Energy balances in sugar cane, coffee and natural vegetation in the northeastern side of the São Paulo state, Brazil

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Abstract.

Under land and climate change scenarios, agriculture has experienced water competitions among other sectors in the São Paulo state, Brazil. On the one hand, in several occasions, in the northeastern side of this state, nowadays sugar-cane is expanding, while coffee plantations are losing space. On the other hand, both crops have replaced the natural vegetation composed by Savannah and Atlantic Coastal Forest species. Under this dynamic situation, geosciences are valuable tools for evaluating the large-scale energy and mass exchanges between these different agro-ecosystems and the lower atmosphere. For quantification of the energy balance components in these mixed agro-ecosystems, the bands 1 and 2 from the MODIS product MOD13Q1 were used throughout SAFER (Surface Algorithm for Evapotranspiration Retrieving) algorithm, which was applied together with a net of 12 automatic weather stations, during the year 2015 in the main sugar cane and coffee growing regions, located at the northeastern side of the state. The fraction of the global solar radiation (R_G) transformed into net radiation (Rn) was 52% for sugar cane and 53% for both, coffee and natural vegetation. The respective annual fractions of Rn used as λE were 0.68, 0.87 and 0.77, while for the sensible heat (H) fluxes they were 0.27, 0.07 and 0.16. From April to July, heat advection raised λE values above Rn promoting negative H, however these effects were much and less strong in coffee and sugar cane crops, respectively. The smallest daily Rn fraction for all agro-ecosystems was for the soil heat flux (G), with averages of 5%, 6% and 7% in sugar cane, coffee and natural vegetation. From the energy balance analyses, we could conclude that, sugar-cane crop presented lower annual water consumption than that for coffee crop, what can be seen as an advantage in situations of water scarcity. However, the replacement of natural vegetation by sugar cane can contribute for warming the environment, while when this occur with coffee crop there was noticed cooling conditions. The large scale modeling satisfactory results confirm the suitability of using MODIS products together with weather stations to study the energy balance components in mixed agro-ecosystems under land-use and climate change conditions.

Key-words: remote sensing, net radiation, latent heat flux, sensible heat flux, agro-ecosystems.

1. INTRODUCTION

In the northeastern side of São Paulo state, sugar cane (*Saccharum officinarum*) and coffee (*Coffee Arabica L.*) crops, are important for the Brazilian agriculture. Sugar cane is an annual crop while coffee is a perennial crop; both are replacing the natural vegetation, composed by a mixture of Savannah and Atlantic Coastal Forest species. However, nowadays; sugar cane is also invading the coffee areas[1]. The larger expansion of sugar cane has been consequences of both sugar and alcohol productions, but also with the perspective of generating renewable energy[2].

The negative effects of the sugar cane expansion, in areas before occupied by natural vegetation and coffee could be more harmful when comparing with those from the fossil fuel exploration, regarding greenhouse gas emissions[3-4]. Aiming bioenergy production, a crop should be fast growing and high yielding with its energy output exceeding fossil

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fuel energy input. In terms of satisfying these criteria, sugarcane is currently the most promising energy crop[5]. However, its expansion could affect the large scale energy available partition[6] and there are many concerns about the impacts on the carbon cycle[7], further affecting the radiation balance[8]. Anderson-Teixeira et al.[9] have also reported energy balance alterations as consequences of the sugarcane crop expansion.

Under these land-use and climate change conditions, the use of tools for quantifying the energy balance components on a large scale is relevant for supporting policy planning and decision-makings about the natural resources. The difficulties of measuring and analyzing these components by only field measurements highlighted the importance of coupling remote sensing and weather data, what have been successfully done in energy crops under different environmental conditions[3,10].

The SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm is applied in the current research to estimate the energy balance components in sugar cane and coffee crops comparing the results with those for natural vegetation in the northeastern side of São Paulo state. The algorithm was developed and validated in Brazil based on simultaneous field data from four flux towers and Landsat images under strongly thermohydrological contrasting conditions[11,12].

With cropland masks, the energy balance components are analyzed by the coupled use of MODIS images and weather data. The results may subsidize policies for a rational sugar cane and coffee water managements, being the analyses very useful under the actual scenario of water competitions between these crops and with other sectors in the Brazilian Southeast, as consequences of both climate and land use changes.

2. MATERIAL AND METHODS

2.1. Study area, crop stages and data set

Fig. 1 shows the location of the study area in the northeasten side of inside the São Paulo state, Brazil, together with the crop land masks and the net of agrometeorological stations used for the weather data interpolation processes.

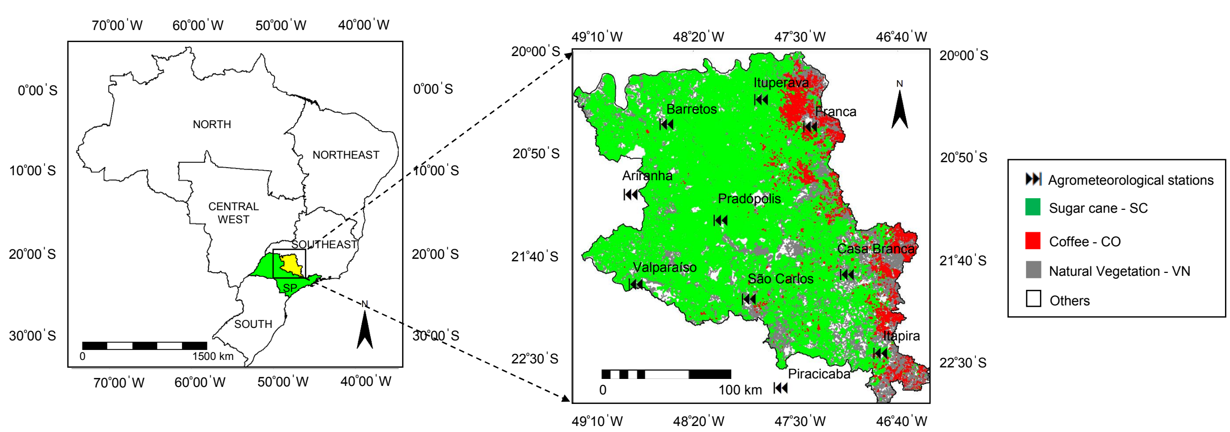

Figure 1. Location of the study area inside the northeastern side of the São Paulo state, Brazil, the crop land masks and agrometeorological stations used for the weather data interpolation processes.

The study area is composed by sugar cane (SC) and coffee (CO) interspaced with natural vegetation (NV). This last class is a mixture of Savannah and Atlantic Coastal Forest species. Some of the areas before occupied by coffee are nowadays replaced by sugar cane crop.

The sugar cane areas interspaced with natural vegetation, concentrated at the left side of the study area (see Fig 1), present two well-defined seasons, one rainy and hotter and the other one dry and colder. According to Cabral et al.[13], the long-term maximum precipitation occur in December (274 ± 97 mm month^{-1}) and the minimum one is between July and August (27 ± 34 mm month^{-1}); the annual value is 1517 ± 274 mm yr^{-1}. The mean air temperatures in January and July are respectively 24 ^{o}C and 19 ^{o}C; the annual average is 22 ^{o}C.

