JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D13, 8475, doi:10.1029/2002JD002341, 2003

Regional fuel load for two climatically contrasting years in southern Africa

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Received 19 March 2002; revised 14 August 2002; accepted 6 October 2002; published 19 February 2003.

[1] Available fuel loads for burning in savanna ecosystems in the southern African region have been estimated using a new Fuel load-Net Primary Production model based on ecophysiological processes such as respiration and Potential Evapotranspiration. The model outputs 15-day standing available fuel load layers for an entire year (a total of 24 layers). Published data from the Southern African Fire-Atmosphere Research Initiative (SAFARI-92) project and from the Southern African Regional Science Initiative (SAFARI 2000) field campaigns were generally in agreement with the estimations. Consistently with previous studies, precipitation was recognized to be the major climatic driver for fuel production. As a consequence, even though there was a regional increase in precipitation in 1999–2000 as compared to the 1991–1992 periods, the temporal and spatial variability in precipitation at fine scales (site level) was important enough to restrict generalities over the entire region for fuel load production. Four areas of interest, Etosha National Park (Namibia), Mongu (Zambia), Kasama (Zambia), and Kruger National Park (South Africa), were selected to reconstruct an aridity gradient and analyze their fuel load variability over the two years. These areas presented contrasting fuel load distributions for the two very different studied periods with arid areas producing heavier fuel loads in 1999–2000, and the more humid areas producing heavier fuel loads in 1991–1992. The consequences of such fuel load variability and the use of such results are discussed. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 9305 Information Related to Geographic Region: Africa; *KEYWORDS:* climate, precipitation, net primary production, Fire, NOVI, tree cover

Citation: Hély, C., P. R. Dowty, S. Alleaume, K. K. Caylor, S. Korontzi, R. J. Swap, H. H. Shugart, and C. O. Justice, Regional fuel load for two climatically contrasting years in southern Africa, *J. Geophys. Res.*, *108*(D13), 8475, doi:10.1029/2002JD002341, 2003.

1. Introduction

[2] Savanna ecosystems cover about 20% of the Earth's surface (40% of Africa) [*Atjay et al.*, 1987]. Annually, about 2.5 GT dry matter (dm) burn in tropical savannas [*Delmas et al.*, 1991; *Dwyer et al.*, 2000]. African savanna fires (natural and man-made) dominate all other types of fires that understandably influence the atmospheric chemistry in the tropics [*Scholes and Andreae*, 2000]. African savannas have been increasingly receiving much attention from the research community with the increasing awareness of the impact of large-scale phenomena, such as global climate change and land-use change. The Southern African Regional Science Initiative (SAFARI 2000) is an international science initiative aimed at developing a better understanding of the southern African land-atmosphere-human system [*Swap et al.*, 2002]. This initiative has been built on the success of the Southern African Fire-Atmosphere Research Initiative (SAFARI-92), which showed that it was feasible to characterize, quantify, and validate estimates of regional emissions [*Lindesay et al.*, 1996]. SAFARI-92 also highlighted the complex nature and variability of African savannas in terms of vegetation composition, environmental conditions and land use patterns. These factors influence the quantity, distribution, and moisture content of savanna fuels and thus directly influence ignition potential, fire behavior, and emission chemistry [*Shea et al.*, 1996]. *Scholes et al.* [1996] suggested that, among other input factors to the emission model, constraining the fuel load model by climate greatly reduces uncertainties in the emission estimates.

[3] Large areas of the subtropics are made up of mixed life-form, heterogeneous vegetation in the form of shrublands, savannas and open woodlands [*Huntley and Walker*, 1982; *Bourlière*, 1983; *Sarmiento*, 1984; *Tothill and Mott*, 1985; *Scholes and Walker*, 1993]. Few productivity-mod-

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0148-0227/03/2002JD002341$09.00

eling efforts have focused on these systems, even though they are of considerable interest at the regional and global scales because of the relatively high productivity in some areas [*Scholes and Hall*, 1996] and the occurrence of frequent and extensive vegetation fires [*Justice et al.*, 1996]. Since available fuel load is the net outcome of Net Primary Production (NPP) minus removal activities (namely decay and herbivory), a new regional model incorporating physiological and ecological processes has been developed that accounts for the spatial and temporal variability (C. Hély et al., A temporal and spatially explicit primary production model for savanna fuel load allocation over the southern African region, submitted to *Ecological Applications*, 2002, hereinafter referred to as Hély et al., submitted manuscript, 2002), to be applied at the subcontinental scale.

[4] This study focuses on characterizing and quantifying the available fuel types and their accumulated loads over two contrasting years, using the new Net Primary Productivity model based on the Light Use Efficiency approach with a 15-day time step from 1 September to 31 August of a given growing year (Hély et al., submitted manuscript, 2002). The objectives of the present study are threefold: (1) To briefly present the Net Primary Production model with the fuel allocation, (2) to determine the input factors with the greater impact on the output by conducting a sensitivity analysis of the model based on the 1991–1992 growing year, and (3) to compare the SAFARI-92 observational period (1991–1992) with the SAFARI 2000 observational period (1999–2000). These two years represent climatic extremes for southern Africa with 1991–1992 being an extremely dry time and 1999–2000 being an extremely wet period. Indeed, 1991–1992 was abnormally dry due to an El Niño-Southern Oscillation event [*Lindesay et al.*, 1996], whereas 1999–2000 was very wet due mainly to the presence of multiple land falling tropical cyclones.

2. Material and Methods

2.1. Kalahari Region

[5] The region selected for study was savanna occurring on Kalahari sands. For the purpose of this study, the Kalahari is defined as a region that contains extensive areas of various heterogeneous vegetation types. The benefits of using information collected along the Kalahari transect include a strong natural rainfall gradient that is related to an equally strong gradient in vegetation. This region was also the subject of an intensive wet season SAFARI 2000/Kalahari Transect ground campaign to characterize vegetation structure/composition and to validate remote sensing of vegetation [*Otter et al.*, 2002]. This is an area of contiguous basins with a shared sedimentary history. Sand is by far the most extensive surface lithology of the Kalahari Group sediments [*Thomas and Shaw*, 1991], forming one of the largest sand seas in the world [*Baillieul*, 1975; *McKee*, 1979]. This region spans a strong and systematic precipitation gradient from the moist tropics to the arid subtropics. The Kalahari supports vegetation ranging from arid shrubland, the ‘‘Kalahari Desert’’, through a gradient of savanna complexes to open, drought-deciduous Kalahari woodland and evergreen forest. Model parameters have been based on data from field sites in the Kalahari.

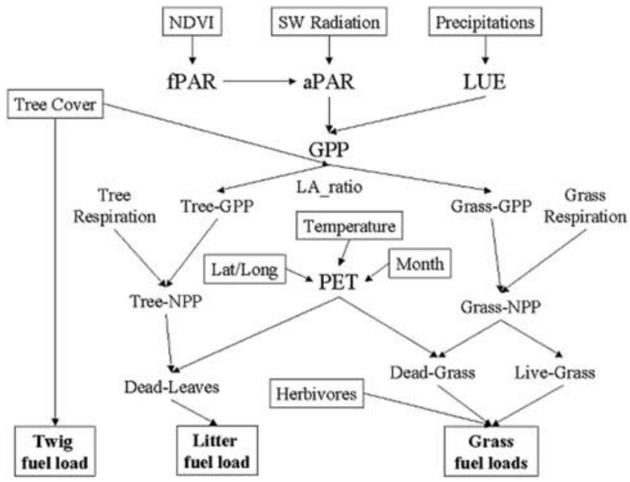

Figure 1. Components of the Fuel Load-Net Primary Production Model. Input data are indicated with plain font in rectangles, processing steps without frame, and output data, namely the different fuel types, with bold font in rectangles.

2.2. Net Primary Production Model Presentation

[6] The NPP model is designed to simulate primary production on a regional scale. A brief overview of the model is presented with model configuration presented in Figure 1 and main relationships reported in Table 1. A detailed discussion can be found in the work of Hély et al. (submitted manuscript, 2002). The model runs on 15-day steps over one year (from the end of the dry season (beginning of September) to the end of the following dry season (end of August)). The model prescribes the fraction of Photosynthetically Active Radiation (fPAR) from remote sensing data, i.e. it decouples model simulations of NPP from the dynamics of leaf area and radiation absorption by the canopy. The Light Use Efficiency (LUE), derived from empirical relationships based on data measured along the Kalahari transect (Table 1 and Figure 2), is used to determine the Gross Primary Production (GPP) in terms of grams of carbon/m^2 (Table 1 and Figure 1). For each time step, the GPP is partitioned to tree and grass components (GrassGPP and treeGPP) using the leaf area ratio (LA ratio). GrassGPP and treeGPP are subsequently reduced to Net Primary Production of carbon by incorporating respiratory carbon expenditures (Table 1 and Figure 1). The Potential Evapotranspiration (PET), driven by air temperature, is then compared with the cumulated precipitation over the time step. If PET is greater than precipitation, tree leaves and grass die proportionally to the stressing ratio PET to precipitation (Table 1). These dead loads will increase the loads of litter tree leaves and dead grass, respectively, accumulated from the previous time step (Figure 1). Loads of live green and dead grass fuel types are also affected by herbivory, which reduces live grass preferentially over dead grass. The model output reports the changes in the effective loads of the different components over a total of 24 time steps across the year. Because southern African fires are

