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Evaluation of the effect of selective logging on the energy–water and carbon exchange processes

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Abstract This paper discusses the effect of selective logging on the energy, water, and carbon exchange of tropical forest. We apply multi-objective sensitivity analysis and parameter estimation procedures (MOGSA-UA and MOSCEM-UA) developed at the University of Arizona, USA, to the Simple Biosphere Model 2 (SiB2) at a single site in the Amazon Basin (specifically, the Santarém km 83 – LBA site) under two different conditions, i.e. before and after selective logging of the natural forest. It is assumed that logging did not change soil parameters and the results confirm our working hypothesis that the limited changes in the vegetation cover also do not greatly affect the preferred model parameter values in these two cases. However, the results do show that parameter identification procedures are able to retrieve meaningful values for the parameters and do yield an improvement of between 30 and 70% in the root mean square error when compared to using the default parameter values in SiB2.

Key words Amazonia; carbon flux; energy–water fluxes; LBA; MOGSA-UA; MOSCEM-UA; parameter estimation; selective logging; SiB2

INTRODUCTION

The Amazon Basin contains the largest extent of tropical forest on Earth with over 5×10^6 km^2. Deforestation has increased during the last 30 years due to regional development (over 500 000 km^2 in Brazil). Studies have shown that the effect of rainforest clearing may affect the regional and global climate systems (e.g. Nobre *et al.*, 1991) and, consequently, the importance of defining appropriate parameter values in SVAT models of the Amazon rainforest (e.g. Rocha *et al.*, 1996; Sen *et al.*, 2000). The second generation of the Simple Biosphere Model (SiB2; Sellers *et al.*, 1996a) has been widely used to describe heat, water, momentum, and carbon fluxes, including those of the Amazonian rainforest (e.g. Sellers *et al*., 1986, 1996a,b). At the same time, new and powerful techniques for parameter estimation using a multi-objective approach have been developed (e.g. Duan *et al*., 1992; Yapo *et al*., 1998; Gupta *et al*., 1999; Bastidas *et al*., 1999; Vrugt *et al*., 2003). These techniques are based on the simultaneous minimization of different error functions.

SITE

The site for which data are available belongs to the Large Scale Biosphere–Atmosphere (LBA) Experiment in Amazonia, an international research initiative whose main goals are to study the climatology, ecology, biogeochemistry and hydrology of the Amazon rainforest. In particular, the LBA experiment seeks to understand the regional influence of the Amazon Basin as well as the impacts of land-use change on regional and global climate. The study site is located at the FLONA (Floresta Nacional) at Tapajós km 83 (Cuiabá–Santarém Highway), approximately 70 km south of Santarém, Pará (3.01030°S, 54.58150°W). The vegetation is a tropical humid forest on a broad flat plateau. The site had been selectively logged between September and December 2001. The average temperature is around ~26°C (minimum ~21°C, and maximum ~31°C) retrieved on Fluxnet webpage (Fluxnet, 2004). Precipitation is over 2000 mm year^{-1} and occurs mainly during the rainy season (late December to July). The wind direction is generally from the east and the average wind velocity is ~2-4 m s^{-1} (Miller *et al*., 2004). The soil is mainly clay with some patches of sandy soil.

The measurements were made from a 67-m tall tower. The turbulent fluxes of sensible heat, latent heat, CO_2 and momentum were measured at 64 m using the eddy covariance technique. The meteorological and flux measurements were acquired using data loggers. For further information, please refer to Miller *et al*. (2004), and Rocha *et al*. (2004).

SIMPLE BIOSPHERE MODEL 2 (SiB2)

Important characteristics of the SiB2 model include: the use of a realistic parameterization of the canopy photosynthesis-conductance; the possibility of using satellite data to describe the vegetation phenology (not used in this study); a modified hydrological submodel; and a “patchy” snowmelt description (also not used in this study). In this new version of SiB, the number of vegetation layers is reduced to one and the number of vegetation types to nine. The three soil layer parameterization were retained (surface, rooting zone, and a deep soil layer). Modelled latent heat, sensible heat and the carbon fluxes are calculated from the atmospheric boundary conditions, the prognostic variables of SiB2, the three aerodynamic resistances and the two surface resistances.