Following Silva et al.[14], the sugarcane phases may be divided into four. Phase 1 – Germination and Establishment, from January to February. This phase denotes activation and subsequent sprouting of the vegetative bud. It is influenced by soil moisture, soil temperature and soil aeration. Phase 2 – Tillering, starting from around 40 days after the initiation of the growing cycle and may last up to 120 days (February-April), being influenced by variety, solar radiation, air temperature, soil moisture and fertilization. Phase 3 – Grand Growth, from 120 days after the starting of the growing cycle lasting up to 270 days in a 12-month crop (May-September). High both, soil moisture and solar radiation levels, favor better cane elongation during this phase. Phase 4 – Ripening and Maturation. Lasts for about three months starting from 270-360 days after the growing cycle initiation (September-December). High solar radiation levels and low soil moisture conditions are favorable during this phase, being characterized by slower growth activity[15]

The coffee areas interspaced with natural vegetation, concentrated at the right side of the study area (see Fig 1), present also a rainy season and a dry winter somewhat similar to the sugar cane areas, however, due to higher altitudes, the long-term annual air temperatures range lower, from 18 to 20 ^{o}C, due to higher altitudes between 700 and 1100 m[16]. According to Camargo & Camargo[17] and Junior et al.[18] the coffee crop in Brazil, differently from sugar cane which complete its average growing cycle in 12 months, takes two years for its all crop stages. Six coffee phases are considered, starting in September of each year. Phase 1 – Vegetative with bud formation, during seven months, normally from September to March. Phase 2 – Vegetative, between April and August, when occurs the transformation of the vegetative to reproductive buds. At the end of this phase, around July and August, the plants enter in relative dormancy stage. Phase 3 – Flowering and grain expansion, normally from September to December. Phase 4 – Grain formation, normally from January to March. Water stress can be detrimental to the grain development. Phase 5 – Grain maturation. Moderate water stress can benefits the grains. Phase 6 – senescence and death of the non-primary productive branches, which generally occur in July and August. In this last stage occur the self-pruning process represented by senescence, when the productive branches wither and die, limiting the biomass productuion.

For the large-scale modeling, MODIS images were used during the year 2015 together with ten agrometeorological stations from the National Meteorological Institute – INMET in the study area, considering the three crop land masks. Global solar radiation (RG), air temperature (T_a), relative humidity (RH) and wind speed (u) were taken to calculate te reference evapotranspiration (ET0) by the Penman-Monteith method[19]. The weather input modelling parameters, RG, T_a and ET0 were averaged for over the 16-day composing periods from the MODIS MOD13Q1 reflectance products (spatial resolution of 250 m) and interpolated by using the moving average method to create grids with the same spatial resolution as the satellite images.

2.2. Large-scale energy balance modelling

For the surface albedo (α_0) calculation, the following equation was applied[20]:

$$\alpha_0 = a + b\alpha_1 + c\alpha_2 \tag{1}$$

where a, b and c are regression coefficients, considered as 0.08, 0.41, 0.14, obtained under different Brazilian vegetation types and thermohydrological conditions[10].

Surface temperature (TS) was estimated based as a residual in the daily radiation balance[10]:

$$TS = \sqrt[4]{\frac{RG - \alpha_0 R_G + \varepsilon_A \sigma T_a{}^4 - Rn}{\varepsilon_S \sigma}} \tag{2}$$

where RG and T_a are, respectively, the daily values of incident global solar radiation and air average temperature interpolated from the agro-meteorological stations; Rn is the daily net radiation; ε_A and ε_S are respectively the atmospheric and surface emissivities; and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}).

The radiation balance parameters ε_A and ε_S were calculated as follows[10]:

$$\varepsilon_A = a_A(-\ln\tau)^{b_A} \tag{3}$$

$$\varepsilon_S = a_S \ln \mathrm{NDVI} + b_S \tag{4}$$

where τ is the short-wave atmospheric transmissivity calculated as the ratio of RG to the incident solar radiation at the top of the atmosphere; NDVI is the Normalized Difference Vegetation Index; and a_A, b_A, a_S and b_S are regression coefficients 0.94, 0.10, 0.06 and 1.00, respectively.

The long-wave atmospheric radiation (RL_a) was calculated based on the physics concepts of the Stefan-Boltzmann law and Rn was obtained through the equation of Slob[10]:

$$RL_a = \sigma\ \varepsilon_A T_a^4 \tag{5}$$

$$Rn = (1-\alpha_0)RG - a_L\tau \tag{6}$$

where the regression coefficient a_L was spatially distributed through its relationship with T_a:

$$a_L = cT_a - d \tag{7}$$

and c and d are regression coefficients found to be 6.99 and 39.93.

The evapotranspiration (ET) was calculated and transformed into λE[10]:

$$\frac{ET}{ET0} = \left\{\exp\left[a_{sf} + b_{sf}\left(\frac{T_S}{\alpha_0 \mathrm{NDVI}}\right)\right]\right\}\frac{ET0_{yr}}{5} \tag{8}$$

where a_{sf} and b_{sf} are the regression coefficients 1.8 and -0.008, respectively[10]. The correction factor ($ET0_{yr}/5$) was applied for atmospheric demand calibration, where $ET0_{yr}$ is the mean annual daily grid of the reference evapotranspiration (ET0) in the study region for 2015, and 5 mm d^{-1} is that for the original modeling.

For soil heat flux (G), the equation derived by Teixeira, 2010[12] was applied:

$$\frac{G}{R_n} = a_G \exp(b_G \alpha_0) \tag{9}$$

where a_G and b_G (3.98; -25.47) are the regression coefficients.

The sensible heat flux (H) was then estimated as residue on the energy balance equation:

$$H = R_n - \lambda E - G \tag{10}$$

3. RESULTS AND DISCUSSION

3.1 Weather drivers

The weather-driving forces for the surface energy partition are RG, T_a, precipitation (P), and the atmospheric demand represented by ET0. These parameters are presented in Fig. 2 on a 16-day time-scale in terms of Day of the Year (DOY), during 2015 as average pixel values for each crop land class: sugar cane (SC), coffee (CO) and natural vegetation (NV).

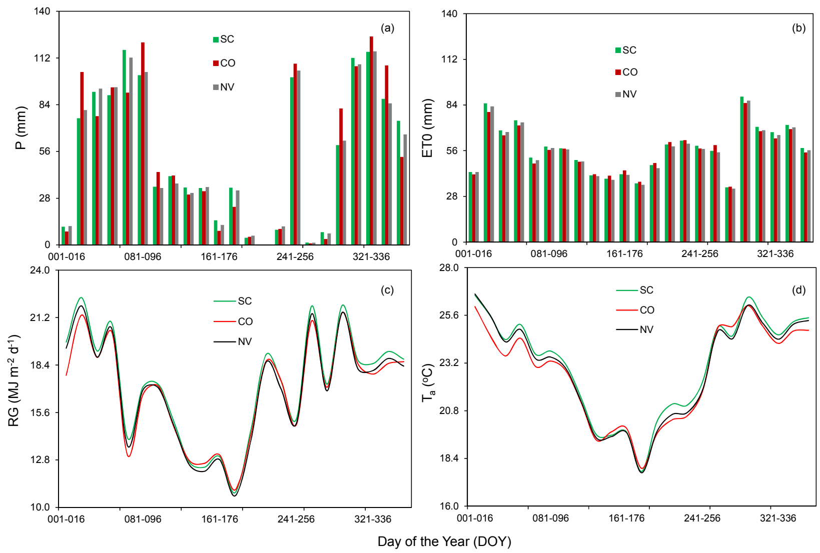

Figure 2. Average16-day pixel values for the weather variables during 2015 in sugar cane (SC), coffee (CO) and natural vegetation (NV) in terms of Day of the Year - DOY, in the northeastern side of São Paulo state, Brazil. (a) Precipitation (P); (b) reference evapotranspiration (ET0); (c) incident global solar radiation (RG); and (d) air temperature (T_a).

