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## Original Research

Estimating Grazing Potentials in Sudan Using Daily Carbon Allocation in Dynamic Vegetation Model<sup>☆</sup>Niklas Boke-Olén<sup>a,\*</sup>, Veiko Lehsten<sup>a</sup>, Abdulhakim M. Abdi<sup>a</sup>, Jonas Ardö<sup>a</sup>, Abdelrahman A. Khatir<sup>b</sup><sup>a</sup> Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden<sup>b</sup> ARC-Agricultural Research Corporation, El Obied Agricultural Research Station, ZC 51111; El Obied, Sudan

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## ABSTRACT

Livestock production is important for local food security and as a source of income in sub-Saharan Africa. The human population of the region is expected to double by 2050, and at the same time climate change is predicted to negatively affect grazing resources vital to livestock. Therefore, it is essential to model the potential grazing output of sub-Saharan Africa in both present and future climatic conditions. Standard tools to simulate plant productivity are dynamic vegetation models (DVMs). However, as they typically allocate carbon to plant growth at an annual time step, they have a limited capability to simulate grazing. Here, we present a novel implementation of daily carbon allocation for grasses into the DVM Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) and apply this to study the grazing potential for the Kordofan region in Sudan. The results show a latitudinal split in grazing resources, where the northern parts of Kordofan are unexploited and southern parts are overused. Overall, we found that the modeled grazing potential of Kordofan is 16% higher than the livestock usage reported in the Food and Agricultural Organization of the United Nations, indicating a mitigation potential in the form of a spatial relocation of the herds.

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## Introduction

Livestock provide an important source of income and nutrition for pastoral and agropastoral production systems in sub-Saharan Africa (Turner et al., 2014). In the Sahel, livestock are essential in maintaining local food security and serve as assets that compensate communities for interannual fluctuations in crop production (Turner and Williams, 2002). The human population in the Sahel is increasing at an annual rate of approximately 4% and is projected to reach nearly 1 billion by 2050 (Abdi et al., 2014). Hence, Sahelian livestock populations, which are already several hundred million in size, will likely increase to sustain the growing human population. Furthermore, models predict that climate change in the 21st century will negatively impact grassland and savanna forage productivity, thus altering grazing potential and livestock densities (Niang et al., 2014; Boone et al., 2018). Sudan, in particular, has witnessed an increase in both temperature and the frequency of droughts over the past 4 decades (Elagib and Elhag, 2011). Pastoralists have adapted to the spatiotemporal variability of climate by moving their herds to follow the rains. At the onset of the Sahelian dry season,

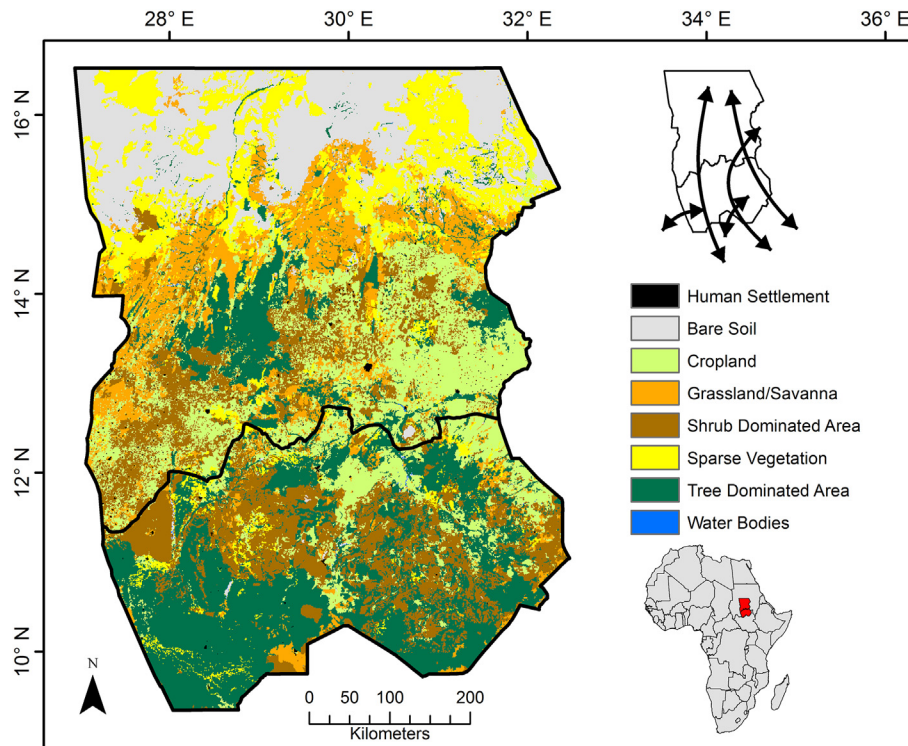
pastoralists move their herds south to the Sudano-Guinean zone and return north when the rains resume the following year, thus establishing transhumance corridors (Fig. 1). Consequently, grazing resources depend on the availability of open rangelands and transhumance corridors (Turner et al., 2011). The expansion of cropland to meet the food demand of an increasing population has already reduced transhumance corridors, igniting conflicts between pastoralists and agriculturalists in some parts of the Sahel (Hein et al., 2011; Sissoko et al., 2011; Turner et al., 2011; Turner et al., 2016). This confluence of factors demonstrates the need to assess the potential impact of climate change on grazing resources to aid policymakers and communities in developing novel approaches that enhance the resilience of pastoral systems (IPCC, 2014).

