Modeling Coffee Agroforestry Systems with the Process-based Model CAF 2014

Technical Note on the Implementation of the SAbERES Project **(Draft)**

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Context of the study

In a series of project's internal weekly exchange and planning events, the IIASA team has identified several research tracks, including "track 3" - estimating economic viability of the shaded vs. unshaded production and analysis/identification of factors that could support the former. This track is relevant to the project development, because it supports achieving following goals: • adoption of

new objectives/laws/strategies/plans in the agricultural sector; • reduction in CO2 emissions/deforestation; • increase in the producer's income due to application of more beneficial management alternatives; and • afforestation/reforestation or restoration of ecosystem. This document provides a short update on IIASA's work related to track 3, which included literature review, data collection/extraction/processing, and modeling including sensitivity analysis.

Method and rationale

One of the major components in economic assessment of agricultural activities is the estimation of crop yield. The modeled yield estimates are uncertain because of large number of factors: crop feedback on observed weather and pest outbreaks. There is also uncertainty induced by market price fluctuations both for the product and for the inputs required to produce it e.g. fertilizer, fuel, labor as well as the availability of those. While these challenges are pertinent to the modeling of annual crops cultivation, they are exacerbated in modeling of perennial crops e.g. fruit trees (as impact on trees in a particular year may have consequences in future years) and even more so in agroforestry production systems such as coffee (as there is a complex interaction between coffee and the trees within an ecosystem). Recognizing the complexity of the coffee growth modeling task and respective challenges and limitations, we have employed the state-of-the-art process-based coffee agroforestry model CAF2014 [1] to address the questions relevant to "track 3" also aiming at exploring the model's potential for modeling yields under climate change. The benefits of using a process-based model include transparent outputs expressed in physical units of ton of product per hectare that is suitable for use in economic estimates (as compared to unit-less suitability estimates) and explicit accounting for management practices (e.g. pruning and thinning). While these factors can provide useful information, they are subject to model calibration and validation, which has not been fully carried out for the model, whereas multiple applications of the model have been reported (e.g. [4], [5]). From that perspective, the results obtained in our exploratory analysis are similar in nature with the state-of-the-art applications published in the literature.

Preliminary considerations

1. Yield units

The CAF2014 model output of coffee yield is expressed in tDM/ha (DM stands for dry matter). The officially reported yields in SIAP database [6] for coffee ("café cereza") are expressed likely as cherry fresh weight[1]. The water content in harvested coffee cherry can vary according to literature (53% in [7], 55-60% in [8], 65% in [9]). We have employed the value of 53% from [7], which is specific to Chiapas, Mexico, and in the description of the coffee cherry drying process refers to the official Mexican standard NOM-116-SSA1 6276.

1 Yield, the unit of measurement is tons per hectare, with the exception of crops that have another metric which is indicated in the name of the crop (coarse, bunch, plant, among others). As translated from SIAP [6] documentation file "Diccionario_agricola_2003_a_2023.xlsx": "Rendimiento, la unidad de medida son toneladas por hectárea, con excepción de los cultivos que tienen otra métrica la cual se señala en el nombre del cultivo (gruesa, manojo, planta, entre otros)."

2. Reported vs. modeled yields

Reported yields include a plenty of factors beyond those represented in the model such as pest and diseases (e.g. coffee leaf rust represents a major threat [10]), socioeconomic constraints (e.g. labor force availability during the harvest period can be a limiting factor [10]), which all can lead to inefficiencies and therefore suboptimal yields. From that perspective, one should generally deem modeled yields as representing *potential* yields and therefore a model's overestimation of the reported value should not come as a surprise.

3. Local conditions representation

While the CAF2014 model is rich in parameters (about one hundred values are describing a site/plot), even in the exemplified applications using measured data from research stations at coffee growing plots it was not possible to calibrate the full set of models' parameters leaving large part at default values [2] collected from diverse literature sources [3]. In our analysis we reuse this default parametrization, including management (fertilizer application, thinning of trees, pruning), which is not specific to any Mexican state and constrain the representation of local conditions to daily weather inputs from the ISIMIP climatic datasets [11], [12] and soil information from the GEO-BENE database [15]. While there is a publicly available database providing historical records from individual weather stations comprising a network covering the territory of Mexico [13], there are a few issues hindering it's use in modeling e.g. gaps in daily records and a rather sparse set of provided variables (e.g. lack of incident solar radiation data).