From the four weather parameters in Fig. 2, P was the most variable along the year with the highest values happening during the first and the last three months. The moisture conditions in the root zones will affect the energy partitions. The annual total were 1253, 1277 and 1245 mm yr^{-1} for the sugar cane (SC), coffee (CO) and natural vegetation (NV) agro-ecosystems with the standard deviation between 11 and 12 mm yr^{-1}. These values are bellow the long-term value of the study area, and they were not well distributed along the whole year. A period from July to October, with several 16-day values bellow 10 mm is noticed for all analyzed agro-ecosystems.

The short rainfall amounts happened occurred from Phase 3 to Phase 4 of the generalized sugarcane growing cycle, which should have caused some crop water deficit, when its crop water requirements are high. Cabral et al.[13] reported a 13% of biomass reduction in relation to the regional average in São Paulo state, Brazil, because of the lower water availability observed during the initial 120 days of cane re-growth. For rainfed sugarcane crop, a total precipitation for a growing season between 1100 and 1500 mm with good distribution is considered adequate. However, the rainfall reduction during the sugar cane Phase 3, should have caused some crop water deficit, when the crop water requirements are high, further affecting the energy partition, by reducing leaf area and the number of tillers and leaves per stalk[21]. However, during Phase 4, rains are not desirable because they lead to poor juice quality[15], then, the high amounts at the end of the year, coinciding with this phase was not favorable for sugarcane. Considering the ET0 values, one can see two peaks with the smallest ones happening at the middle of the year, however, with also low differences between the agro-ecosystems than in the case of precipitation. The annual corresponding values for ET0 were 1321, 1297 and 1293 mm yr^{-1}, with small SD values from 3 to 4 mm yr^{-1}. The lowest values in the middle of the year, from May to July, coincide with the sugar cane Phase 3, reducing cane elongation during this phase. In relation to R_G and T_a the difference were smaller among the agro-ecosystems with average annual values around 17 MJ m^{-2} day^{-1} and 23.0 ^{o}C, respectively. Then the highest atmosphere demands in sugar cane could be probably attributed to low air humidity and/or high wind speed conditions.

The weather conditions also strongly affect the coffee crop stages[17]. As its growing cycle takes two years, some coffee phases will coexist together. Rainfall should be well distribute for good yield. At the start of the year, for the period involving Phases 1 and 4 there was only a 16-day (DOY: 001-016) period with precipitation bellow 10 mm in January. In Phase 2 precipitation is important for the transformation of the vegetative to reproductive buds. During this period precipitation declined reaching to values close to zero at the end of July (DOY 209-224). In Phase 3 (September – November) a period of some water stress is desirable, as the main flowering happens during a period of water stress following by good water availability. However two 16-day period with low rainfall amounts is verified from September to October (DOY 257-288. In Phase 4 water stress may wilt the fruits, but only during the period from DOY 001 to 016 the rainfall amount was short, bellow 10 mm. In Phase 5 the water requirements decline and some water deficit during this phase will favor the coffee growth. The period with low rainfall amounts from May to June were also inside this phase. Conditions of low RG levels from May to August coincided with low precipitation amounts, than reducing the atmospheric demand (ET0). The air temperature regulates the vegetative growth and reproductive buds, being high values associated with water deficit during booming the reason for flower abortion and growth reduction[22]. However, the higher values, above 23 ^{o}C occurred under conditions of good rainfall availability.

3.2 Modeling input parameters

Fig. 3 presents the spatial distribution for some of the 16-day average daily surface albedo (α_0) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015 inside the northeastern side of the São Paulo (SP) state, Southeast Brazil.

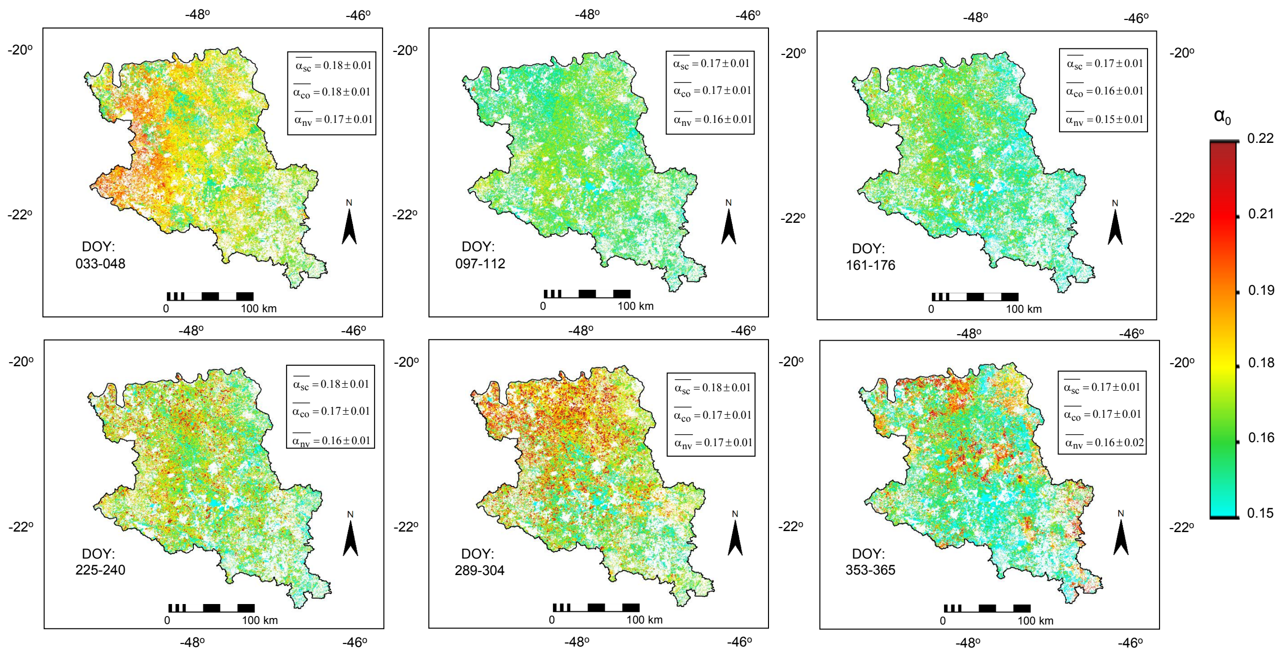

Figure 3. Spatial distribution for some of the 16-day average daily surface albedo (α_0) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of the São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

Sugar cane crop is concentrated on the left side of Fig. 3 while most of the coffee crop are on the right side of this figure. Natural vegetation is in between these two agro-ecosystems (see also Fig. 1). Besides RG levels, the spatial and temporal variations in the shortwave radiation balances in all agro-ecosystems, are also strongly affected by α_0, which pixels values ranged from 0.15 to 0.22 along the year 2015.. As a darker surface the ecosystem NV, presented lower values, consequently will have higher available energy than the brighter SC and CO ecosystems. However, even with different spatial and temporal behaviours along the year, with alternate higher and lower α_0 values for the SC and CO classes, both presented an annual average of 0.17, while for the NV it was 0.16. It has been also reported that, besides the vegetation types and stages, α_0 will also depend on the soil moisture and crop management[11,23].