Early grazing models were developed with the aim of either understanding system dynamics or analyzing management strategies (Tietjen and Jeltsch, 2007). None of the 41 models reviewed by Tietjen and Jeltsch (2007) take atmospheric CO<sub>2</sub> into account, and this important limitation might provide a conservative estimate of grazing potential. However, atmospheric CO<sub>2</sub> concentrations can be accounted for when studying grazing by using dynamic vegetation models (DVMs). This has already been done to study the interactions between grazing and climate change (Bachelet et al., 2000), feeding potential of different grazing intensities (Rolinski et al., 2015) or the effect of management on carbon balance (Chang et al., 2016). Several DVMs also simulate vegetation dynamics and interactions in response to climate variability. They commonly use a set of plant functional types (PFTs), each represented by

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**Figure 1.** Land cover of the Kordofan region according to the GLC-Share 2014 land cover dataset from the Food and Agriculture Organization (FAO; Latham et al., 2014). The figure on the top right shows general transhumance corridors in North and South Kordofan between the dry and rainy seasons based on data from the United Nations Joint Logistics Center, FAO, and Sudan Interagency Mapping initiative. (For a correct representation of the color scale, the reader is advised to the online version of this manuscript).

parameters that control for the influence of climate on growth and carbon allocation.

One of the obstacles in correctly simulating grazing in DVMs is the temporal scale at which the simulations are performed. While many processes are typically represented at a daily scale, others are performed at the annual scale. For example, in the DVM LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator; Smith et al., 2001), the allocation of carbon between PFT compartments is done at the end of each simulation year, making a daily grazing scheme impossible to implement without substantial changes to the model. Therefore, grazing can have no direct feedback within the year but can only be performed at the end of each simulation year. To accurately simulate feedback between grazing and vegetation, a daily carbon allocation scheme for grasses is implemented in the DVM LPJ-GUESS. This allows for the simulation of the livestock potential of an area (i.e., maximum amount of livestock an area can support). Thus, the aim of this study is to use daily carbon allocation for grasses to simulate livestock potential of the Kordofan region in Sudan, a region with a high livestock population that serves as an important source of livelihood for the inhabitants (El Tahir et al., 2010).

## Material and Methods

### Study Area

The study area comprises the Kordofan region (North and South Kordofan) in central Sudan (see Fig. 1). The area covers approximately 380 000 km<sup>2</sup> with mostly sedentary rural inhabitants (63%) and pastoralists (24%). Traditional natural grazing, involving use of uncultivated, fallow land and crop residues, is the main source of feed for the livestock species. The annual rainfall gradient is typically Sahelian with < 100 mm in the northern border to > 800 mm at the southern border. The rainy season is from July to September. The northern parts of the region are arid and mostly covered with sparse vegetation and desert scrub. Central parts of North Kordofan are composed of sandy soils, and the land