OPTIMIZATION ALGORITHM

Recent studies have demonstrated that even simple manual adjustment of model parameters can result in significant improvement in the model performance

(Lettenmaier *et al.*, 1996; Nijssen *et al.*, 2003). Although the "manual-expert" approach can give very good results, there is a need for fast reliable computer-based methods. The MOSCEM (Vrugt *et al.*, 2003) is an automated method that uses a multi-objective optimization approach based on a Markov Chain Monte Carlo Sampling strategy to evolve an initial population randomly selected from within a pre-established feasible range towards an approximation of the optimal Pareto region. The goal is to identify a reasonable small parameter range which guarantees "optimal" model performance in terms of reproducing observations. Because no model is "perfect" and the data collected are subject to observational errors, it is impossible to find a unique solution. The use of multiple objectives allows the model to constrain to be consistent with observations. Such consistency is achieved via the use of different streams of information (e.g. turbulent heat and carbon fluxes).

DATA

The data were collected every 30 minutes between 29 June 2000 and 16 December 2003 and sampled both pre-logging and post-logging sub-periods. The pre-logging period was from 29 June 2000 to 31 August 2001, the post-logging period the remainder. The data contain all the necessary forcing variables for SiB2, i.e. incoming solar radiation, net radiation, air temperature, precipitation, wind speed, specific humidity; and the following flux observations: net ecosystem exchange, and latent and sensible heat flux.

SiB2 needs an uninterrupted time series of forcing variables, therefore gap filling procedures were applied. If the gap period was less than two hours, adjacent data were interpolated. If the gap was greater than two hours, the average value for the same time period over the previous and subsequent 20 days was used. No gap filling was applied to the flux time series. For quality control, a filtering procedure was used which ignored fluxes that were outside plausible minimum and maximum values. For further information, please refer to Miller *et al.* (2004).

METHODS

The SiB2 model has 44 parameters. Because of the lack of measurements, the initial moisture conditions in the three soil layers were also optimized as in previous studies. The parameters are listed in Table 1. The "default" field corresponds to non-optimized, *a priori* parameter values taken from Sellers *et al.* (1996a,b) and the LDAS website (LDAS, 2004).

Following Bastidas *et al.* (1999, 2003) and Demarty *et al.* (2004), the Multi-objective Generalized Sensitivity Analysis algorithm (MOGSA; Bastidas *et al.*, 1999) was used to identify the sensitive parameters, reduce the dimensionality of the optimization problem, and choose the feasible ranges for the optimized parameters. Several parameters were also fixed and their values prescribed because site information was available. The following procedure was then used for parameter identification. First, the sensitive parameters and those not estimated from site information were optimized for the pre-logging case using the MOSCEM algorithm (a list of all the