The bluish area in Fig. 3 represent most the NV species of Savannah and Atlantic Coastal Forest, which present low α_0 values favouring, consequently, a higher available energy to their vegetated surfaces, as they are darker than crops. However, the α_0 spatial variations were low with standard deviation (SD) from 0.01 to 0.02, with no strong distinctions among the mixed agro-ecosystems.

The α_0 values in the current study are close to the lower end of those reported in between 0.15 and 0.26, for tropical natural vegetation[24]. Our lower values are probably due to the high both solar radiation levels and moisture conditions in the northeastern side of the São Paulo state. The relation of α_0 with environmental and moisture conditions is in accordance with other more recent studies[10,25-27].

Fig. 4 shows the spatial distribution for some of the 16-day average daily Normalized Difference Vegetation Index (NDVI) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) agro-ecosystems, during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil.

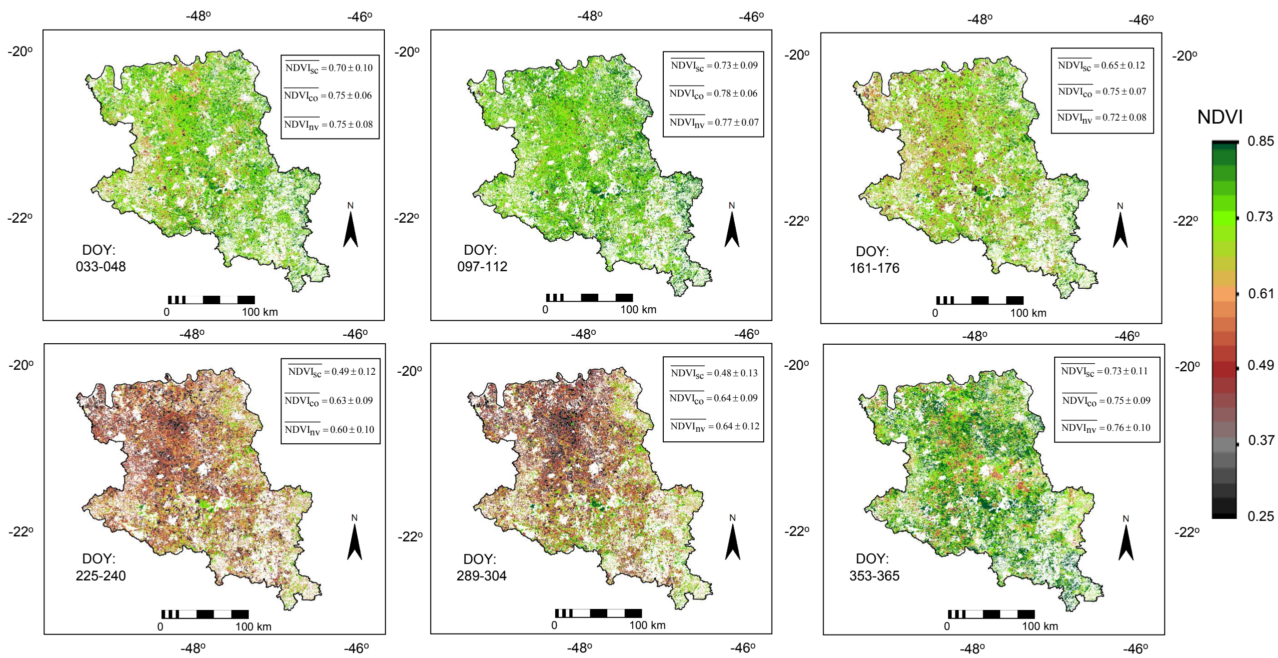

Figure 4. Spatial distribution of some of the 16-day average daily Normalized Difference Vegetation Index (NDVI) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

The distinctions of the NDVI values between the SC and CO classes, are much clear than in the case of α_0, with the highest average for the second one, mainly during the driest and coldest conditions of the year (see Figures 2 and 4). The lower values for SC coincided with its ending Phase 3 to Phase 4 (Grand Growth to Ripening and Maturation). However, the NDVI values between classes CO and NV were similar. The annual average were 0.62, 0.71 and 0.70 for the SC, CO and NV agro-ecosystems. As there is a relation between the latent heat flux (λE) and NDVI[28], as a first guess, the annual crop water consumption from SC class should be the lowest among the analysed agro-ecosystems.

Fig. 5 presents the spatial distribution for some of the 16-day average daily surface temperature (TS) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil.

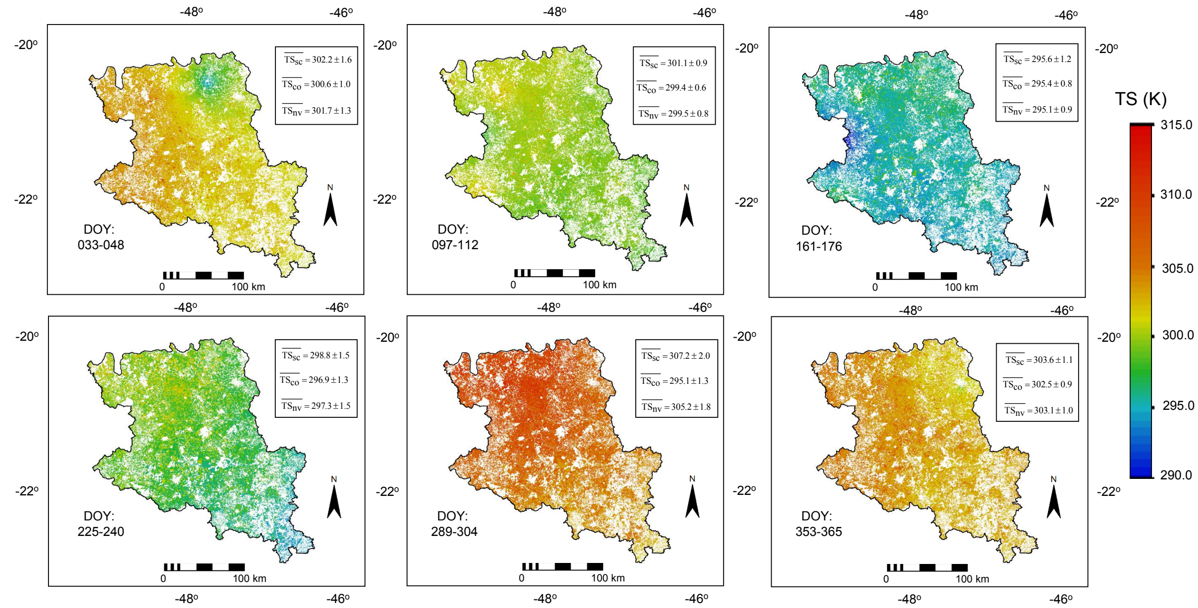

Figure 5. Spatial distribution for some of the 16-day average daily surface temperature (T_0) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