Results

1. Climate change impacts

Figure 1 illustrates the outputs of a non-calibrated coffee agroforestry model CAF2014 with minimum modifications in the configuration from the original version. Obtained outputs correspond to historical weather data [11] and SSP585 GFDL ISIMIP climate projection [12] for a semi-randomly chosen location in Chiapas[2]. Figure 1 illustrates that water availability (WA) shows more intermittence in the projected future resulting in degradation of coffee plant leaves (LAI) and respectively lowering the yields. As the figure suggests, tree-shaded coffee production seem to provide more benefits for the yield in the future than historically (as compared to open sun system), while likely not fully solving the looming problem. The absolute values on the figures cannot be fully trusted, yet seem to qualitatively represent a plausible outcome of the SSP585 (high degree of warming) scenario. From that perspective, there is potential in use of the state-of-the-art coffee modeling in the SAbERES project.

2. Relative yields

While the model provided qualitatively plausible climate change impact estimates, a similar comparison of different geographic locations that report substantially different yield levels for historical period presents an apparent interest as this information could potentially describe spatial variation of production potential. At this point we employed equal model setup from the previous step while replacing only geographical position and weather data with those corresponding to a semi-randomly selected location in Oaxaca[3]. The historical daily weather dataset for these specific locations in Chiapas and Oaxaca is derived from [11] by converting all six meteorological variables

2 Mexico / Chiapas / Altamirano, https://es.wikipedia.org/wiki/Altamirano_(Chiapas). Coordinates: 16°44′10″N 92°02′20″W.

from daily weather files used by the EPIC model [14] (solar radiation, min and max temperature, precipitation, relative humidity, wind speed) into the file format required to drive the CAF2014 model (i.e. except for minor re-formatting, replacing relative humidity with a corresponding value of water vapor pressure). Since the spatial resolution of the weather dataset is rather coarse (half arc-degree) and the data represent re-modeled weather interpolation, we did not aim at a precise reproduction of the inter-annual variability of the yields and only posed the question whether the relation to each other of the two average coffee yields obtained from the model for the two locations corresponds to the respective relation in reported data [6]. Location in Chiapas has higher average yields than that in Oaxaca (2.6 vs. 1.5 ton of coffee cherry / ha; values averaged over 2003-2015 from those reported annually [6]). The harvested areas at the two locations are reported to be nearly equal (about two thousand ha in 2015; indicating comparable scale of production at the respective municipalities' level). Figure 2 illustrates, disregarding the scale (including units – fresh cherry or dry matter), the expected (correct) yields relation, where the location in Chiapas has higher average yields than that in Oaxaca, which is explained by difference in water availability in the soil. In modeling, we used the extended time period starting in 1995 to account for (skip) the initial growing stage (non-yielding) of the coffee plants.

3. Absolute yields

The summary of the obtained results (using approximate visual estimate of an average of annual values over 2003-2015 from Figure 2) is provided in Table 1.

Table 1. Modeled and reported yields for two tested locations. Averages of annual values over 2003-2015.

	Chiapas/Altamirano	**Oaxaca/Santiago Xanica**
Modeled yield, ton dry matter/ha	1.7	0.8
Modeled yield, coffee cherry ton /ha (fresh matter) at 53% water content	3.6	1.7
Reported yield, coffee cherry ton /ha (fresh matter)	2.6	1.5
Reported yield, ton dry matter /ha	1.2	0.7
Model's overestimation, %	38	13

Taking into account that the CAF2014 model barely received any location specific setup apart from setting correct latitude and using weather data, and that by construction the model does not account for pests and diseases (therefore estimating only potential yields), these results look plausible and promising.