Table 1. Key Relationships and Key Values Used in the Fuel Load Model[a]

Variable/Relationships	Equation	Source
Light section: Incident photosynthetically active radiation (*PAR*), J m^{-2} 15-day^{-1}	$PAR = \sum_{i=1}^{15} (0.5 \times \downarrow SW_i)$	[*Jones*, 1992, p. 24]
Fraction photosynthetically active radiation (*fPAR*)	$fPAR(t)_{[i,j]} = 1.67 \times NDVI(t)_{[i,j]} - 0.08$	[*Prince and Goward*, 1995]
Absorbed photosynthetically active radiation (APAR), J m^{-2} 15-day^{-1}	$APAR(t)_{[i,j]} = fPAR(t)_{[i,j]} \times PAR(t)_{[i,j]}$	
Light Use Efficiency (*LUE*), g-C J^{-1}	$X_{PRCP} = 0.4 \times PRCP(t-1)_{i,j} + 0.6 \times PRCP(t)_{i,j}$ $f_1 = 0.0138 \times X_{PRCP} + 0.05$ $f_2 = 1.89$ $LUE(t)_{i,j} = \frac{(f_1+f_2) - \sqrt{(f_1+f_2)^2 - 4(0.95 \times f_1 \times f_2)}}{2 \times 0.95}$	[*Dowty et al.*, 2002]; Empirical relationships based on weighted precipitation (X_{PRCP}) and site location. See Figure 2 for detailed explanations
Gross Primary Production section (GPP), g-C m^{-2} 15-day^{-1}	$GPP(t)_{[i,j]} = LUE(t)_{[i,j]} \times APAR(t)_{[i,j]}$	
Tree/Grass partitioning section: Leaf Area Ratio (*LAR*) of Tree Leaf Area (*TLA*) to Grass Leaf Area (*GLA*)	$LAR_{[i,j]} = \frac{TLA_{[i,j]}}{GLA_{[i,j]}} = 0.0006 \times \left(TreeCover_{[i,j]}\right)^{2.6756}$	*TLA* determined from stem map data, wet season leaf mass allometry, and specific leaf area estimates [*Goodman*, 1990].
Allocation of *GPP* into tree (GPP_{TREE}) and grass (GPP_{GRASS}).	$\mathrm{GPP_{TREE}}(t)_{[i,j]} = \mathrm{GPP}(t)_{[i,j]} \times \left(\frac{LAR_{[i,j]}}{1 + LAR_{[i,j]}}\right)$ $\mathrm{GPP_{GRASS}}(t)_{[i,j]} = \mathrm{GPP}(t)_{[i,j]} - \mathrm{GPP_{TREE}}(t)_{[i,j]}$	
Respiration section: Leaf dark Respiration ($Rleaf_{GRASS}$), g-C m^{-2} 15-day^{-1}	$Rleaf_{GRASS}(t)_{[i,j]} = \kappa \times p \times \frac{12g - C}{mol} \times LAI_{GRASS}(t)_{[i,j]}$	*K*: respiration rate [2 × 10^{-6} mol-C m^{-2} s^{-1}] [*Woodward et al.*, 1995]; *p*: time constant [1,296,000 s 15-day^{-1}]; LAI_{GRASS}: grass specific leaf area [2 m^2 kg^{-1}]
Grass non-leaf maintenance Respiration ($Rmaint_{GRASS}$), g-C m^{-2} 15-day^{-1}	$Rmaint_{GRASS}(t)_{[i,j]} = 0.5 \times M_{GRASS}(t)_{[i,j]} \times \frac{K_M}{24} \times e^{-.0504}$	From *Woodward et al.* [1995]; Belowground biomass : 50% of total grass biomass; K_M: constant of proportionality [0.7 yr^{-1}]
Grass Growth Respiration ($Rsynth_{GRASS}$)	$Rsynth_{GRASS}(t)_{[i,j]} = \left[\begin{array}{l} GPP_{GRASS}(t)_{[i,j]} - Rleaf_{GRASS}(t)_{[i,j]} \\ -Rmaint_{GRASS}(t)_{[i,j]} \end{array}\right] \times \frac{K_S}{1+K_S}$	K_S: constant of proportionality for dependence of growth respiration on mass of new tissue synthesized [0.3 g/g]

Table 1. (continued)

Variable/Relationships	Equation	Source
Grass Net Primary Productionsection (NPP_{GRASS})	$NPP_{GRASS}(t)_{[i,j]} = GPP_{GRASS}(t)_{[i,j]} - \begin{pmatrix} Rleaf_{GRASS}(t)_{[i,j]} + \\ Rmaint_{GRASS}(t)_{[i,j]} + \\ Rsynth_{GRASS}(t)_{[i,j]} \end{pmatrix}$	
Water stress section: Index of water availability (ω); Fraction of tree leaf death ($fDead_{TREE}$) and Fraction of grass leaf death ($fDead_{GRASS}$)	$\omega(t)_{[i,j]} = \frac{PRCP(t)_{[i,j]}}{PET(t)_{[i,j]}}$ $\omega(t)_{[i,j[} \geq 1 \quad fDead_{GRASS} = fDead_{TREE} = 0$ $\omega(t)_{[i,j]} < 1 \left\vert \begin{array}{l} fDead_{GRASS} = 1 - \omega(t)_{[i,j]} \\ fDead_{TREE} = \sum_{\tau=t}^{\tau=t^*} \left(\frac{1-\omega(\tau)_{[i,j]}}{d_{TREE}} \cdot \frac{1}{(t-\tau)+1} \right) \end{array} \right.$	PET [*Thornthwaite*, 1948]; d_{TREE} is set to 4 and limits the maximum fraction of leaf death to 25% for any single time step
Herbivory section: Rate of Total energy demand by herbivores (E_{TOTAL}), MJ m^{-2} 15-days^{-1}	$E_{TOTAL} = 0.4 \times (M_{LSU})^{0.84} \times N_{LSU} \times 15$	From *Scholes et al.* [1996]; Mean mass of a livestock unit (M_{LSU}) [150 × 10^3 g], and number of livestock units per square meter (N_{LSU}); Carbon fraction ($Cfrac_{GRASS}$) [0.45], Grass digestibility (G_{DIGEST}) [0.60], and Grass energy content (G_{ENERGY}) [0.018 MJ/g]
Total forage required (F_{TOTAL})	$F_{TOTAL} = \frac{Cfrac_{GRASS} \times E_{TOTAL}}{G_{DIGEST} \times G_{ENERGY}}$	

[a]Extracted from Hély et al. (submitted manuscript, 2002).

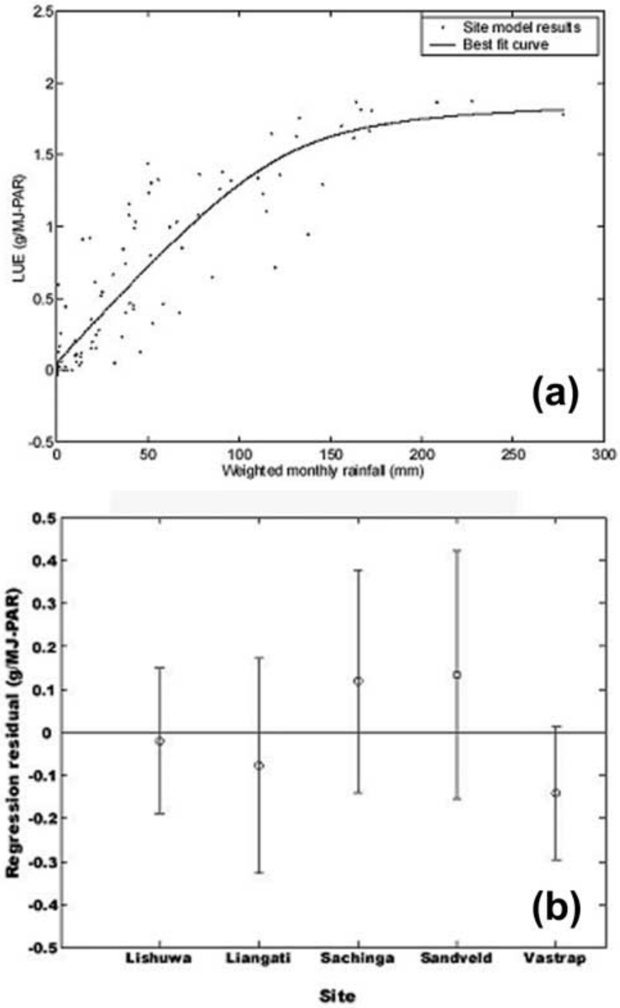

Figure 2. Derivation of the LUE-Precipitation relationship from field measurements (precipitation, LAI, and LUE) in five sites located along the Kalahari transect. The Tree Cover percentage variable (TC) is implicitly included in the analysis as the five sites differ also from their TC value (from 58% in Lishuwa site located on the northern end of the transect to 5% in the southern Vastrap site). First, the three coefficients representing the parameters involved in y_1 and y_2 were derived for each of the five sites. Each parameter range was then derived from its minimum and maximum values reached along the Kalahari transect. Second, 30 000 runs of the combination and smoothing of f_1 and f_2 (following the *Collatz et al.* [1992] approach), using random coefficient values within respective ranges were computed. The best fit, minimizing the sum of squares residuals is presented in a), while the residual dispersion per site are reported in b).

mainly surface fires, the different fuel types with their available quantity are presented (litter as dead tree leaves, dead grass, live grass, and small diameter twigs). For the purposes of this study, live tree leaves are not considered as fuel, and therefore are not presented. Additionally, as almost no information was available on the production of small twigs over time, this fuel type is not explicitly calculated by the NPP model, but is rather empirically estimated from the Tree Cover percentage [*Hansen et al.*, 2000], using a relationship derived from SARAFI-92 data [*Shea et al.*, 1996; *Trollope et al.*, 1996], field data during the SAFARI 2000 dry season campaigns and additional nonrelated field campaigns (R. J. Scholes, personal communication, 2000). This fuel types is, therefore, set constant over the year, and it represents the available load of twigs accumulated over several years between two fire occurrences (fire frequency).