TS affects the energy available, by interfering in the long wave radiation balance. From the three analysed agro-ecosystems, there were no significant differences, all presenting averages annual values of 300 K, with low spatial variations. The magnitudes along the year followed those for RG and Ta (see Fig. 2c,d and 5). With low differences between α_0 and TS, one should firstly expected that, even the ecosystem SC class presenting lower NDVI than the others, the available energy would not be so different among the analysed agro-ecosystems, with the radiation balance probably much depending on the solar radiation levels. In addition, the energy partition will vary depending on the root zone moisture conditions and the crop stages and management of the SC and CO classes.

3.3 Energy balance components

Fig. 6 shows the spatial distribution for some of the 16-day average daily net radiation (Rn) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil.

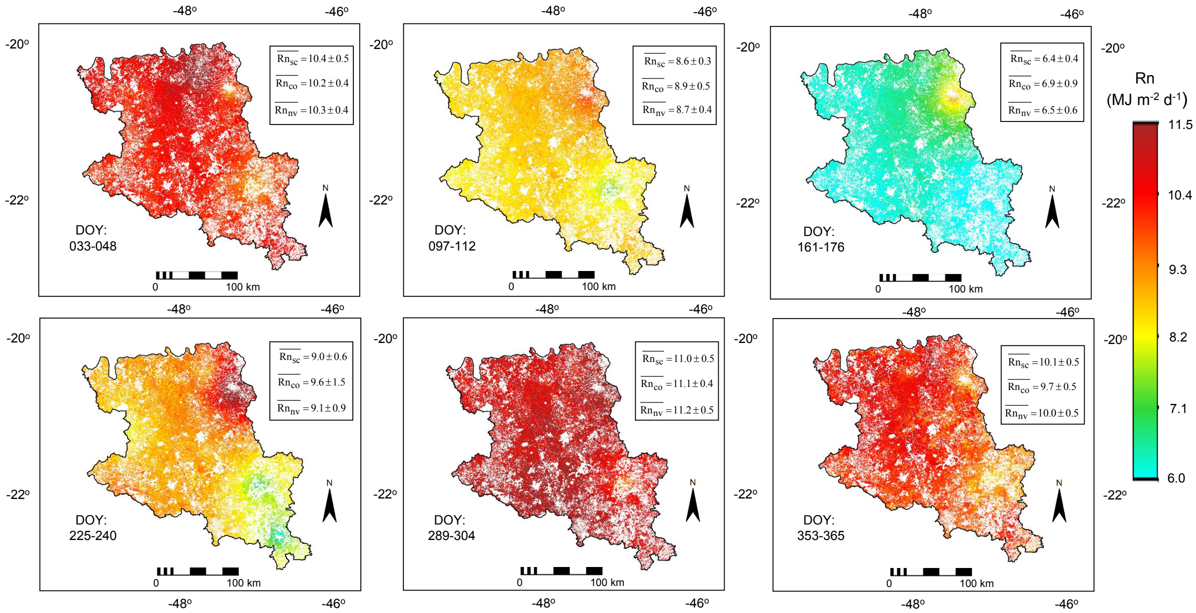

Figure 6. Spatial distribution for some of the 16-day average daily net radiation (Rn) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

The lower Rn pixel values were in the middle of the year, when they reached close to 6.0 MJ m^{-2} d^{-1}, while the maximum ones above 10 MJ m^{-2} d^{-1}, happened at the start and at the end of the year. All ecosystems presented averages of 9.0 MJ $m^{-2}d^{-1}$; however, with small spatial variation, as one can see by the standard deviation (SD) values ranging from 0.3 MJ m^{-2} d^{-1} to 1.5 MJ m^{-2} d^{-1}. The highest end of this range was for CO class, mainly in the right upper side of Fig. 6 in DOY 225-240 (August) happening when coexist plants in coffee Phases 2 and 6.

To see more in-depth the variation the energy availability to the different agro-ecosystems along the year, Fig. 7 shows the curves for the 16-day Rn pixel average values (a) and their fractions to RG (b) for sugar cane (SC), coffee (CO) and natural vegetation (CO), during the year 2015.

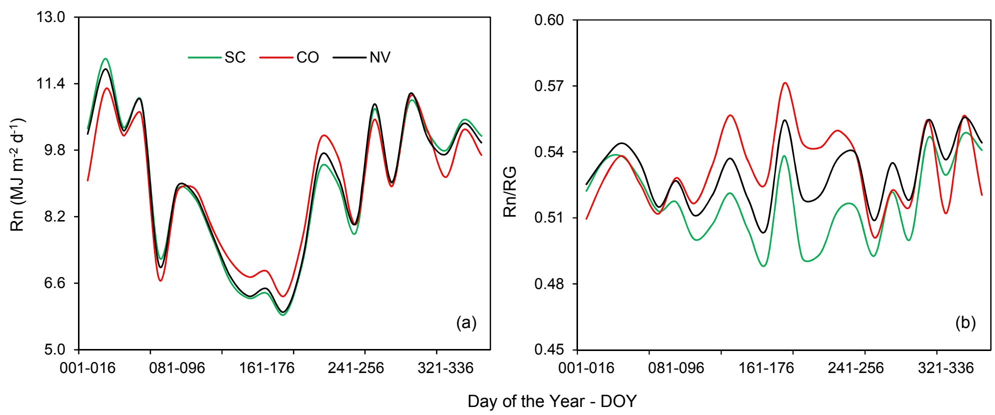

Figure 7. Trends of 16-day average pixel values for the daily net radiation (Rn) and their ratios to global solar radiation (RG) for sugar cane (SC), coffee (CO) and natural vegetation (NV) agro-ecosystems, during the year 2015, in the northeastern side of São Paulo (SP) state, Southeast Brazil.

From Figures 2c and 7a, the strong dependence of Rn on RG is confirmed for all analysed agro-ecosystems. Along 2015, Rn average values for the SC and VN classes were similar, but those for CO were a little lower, at the start and at the end of the year, coinciding with Phases 1 and 4 of coffee crop. However, at the middle of the year CO values were higher, when mixed coffee plants were in Phases 2, 5 and 6.

Considering the Rn/RG (Fig. 7b), the average values were higher for coffee crop, mainly in the middle of the year. They ranged from 0.49 to 0.55; 0.50 to 0.57; and 0.50 to 0.56, for respectively, SC, CO and NV classes. The average annual value of 50-55% is in agreement with field measurements in the semi-arid region of Brazil[11] and with studies involving other agro-ecosystems[29-30], what give confidence to the remote sensing methods tested here on large-scales by using the MOD13Q1 product and agrometeorological stations.