3 Mexico / Oaxaca / Santiago Xanica, https://en.wikipedia.org/wiki/Santiago_Xanica. Coordinates: 16°00′N 96°14′W.

4. Sensitivity to input parameters

As the unadjusted model produced a considerable overestimation of the average yield for the test location in Chiapas/Altamirano, it is of interest to analyze whether parameters included in the model can be adjusted to reduce the gap between the estimated and the reported yields i.e. lower the modeled yields. In the subsections below we report on the effects caused by a change in just one parameter while keeping the rest of the default model setup except for always setting location and weather specific to the test location in Chiapas/Altamirano.

4.1. Fertilizer application

As illustrated in Figure 3, ramping up N fertilizer application from zero to 100% of the default setting (150 kg N/ha/year) leads to about 55% average yield increase – approximately from 1.1 to 1.7 tDM/ha/year. This level of fertilizer impact is fully covering the model yield overestimation interval for Chiapas/Altamirano as indicated in Table 1. Hence, by only changing the modeled fertilizer application, CAF2014 model would be able to reproduce the average reported yield in this test location.

4.2. Tree thinning and pruning

As illustrated in Figure 4, management of the trees in the agroforestry coffee growing system may have substantial impact on coffee yields. The average yield modeled for low intensity management (less thinning, pruning) and more intense management demonstrates an increase from 0.4-0.6 to 1.6-1.7 tDM/ha/year, which is about 180-300% of increase. The scale of this impact fully covers the model yield overestimation interval for Chiapas/Altamirano as indicated in Table 1.

4.3. Soil properties

In order to explore options for providing the CAF2014 model with more location-specific input data, we have analyzed soil information available in the GEO-BENE database [15] for the two test locations in Chiapas and Oaxaca. The data retrieved by querying for the two locations are presented in Table 2 and Table 3. Based on the obtained zone representative soil typelogical units (ZoneSTU), additional database queries have been caried out to obtain parameters by soil layer resulting in Table 4. These data were aggregated to an averaged single soil layer profile as presented in Table 5, which demonstrates rather small difference in two key parameters usen by CAF2014 model – water content at field water capacity (FWC, mm/mm) and water content at wilting point (WP, mm/mm), as well as only a small variation in total available water (TAW), which is (0.29-0.25)/0.25 = 0.16 = 16%. However, while test locations in Chiapas and Oaxaca have similar soils and these soils are also similar to CAF2014's default soil as it regards the FWC (CAF2014's parameter WCFC[4] = 0.63*0.65 = 0.41), there is a substantial difference between GEO-BENE's WP values and the default value of the respective CAF2014's wilting point (parameter WCWP = WCST*FWCWP = 0.63*0.41 = 0.26). Figure 5 illustrates the effect of adjusting the default value of 0.26 to 0.12 which is the most extreme value from Table 5. While at location in Chiapas making such an adjustment has only a minor effect on leaf area index of both coffee plants and trees and almost no impact on coffee yield, in the test location in Oaxaca the respective impacts are much more pronounced.

Table 2. Data retrieved for the test location in Chiapas from the GEO-BENE database (query for ZoneLon = -92.25 and ZoneLat = 16.75).

HRU	ZoneLon	ZoneLat	ZoneAlti	ZoneSTU	ZoneArea
312	-92.25	16.75	905	Ao	8194.32

4 Here and further, the CAF2014 parameters' meanings are rather an expert opinion because of a gap in the documentation of the model's parameters.

HRU	ZoneLon	ZoneLat	ZoneAlti	ZoneSTU	ZoneArea
352	-92.25	16.75	1088	Ao	16388.64
413	-92.25	16.75	1364	Ne	8194.32
432	-92.25	16.75	1319	Ao	24582.96
433	-92.25	16.75	2031	Ne	65554.56
442	-92.25	16.75	1501	Ao	8194.32
443	-92.25	16.75	2339	Ne	24582.96
452	-92.25	16.75	1542	Ao	90137.52
453	-92.25	16.75	1847	Ne	49165.92

Table 3. Data retrieved for the test location in Oaxaca from the GEO-BENE database (query for ZoneLon = -96.25 and ZoneLat = 16.25).