2.3. Presentation of the Input Data

2.3.1. Vegetation

[7] The spatial variability of savanna vegetation over the southern African region is explicitly taken into account by the vegetation grid based on tree cover percentage (pixel size 1 km^2) produced at the Department of Geography at the University of Maryland [*Hansen et al.*, 2000] and derived from data acquired in 1992–1993 from NOAA's AVHRR. This vegetation map was set constant and used for both growing year simulations.

[8] The temporal variability of vegetation is captured by using the 8 km resolution 15-day Normalized Difference Vegetation Index (NDVI) product produced by the NASA Global Inventory Monitoring and Modeling Studies (GIMMS) group [*Los et al.*, 1994]. A NDVI time series representative of each studied year (1991–1992 and 1999–2000) was used with 1–15 September being the first time step and 16–31 August of the next corresponding year being the last simulation step.

2.3.2. Radiation

[9] Absorbed Photosynthetically Active Radiation (APAR) is used to estimate the Gross Primary Production (GPP). The Data Assimilation Office (DAO) at the Goddard Space Flight Center's Distributed Active Archive Center (DAAC) provides radiation data from the past decades using version 1 of the Goddard Earth Observing System (GEOS-1) atmospheric general circulation model [*Schubert et al.*, 1993]. Among the different types of radiation data, the net downward shortwave radiation at ground level [in W/m^2] was selected. Data were compiled to represent the sum of incoming radiation over 15 days since the fuel load model processes data on a 15-day basis. We used the 1991–1992 radiation data for the corresponding selected year, but since the DAO only provides data from 1980 to 1993, we computed the mean monthly values over the entire time period to be representative of a mean year, and we applied them to the 1999–2000 year. For both years, pixel size resolution was 2 degrees latitude by 2.5 degrees longitude as the standard resolution of GEOS-1.

2.3.3. Meteorological Variables

[10] Monthly mean temperature and monthly cumulated precipitation are needed to compute the Light Use Efficiency (LUE) and PET. These monthly meteorological variables were computed and interpolated over southern Africa (0.5-degree pixel size resolution) using the National Climatic Data Center (NCDC) Global Surface Summary of Day Data, Version 6. For 1999–2000, a preformatted subset of the climate station data for southern Africa, was extracted from the NCDC. These data are included in the SAFARI 2000 data CD-ROM [*Privette et al.*, 2001].

2.3.4. Grazing Uptake

[11] Herbivory is an important factor that can reduce potential fuel load of dead and green grass by anywhere

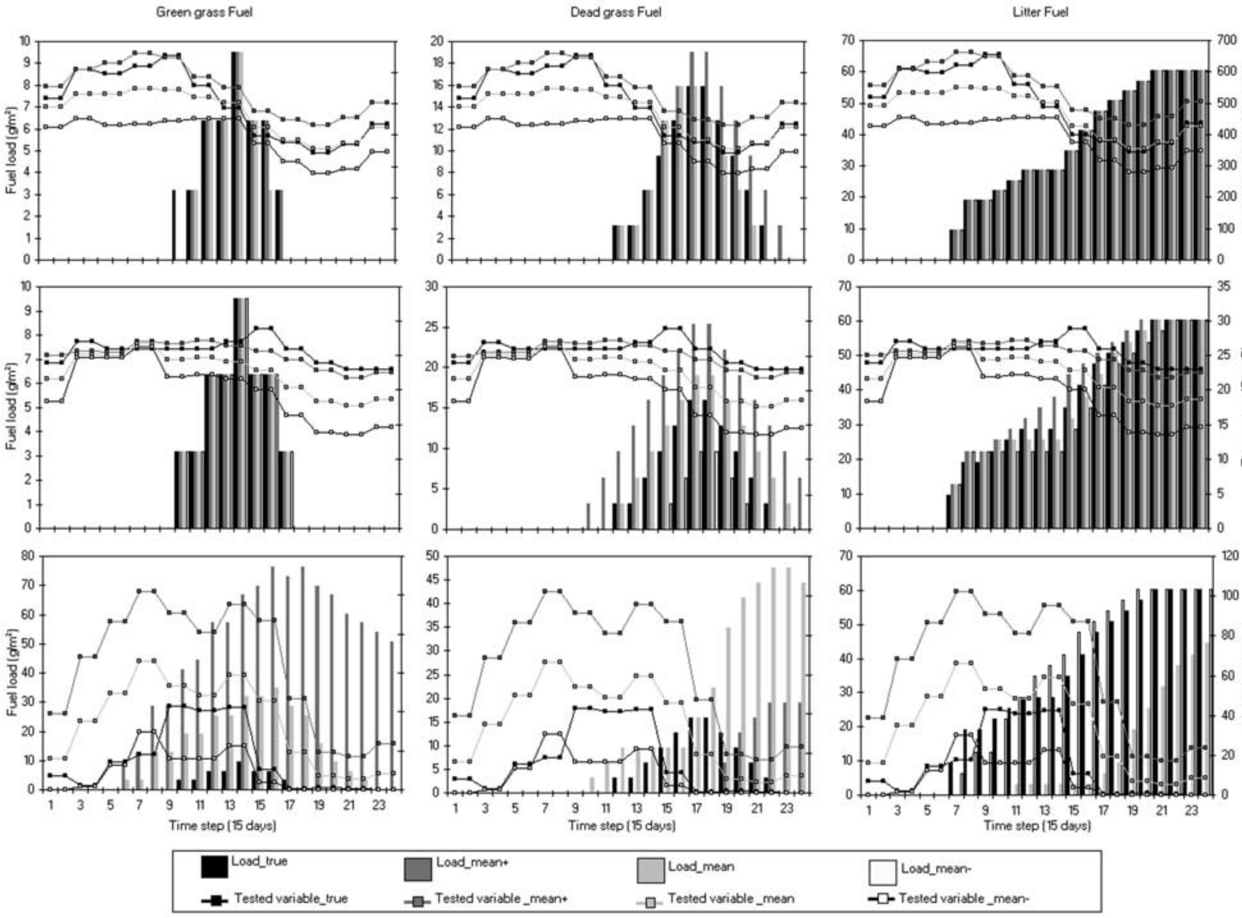

Figure 3. Sensitivity analysis on an Etosha site with 28% of Tree Cover. Radiation, Temperature, and Precipitation are the three climatic variable tested. For each test, one of these variable varies from the Mean − Sd.Dev (mean−) toward Mean, Actual data (True), and Mean + Sd.Dev (mean+), while the two other ones are set equal to the true values. For each test, the temporal change in the 3 fuel type loads, namely green and dead grass, and litter (dead tree leaves) are reported.

from 15 to 80% in unusually productive and nutritious ecosystems [*van Wilgen and Scholes*, 1997]. To account for the effect of big herbivores (cattle and wildlife) and their spatial distribution, a database from Peter de Leeuw (International Livestock Center for Africa, personal communication, 1999) was used. The model only takes into account herbivory for the grass layer since data concerning browsing is sparse and the effect of browsing is believed to be negligible [*Scholes and Walker*, 1993]. Therefore, only herbivory by large mammals is considered here, and the number of livestock units per pixel is set constant over the two growing seasons despite the drought years of 1991–1992. In order to estimate the total forage required per pixel, the Livestock Unit is set constant to 150 kg as in the work of *Scholes et al.* [1996], and the amount of grass depleted by grazing is assumed to be evenly distributed between months. Calculation of the total amount of forage required by herbivores, F_{TOTAL}, [g-C m^{-2} 15-days^{-1}] is based on the total energy demand by herbivores over a 15-day period (E_{TOTAL}) [MJ m^{-2} 15-days^{-1}] as defined by *Scholes et al.* [1996], the grass digestibility, the grass energy content, and the grass carbon fraction (see Table 1 for equations). Grazed material is first removed from the green grass. If the predicted grazing needs are unsatisfied, the remainder is removed from the dead grass compartment, for which digestibility, energy content, and grass-carbon-fraction are assumed to be the same as for the green grass.