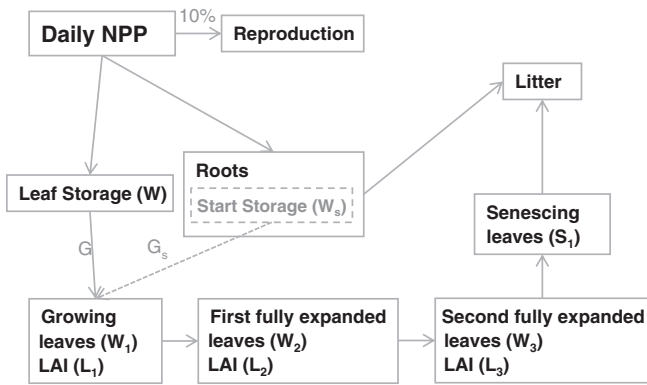
cover is a mosaic of *Acacia senegal* savanna, cropland, and patches of dense woodland. The heavy clay soils of South Kordofan host woody savanna dominated by *Acacia seyal* and *Balanites aegyptiaca*. The livestock population of approximately 20 million (El Tahir et al., 2010) is highly mobile due to pastoral transhumance and in 2010 consisted of roughly 30% cattle, 38% sheep, 26% goats, and 6% camels (Behnke, 2012).

### LPJ-GUESS and Daily Carbon Allocation for Grasses

We implemented daily carbon allocation in LPJ-GUESS version 3.0 (Smith et al., 2001; Smith et al., 2014) for C3 and C4 grasses. This distinction represents grasses with two different carbon fixation pathways (termed C3 and C4 photosynthesis). LPJ-GUESS is a dynamic vegetation model that simulates the potential vegetation described by PFT. The model simulates both tree and grass species, but the daily carbon allocation was implemented for grass species only. The implemented functions and changes to the model are based on the theory from Johnson and Thornley (1983). It estimates how carbon from photosynthesis is distributed across the plant for each simulated day. LPJ-GUESS was simulated with 1901–2011 climate data (temperature, precipitation, and solar radiation) from a global meteorological dataset (Weedon et al., 2014) with 0.5-degree spatial resolution. The climate dataset was obtained from <http://www.eu-watch.org/>.

The carbon flux from leaf storage (Fig. 2, G) is calculated by using the amount of carbon in the pool ( $W$ , kgCm<sup>-2</sup>), the growth factor ( $\mu$ , restricted to be between 0 and 1, Eq. (2)), and daily phenology (phen, scalar 0 – 1) as shown in Eq. (1). The growth factor ( $\mu$ ) is calculated using a dimensionless PFT-specific parameter ( $c_{\text{PFT}}$ ), temperature ( $T$ , °C), and the PFT-specific optimum temperature ( $T_{\text{opt}}$ , °C) (Eq. (2)). The optimum temperature is 20°C for C3 (Johnson and Thornley, 1983) and 30°C for C4 since C4 has a higher optimum temperature compared with C3 (Yamori et al., 2014).

Daily phenology is assigned the minimum value of the ratio between water supply and water demand for full leaf cover and the ratio between growing degree days above 5°C (gdd5) and life form specific



**Figure 2.** Flowchart describing the carbon pools used for the daily carbon allocation model for grasses on a daily time scale. This model is implemented into LPJ-GUESS.

*gdd5* value (*gdd5<sub>lifeform</sub>*; the life form specific value enables separate values for C3 and C4 grasses) to reach full leaf cover (Eq. (3)).

$$G = W \cdot \mu \cdot phen \tag{1}$$

$$\mu = c_{pft} \cdot \frac{T}{T_{opt}} \tag{2}$$

$$phen = \min \left( \frac{w_{supply}}{w_{demand}}, \frac{gdd5}{gdd5_{lifeform}}, 1 \right) \tag{3}$$

The implemented daily carbon allocation model uses the main part of the state-variables as described by Johnson and Thornley (1983) and shown in Eqs. (4) to (7). The rate of carbon flux between  $W_1$  and  $W_2$  is twice as fast compared with the flux between the other pools ( $W_2$  to  $W_3$  and  $W_3$  to  $S_1$ ), similar to how Johnson and Thornley (1983) do it. The transfer rate constants ( $\gamma$  and  $\alpha$ ) are described in Eqs. (8) and (9) and are restricted to a value between zero and one. To ensure that the senescence does not increase with temperature or halt when the temperature drops, a constant transfer rate ( $\alpha$ ) from  $W_3$  to  $S_1$  is used combining  $c_{pft}$  and a senescence factor ( $S_{fac}$ ) (Eq. (9)). The same rate ( $\alpha$ ) is used to transfer material to litter and is equal to  $\alpha S_1$  (Eq. (7)).