HRU	ZoneLon	ZoneLat	ZoneAlti	ZoneSTU	ZoneArea
352	-96.25	16.25	686	Be	8215.01
452	-96.25	16.25	1777	Nd	246450.30
552	-96.25	16.25	2789	Nd	41075.05

Table 4. Data retrieved from the GEO-BENE database for the three major soil typological units (STUs) present in the test locations of interest (exemplified by 1st and 3rd soil layers). FWC is the water content at field water capacity (mm/mm), WP is the water content at wilting point (mm/mm), KS is saturated hydraulic conductivity (mm/hour).

ZoneSTU	FWC1	WP1	FWC3	WP3	KS1	KS3
Ao	0.38	0.09	0.41	0.13	14.01	7.76
Nd	0.47	0.13	0.47	0.17	17.59	11.44
Ne	0.39	0.11	0.42	0.15	9.54	7.81

Table 5. Selected data aggregated from Table 4 over all five soil layers. TAW is the total available water content (FWC - WP, mm/mm).

ZoneSTU	FWC	WP	TAW
Ao	0.40	0.12	0.28
Nd	0.45	0.16	0.29
Ne	0.40	0.15	0.25

Conclusion

The CAF2014 model demonstrates reasonable behavior and sensitivity to the explored input data and parameters. With suitable calibration, the model is expected to be able to reproduce period average coffee yields for shaded coffee production in selected locations in Chiapas and Oaxaca.

Limitations and further work

The presented results rely on the modeling approach, which bears considerable uncertainty, therefore the presented outcomes have to be considered indicative and illustrative. Adjusting model parameters could provide improved estimates.