2.4. Sensitivity Analysis on Climate Input Data

[12] A sensitivity analysis has been conducted on climatic data covering the 1999–2000 growing year (Hély et al., submitted manuscript, 2002). The main hypothesis was that the model should be most sensitive to precipitation because this abiotic factor is effectively the most limiting factor for productivity over the southern African regions [*Scholes et al.*, 1996; *van Wilgen and Scholes*, 1997]. In order to test this hypothesis, four scenarios presenting (1) True, (2) Mean, (3) Mean + one Standard Deviation, and (4) Mean − one Standard Deviation values of 1991–1992 climatic data were tested over Etosha and Kasama as these regions are the driest and wettest regions, respectively. While "Mean" refers to the average value over the entire African region for a given month, the "True" scenario takes into account the effective recorded climatic values in the focused pixel. In order to compare the 1991–1992 and 1999–2000 growing years, we present here the results from the sensi-

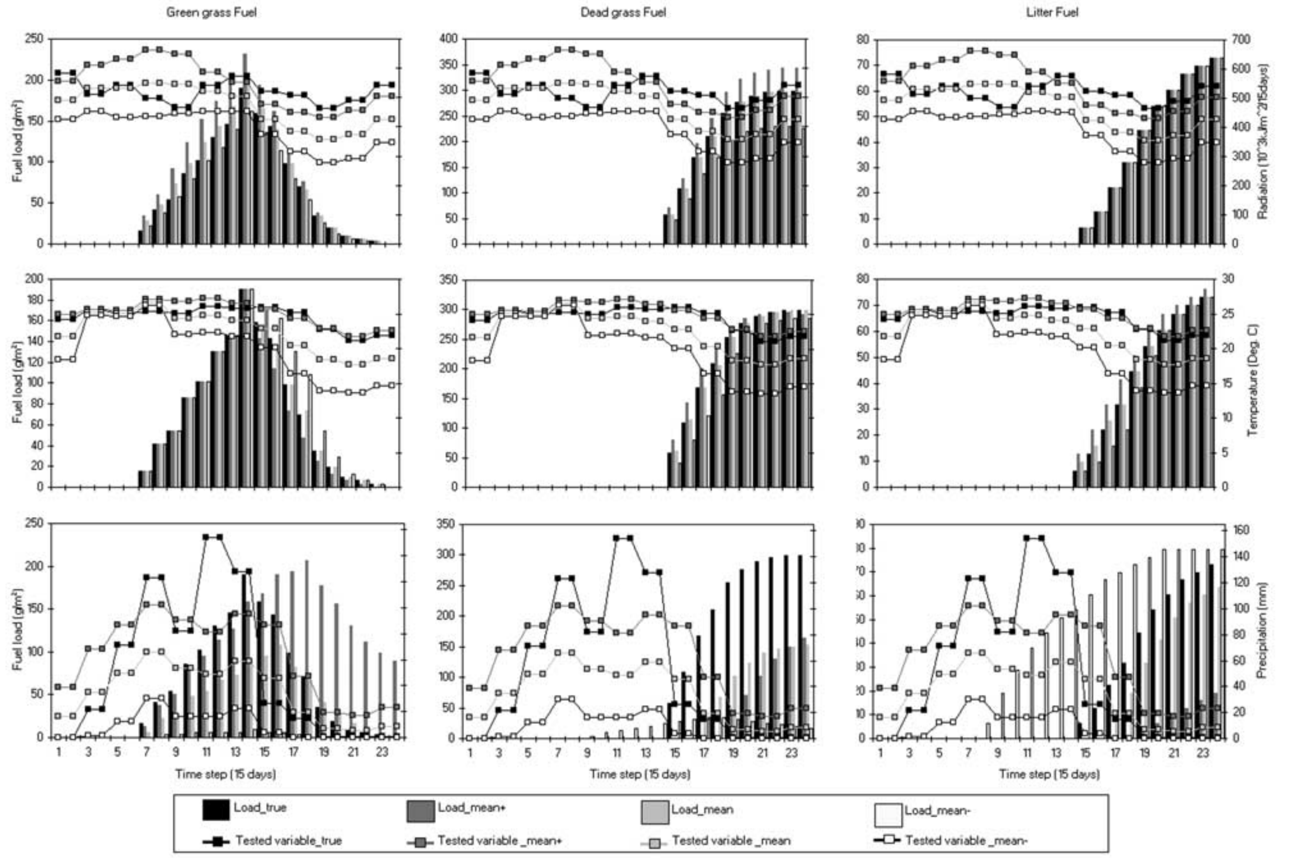

Figure 4. Sensitivity analysis on a Kasama site with 32% of Tree Cover. Radiation, Temperature, and Precipitation are the three climatic variable tested. For each test, one of these variable varies from the Mean − Sd.Dev (mean−) toward Mean, Actual data (True), and Mean + Sd.Dev (mean+), while the two other ones are set equal to the true values. For each test, the temporal change in the 3 fuel type loads, namely green and dead grass, and litter (dead tree leaves) are reported.

tivity analysis conducted on climatic data covering the 1991–1992. As in the work of Hély et al. (submitted manuscript, 2002), results are presented for forested sites with 28 and 32% TC for Etosha and Kasama, respectively (Figures 3 and 4).

2.5. Comparison of the 1991–1992 and 1999–2000 Fuel Load Productions

[13] The model performance is analyzed by comparing outputs from different TC percentages in a given area, and by comparing different areas covering a wide range of precipitations, and where field measurements were available. The selected areas of interest are: Mongu and Kasama in Zambia for relatively moist areas, and Etosha National Park in Namibia, and Kruger National Park in South Africa, representative of semiarid/arid areas. In each area, the 3 pixels are selected to represent TC percentages centered on 0, 30, and 50% for all regions except for Etosha (only 0 and 30%) because the maximum TC percentage according to the UMD tree cover map is 33% in the park region. Moreover, in each area, the 3 selected pixels are in the same neighborhood (less than 10 km apart), so they share the same climatic data. In this analysis section, monthly climatic variables (precipitation, temperature, and radiation) are set to the monthly mean values all over Africa. Moreover, as a consequence of the previously presented sensitivity analysis, precipitation is the only climatic variable presented in combination with the temporal fuel load changes (Figures 6, 7, and 8 for green and dead grass, and litter, respectively) over the two growing years.

[14] Since field campaigns during SAFARI-92 and SAFARI 2000 were conducted in late August and September, a comparison of total fuel loads (including green and dead grass, litter, and twigs) at the beginning of the fire season and at the end of August are presented for the three TC percentages and over the two studied years.

3. Results

3.1. Sensitivity Analysis

[15] Sensitivity analysis of simulation results indicates that precipitation is the most influential climatic variable on fuel productivity across the southern African Region. Indeed, Etosha and Kasama sites (Figures 3 and 4, respectively) are representative of the rainfall gradient extremities, and present similar highly variable signatures related to precipitation variability. Higher amounts of precipitation sustain longer green grass simulated production (in Etosha the grass production could start growing 2 months earlier), and delay simulated grass and tree leave death (litter) for

longer time periods. Temperature only slightly influences simulated productivity (Figures 3 and 4). Cooler temperatures during or toward the end of the rainy season favor simulated green grass production and delay the senescence and death of tree leaves up to 3 months when 5 to 10°C cooler (from 20–25 to 15°C). Radiation fluctuations during the year do not appear to affect the simulated litter productivity (Figures 3 and 4). However, radiation slightly influences the grass compartment with lower radiation quantities producing lighter simulated green and dead grass loads.

3.2. Comparison of 1991–1992 and 1999–2000 Growing Years

[16] As a result of precipitation variability (Figure 5), the two years present spatial and temporal differences in the simulated fuel load production (Figures 6–8). Generally, 1999–2000 was wet relative to 1991–1992 for the most arid region (Etosha), whereas it was dry for the more humid regions (Mongu and Kasama) again relative to 1991–1992. However, it is worth noting that even though the year 1999–2000 was significantly dryer in Kasama than in 1991–1992, the maximum amount of precipitation for a 15-day period during the year 1999–2000 in Kasama (75 mm in February 2000, see Figure 6) is still higher than maximum precipitation over the two years for drier regions (61 and 59 mm for Etosha and Kruger, respectively). Temporally, for regions such as Mongu and Kruger, it was particularly wet in the first half of the rainy season of 1991–1992 (November–January, see Figure 6), whereas the year 1999–2000 was wetter during the second half of the rainy season (February–May). The extended rainy season in 2000 resulted in a potential late fire season beginning (mid-June 2000), whereas the starting date for fire season in 1992 could have been as early as beginning of May in arid regions such as Etosha.

[17] When the TC effect on grass production has been removed, simulated grass production is still highly affected by the precipitation amount (Figures 6 and 7 for green and dead grass, respectively). However, as a fuel type, green grass is not very important since it has almost disappeared (transformed as dead grass, or removed by herbivores) when the fire season starts in May or June for both years (except in 1991–1992 in Mongu and Kasama regions). Dead grass, on the other hand, as the most important fuel type for fire propagation, presents important quantities at the beginning of the fire season, could be still important at the end of August for both years if no fire event has been recorded in the previous months. As for the green grass from which compartment dead grass is created, the more important the precipitation, the heavier the dead grass fuel load. An area such as Kruger shows that the total amount of precipitation is more important than the timing of precipitation, since even though the region experienced a long rainfall delay with almost no rain from September 1999 to January 2000, the final total amount of dead grass for a 5% TC is equivalent to the amount produced in 1991–1992 (Figure 7) when the total amount of rain was almost the same but occurred earlier.

