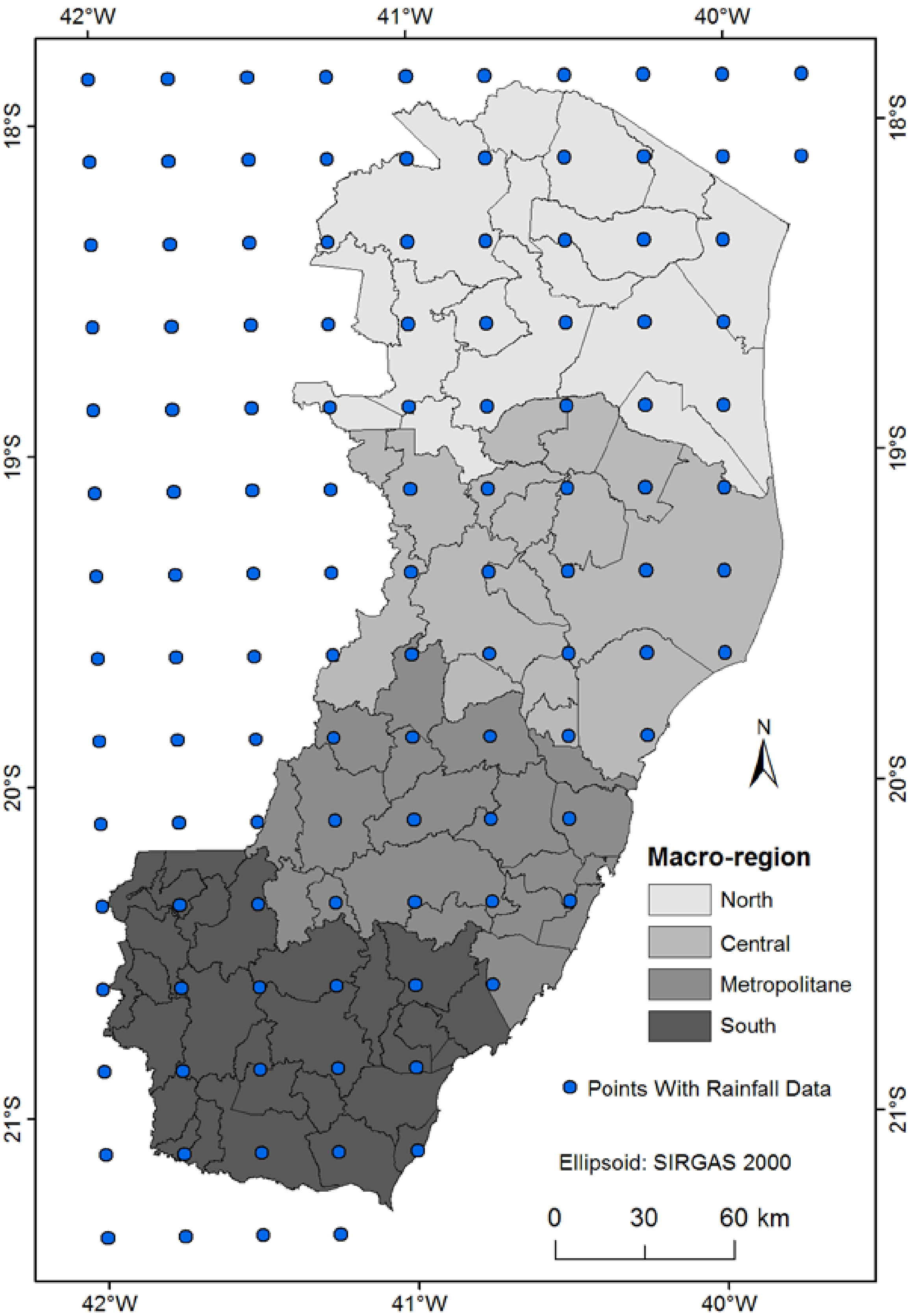


Figure 2. Political division of the state of Espírito Santo (municipalities and macro-regions), and grid with the monthly average precipitation points used in the study. Source: Adaptation of GEOBASES and XAVIER et al. (2016).