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Figures

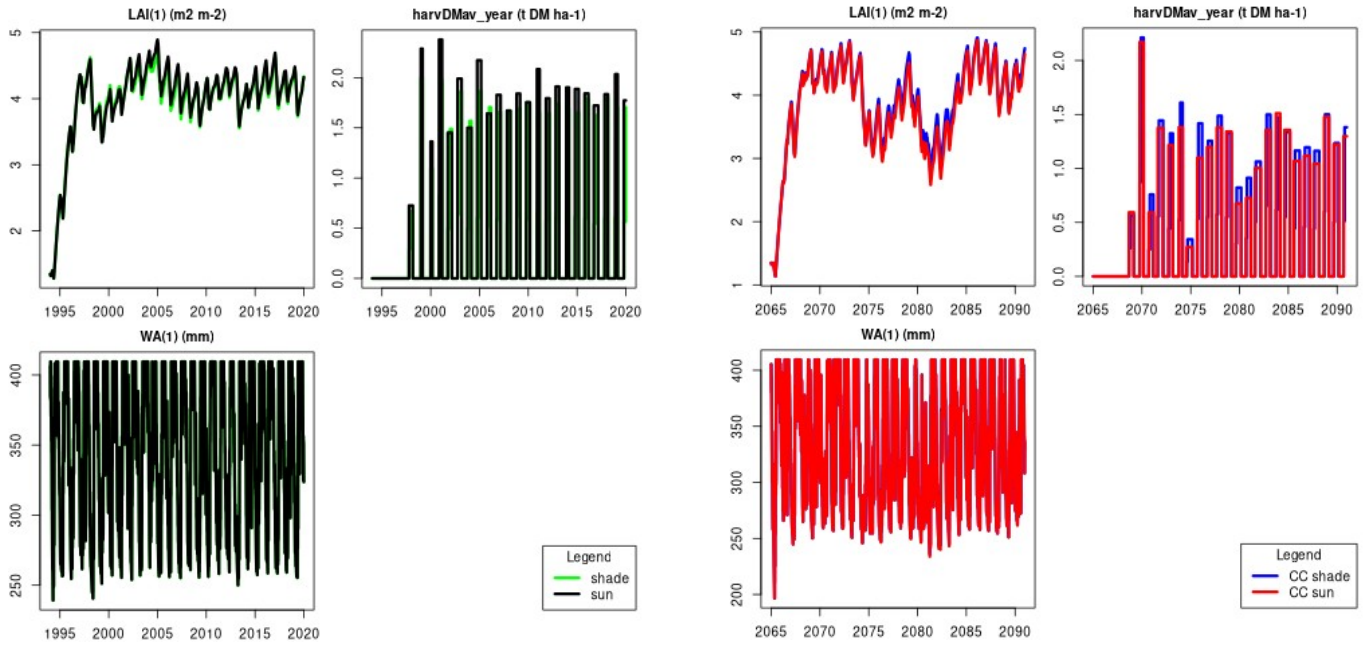


Figure 1. Comparison of the selected outputs of the default CAF2014 model for historical (left panel) and SSP585 projected (right panel) weather data for a location in Chiapas and open sun (black, red) and tree-shaded (green, blue) production systems. LAI(1) is the coffee leaf area index, harvMDav_year is the coffee yield (dry matter), and WA(1) is water availability in the soil.

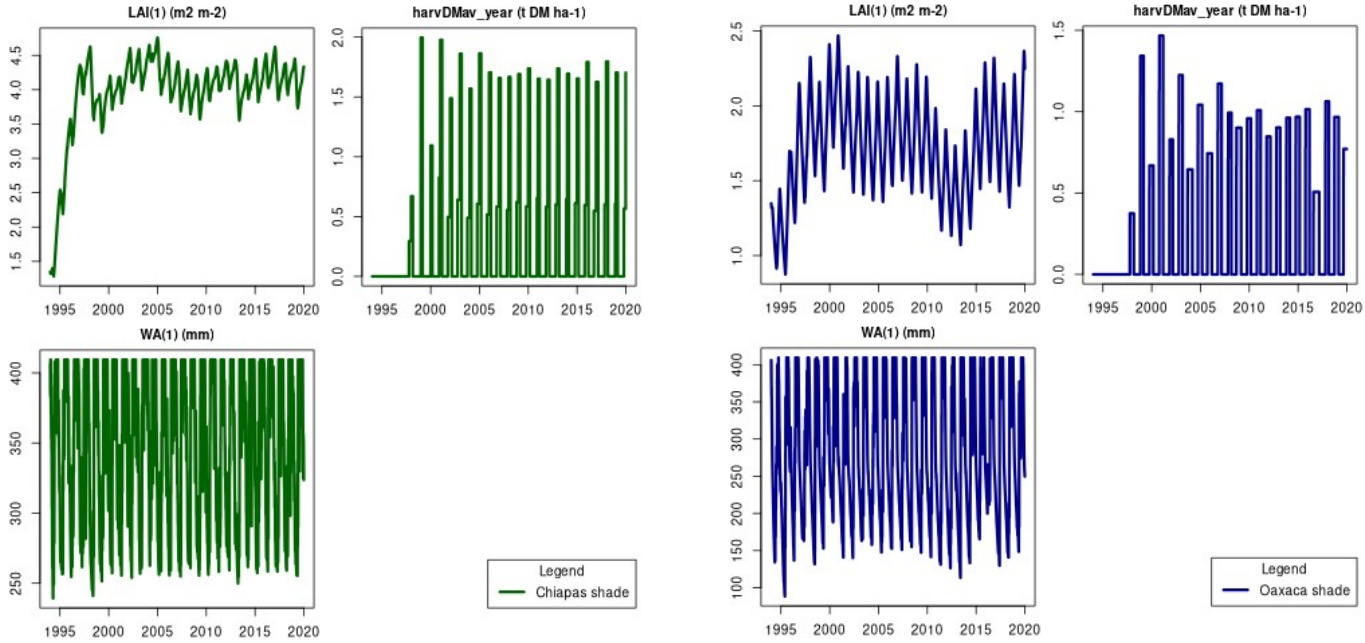


Figure 2. Comparison of the selected outputs of the default CAF2014 model using historical weather data for two locations – Chiapas / Altamirano (left panel) and Oaxaca / Santiago Xanica

(right panel) under tree-shaded production system. LAI(1) is the coffee leaf area index, harvMDav_year is the coffee yield (dry matter), and WA(1) is water availability in the soil (note the difference in scale in the left and right panels).