$$\frac{dW_1}{dt} = G - 2\gamma W_1 \tag{4}$$

$$\frac{dW_2}{dt} = 2\gamma W_1 - \gamma W_2 \tag{5}$$

$$\frac{dW_3}{dt} = \gamma W_2 - \alpha W_3 \tag{6}$$

$$\frac{dS_1}{dt} = \alpha W_3 - \alpha S_1 \tag{7}$$

$$\gamma = c_{pft} \cdot \frac{T}{T_{opt}} \tag{8}$$

$$\alpha = c_{pft} \cdot S_{fac} \tag{9}$$

Each compartment ( $W_1$ ,  $W_2$ , and  $W_3$  in Fig. 2) is converted to leaf area index (LAI) by multiplying its carbon content with the specific leaf area (SLA) corresponding to each PFT. The total LAI is calculated each day as the sum of  $L_1$ ,  $L_2$ , and  $L_3$  and used by LPJ-GUESS photosynthesis and respiration functions to calculate daily net primary production (NPP). The “start storage” ( $W_s$ , see Fig. 2) pool is activated when there are favorable conditions for growth ( $phen > 0.5$ ) and low LAI ( $<$

0.1). Once those conditions are met, 20% of the carbon in  $W_s$  will be allocated ( $G_s$ ) to  $W_1$ .

Once a grass individual is established and has survived its first year, the daily carbon allocation formula takes over and simulates daily growth for that individual until it dies. At the end of each simulated day, 10% of NPP is put into the reproduction pool and the rest is separated into leaf storage, roots, and “start storage” ( $W_s$ , see Fig. 2). The “start storage” enables growth when the grass has low LAI and conditions are favorable ( $phen > 0.1$  in Eq. (3) and  $LAI < 0.1$ ). The amount of carbon allocated to leaf storage and roots is controlled by the current state, water, and nitrogen availability and follows the carbon and nitrogen (C-N) allocation rules of LPJ-GUESS as described by Smith et al. (2014). However, in our implementation, the allocation function is updated daily. The total root carbon used to calculate the allocation fractions includes the carbon in the start storage pool ( $W_s$ , see Fig. 2), which is a fraction ( $s_{tor}$ ) of the root carbon content that is estimated in the calibration.

**Model Calibration**

Because of the lack of site-measured flux data within the region (except for Demokeya), we calibrated the model using an Australian site with similar conditions and validated it using the Demokeya data. The reasoning for this was that the model should be calibrated at a grass-only site to remove the influence of trees from the calibration. For calibration, we used daily net ecosystem exchange (NEE) flux measurements for Daly River Pasture (AU-DaP, latitude -14.0633, longitude 131.3181) located 62 km southwest of Pine Creek, Northern Territory, Australia. The measured NEE data cover yr 2008 – 2010. Both observed and modeled NEE were filtered with a 7-d running average. Each parameter ( $c_{pft}$ ,  $S_{fac}$ , and  $s_{tor}$ ) was sampled within reasonable limits estimated from Johnson and Thornley (1983) and expert knowledge. Because the site is moderately grazed, the grazing intensity parameter ( $graz_{int}$ , see next section for more detailed information) was also sampled and estimated in the calibration. The calibration procedure was done with tree PFTs turned off and repeated 5 000 times. For every calibration run, the correlation coefficient and root-mean-squared error (RMSE) between modeled and measured NEE were calculated. The final calibrated parameters were selected by ranking the correlation coefficient and RMSE (in ascending order) and selecting the lowest combined rank. In case of a tie, the correlation coefficient was favored.

The calibration was validated using daily net ecosystem exchange (NEE) flux measurements for Demokeya (SD-Dem, lat 13.2869, long 30.4792) located within the study area in Sudan. The measured NEE for Demokeya ranges from 2007 to 2009. To account for site-specific differences in grazing, the grazing intensity ( $graz_{int}$ ) was reparameterized (2 000 repetitions) for Demokeya using the same ranking method as described earlier. Because Demokeya consists of both trees and grass, the validation was carried out with tree and grass PFTs included. We compared the 1995–2005 daily average LAI against average normalized difference vegetation index (NDVI) to evaluate the spatial pattern of the calibrated parameters. GIMMS (Global Inventory Modeling and Mapping Studies) NDVI version 3 (Tucker et al., 2005) was resampled to match the 0.5-degree spatial resolution of the modeled LAI using bilinear interpolation. We assumed that grazing intensity of the study area was the same as the parameterized value for Demokeya to facilitate comparison with remotely sensed NDVI.