[18] The amount of simulated litter in late August, for a given TC, is almost the same for both years, but it varies within the year according to the timing of precipitation (Figure 8).

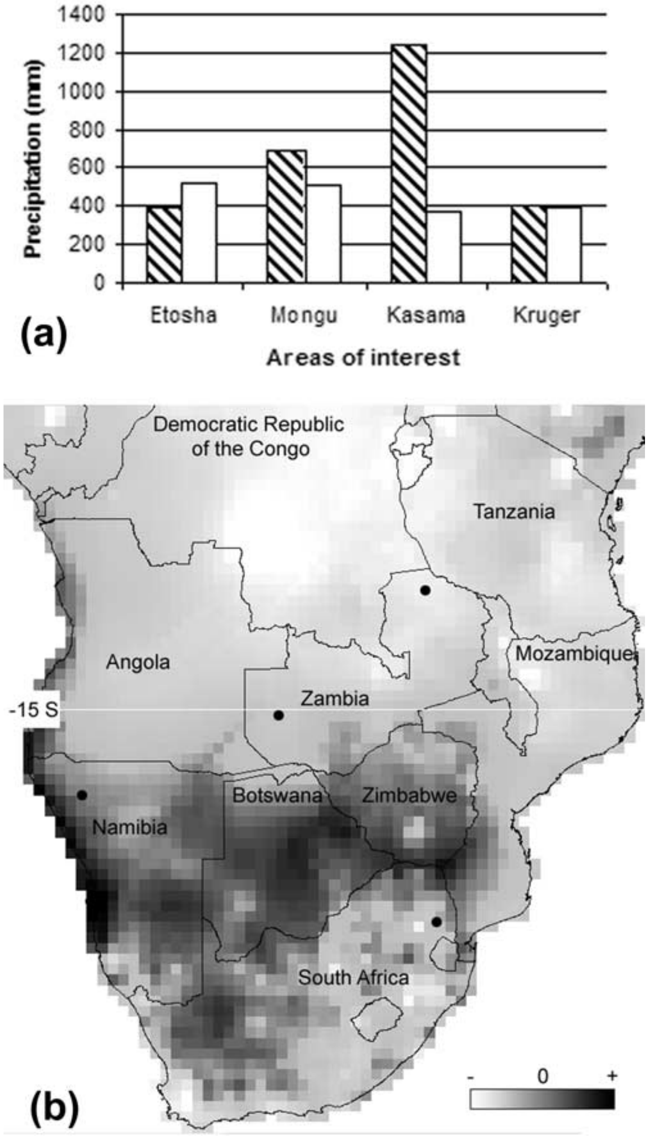

Figure 5. Variability in the cumulated precipitation over 1991–1992 and 1999–2000 years over the entire southern African region. (a) Cumulated precipitation (in mm) for four areas in 1991–1992 (hatched) and 1999–2000 (plain). (b) Difference (in percents) between cumulated precipitation in 1999–2000 and 1991–1992 relative to 1999–2000. The four black dots represent the areas of interest. The darker is the gray, the more precipitation in 1999–2000 as compared to 1991–1992. Notice the pattern delineated by latitude 15°S, with more precipitation over the southern region than over the northern region represented by Angola, Zambia, northern Mozambique and Zaire.

[19] If the minimum grass fuel load to sustain fire spread is assumed to range between 200 and 250 g/m2 [*van Wilgen and Scholes*, 1997; *Hély et al.*, 2003], fuel loads present spatiotemporal variability (Figure 9) that may compromise fire spread in sites where there is a canopy cover. Indeed, all open grasslands in the four areas of interest present total simulated grass loads (green plus dead grass) higher than the 200 g/m^2 threshold, for both fire periods in the two

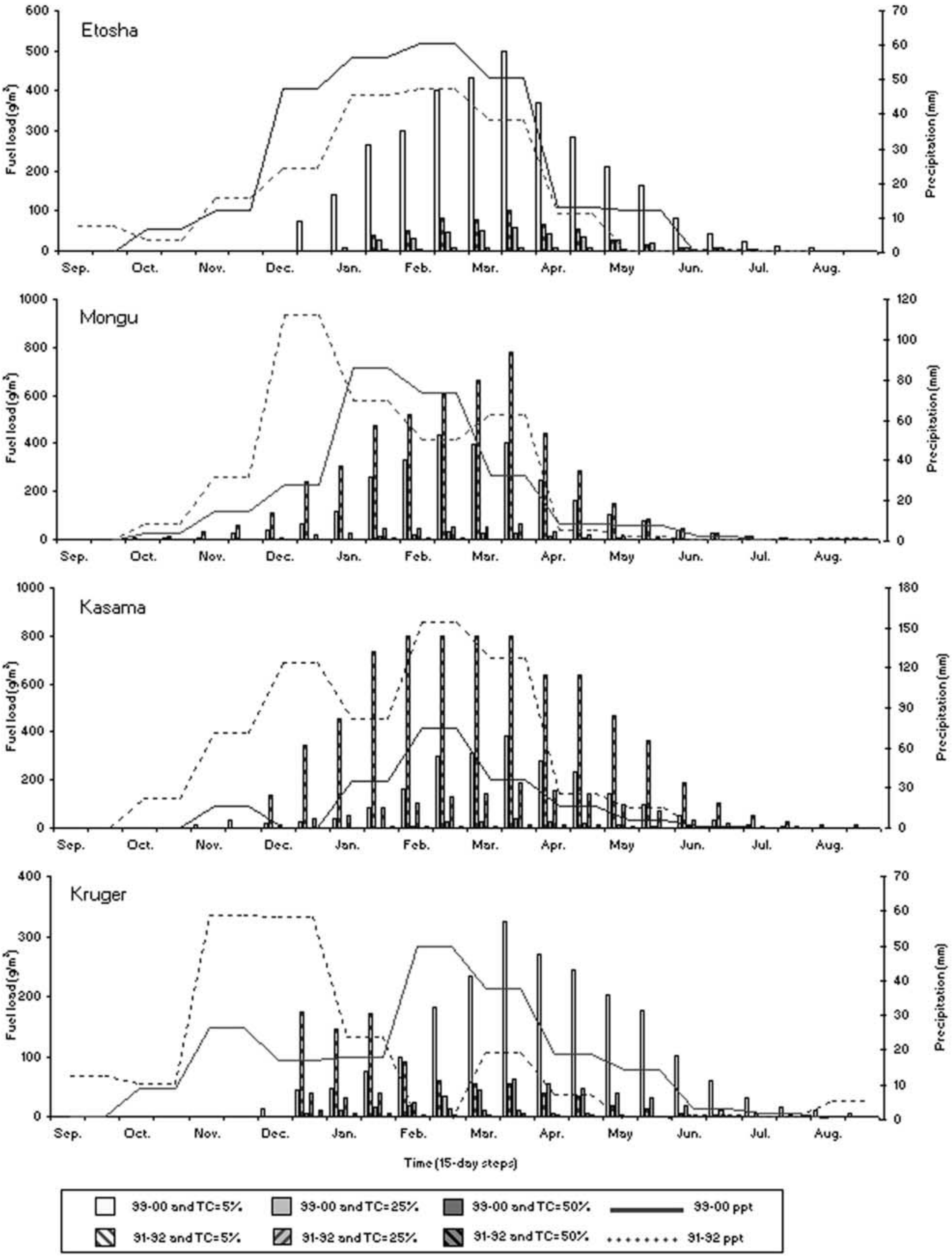

Figure 6. Temporal change in the green grass fuel load for four regions (Etosha, Mongu, Kasama, and Kruger) according to the Tree Cover percentage (TC), and Precipitation (ppt in mm).