Accounting of the Green Water Footprint

Green WF was accounted by using the methodology established in the Water Footprint Assessment Manual (HOEKSTRA *et al.*, 2011), adapted for each crop under study (native vegetation, pasture, coffee, forestry and other agricultural crops). Green WF was spatially calculated for the entire state, in 1 x 1-km pixels, based on the Climatic Water Balance (CWB), using the method of THORNTHWAITE & MATHER (1955), from which the actual crop evapotranspiration (ETR) was obtained using control rainfall and evapotranspiration data (ET_0). The elements of CWB were spatially calculated following an adaptation of the methodology presented in CECÍLIO *et al.* (2012). The description of the data used and the calculation procedures performed are described below.

Green WF was calculated in the same way for all land use classes according to Equation 1.

$$WF_{green} = 10\, ETR\, area \qquad (1)$$

Where,

WF_{green} = monthly green water footprint, m3;
ETR = monthly average actual crop evapotranspiration, mm; and
Area = cropped area, hectares.

In the native vegetation class, all natural vegetation was considered by joining the areas of native forest, vegetation in the early stage of regeneration, swamp, sandbank and mangrove. In the forestry class, the areas of eucalyptus, pine and rubber tree were considered together.

Data on rainfall and evapotranspiration

The average monthly rainfall data from 1980 to 2013 were obtained from the work of XAVIER *et al.* (2016), with spatial resolution of 0.25º (Figure 2). The interpolators indicated by SILVA *et al.* (2011) for downscaling the monthly precipitation maps to spatial resolution of 1 km.

The monthly average potential evapotranspiration data were calculated using the method of Hargreaves and Samani (HARGREAVES & SAMANI, 1985), Equation 2, by correcting the values through the adjustment proposed by ZANETTI *et al.* (2019), for Espirito Santo, Equation 3:

$$ET_0^{HS} = 0{,}0023 R_a \left(T_{max} - T_{min}\right)^{0,5} \left(T_{med} + 17{,}8\right) \qquad (2)$$

$$ET_0 = \left(1.08 ET_0^{HS} - 0.81\right) NDA \qquad (3)$$

where,

ET_0^{HS} = potential evapotranspiration, daily average of each month, calculated by the method of Hargreaves and Samani, mm;
ET_0 = monthly potential evapotranspiration, mm;
T_{max}, T_{min} and T_{med} = monthly maximum, minimum and average temperatures, respectively, ºC;
Ra = extraterrestrial solar radiation, daily average of each month, mm day^{-1}; and
NDA = number of days of each month in the year.

The maximum and minimum temperature data were obtained from the application of multiple linear regression equations (Equation 4), in which Tmed was determined by the mean between T_{max} and T_{min}.

$$Ti = \beta_0 + \beta_1\, Alt + \beta_2\, Lat + \beta_3\, Long \qquad (4)$$

Where,

Ti = maximum and minimum regular monthly temperatures, °C;
Alt = altitude, m;
Lat = latitude, decimal degrees;
Long = longitude, decimal degrees; and
β_0, β_1, β_2 and β_3 = parameters of the equation.

The parameters used in Equation 4 to estimate monthly maximum and minimum air temperatures were those proposed by CASTRO *et al.* (2010).

Altitude data were obtained from the TOPODATA Digital Elevation Model, developed by the National Institute for Space Research (LIU *et al.*, 2009), which represents a refinement of the MDE SRTM, with a spatial scale of 30 meters. For the use of this DEM, a reclassification with a spatial resolution of 1 km was previously performed.

Calculation of climatological water balance

The CWB was calculated using monthly average crop evapotranspiration (ETc) and monthly average rainfall data. The ETc was obtained by multiplying the values of ET_0 and the crop coefficient (Kc) shown in Table 1.

Table 1. Mean values of crop coefficients (K_c) and effective depth of the root system (Z)

Crop	K_c	Source	Z (m)	Source
Pineapple	0.37	a	0.45	a
Banana	0.98	a	0.70	a
Coffee	1.01	a	1.20	a
Sugar cane	0.80	a	1.60	a
Coconut	0.80	a	1.00	c
Eucalyptus	0.82	b	1.50	a
Papaya	0.87	a	0.30	c
Pasture	0.80	a	1.00	a
Rubber tree	0.98	a	1.50	a

a: ALLEN et al. (1998); b: ALVES et al. (2013); c: MIRANDA et al. (2007).

For native vegetation classes (native forest, vegetation at early regeneration stage, sandbank, mangrove and swamp), pine, temporary and permanent crops, the Kc equal to 1.00 was adopted and for thick vegetation it was used 0.80 (same pasture value). There are uncertainties about these values due to unavailability of specific data in the literature.