Table 1. List of SiB2 parameters, ranges, default values, and optimized ranges

	Name	Description	units	Default	Pre-logging			Post-logging		
					Median	Min	Max	Median	Min	Max
1	g1	momentum transfer coefficient (G1)	-	1.449	1.304	1.3	1.321	1.309	1.301	1.313
2	Zs	ground roughness length	m	0.05						
3	ztz0	momentum transfer coefficient (G4)	-	11.785						
4	z2	top canopy height	m	35	31.3	30	32.4	31.4	30.4	31.6
5	Zc	inflection height	m	28	27.9	26.5	29.1	27.8	27.1	27.9
6	z1	bottom canopy height	m	1	1.1	0.8	1.2	0.9	0.8	0.9
7	vcover	vegetation cover	-	1	0.92	0.85	1	0.93	0.9	0.93
8	Chil	leaf angle distribution	-	0.1						
9	tran11	leaf transmittance (VIS, live)	-	0.05						
10	tran12	leaf transmittance (VIS, dead)	-	0.001						
11	tran21	leaf transmittance (NIR, live)	-	0.25						
12	tran22	leaf transmittance (NIR, dead)	-	0.001						
13	ref11	leaf reflectance (VIS, live)	-	0.1						
14	ref12	leaf reflectance (VIS, dead)	-	0.16						
15	ref21	leaf reflectance (NIR, live)	-	0.45						
16	ref22	leaf reflectance (NIR, dead)	-	0.39						
17	Effcon	intrinsic quantum efficiency	mol mol^{-1}	0.08	0.073	0.07	0.088	0.074	0.072	0.081
18	gradm	stomatal slope factor	-	9	7.1	7	7.3	7.2	7.1	7.3
19	binter	minimum stomatal conductance	mol m^{-2} s^{-}	0.01	0.013	0.011	0.015	0.008	0.008	0.01
20	respcp	respiration fraction of vmax	mol m^{-2} s^{-1}	0.015						
21	atheta	coupling coefficient	-	0.98	0.86	0.81	0.91	0.84	0.81	0.85
22	btheta	coupling coefficient	-	0.95	0.81	0.8	0.86	0.8	0.8	0.84
23	rootd	rooting depth	m	1.5	*8.6*		*4.4*		*13.0*	
24	phc	half inhibition water potential	m	-200						
25	trda	temperature inhibition (s5)	K^{-1}	1.3						
26	trdm	half temperature inhibition (s6)	K	328						
27	trop	temperature coefficient (298)	K	298						
28	slti	temperature inhibition (s3)	K^{-1}	0.2						
29	shti	temperature inhibition (s1)	K^{-1}	0.3						
30	hlti	half inhibition temperature (s4)	K	288						
31	hhti	half inhibition temperature (s2)	K	313						
32	zlen	leaf length	m	0.17*						
33	zlw	leaf width	m	0.07*						
34	sodep	total soil depth	m	3.5	*12.5*		*6.5*		*20.0*	
35	sorefl	soil reflectance (VIS)	-	0.11						
36	soref2	soil reflectance (NIR)	-	0.225						
37	bee	soil wetness exponent	-	8.52	*8.38*		*6.4*		*9.88*	
38	phsat	soil water potential at saturation	m	-0.36	*-0.37*		*-0.40*		*-0.33*	
39	satco	soil sat hydraulic conductivity	m s^{-1}	2.5 E-06	*6.00E-05*		*0.00*		*1.60E-04*	
40	poros	Porosity	-	0.48	*0.51*		*0.40*		*0.57*	
41	slope	mean topographic slope	-	0.01*						
42	zlt	leaf area index	-	6.5*	7.33	5.76	7.99	7.68	6.56	7.83
43	green	canopy greenness fraction	-	0.905	0.89	0.8	0.93	0.87	0.85	0.87
44	vmax0	Max Rubisco capac at canopy top	mol m^{-2} s^{-1}	1.00E-04	9.00E-05	8.30E-05	1.01E-04	9.10E-05	9.10E-05	9.50E-05
45	www1	ground soil wetness fraction	-	0.8**	0.49	0.4	0.68	0.74	0.44	0.88
46	www2	root zone soil wetness fraction	-	0.8**	0.72	0.59	0.86	0.95	0.94	0.96
47	www3	deep soil wetness fraction	-	0.8**	0.88	0.75	0.94	0.97	0.95	0.97

* set based on gathered information from different literature sources

parameters of the model, default/fixed values and optimization values is shown in Table 1). Then the several parameters related to the soil properties (*rootd*, *sodep*, *bee*, *phsat*, *satco*, *poros*) were fixed (to the median value of the range obtained prior to logging) for both the pre- and the post-logging case, and a new optimization for 13 vegetation-related parameters and the initial moisture states was made in both cases. Thus, it was assumed that the soil parameters would not change as a result of the logging. The results are shown in Table 1 and Fig. 1. The number of sample solutions in the Pareto set was reduced from 250 to 25 by selecting the sample points with bias values closest to zero. This set of 25 solutions is hereafter referred to as the "preferred" solutions set (Table 1).