Fig 8. presents the spatial distribution for some of the 16-day average daily latent heat flux (λE) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil.

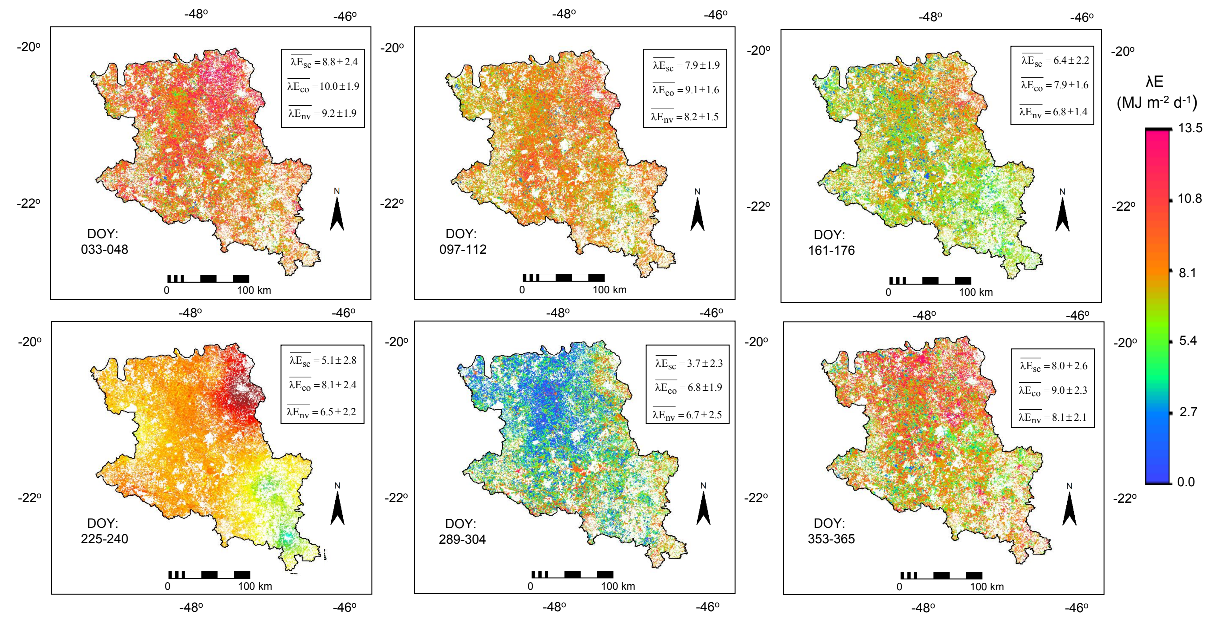

Figure 8. Spatial distribution for some of the 16-day average latent heat flux (λE) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

Much more distinct λE pixel values among the agro-ecosystems are noticed than in the case of Rn and with higher spatial variations as one can see by the standard deviation values. λE ranged from close to zero to becoming higher than 13 MJ m^{-2} d^{-1} in the mixture of classes. The lowest values were for SC, with an average mean annual value of 6.1 ± 2.2 MJ m^{-2} d^{-1}, followed by natural vegetation (6.9 ± 1.8 MJ m^{-2} d^{-1}) and coffee, with the highest average rate of 7.8 ± 1.8 MJ m^{-2} d^{-1}. Besides the lowest λE, the SC agro-ecosystem presented also the largest spatial variation. Considering all classes, the highest and the lowest λE rates were, respectively in January and at the end of October.

Fig. 9 shows the curves for the 16-day λE average values (a) and their fractions to Rn (b) for sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015.

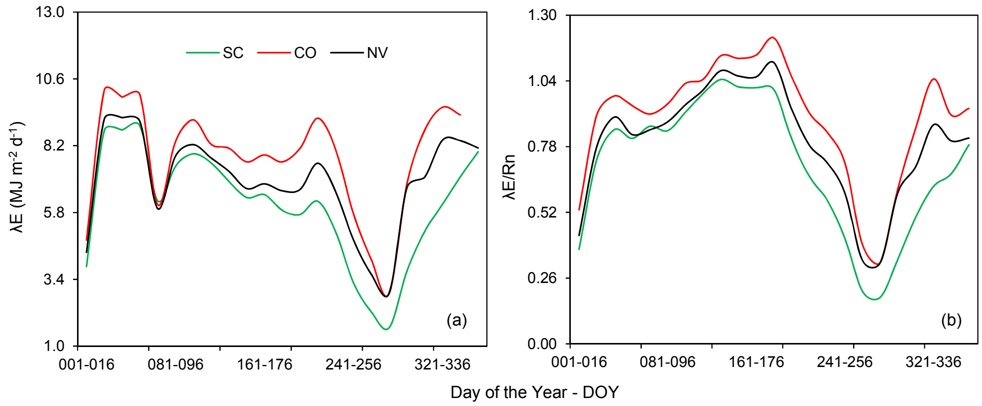

Figure 9. Trends of the 16-day average pixel values for the latent heat flux (λE) and their ratios to net radiation (Rn) for sugar cane (SC), coffee (CO) and natural vegetation (NV) agro-ecosystems, during the year 2015, in the northeastern side of São Paulo (SP) state, Southeast Brazil.

For all the analysed agro-ecosystems, the λE values started in 2015 with low average values bellow 5.0 MJ m^{-2} d^{-1} (2.0 mm d^{-1}), due to the low rainfall amounts during the first half of January (see Figures and 2a and 9a). After the first rains, λE followed the solar radiation levels, but the reduction in August was because the short period with declining of precipitations. It is clear that almost all periods of the year, coffee (CO) λE values were the highest, while for sugar cane (SC) they were the lowest ones. Natural vegetation (NV) presented intermediary fluxes.

The differences among the agro-ecosystems also arise for the λE/Rn ratio, but with different shapes of the curves. This ratio indicates the soil moisture in the root zones, evidencing two periods with lower water availability with λE/Rn values bellow 0.60. For all agro-ecosystems one of this period was at the first half of January, however for sugarcane there was a longer period of water stress from the first half of August to the end of October, when λE/Rn dropped below 0.20, while for coffee and natural vegetation this water stress was shorter, from September first half of October. In sugar cane, this low soil moisture conditions should be favorable during the ripening and maturation of the canes (Phase 4) while in coffee crop this water stress conditions could have affect the vegetative development and bud formation, for plants in Phase 1 and the flowering and grain expansion, for plants in Phase 3.