Available water capacity (AWC) was determined by multiplying the AWC per unit depth and the effective depth of the root system (Z) of the crops (Table 1).

For native vegetation (native forest, early stage of regeneration, sandbank, mangrove, swamp and pine), it was used Z equal to 1.5 m. For temporary crops, 0.30 was adopted, and for permanent crops and thick vegetation, it was used 1.00. Similarly, there are uncertainties about these values due to unavailability of data in the literature.

The AWC per unit depth was determined according to the average physical properties of the soils, using the values shown by PEREIRA *et al.* (2002):

- Heavy textured soils: 200 mm/m;
- Medium textured soil: 140 mm/m;
- Coarse textures soils: 60 mm/m.

The average soil texture classes were obtained as performed by SILVA *et al*. (2011):

- Heavy textures soils: Latosol, Nitisols, Cambisols, Molisols, Gleysols and Organosols;
- Medium textured soils: Ultisols and Litolic Neosol;
- Coarse textured soils: Spodosols, Quartzarenic neosol and Fluvic Neosol.

The soil map used in the study (Figure 3) was obtained from the database of the Integrated System of Geospatial Bases of the State of Espírito Santo (GEOBASES).

By using the calculation of the BHC, the values of real evapotranspiration (ETR) were obtained, in monthly and annual scales, for each pixel (1 km x 1 km) in the state of Espírito Santo.

The areas of rocky outcrop, built-up area, rupestrian field/altitude, mining extraction, water mass, exposed soil and others were not accounted for in the green PH calculations, considered unproductive areas.

Green water footprint

The green WF sustainability assessment was based on the Water Footprint Assessment Manual (HOEKSTRA *et al*., 2011), based on the interpretation of water scarcity (WS) indicators per municipality:

$$WS_{green} = \frac{\Sigma WFgreen}{\mathbf{W}Agreen} \quad (5)$$

where,

ΣWFgreen = sum of the green WF of the different vegetable cover; and
WAgreen = green water availability.