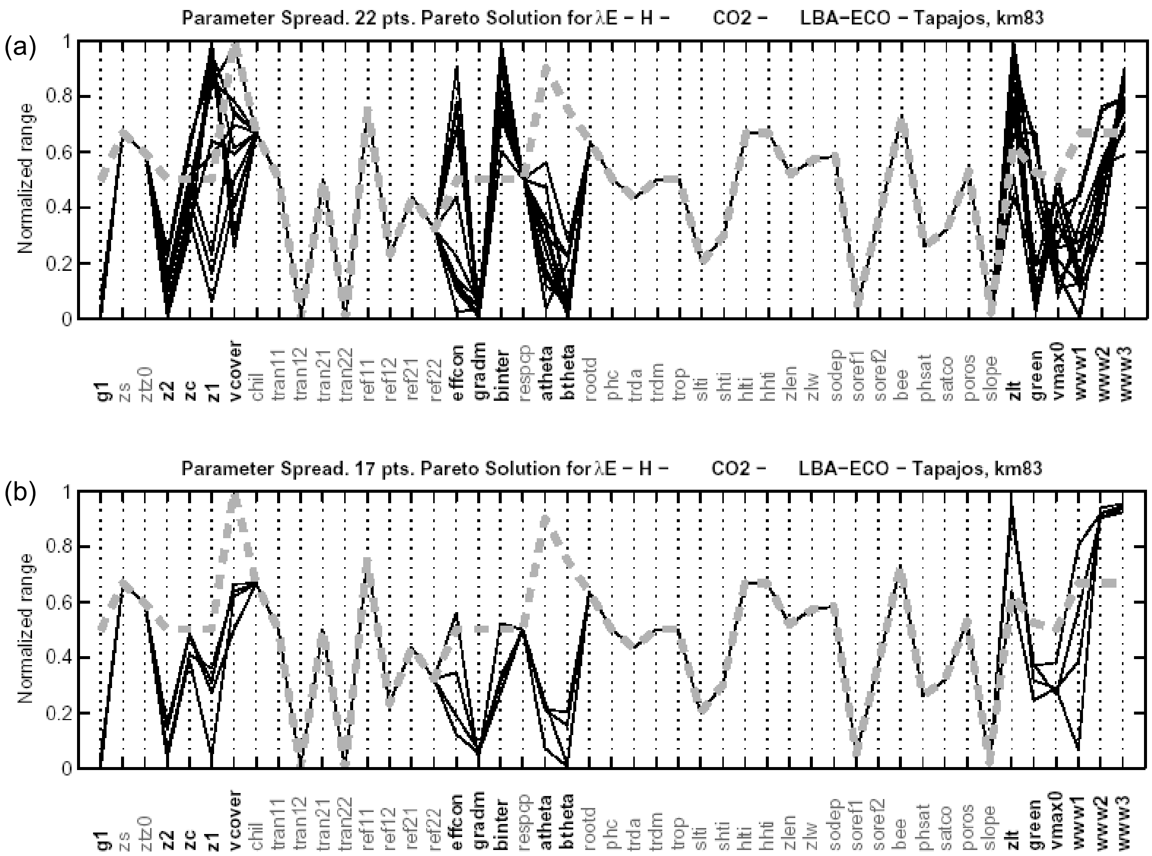

Fig. 1 Parameter spread plot. The black lines correspond to the preferred parameters, while the dashed grey line corresponds to the default set of parameters in (a) the pre-logging case, and (b) post-logging cases, respectively.

RESULTS AND DISCUSSION

Table 1 includes the results of the optimization for both cases and selective logging seems to have little effect for more than half of the optimized parameters. The parameters which are impacted are: *g1*, *z2*, *zc*, *z1*, *vcover*, *effcon*, *gradm*, *atheta*, *btheta*, *vmax0*. Any small changes in parameters used in the turbulent transfer submodel (*g1*, *z2*, *zc*, *z1*, *vcover*) presumably reflect the impact of selective logging on average tree height, vegetation cover, etc. Two (of the eight) parameters in the photosynthesis-conductance submodel had small differences, specifically the *green* parameter decreased after the logging as did *binter*. We do not have an explanation for these changes.

Table 2 Correlation coefficient, root mean square error, and bias pre- and post-logging and each flux.

	Pre-logging default			Pre-logging optimized			Post-logging default			Post-logging optimized		
	R	*RMSE*	*BIAS*	*R*	*RMSE*	*BIAS*	*R*	*RMSE*	*BIAS*	*R*	*RMSE*	*BIAS*
λE	0.6	130.4	–20.5	0.9	71.5	24.2	0.53	139.4	–32.8	0.85	81.9	9.9
H	0.71	120.5	26.1	0.85	35.4	–17.9	0.71	125	36.5	0.78	50.9	–5.4
CO_2	0.5	10.6	2.8	0.8	6.8	0.2	0.4	11.4	4.1	0.73	7.6	1.2