**Grazing Potential**

Grazing potential was simulated by assuming grazing occurred each day grass LAI was above 0.1. It was modeled by removing a fraction of leaf each simulation day. The amount was controlled by a grazing intensity parameter ( $graz_{int}$ ) that could take values from 0.1% up to a maximum of 100%. Grazing also affected nitrogen by removing the same relative amount of nitrogen as carbon from the grass individual.

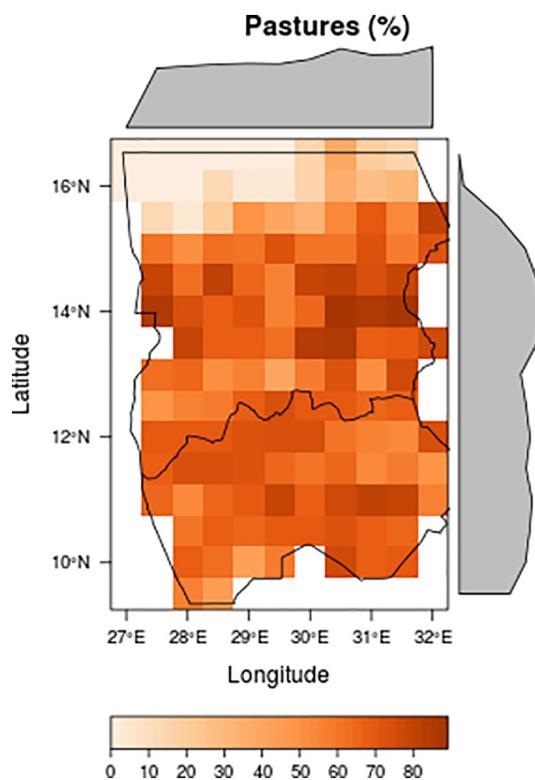
However, 97% of the removed nitrogen was added back to the soil as manure and urine fertilizer as estimated by Rufino et al. (2006) for a similar rangeland in Mali. The  $\text{graz}_{\text{int}}$  was increased stepwise at intervals of 0.5% in order to find the approximate intensity that provides highest average carbon output (grazing material) for yr 1995–2005. The simulation of a grid cell was stopped when the grazing output was lower than the grazing intensity at the step before, which gave an estimate of the total unconstrained grazing potential per grid cell.

We used the tropical livestock units (TLU) as a standardized measure of livestock types (1 TLU = 1 camel, 0.7 TLU = 1 cow/bull, 0.1 TLU = 1 sheep/goat) for yr 2005 to assess the feed requirement. We selected the TLU as a standard unit of measurement because official estimates of livestock numbers roughly correspond to surveyed livestock biomass consumption when different species are converted to their TLU equivalent (Behnke and Osman, 2012). Each TLU was converted to carbon requirement by multiplying it with 2 372 (kg dry mass  $\text{TLU}^{-1}$ ) to obtain dry mass per TLU (kg dry mass  $\text{TLU}^{-1} \text{yr}^{-1}$ ) and then multiplied by 0.45 to obtain carbon content (kgC  $\text{TLU}^{-1} \text{yr}^{-1}$ ) following Abdi et al. (2014). The pasture area (Fig. 3) estimated by Ramankutty et al. (2010) was used to convert the modeled grazing potential into a grid cell ( $0.5 \times 0.5$  degree) total by multiplying the modeled grazing potential (kgC  $\text{m}^{-2} \text{yr}^{-1}$ ) by the grid cell pasture area ( $\text{m}^2$ ).