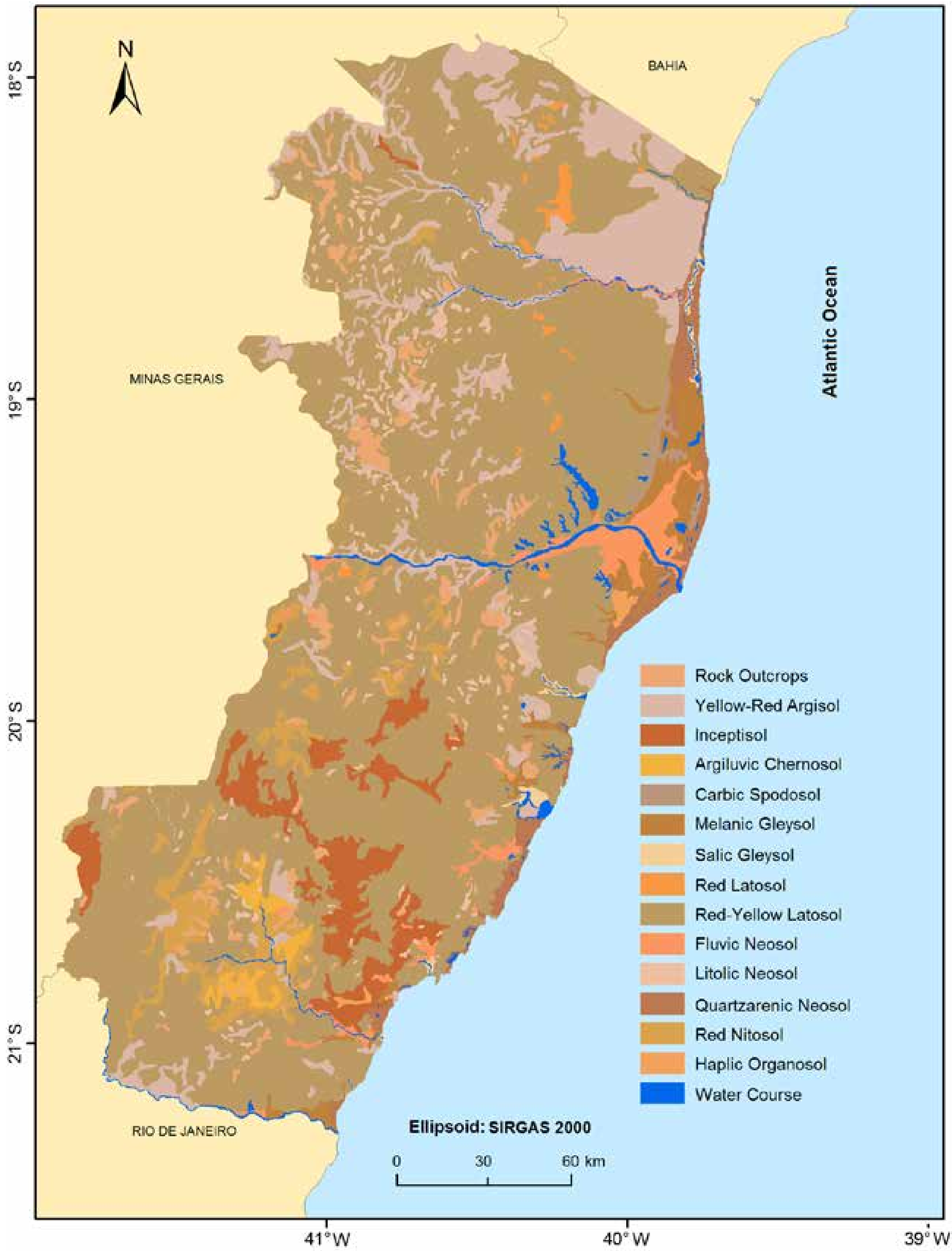


Figure 3. Soil classes mapped in the state of Espirito Santo. Source: Adapted from GEOBASES.

Green water availability (WA_{green}) was set by Equation 6 (HOEKSTRA et al., 2011):

$$WA_{green} = ET_{green} - ET_{env} - ET_{unprod} \qquad (6)$$

In which,

ET_{green} = volume corresponding to the evapotranspiration of all rainfall, m³/month;
ET_{env} = volume corresponding to environmental evapotranspiration, that is, native vegetation, m³/month, and
ET_{unpro} = volume corresponding to the evapotranspiration of unproductive areas, m³/month.

The ET_{green} was considered as equivalent to the total rainfall in each municipality, using the monthly average rainfall data.

Environmental evapotranspiration was calculated by summing the evapotranspiration of native forest areas, early stage of regeneration, sandbank, mangrove and marsh(wetland).

The unproductive areas, referring to rocky outcrop, built-up area, rupestrian/altitude field, mining extraction, water mass, exposed soil and others, were not considered in the green WF sustainability calculations. Since the values of these areas were not calculated for their WF_{green}, this was not subtracted from WA_{green}, therefore, making no difference in the calculation of WS_{green}.

Green water scarcity is considered environmentally sustainable when it has a value of up to 1 (100%), meaning that only available green water is consumed. Consequently, values greater than 1 represent a scarcity considered unsustainable (HOEKSTRA *et al.*, 2011).

RESULTS AND DISCUSSION

Figure 4 shows the green WF values calculated for the principal vegetation cover (native vegetation, pasture, coffee, forestry and other agricultural crops) in Espírito Santo. The average green WF totaled 47.5 billion m³/year in the state. The volume with the highest use occurred in the pasture class, followed by native vegetation, coffee, forestry and the total of other crops with smaller area (papaya, pineapple, banana, sugar cane, coconut and other temporary and permanent crops).

LEAL *et al.* (2018), in a study in the Itapemirim river basin, obtained similar results, by observing that the pasture class represented 54% of total green WF, followed by native vegetation with 26% and agriculture representing 20%.

The pasture class resulted in higher green WF due to its larger coverage area, representing 46% of the state territory. Similarly, the other classes also followed the magnitude of their coverage areas (Table 2).