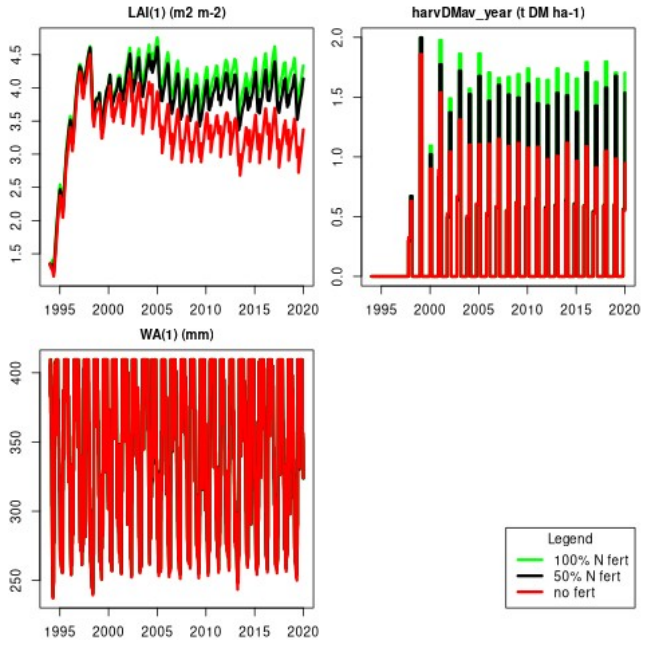


Figure 3. Sensitivity to fertilizer application (levels of 0%, 50%, and 100% are relative to default setting) for the test location in Chiapas/Altamirano and the default model setup (except for location and weather).

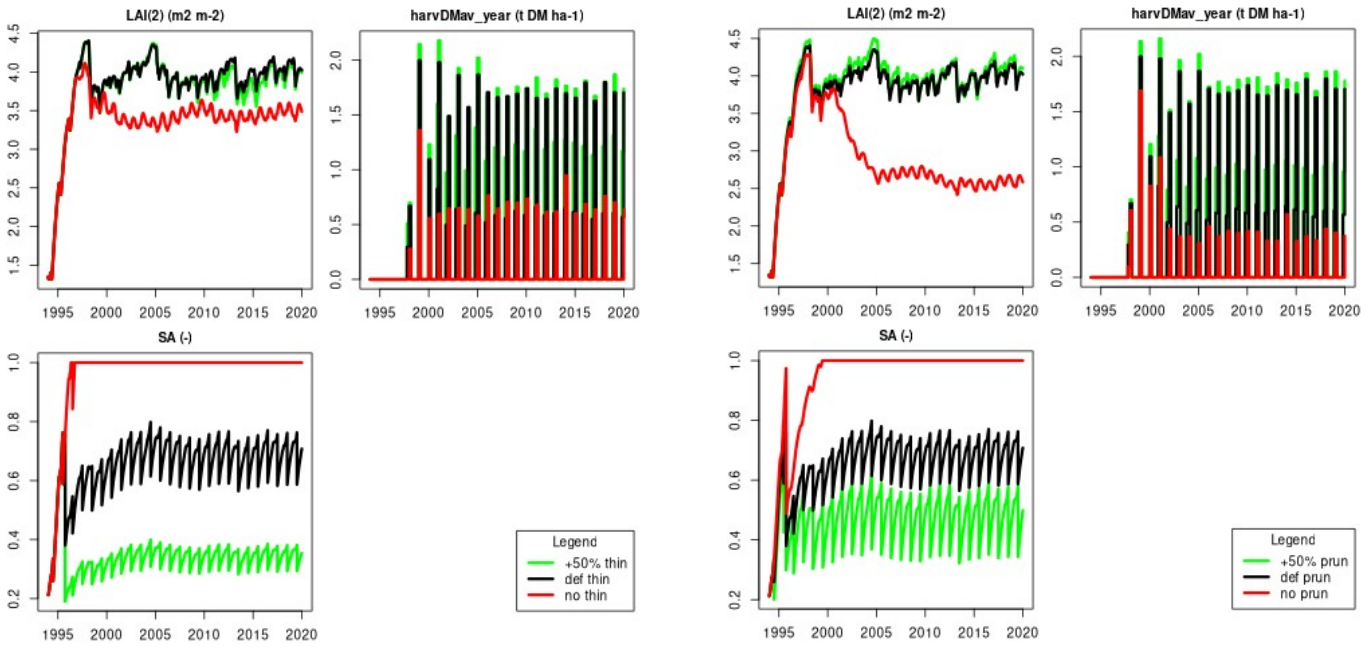


Figure 4. Sensitivity to tree thinning (left panel) and tree pruning (right panel) for the test location in Chiapas/Altamirano employing the default model setup (except for location and weather). Levels