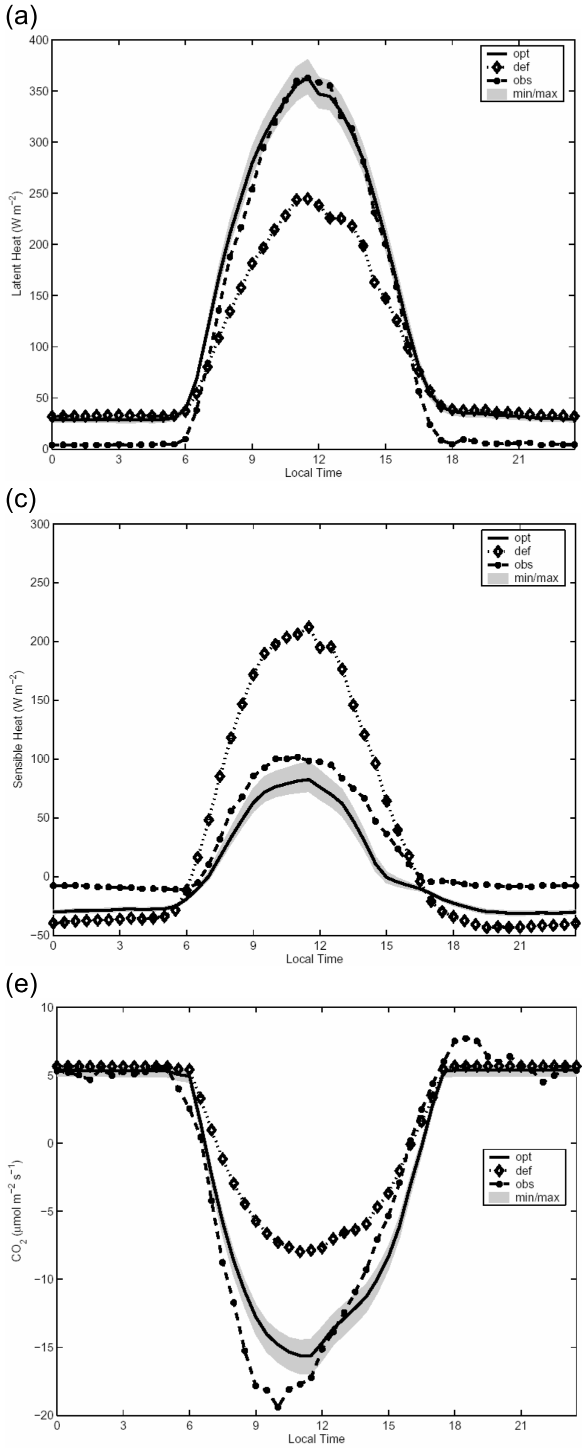

Fig. 2 Mean diurnal cycle of surface fluxes calculated using the default and optimized parameters compared with observations. The grey shaded area represents the area between the minimum and the maximum values found in the optimization. Pre-logging case latent heat, sensible heat and CO_2 fluxes are shown in (a), (c), and (e); while the equivalent fluxes in the post-logging case are shown in(b), (d) and (f), respectively.

According to Nepstad *et al*. (1994) and Sen *et al.* (2000), the rooting depth (*rootd*) may be ~8 m, or more. The median optimum value in this study is 8.6 m, with the minimum and maximum values in the sampled Pareto set between 4.4 and 13.0 m. The soil depth (*sodep*) parameter is strongly correlated to the rooting depth (it is the sum of the three soil layers in the model) and the median optimum value is 12.5 m (minimum 6.5; maximum 20.0) in this study, a value that seems more reasonable than the default assumption of 3.5 m.

All three initial soil wetness fraction conditions are greater after the logging than before. The values before logging are for late June during the transition from the wet to the dry season. The values after logging are for the dry season. These results highlight the importance of proper initialization of models: this topic merits further research.

The *RMSE* (root mean squared error) for the pre-logging case is lower than for the post-logging case for all three measured fluxes (Table 2). However, the preferred parameters seem to have more variation in the pre-logging case. This could be due to the different lengths of the study periods: the post-logging data series is approximately twice as long as the pre-logging case, thereby providing additional information with which to identify parameter values.

Figure 2 shows the mean diurnal cycle computed for each flux. The default parameter set does not properly simulate energy partition; its use results in under-estimates of the latent heat flux, especially during the day (in both cases), and over-estimates the sensible heat flux. The improvement in the simulation of the turbulent heat fluxes after the parameter estimation is significant, about 40–45% better for the latent heat and 60–70% for the sensible heat flux, both before and after logging.

The CO_2 flux includes no filters (such as restricting values based on friction velocity) and both the default and optimized solutions overestimate observations, presumably because not all the flux is adequately measured. However, there is a significant improvement, about 35%, when using the optimized parameter set.

CONCLUSIONS

The primary results of this study are as follows:

- As in Nepstad *et al*. (1994) and Sen *et al*. (2000), the preferred rooting depth is around 8 m for both undisturbed forest and selectively logged forest, inconsistent with the default value of 1.5 m taken from Sellers *et al*. (1996b).
- There is little difference between the optimized parameter values before and after logging, suggesting that selective logging has little significant impact on the overall behaviour of the forest.
- The soil wetness fraction (initial condition) parameters are the only three parameters that really cause differences between the two cases. This highlights the need to provide proper initialization of land surface models and the influence that the soil moisture can have in parameter identification procedures.
- Optimization significantly improved the model performance in both cases relative to when using default parameters, with improvements in the range of 30–70% in simulated fluxes.

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