When using Equation 1 to calculate green WF, the values tend to follow the magnitude of the area of municipalities as the calculation is performed in units of volume of water consumed as

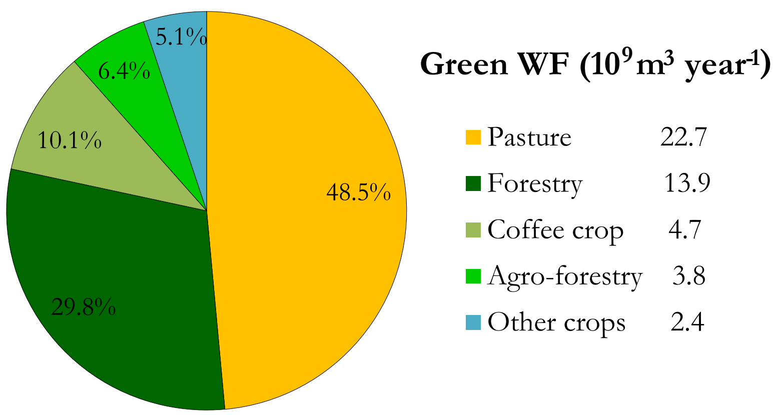


Figure 4. Water footprint of the main types of land use in the state of Espírito Santo in 2007/2008.

Table 2. Primary land uses in Espírito Santo (%), in 2007/2008, overall and per macro-region and average rainfall (mm)

Description	State	South	Metropolitan	Central	North
Pasture[1]	46.0	52.8	32.0	41.0	54.3
Native Vegetation[2]	25.3	22.7	37.1	27.7	17.5
Coffee crop	8.6	11.2	9.2	9.5	5.5
Silvicultura[3]	6.0	1.9	4.9	7.7	8.3
other crops[4]	4.7	3.6	5.5	3.2	6.3
Average rainfall	1,279	1,404	1,331	1,179	1,108

1: Pasture and thick vegetation; 2: Native wood, vegetation in the early stages of regeneration, swamp, sandbank and mangrove; 3: Eucalyptus, pine and rubber tree; 4: All agricultural crops except coffee.

recommended in the Water Footprint Assessment Manual (HOEKSTRA *et al*., 2011). This method, while consistent, is not effective for comparing different areas such as municipalities or regions. In this case, it was decided to present the results in a relative manner, based on the availability of the main source of water for the occurrence of green WF, that is, rainfall.

Therefore, Figure 5 shows the average relations between the green WF of the principal land uses and the volume of precipitated water in the municipalities of the four macro-regions of the state. The areas considered unproductive (rocky outcrop, built-up area, rupestrian /altitude field, mining extraction, water mass, exposed soil and others) were excluded from the calculation.

In both results, using absolute as well as the relative value (Figures 4 and 5), the green WF of each type of land use, in addition to the area of occupation and regional rainfall, also depends on the characteristics adopted in the calculation of evapotranspiration and water balance (K_c, Z and AWC). As the mean values found in the literature have been adopted, and as in some cases, arbitrary values have been adopted due to unavailability of specific data in the literature, there are some uncertainties related to the results, and the estimates obtained are more appropriate for regional comparisons.

As shown in Figure 5, whose values were calculated in a relative manner, pasture remains the class that most incorporates green water in the North (53%), South (41%) and Central (36%) macro-regions. The regions with the lowest rainfall and the largest pasture area, such as the Northern macro-region (Table 2), have the highest proportion of green WF.

In the Metropolitan macro-region, the largest consumer is the native vegetation class, with 25% of all average rainfall. The native vegetation class also has a significant representation (second largest) in the other macro-regions of the state, with about 21% in the southern macro-region, 28% in the central and 18% in the north.

LEAL *et al*. (2018) also analyzed the relationship between rainfall and green water footprint. Although the calculation procedures were relatively different, the results were similar, with pasture representing about 40% of the average rainfall depth, followed by native vegetation.

Figure 6 presents the results of the total percentage of precipitated water that is converted into green footprint consumed for each municipality of the four state macro-regions.

The municipalities Presidente Kennedy (South), Laranja da Terra (Metropolitan), Marilandia (Central) and Mucurici (North) represent the largest consumers of the total volume of rainwater in each macro-region they are inserted.

Regarding macro-regions, the largest consumer of rainwater by WFgreen is the Northern macro-region, with about 89%, which can be explained by the occurrence of lower annual average rainfall,