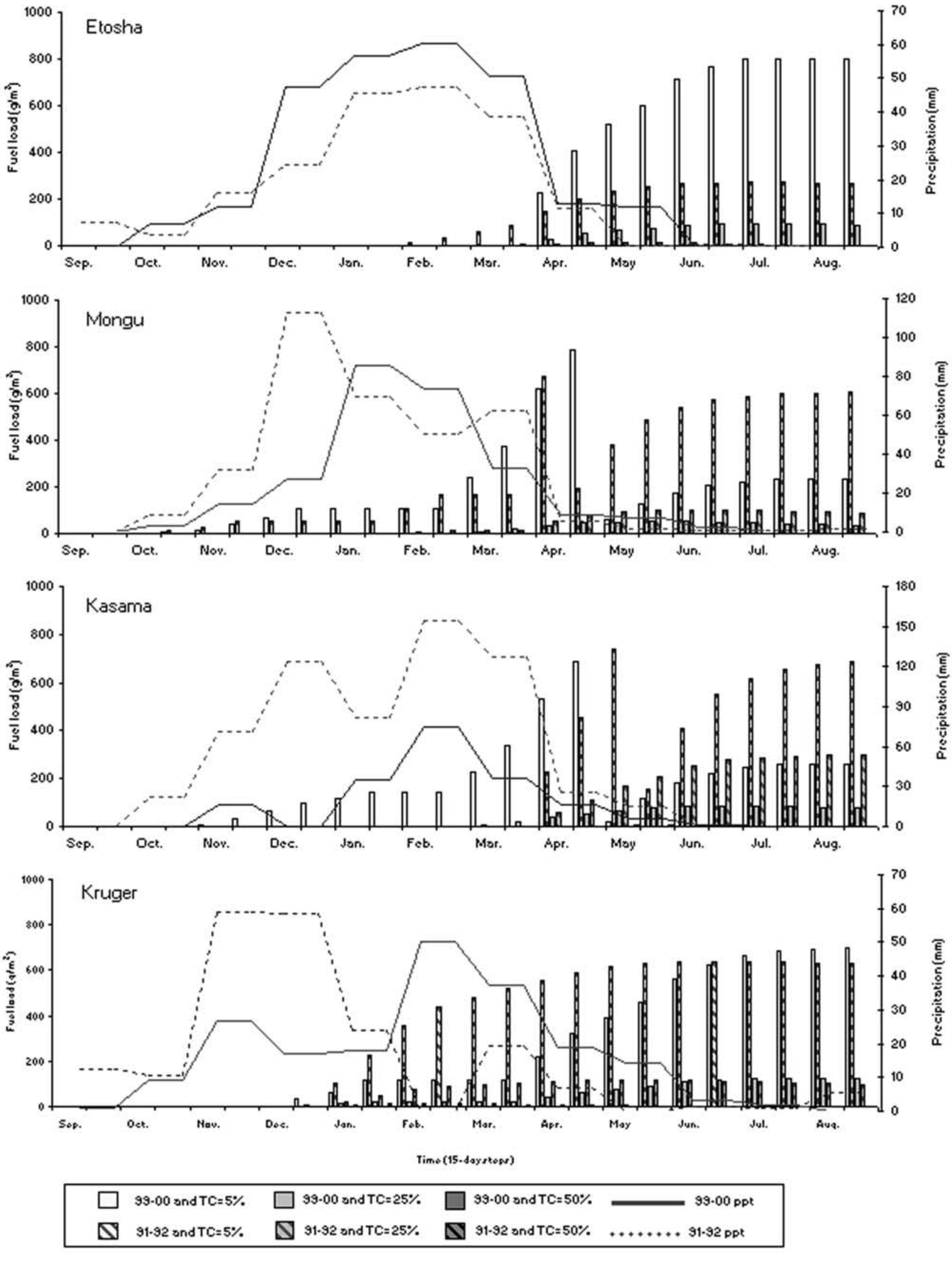

Figure 7. Temporal change in the dead grass fuel load for four regions (Etosha, Mongu, Kasama, and Kruger) according to the Tree Cover percentage (TC), and Precipitation (ppt in mm).

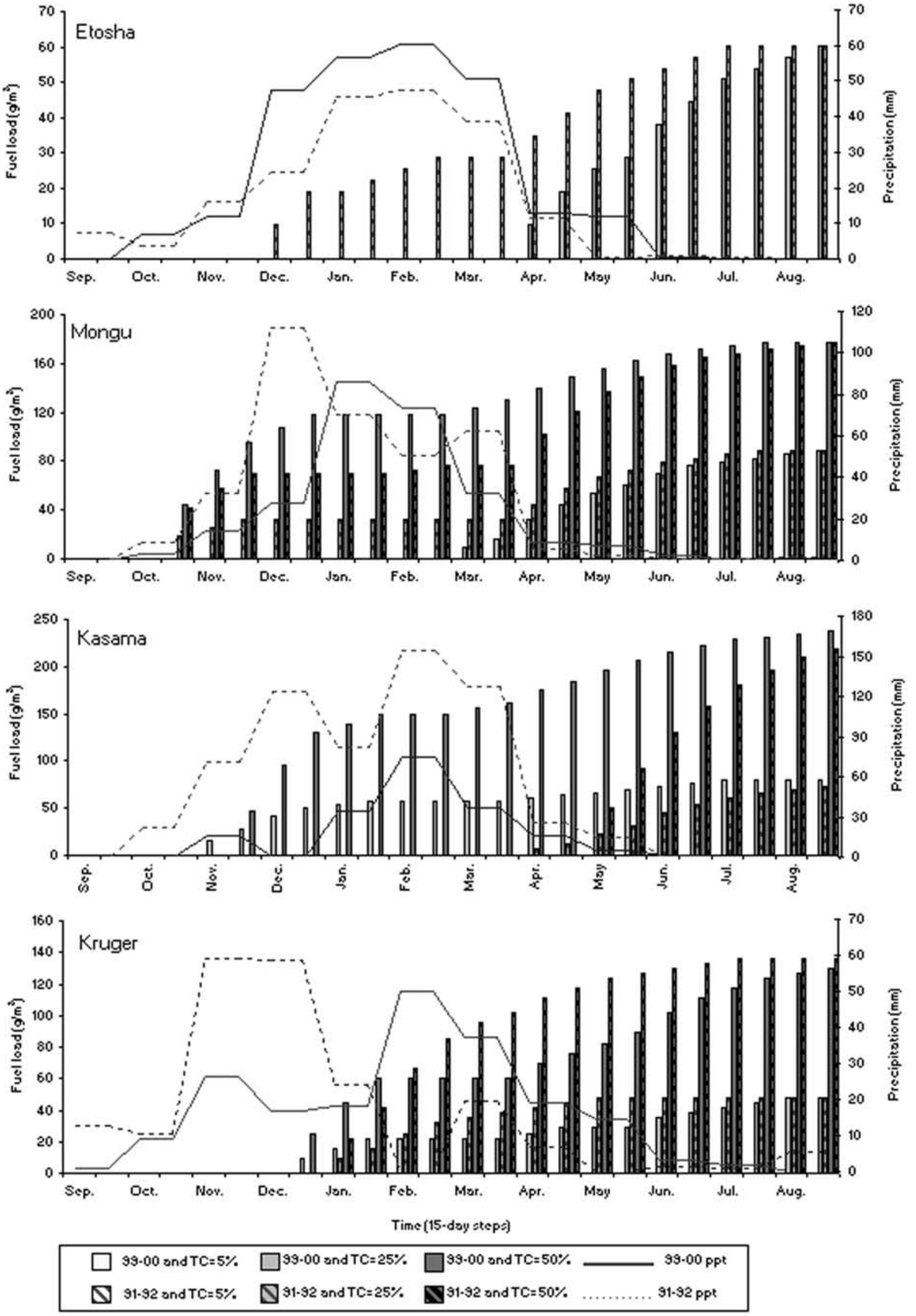

Figure 8. Temporal change in the litter fuel load for four regions (Etosha, Mongu, Kasama, and Kruger) according to the Tree Cover percentage (TC), and Precipitation (ppt in mm).

studied years. However, for sites with 30% of TC, only in Kasama are simulated grass fuel loadings sufficient to sustain fire spread. For sites with higher percentages of TC, the simulated grass fuel loadings are not sufficient enough to sustain fire, neither at the beginning of the fire season, nor at the end of August. Available data on grass from field campaigns and literature and from simulated loads range in the same order of magnitude (Figure 9), and they are quite close considering the high spatial variability in precipitation. When considering total fuel load (including grass, litter, and twigs in Figure 10), the simulated loads and loads extracted from literature or field campaigns are still in the same order of magnitude and range. For Kruger sites, only data in 2000 dealing with open grasslands (no woody fuel recorded) are reported here since TC percentages for closer-canopy sites were not explicitly recorded, and measured loads seemed to be very heavy (as compared to the simulated or the recorded data in 1992), with grass load ranging from approximately 300 to 700 g/m^2 where woody fuels were also presenting heavy loads. Regional variability between the 1991–1992 and the 1999–2000 fuel load availability at the end of August is reported in Figure 11 where the map presents the relative difference in percent between both years. Fuel load distributions are not normally distributed and the spatial heterogeneous pattern is related to the difference of cumulative precipitation between the two years presented in Figure 5.

4. Discussion

[20] This fuel load production model, based on a new Net Primary Productivity model (Hély et al., submitted manuscript, 2002), seems to simulate efficiently the vegetation growth over one growing season, especially when the high variability of precipitation in space and time is taken into account (Figures 5 and 6) and is added to the fact that reported simulated loads of grass or total fuel loads (Figures 9 and 10, respectively) come from only one pixel for a given TC percentage in a given area of interest. Moreover, data from literature review are not always explicit about the TC percentage of the studied sites [*Shea et al.*, 1996]. Finally, the way field measurements are realized may influence the fuel load estimation. For instance, the Kruger grass loads in 2000 (T. Landmann, personal communication, 2002) were estimated from the Disc Pasture Method [*Trollope et al.*, 1996], but we believe that this method may be less accurate when grass is sparse in stands with relatively important TC percentage. Moreover, data from Kruger area seem to present a natural high variability in fuel loads. For all these arguments on data quality, simulated and empirical data are in a good agreement.