## Results

### Model Calibration

The model calibration at Daly River Pasture gave the best correlation coefficient of 0.63 (unit less correlation coefficient) and RMSE of 1.7 (gC  $\text{m}^{-2} \text{d}^{-1}$ ) when comparing modeled NEE to measured NEE flux. This was achieved for the parameter values  $c_{\text{pft}, \text{C}_4} = 0.020$  (Eqs. (8) and (9)),  $\text{stor} = 0.07$  (fraction of root carbon content that are allocated to “start of storage pool”),  $S_{\text{fac}} = 0.98$ , and  $\text{graz}_{\text{int}} = 2.22\%$ . The



**Figure 3.** Percentage of grid cell classified as pasture based on data from Ramankutty et al. (2010). The gray graphs in the margin represent the relative distribution of the average latitudinal and longitudinal bands.

reparameterization of  $\text{graz}_{\text{int}}$  gave for Demokeya a value of 2.19%, and the validation gave an RMSE of 0.7 gC  $\text{m}^{-2} \text{d}^{-1}$  and correlation coefficient of 0.63. The validation showed some inconsistencies over the seasons (Fig. 4). The model underestimated NEE (positive = carbon uptake, negative = carbon release to the atmosphere) during the dry seasons (NEE flux close to zero) and during the growing season of yr 2008 and 2009 (Fig. 4, left). However, the modeled LAI for Kordofan shows a good agreement to remotely sensed NDVI with the expected saturation (see Fig. 4, right) as LAI increases (Gamon et al., 1995).

### Grazing Potential in Kordofan

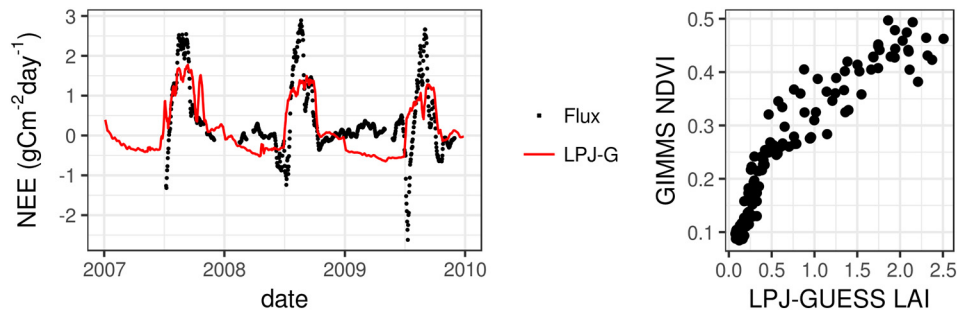
There was a spatial mismatch between grazing potential and reported livestock (TLU) feed requirement (Fig. 5). The estimated total unconstrained grazing potential of the area was 8 098 MgC (see Fig. 5, left), and the TLU grazing requirement was 7 000 MgC (see Fig. 5, middle). The total unconstrained grazing potential of the area was  $\approx 16\%$  higher than the total reported TLU feed requirement. This means that grazing can be increased compared with 2005 TLU levels. The northward shift between the feed requirement and grazing potential indicates that there was a positive difference for latitudinal band between  $13^\circ\text{N}$  and  $15^\circ\text{N}$  and a negative difference between  $9.5^\circ\text{N}$  and  $12^\circ\text{N}$  (see Fig. 5, right panel). The latitudinal relationship found in the modeled grazing potential (see Fig. 5, left panel) was not observed in the pasture area data (see Fig. 3).

## Discussion

Savannas play an important role in the carbon cycle because they dominate interannual variability in  $\text{CO}_2$  uptake in terrestrial ecosystems (Ahlström et al., 2015) because of their large global coverage (Grace et al., 2006). To increase our ability to model these systems and include grazing on a daily scale, we implemented a daily carbon allocation for grasses into the dynamic vegetation model LPJ-GUESS that was calibrated using an Australian site and validated using a site within a site in the Kordofan region of central Sudan. Our findings indicate that the modeled grazing potential of the region is 16% higher than the reported livestock usage with a spatial mismatch between modeled and reported values.

It has been stated as early as the 1960s that livestock populations in central Sudan exceed the carrying capacity of the rangelands (Wilson, 1977). This has been reiterated throughout the 1980s and 1990s (D'souza and Shoham, 1985; Wakeel and Sabah, 1993; Laki, 1994), particularly in the wake of the devastating droughts of those decades. However, recent studies paint a more complex picture. Abdelsalam et al. (2012) observed that soil type also played a critical role in determining rangeland productivity in South Kordofan. Clay soils provided the highest carrying capacity (1 TLU/hectare) and sandy soils the lowest (0.1 TLU/hectare). El Hag et al. (2012) found that management practices also played an important role in the rangelands of North Kordofan. They found that both carrying capacity for livestock and plant density were higher in closed range than open range management systems (where livestock roam free regardless of land ownership).