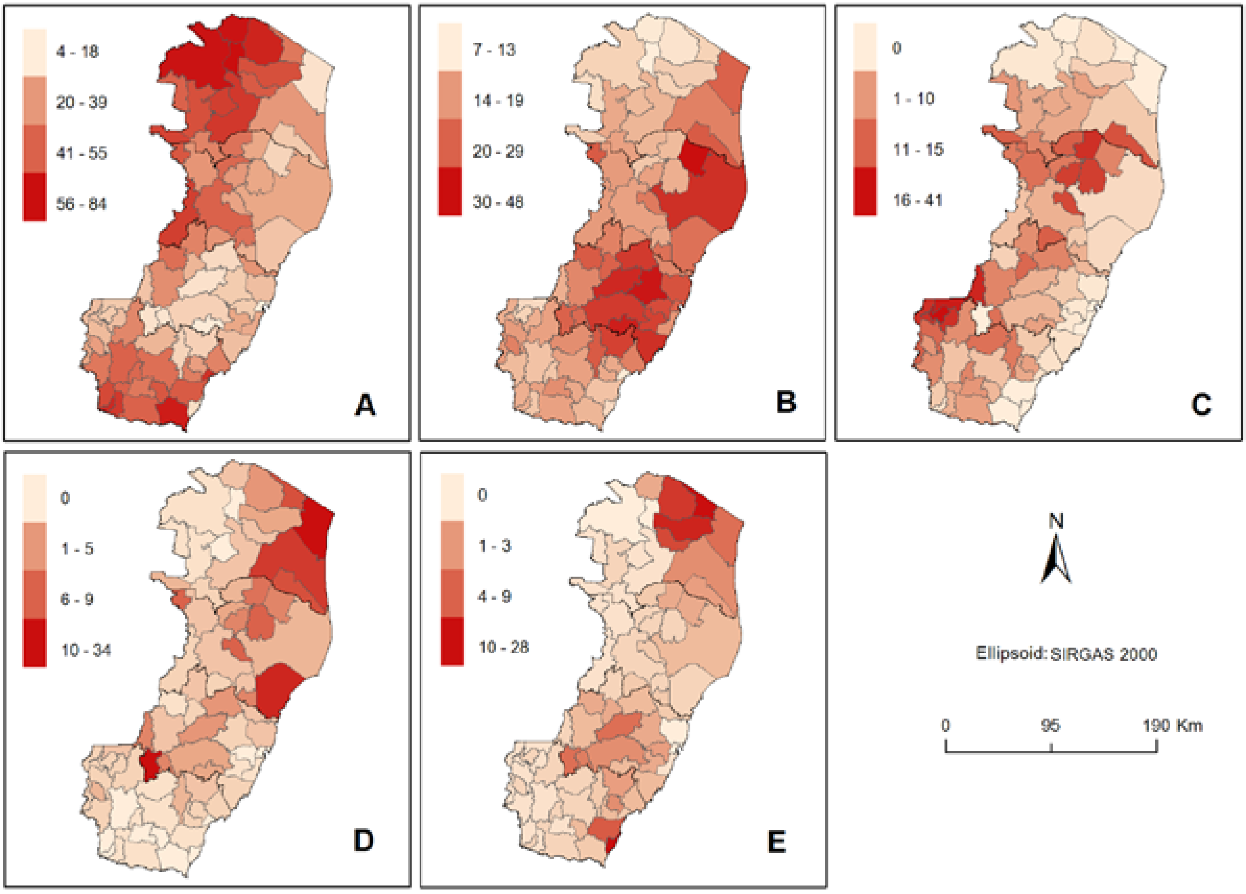


Figure 5. Relationship between green footprint and rainfall (%) for pasture (A), native vegetation (B), coffee (C), forestry (D) and other agricultural crops (E) in the municipalities of Espírito Santo.