[21] The Fuel Load model could be improved to a certain extent by considering improved data inputs such as herbivory, precipitation, and small woody diameter production. Indeed, herbivory data from FAO [*Wint et al.*, 2001; see http://www.fao.org/paat/html/home.htm] and the Programme Against Animal Trypanosomiasis Information System (PAATIS) has been recently released [*Pender et al.*, 2001] and should provide a better spatial coverage and census of the actual herbivores. Litter decomposers such as termites should be also included where data are available. As the sensitivity analysis has confirmed the hypothesis that precipitation is the most important climatic driver for fuel load production, and that the southern African region in general, and special areas in particular such as the Etosha National Park region [*Du Plessis*, 1997] are known to be very heterogeneous, precipitation should present the most accurate spatial and temporal coverage possible. This could be realized by coupling higher resolution ground data to remote sensed data for instance. Potential factors such as temperature, grazing, soil type and nutrient availability, or fire regime are known to influence, sometimes in a synergic way, primary production [*O'Coonor and Bredenkamp*, 1997] so they should not be discarded. The lack of data on fine woody production in the tropical savanna ecosystems made us develop a simple twig load production based on a regional empirical relationship involving only the TC percentage. However, these loads reflect multiyear production. This should be improved in next stages. The implementation of the model to simulate productivity over several years would be valuable in order to catch the effect of interannual variability and to avoid the reset action that occurs at the beginning of September, when some grass and litter fuel should be still on the ground. This multiyear product could provide insight on the effect of climate change over savanna ecosystems, and more particularly the influence of the 18-year rainfall oscillation (known as successive spells of 9 wet and 9 dry years) that is known to affect southern Africa [*Tyson*, 1986].

[22] From a regional point of view, the studied area (mainly covering Namibia, Zambia, Botswana, Zimbabwe, Mozambique, and South Africa) during the SAFARI-92 and SAFARI 2000 initiatives received effectively more rain in 1999–2000 than in 1991–1992 (Figure 5) as a direct consequence of the long lasting La Niña event that followed the 1997–1998 El Niño and the previous El Niño-Southern Oscillation event [*Lindesay et al.*, 1996] that spanned over 1991 and 1992. However, this regional picture hides a highly heterogeneous reality when scaling down from the regional to the local scales (e.g., Figures 6–8). Indeed, 1999–2000 was a very wet year in arid areas such as the Etosha National Park region, whereas it was very dry for more humid areas such as the northern Zambia in the Kasama vicinity. Therefore, as a direct consequence of the precipitation amount and its spatial distribution, fuels, mainly grass and litter, produced over the two contrasting year were different in terms of temporal availability along the year, as well as for particular periods such as the beginning of the fire season (generally earlier in 1992 than in 2000), and the field campaign periods, which in both project initiatives started in late August. Areas classified as relatively moist savannas such as in the Kasama region produced significantly less fuel in 2000 as compared to 1992 due to particularly low local precipitation amount over the 1999–2000. For arid region, conversely, 2000 was highly productive as compared 1992.

[23] Differences in available fuels (composition and quantity) between the two studied years have direct effects on potential fire risks, the size of the area burned (if fire does occur), and on the emissions released during the fire and afterward [*Du Plessis*, 1997; *van Wilgen and Scholes*, 1997; *Ward*, 1990; *Ward et al.*, 1996]. The 15-day time step and the 1 km pixel size model used in this study allows the local temporal and spatial conditions of fuel availability to

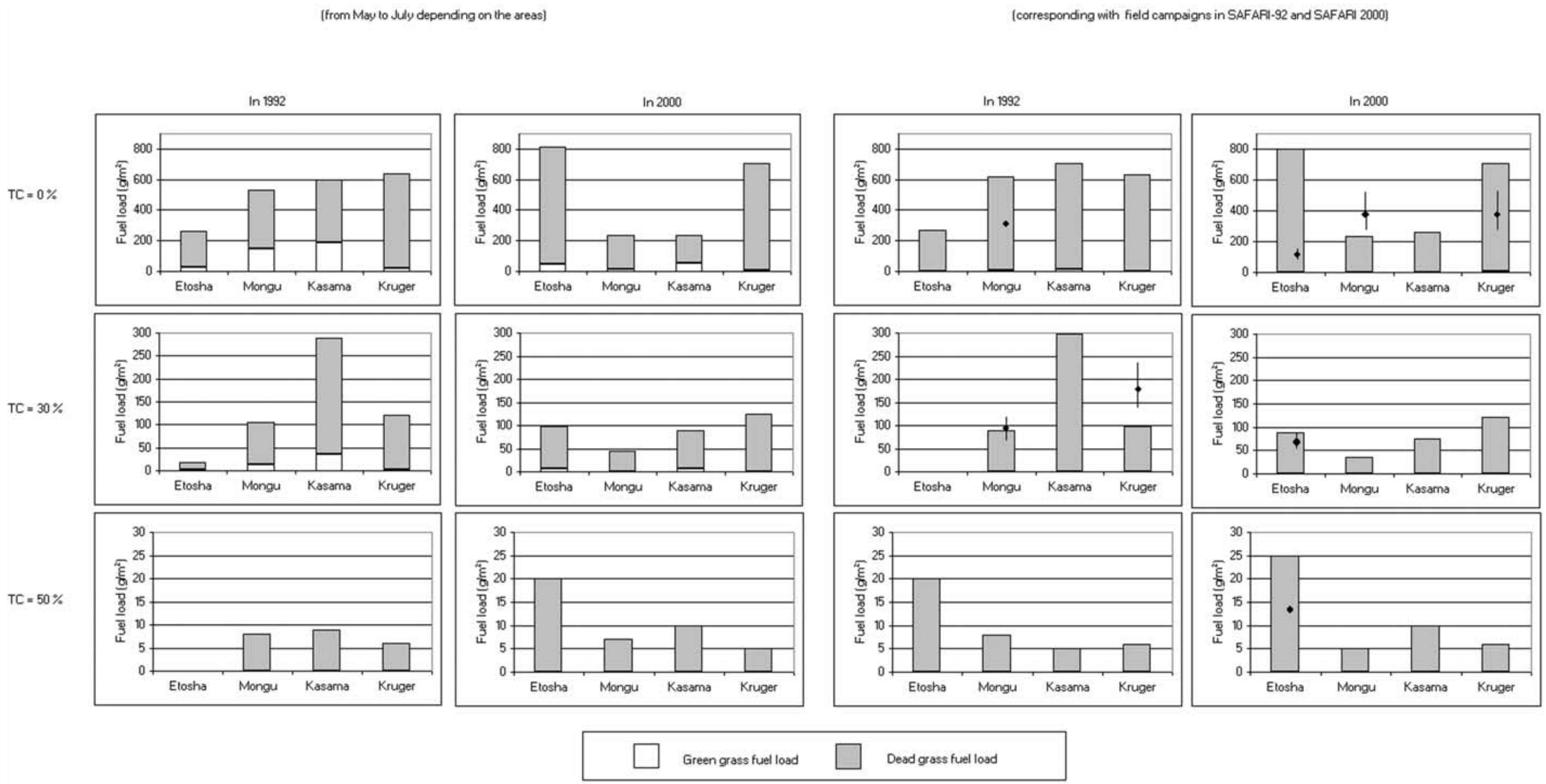

Figure 9. Comparison of total grass loads between the beginning of the fire season and the end of August in Etosha, Mongu, Kasama, and Kruger regions for three different Tree Cover: 0, 30, and 50%). Dot and dots with bars represent mean and range values extracted from the literature (*Shea et al.* [1996] for 1992 data; *Hély et al.* [2003] for 2000 data in Mongu) or from field campaigns (S. Alleaume et al., Using MODIS to evaluate heterogeneity of biomass burning and emissions in Southern African savannas: Etosha National Park Case Study, submitted to *International Journal of Remote Sensing*, 2002, hereinafter referred to as Alleaume et al., submitted manuscript, 2002, for Etosha data in 2000; T. Landman, personal communication, 2002, for Kruger data).