Transforming the λE into water units, we found evapotranspiration (ET) rates from 0.7 to 3.6 mm d^{-1}; 1.2 to 4.1 mm d^{-1}; and 1.2 to 3.7 mm d^{-1} for the SC, CO and NV agro-ecosystems, respectively, with the corresponding average values for the year 2015 were 2.5 mm d^{-1}, 3.2 mm d^{-1} and 2.8 mm d^{-1}. The ET daily values for sugar cane reported by Eksteen et al.[31] are between 1.6 and 2.9 mm d^{-1}, involving different sugarcane varieties and soil moisture conditions. A previous study with sugarcane, under irrigation conditions, in Florida (USA), by Omary and Izuno [37], resulted in minimum daily rates of 0.7 to 1.5 mm d^{-1}, and maximums of 4.5 to 4.6 mm d^{-1}. Our ET sugar cane values are between these two international studies. In relation to coffee crop, in Brazil, Vila Nova et al.[33] reported that for the complete grain maturation, it presented mean ET rates of 3.5 mm d^{-1}, while Oliveira et al.[34] found an average of 2.9 mm d^{-1}. Our ET coffee results are between these two national studies.

The higher λE values for coffee than for sugar cane means a larger annual water consumption of the first crop that should be considered under the conditions of water competition by different sectors. Even the cropland masks involving different crop stages of sugarcane and coffee in the current study, the similarity of our Rn and λE values with those from field measurements in the national and international literature provide confidence for the energy balance analyses by applying the SAFER algorithm to MODIS images throughout the product MOD13Q1.

Fig. 10 shows the spatial distribution for some of the 16-day average sensible heat flux (H) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil.

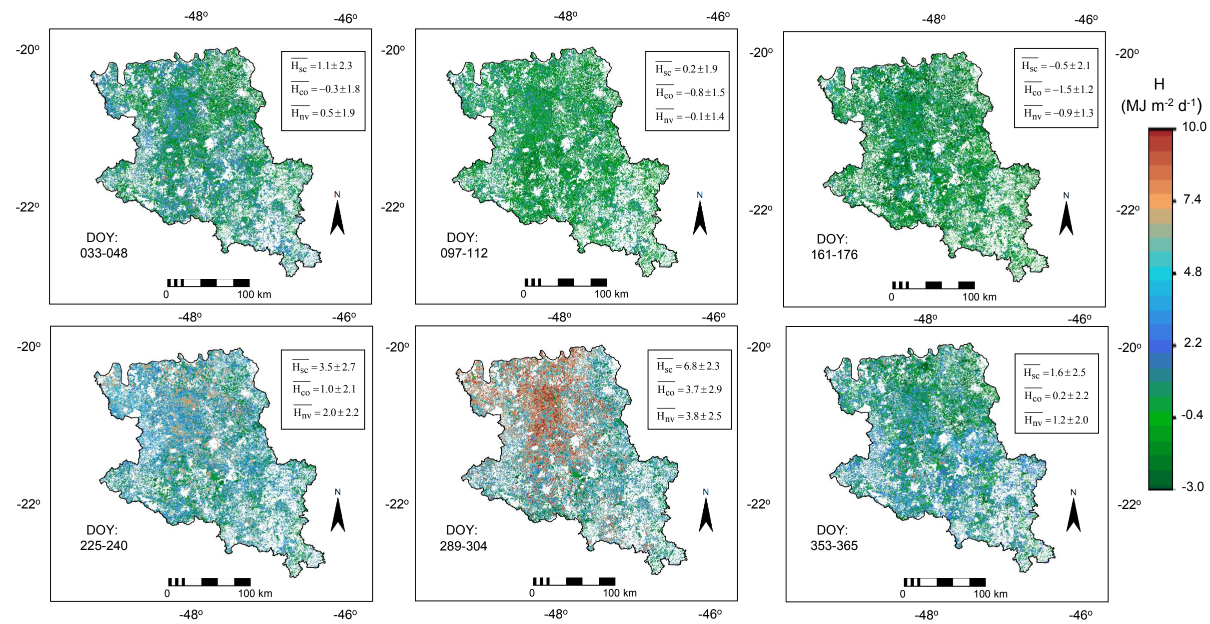

Figure 10. Spatial distribution for some of the 16-day average sensible heat flux (H) values in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV), during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

As in the case of λE, H pixel values among the agro-ecosystems are well differentiated according to the time of the year, but in an inverse way, with the highest values corresponding to the driest soil moisture conditions. They ranged from negative values as low as -3 MJ m^{-2} d^{-1} to high positive ones close to 10 MJ m^{-2} d^{-1}. Among the analysed agro-ecosystems, the lowest H values were for coffee, with an average annual mean of 0.6 ± 1.7 MJ m^{-2} d^{-1}, followed by natural vegetation (1.4 ± 1.8 MJ m^{-2} d^{-1}) and sugar cane, with the highest with 2.4 ± 2.2 MJ m^{-2} d^{-1}. Besides the highest H magnitude, sugar cane presented also the largest spatial variation. Considering all analysed agro-ecosystems, the largest H values were during the driest conditions of the year in the first half of January and from the second half of September to the end of October. The lowest H rates, even negative, were at the end of the first rains of 2015, from the April to the second half of July, when the root zones were uniformly with good moisture.

Fig. 11 presents the curves for the 16-day H pixel average values (a) and their fractions to Rn (b) for sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015.

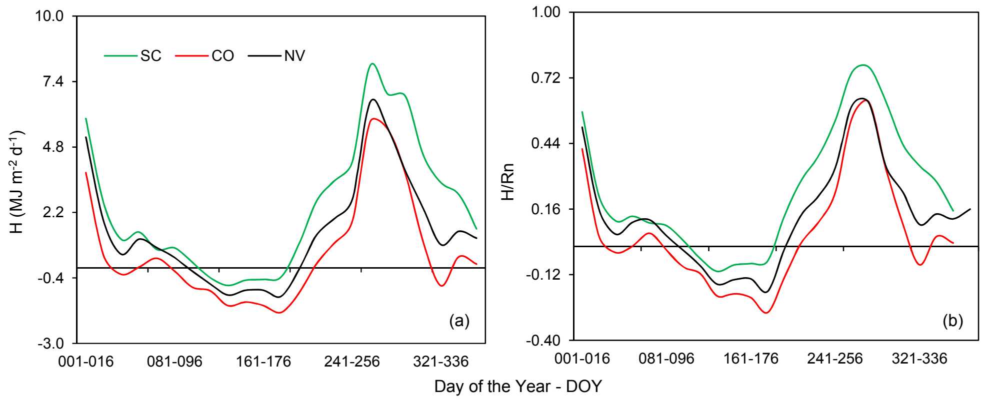

Figure 11. Trends of the 16-day average pixel values for the sensible heat flux (H) and their ratios to net radiation (Rn) in sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015, in the northeastern side of São Paulo (SP) state, Southeast Brazil.

In the middle of the year, the negative H values from April to July indicate horizontal heat advection from the drier and hotter to the wettest and colder areas in all analysed agro-ecosystems (Fig. 11a). The largest average positive values happened in sugar cane (8 MJ m^{-2} d^{-1}) in the second half of September (DOY 257-252), when H represented 74% of Rn (Fig 11b), while the lowest negative H value happened in coffee during DOY 129-144, in May, when the average 16-day value was -1.5 MJ m^{-2} d^{-1}. During the year 2015, the average annual H/Rn fractions were 0.07, 0.16 and 0.27 for coffee (CO), natural vegetation (NV) and sugar cane (SC). These results may represent cooling and warming effects as consequences of the replacement of the natural vegetation by the first and the last crop, respectively. Although sugar cane consuming less water than coffee crop in an annual scale, being a positive aspect under the condition of water scarcity, its higher H rates have to be considered under the conditions of the coupled effects of climate and land use changes.