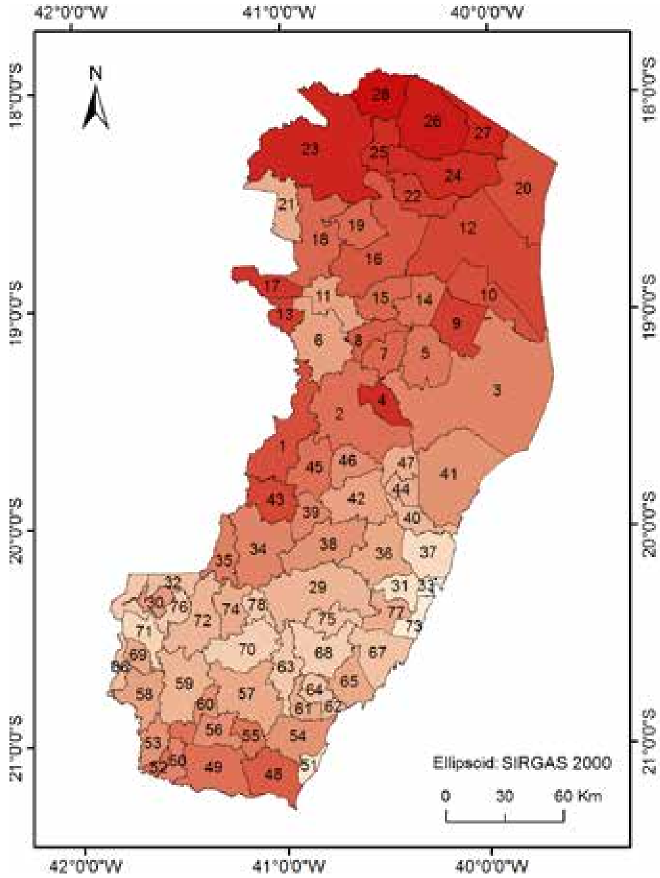
higher pasture percentage and higher annual average real evapotranspiration (higher WF_{green}), followed by Central with 84%, South with 76% and Metropolitan with 73%.

Rainwater consumed for the use of vegetation cover represents an average percentage of 80% of the total rainfall in the state, that is, green WF is the main consumer of surface water in the state. Thus, much of the water available in the soil is absorbed and used by vegetation, leaving less water for underground water recharge.

Several studies report that agricultural production is the main consumer of green water, which shows the importance of the green water component (LEAL *et al*., 2018; LIU *et al*., 2009; MEKONNEN & HOEKSTRA, 2010, 2011b). According to VANHAM & BIDOGLIO (2013), campaigns for water use awareness focuses on water use for the domestic and industrial sectors. However, more attention should be given to water consumption in agricultural production processes. SCHYNS *et al*. (2015) report that studies on water scarcity should be focused not only on blue water, but mainly on green water, as it plays an important role in crop production, pasture, forestry, as can be analyzed through this study.

Green water footprint sustainability

Green WF sustainability is calculated according to water scarcity (WS) indicators. These indicators are based on green water availability (WA) and total green WF (green WF) used monthly. This availability (WA) comes from the process of total evapotranspiration of the rain water (ETgreen), except the natural vegetation evapotranspiration (ETenv) and the evapotranspiration of unproductive areas. Figure 7 shows the results for green monthly environmental sustainability in the state of Espírito Santo.



Nº	Municipality	Rainfall (%)	Nº	Municipality	Rainfall (%)
1	Baixo Guandú	89	40	Fundão	74
2	Colatina	85	41	Aracruz	80
3	Linhares	82	42	Santa Teresa	77
4	Marilândia	93	43	Laranja da Terra	90
5	Rio Bananal	84	44	Ibiraçu	75
6	Pancas	77	45	Itaguaçu	85
7	Governador Lindenberg	86	46	São Roque do Canaã	81
8	São Domingos do Norte	87	47	João Neiva	75
9	Sooretama	91	48	Presidente Kennedy	76
10	Jaguaré	89	49	Mimoso do Sul	85
11	Águia Branca	77	50	Apiacá	82
12	São Mateus	90	51	Marataízes	56
13	Alto Rio Novo	91	52	Bom Jesus do Norte	85
14	Vila Valério	85	53	São José do Calçado	80
15	São Gabriel da Palha	86	54	Itapemirim	80
16	Nova Venécia	88	55	Atílio Vivácqua	84
17	Mantenópolis	92	56	Muqui	81
18	Barra de São Francisco	86	57	Cachoeiro de Itapemirim	76
19	Vila Pavão	86	58	Guaçuí	77
20	Conceição da Barra	89	59	Alegre	74
21	Água Doce do Norte	75	60	Jerônimo Monteiro	80
22	Boa Esperança	91	61	Rio Novo do Sul	76
23	Ecoporanga	95	62	Piúma	73
24	Pinheiros	93	63	Vargem Alta	71
25	Ponto Belo	93	64	Iconha	72
26	Montanha	96	65	Anchieta	76
27	Pedro Canário	95	66	Dores do Rio Preto	73
28	Mucurici	97	67	Guarapari	72
29	Domingos Martins	74	68	Alfredo Chaves	69
30	Irupi	78	69	Divino de Sao Lourenço	76
31	Cariacica	63	70	Castelo	69
32	Ibatiba	73	71	Ibitirama	68
33	Vitória	34	72	Muniz Freire	74
34	Afonso Cláudio	82	73	Vila Velha	55
35	Brejetuba	83	74	Conceição do Castelo	75
36	Santa Leopoldina	76	75	Marechal Floriano	72
37	Serra	64	76	Iúna	71
38	Santa Maria de Jetibá	80	77	Viana	75
39	Itarana	82	78	Venda Nova do Imigrante	71

Figure 6. Relationship between the average total volume of rain water and the green water footprint in the state of Espírito Santo.