The LPJ-GUESS simulation suggests a higher grazing potential in North Kordofan, which might partly be explained by a slightly higher fraction classified as pasture (see for example grassland and open savanna in Fig. 1 and pasture fraction in Fig. 3) in that part of the region. However, the result is also influenced by a higher simulated grazing potential for this area (see Fig. S1). There is also an increase in the grazing potential in the middle part of the Kordofan region (see Fig. 5, left) that cannot be observed in the pasture data (Fig. 3), which shows that the modeled total grazing potential is not only determined by the pasture dataset used. We also found a higher reported TLU feed requirement compared with the simulated grazing potential in mainly the southeastern part of the study region. A potential explanation for this difference could be that the reported TLU does not reflect the true location of the



**Figure 4.** Left: Time series of the result of the model calibration for Demokeya, Sudan. *Black dots* show the observed Net Ecosystem Exchange (NEE) flux and *orange line* the modeled NEE. Positive values indicate an uptake of carbon and negative a release to the atmosphere. Right: Scatterplot between grid cell average 1995–2005 LPJ-GUESS total leaf area index (LAI) and GIMMS NDVI. Please note that LAI and NDVI are not linearly related but typically show a slight saturation as LAI increases.

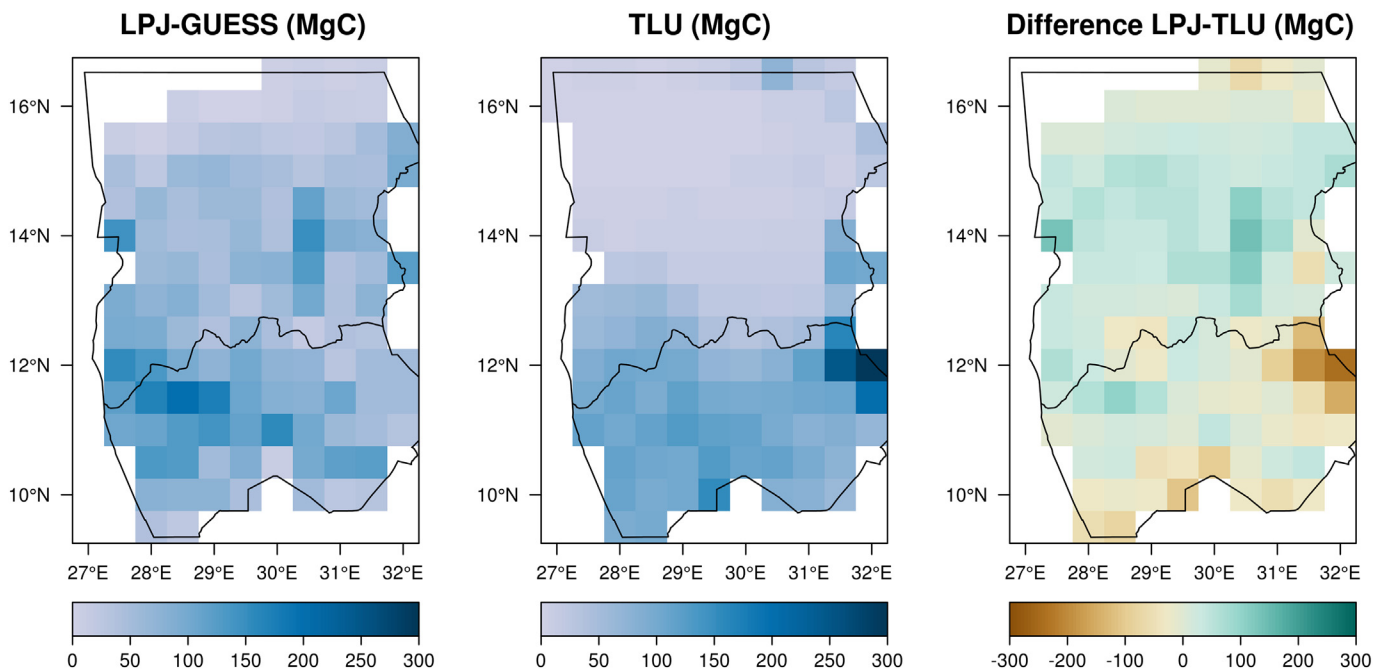
livestock at all times given the mobility of the livestock population in the area (see Fig. 1). In addition, the modeled grazing potential does not follow the spatial distribution of the reported TLU.