To compete the energy balance, the spatial distribution for some of the 16-day average soil heat flux (G) values for the MODIS images in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015 inside the northeastern side of São Paulo (SP) state, Southeast Brazil, are shown in Fig. 12.

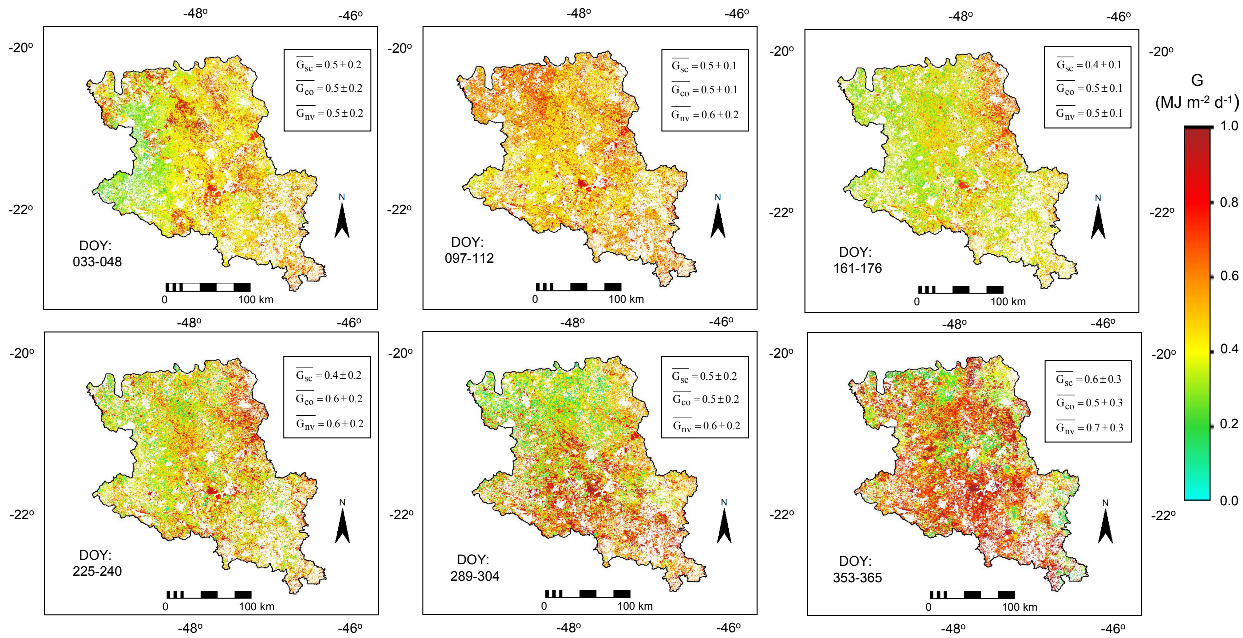

Figure 12. Spatial distribution for some of the 16-day average soil heat flux (G) values for the MODIS images in the mixed agro-ecosystems composed by sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015, inside the northeastern side of São Paulo (SP) state, Southeast Brazil. The over bars means averages showed together with standard deviations.

As in the case of λE and H, although with much lower magnitudes, G pixel values among the agro-ecosystems are well differentiated according to the time of the year. They ranged from close to zero to 1.0 MJ m^{-2} d^{-1}. The spatial variations for all agro-ecosystems are low, ranging from 0.1 to MJ m^{-2} d^{-1}. The average annual G values for sugar cane (SC) and coffee (CO) were the same (0.5 MJ m^{-2} d^{-1}), but for natural vegetation (NV), with a mean value of 0.6 MJ m^{-2} d^{-1} it was a little higher. The low pixel values for daily scales are in agreement with field measurements in irrigated crops and natural vegetation inside the Brazilian semi-arid region[11].

Fig. 13 presents the curves of the 16-day G pixel daily average values (a) and their fractions to Rn (b) for sugar cane (SC), coffee (CO) and natural vegetation (NV) ecosystems, during the year 2015.

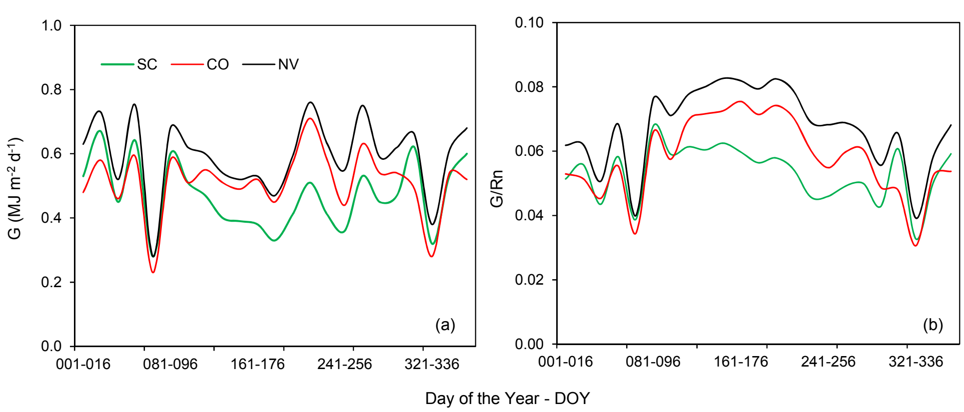

Figure 13. Trends of the 16-day average pixel values for the soil heat flux (G) and their ratios to net radiation (Rn) in sugar cane (SC), coffee (CO) and natural vegetation (NV) agro-ecosystems, during the year 2015, in the northeastern side of São Paulo (SP) state, Southeast Brazil.

The curve shapes in Fig. 13 were somewhat similar of those for λE, but the values for natural vegetation (NV) moved from the intermediary to the upper values. Lower G and its ratio to Rn for sugarcane (SC) were found, mainly the period of DOY 097-304 (April to end October). The average values of Rn partitioned as G were 5%, 6% and 7% for sugar cane (SC), coffee (CO) and natural vegetation (NV).

4. CONCLUSIONS

The coupled use of MODIS images and agrometeorological stations allowed the quantification and analyses of the energy balances in the mixed agro-ecosystems composed by sugar cane, coffee and natural vegetation along the year 2015 in the northeastern side of São Paulo state, Southeast Brazil. The strong dependence of net radiation (Rn) on the global solar radiation (RG) levels is confirmed, however with different fractions, being lower for sugar cane and higher for coffee. It was demonstrated that the daily values of latent (λE), sensible (H) and ground (G) heat fluxes can be estimated in these different kind of vegetations from instantaneous measurements of the reflectances from the MODIS sensor, throughout the application of the SAFER algorithm together with agrometeorological data. The lowest and the highest latent and sensible heat fluxes were respectively for sugarcane and coffee. Although sugar cane consumed less water than coffee crop in an annual scale, being a positive aspect under the condition of water scarcity, its higher sensible heat fluxes have to be considered under the conditions of the coupled effects of climate and land use changes.

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