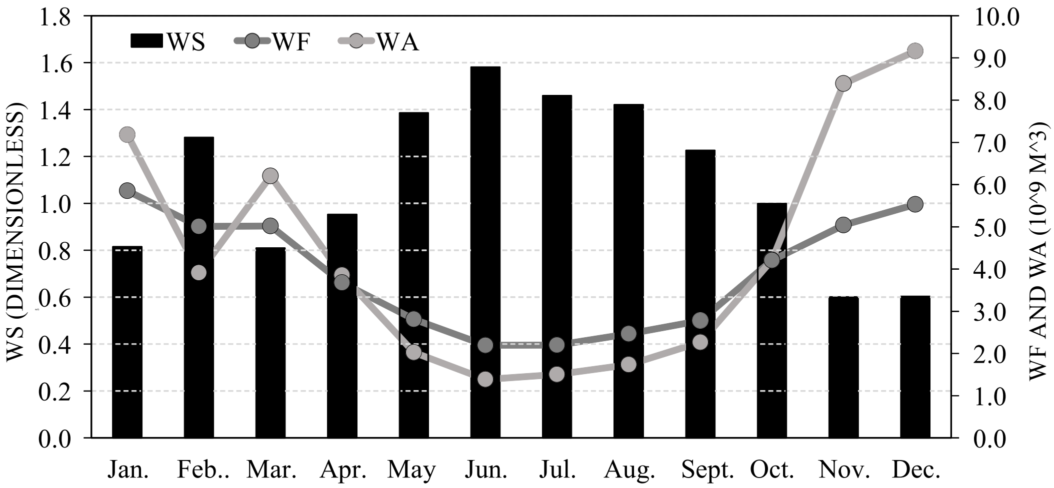


Figure 7. Monthly environmental sustainability of the green footprint in the state of Espírito Santo.

According to the results shown in Figure 7, the green footprint was unsustainable in most months of the year. From May to September, this unsustainability was more significant, especially in June, with scarcity index close to 1.6, due to the lower rainfall rates that occur during this period (drought).

Regarding the availability of green water, the months with the highest rates were January, March, November and December, with 7.2; 6.2; 8.4 and 9.2 billion m³/month, respectively. An excess was found in seven months of the year in relation to the green footprint and availability, especially the months of February, June, July and August, which showed higher indices.

This unsustainability behavior was also analyzed by LEAL *et al*. (2018), in the Itapemirim river basin, which obtained relatively similar results: seven months of the year with the highest representativeness of green water scarcity, also highlighting the month of June, with the highest value.

When the water scarcity values are compared, it is clear that LEAL *et al*. (2018) obtained, especially in the months with less precipitation (May to September), higher EA values than those obtained in this study. This was due to the fact that ETR was considered in this study, while LEAL *et al*. (2018) used potential evapotranspiration (ETP) to calculate green WF of crops, using ETR only for pasture and native vegetation. In addition, LEAL *et al*. (2018) also used a different database from this study regarding evapotranspiration values. That is, the estimates of the crop's green footprint were made by LEAL *et al*. (2018) as if irrigation was used in all crops. However, because most of the crops are not irrigated in the state, only the ETR was used in this study, aiming to obtain better estimates.

CONCLUSIONS

- In estimating the total green WF in the state of Espírito Santo, it was found that pastures had the highest percentage of participation in water consumption, followed by native vegetation, coffee, forestry and other agricultural crops. This sequence followed the same order of magnitude of area of the main classes of land use in the state.
- The green WF represented about 80% of the total annual average volume of precipitation in the state over the studied period. Such relationship was greater in the North (89%) macro-region, followed by the Central (84%), South (76%) and Metropolitan regions (73%
- Water consumption by green WF was unsustainable, that is, it exceeded the availability of water (rainfall) in six months of the year (February, and from May to September), corresponding to the least rainy months in the state of Espírito Santo.

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