The result of our study allows the mobility of livestock to be studied in the form of a potential spatial relocation of herds. However, we are well aware that such a mitigation potential, though showing a promising tool to increase livestock rates from a modeler's perspective, is highly problematic to attain in reality due to land ownership and cultural factors. Furthermore, the estimated grazing potential is unconstrained, meaning that it does not account for other factors such as distance to water sources, inedible plants, soil erosion, and infrastructure. However, we maintain that our results are valuable for decision makers for two important reasons. First, they provide information on areas that have the vegetative potential to provide an increase in livestock numbers. Second, they highlight areas that are facing pressure from overgrazing, which can potentially accelerate and lead to negative feedback that causes land degradation.

The model validation produced an underestimation of NEE during the dry seasons and for the growing seasons in 2008 and 2009 (see Fig. 4). We attribute this to lower WATCH precipitation compared with site measurements during those 2 yr (WATCH precipitation 58% and 64% of site precipitation for yr 2008 and 2009, respectively, data

not shown). Furthermore, one other major influence causing underestimation in the dry season could be the ability of the trees to access water deeper in the soil, which is not captured in the model (Morales et al., 2005). The relationship between LAI and NDVI in the calibrated model (see Fig. 4, right) indicates that we managed to simulate relative vegetation growth during the study period in the form of an expected underproportional functional relation (Gamon et al., 1995). Due to the location of the study area, we only showed calibration for C4 grasses; however, we also performed a calibration for PFT-specific parameters related to C3 grasses using a European site (see Fig. S2).

The implementation of daily carbon allocation for grasses into LPJ-GUESS allows, for the first time, to simulate grazing with a much better representation of the actual processes involved. However, using one single PFT for C4 grasses and one for C3 grasses strongly simplifies the variability of the world. Nevertheless, the daily allocation will in the future make it easier to translate growth parameters measured in the field to parameterize more grass species and hence increase the variability of growth responses. The daily allocation also enables LPJ-GUESS for estimations of wildfires because it provides a more precise estimate on the fuel availability. Lehsten et al. (2009) simulated the pyrogenic carbon release from the African continent by enhancing the temporal resolution in LPJ-GUESS. This enhancement was done by calculating leaf



**Figure 5.** Comparison of yearly grazing potential (MgC/0.5 × 0.5 degree) modeled with LPJ-GUESS (left) and calculated yr 2000 feed requirement (MgC/0.5 × 0.5 degree) from the Tropical Livestock Units (TLU) data (middle). Figure on the right shows the difference (TLU subtracted from LPJ-GUESS). TLU data is from HarvestChoice (2011). For a correct representation of the color scale of the figure on the right, the reader is referred to the online version of this manuscript.

shedding and leaf decomposition on a daily basis instead of the annual time step. However, any effects of wildfire on carbon allocation could only be simulated with an annual resolution, limiting the precision of the simulated carbon release. Given the applicability of a daily carbon allocation for grasses, it becomes obvious that such a model development might also be useful for trees because trees comprise the majority of natural vegetation in terms of carbon storage, as well as NPP in most areas. However, the development of daily carbon allocation for trees is considerably more complicated than for grasses. Trees can assimilate carbon to a larger degree than grasses. Hence, the growth of leaves is less influenced by the amount of assimilating tissue at each point in time and more by the species-specific phenological strategy of trees.

## Implications

We show that the average grazing potential for the Kordofan region in total is 16% higher than the grazing demand from the reported TLU for yr 2005. The incorporated change into LPJ-GUESS makes it possible to study the grazing potential of an area in both the current state and a projected state (e.g., by incorporating effects of climate or land use change). Given the advantages of simulating carbon allocation on a daily scale, we suggest that other DVMs also incorporate a daily allocation scheme for grasses.

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## Appendix A. Supplementary Data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rama.2018.06.006>.

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