for both panels are +50% relative to default setting, default setting, and no thinning/pruning. SA is the share of the shaded area of the plot, LAI(2) is the leaf area index of coffee plants in the shaded area of the plot.

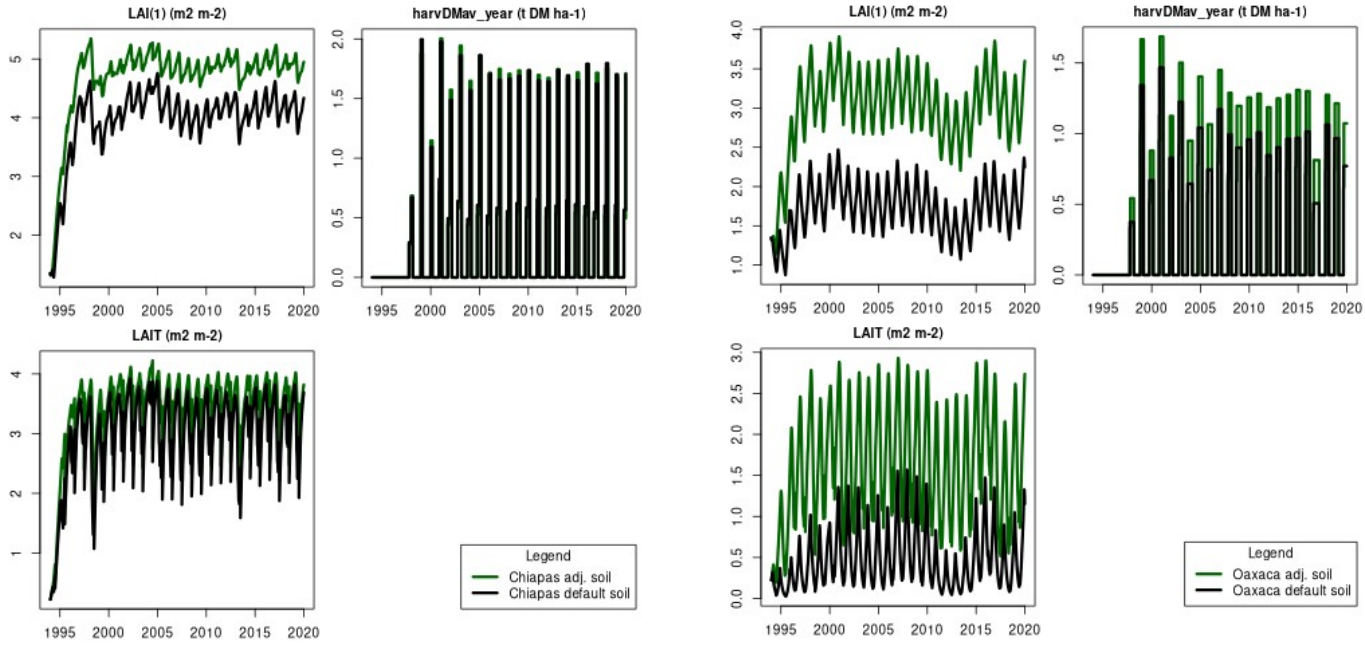


Figure 5. Comparison of the selected outputs of the default CAF2014 model using historical weather data for two locations – Chiapas / Altamirano (left panel) and Oaxaca / Santiago Xanica (right panel) under tree-shaded production system for CAF2014's default and location-adjusted soil parameters (water content at field capacity and wilting point). LAI(1) is the coffee leaf area index, harvMDav_year is the coffee yield (dry matter), and LAIT is the tree leaf area index (note the difference in scale in the left and right panels).