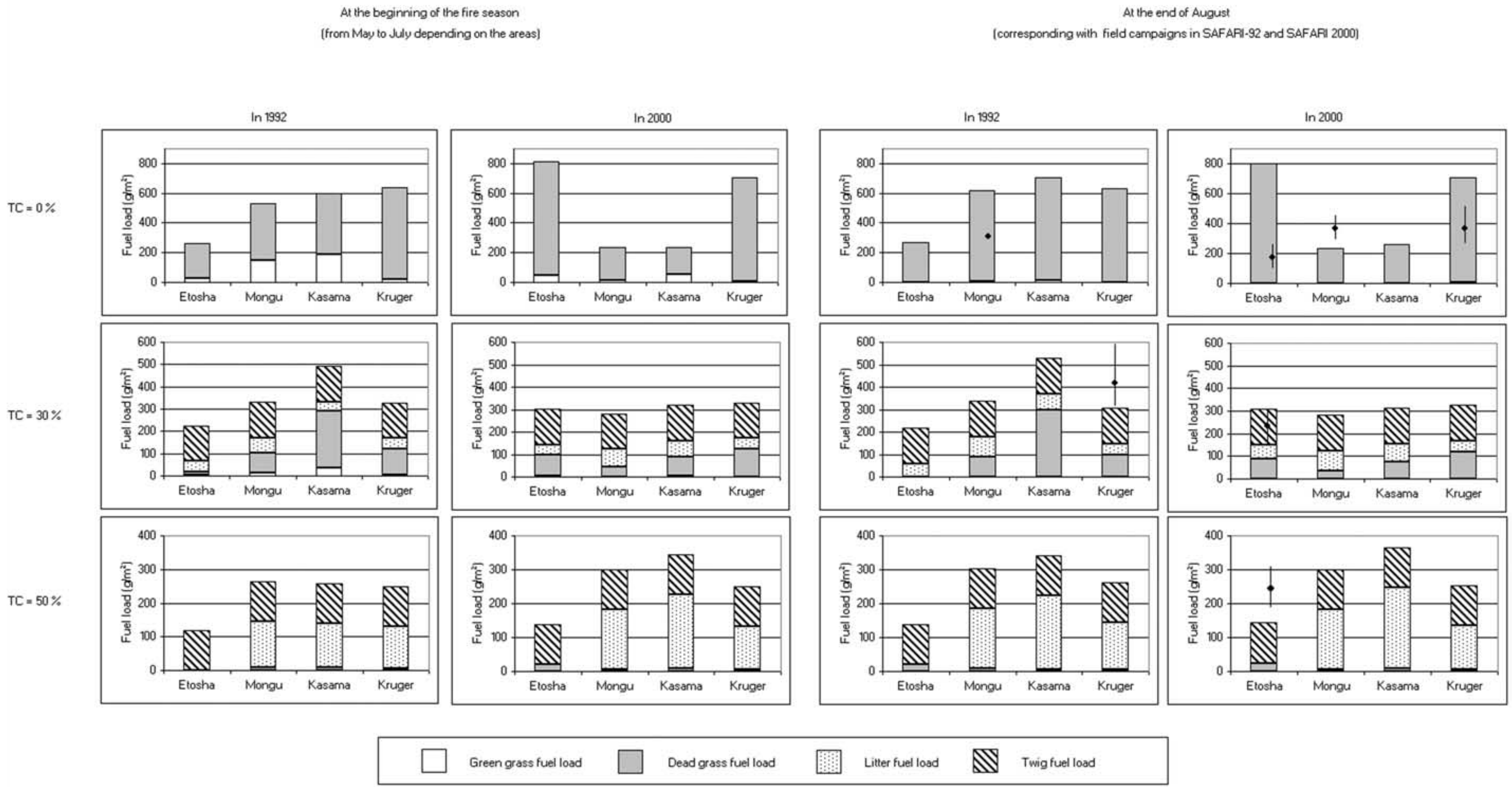

Figure 10. Comparison of total fuel loads and their composition between the beginning of the fire season and the end of August in Etosha, Mongu, Kasama, and Kruger regions for three different Tree Cover: 0, 30, and 50%). Dot and dots with bars represent mean and range values extracted from the literature (*Shea et al.* [1996] for 1992 data; *Hély et al.* [2003] for 2000 data in Mongu) or from field campaigns (Alleaume et al., submitted manuscript, 2002, for Etosha data in 2000; T. Landman, personal communication, 2002, for Kruger data).

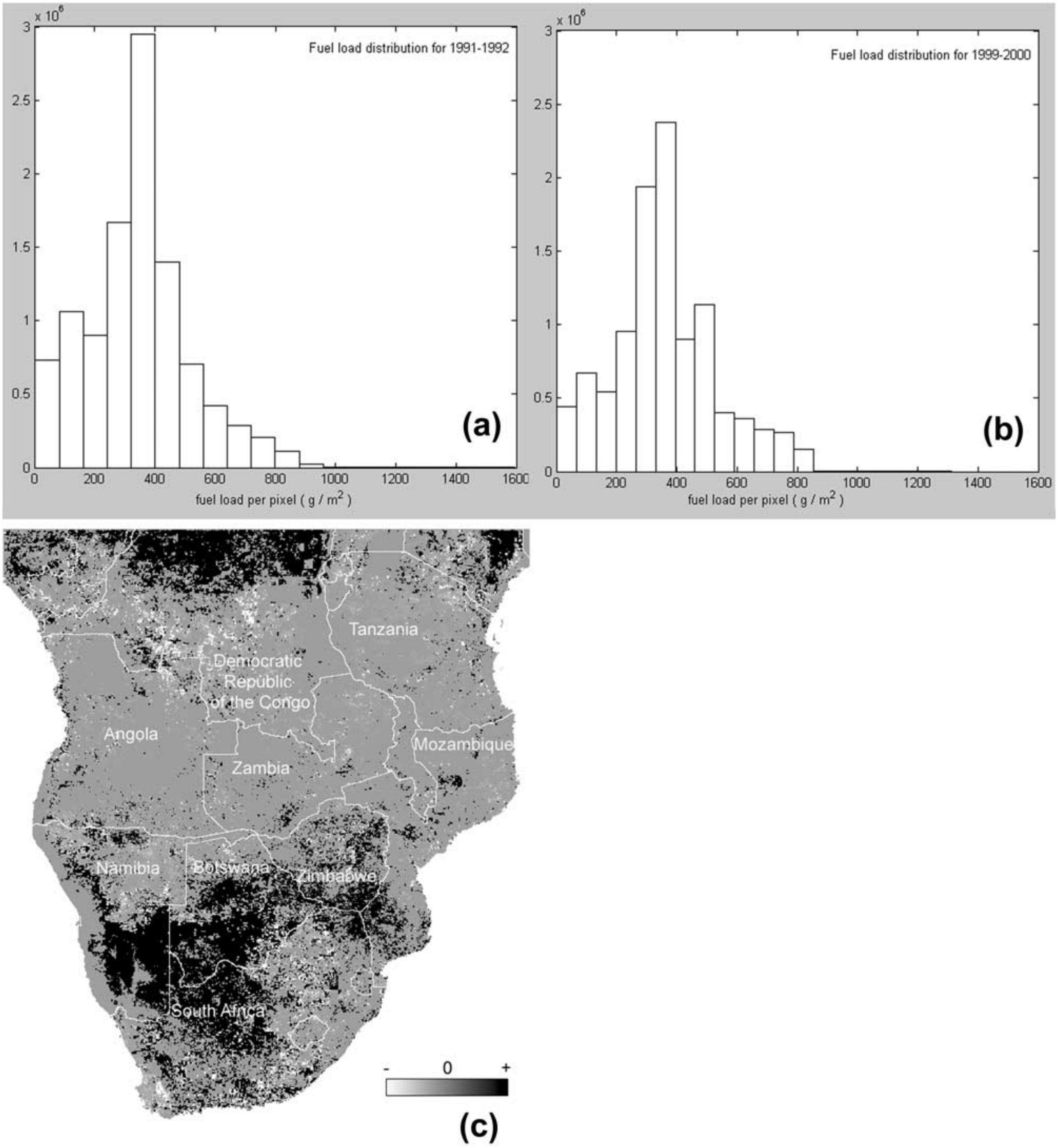

Figure 11. Fuel load distributions and basic statistics for August 1992 and 2000 (Panels (a) and (b), respectively), and regional variability in the difference between total fuel loads available in late August 2000 and 1992 (c): Gray represents no difference, while darker and lighter gradients represent positive and negative differences, respectively.

be described as a consequence of temporally and spatially heterogeneous precipitation. Model output could therefore be used as a management tool to track fire risk, as it depends on the fuel quantity and its moisture content, both being directly affected by the timing and amount of precipitation [*Burgan and Rothermel*, 1984]. These fine spatial and temporal scales are at the same level of fire event scales in terms of size and duration in African savanna. Indeed, even though some savanna fires can spread over thousands of hectares during several days such as the fire that spread on the northern limit of Etosha National Park area in Namibia in September 2000 [*Hély et al.*, 2001], most savanna fires spread during several hours or few days over variable areas from less than one to hundreds hectares depending on the ignition source (mainly man-ignited all over the dry season with increased lightning ignition toward the end of the dry season [*van Wilgen and Scholes*, 1997]). However, the regional extent output provided by the model can also be coupled to products such as the MODIS burned area product [*Roy et al.*, 2002] in order to capture the regional context of biomass burning and to better assess the emissions released. *Korontzi et al.* [2003] have demonstrated that accurate quantification of pyrogenic emission from savanna ecosystems requires a dynamic fuel load model, as opposed to a static approach [e.g., *Scholes et al.*, 1996]. Therefore, this study presents the first step of this spatio-temporal dynamic model and coupled to the tracking of area burned, this product would increase the accuracy of emission calculation as compared to using average fuel load values based on coarse vegetation types.

5. Conclusion/Summary

[24] The implementation of a new fuel load model for the southern African region that is based on ecophysiological processes has been successful to model the spatial and temporal availability of fuel types over the entire region by using a pixel resolution fine enough to capture the high variability in fuel loads as a consequence of the heterogeneity in precipitation. As a consequence, savanna ecosystems surveyed during the SAFARI-92 and SAFARI 2000 initiative present significantly different fuel loads that will directly affect the estimation of emissions from biomass burning.

[25] **Acknowledgments.** This paper was part of the SAFARI 2000 "Southern African Regional Science Initiative". This research was supported by the Southern Africa Validation of EOS program (SAVE-NASA-NAG5-7266), and the InterDisciplinary Science program (IDS-NASA-NAG5-9357). We thank Compton J. Tucker and the Global Inventory Monitoring and Modeling Studies for the NDVI data series, and the Data Assimilation Office (DAO) at the Goddard Space Flight Center's Distributed Active Archive Center (DAAC) for the climatic data.

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