Modelling Gas Exchange and Biomass Production in West African Sahelian and Sudanian Ecological Zones

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Abstract West African Sahelian and Sudanian ecosystems are providing essential services to people and also play a significant role within the global carbon cycle. However, climate and land use are dynamically changing and it remains uncertain how these changes will affect the potential of these regions for providing food and fodder resources or the biosphere-atmosphere exchange of CO₂. In this study, we investigate the capacity of a process-based biogeochemical model, LandscapeDNDC, to simulate net ecosystem exchange (NEE) and aboveground biomass of typical managed and natural Sahelian and Sudanian savanna ecosystems. In order to improve the simulation of phenology, we introduced soil-water availability as a common driver of foliage development and productivity for all these systems. The new approach was tested by using a sample of sites (calibration sites) that provided NEE from flux tower observations and leaf area index data from satellite images (MODIS). For assessing
the simulation accuracy, we applied the calibrated model to 42 additional sites (validation sites) across West Africa for which measured aboveground biomass data were available. The model showed a good performance regarding biomass of crops, grass or trees yielding correlation coefficients of 0.82, 0.94, and 0.77 and Root Mean Square Errors of 0.15, 0.22, and 0.12 kg m\(^{-2}\), respectively. The simulations indicate above-ground carbon stocks of up to 0.17, 0.33, and 0.54 kg C ha\(^{-1}\) m\(^{-2}\) for agricultural, savanna grasslands, and savanna mixed tree-grassland sites. Carbon stocks as well as exchange rates correlated in particular with the abundance of trees, and grass biomass as well as crop yields were higher under more humid climatic conditions. Our study shows the capability of LandscapeDNDC to accurately simulate carbon balances in natural and agricultural ecosystems in semi-arid West Africa under a wide range of conditions, so that it might be used to assess the impact of land-use and climate change on the regional biomass productivity.

1 Introduction

Land-cover- as well as land-use changes significantly affect water, carbon (C) and energy exchange processes between the biosphere and the atmosphere and, thus, climate change (Massad et al., 2019; Pielke et al., 2011). Within the larger biomes, savanna or semi-arid grassland systems have been highlighted as particular important as they are on the one hand assumed to store large amounts of C (Elberling et al., 2003; Scholes and Hall, 1996), and on the other hand experience large C exchanges (Ahlström et al., 2015). Additionally, savannas are vulnerable to climate change, specifically to changing rainfall pattern or increasing fire intensity or frequency (Grossiord et al., 2017; Livesley et al., 2011). In particular the role of West African savanna systems for global C cycling has attracted increasing attention over the last decade (Quenum et al., 2019; Bocksberger et al., 2016; Sjöström et al., 2011) due to considerable changes in climate, but also land cover, such as an extension of agriculture and intensification of forest logging (Odekunle et al., 2008). These changes may already have and will further affect the C exchange rates between semi-arid West African savanna ecosystems and the atmosphere, which might not only affect biomass production but also might threaten biodiversity as well as the livelihood of people (Dimobe et al., 2018; Hartley et al., 2016; Dayamba et al., 2016).

Hence, to better understand impacts of climate and land-use change on biosphere-atmosphere interactions across West Africa, it is important to improve our understanding of ecosystem C cycling and C exchange with the atmosphere by using current knowledge to set up ecosystem models and to test if these models are able to a) realistically represent the sensitive responses of semi-arid ecosystems to climatic variation as well as land-use management, and b) accurately represent C exchange processes as well as c) the distribution of above- and belowground C pools.
Several modelling approaches have been used to describe savanna ecosystem processes and semi-arid cropland development during the past decades, which concentrated on land-use management (Boone et al., 2004) or population dynamics (Tews et al., 2006; Tews and Jeltsch, 2004). If physiological processes were covered, they were treated in very coarse resolution (Scheiter and Higgins, 2009) or for herbaceous species only (Delon et al., 2019; Grote et al., 2009b). Only few terrestrial modelling approaches have been evaluated against field observations in order to assess their ability to simulate ecosystem C dynamics and the biosphere-atmosphere exchange of savanna-type ecosystems (e.g. Whitley et al., 2016; Whitley et al., 2017). It has been particularly highlighted that for these semi-arid systems with strong seasonal variations in plant water availability, it is crucial to represent the plant phenological development, which is something that most models fail to achieve (Pitman, 2003). Indeed, the phenology of deciduous plants including most crops is usually related to temperature development, which is generally the limiting factor in temperate ecosystems (Vitasse et al., 2011; Wesolowski and Rowinski, 2006). For tropical (and sometimes also boreal) regions which are assumed to be evergreen, phenology is often forced or neglected at all (Mougin et al., 1995; Saleska et al., 2003). In savannas, however, the growth of new tissues in grass and trees is often related to the onset of the rainy season, indicating that water availability is a crucial determinant (Kucharik et al., 2006). Models that account for this influence are still rare. However, in only a few models, water supply has been included as a direct impact on budburst that defines the start of growth for grasses in semi-arid regions (Akponikpè et al., 2010; Ivanov et al., 2008; Loustau et al., 1992). Also, Yuan et al. (2007) use simulated soil moisture values as a driver to modify the phenological development of the grass layer of a semi-arid steppe, while Jolly and Running (2004) defined the onset of budburst for a grass-dominated Kalahari ecosystem as the date at which daily precipitation exceeded potential evaporation, and the start of leaf senescence once soil moisture falls below a defined threshold. Nevertheless, while important for grasses, most trees don’t seem to be bound to a minimum water content of the upper soil layers for leaf flushing, possibly because they have access to deeper water reserves (Do et al., 2005).

Thus, the simulation of C balances in semi-arid tropical systems as can be found in West Africa requires a close and consistent link between rainfall, soil, and vegetation processes (Boke-Olén et al., 2016). Moreover, as many of the ecosystem types being found in this region are composed of a tree/shrub layer and a layer of ground vegetation (mainly grasses, sometimes also crops), models should be able to distinguish between different vegetation types and their competition on light and other resources. In addition, it needs to be considered that many of the savanna ecosystems are used by pastoralists or mixed crop-livestock farmers for grazing and cropping (Ker, 1995). Thus, also these management options should be represented in a model.

In this study we parameterized, complemented, and evaluated LandscapeDNDC (Haas et al., 2013), a model framework that uses the soil C-, nitrogen- (N-), and water processes derived from the original DNDC
DeNitrification-DeComposition) models (Li et al., 1992; Kraus et al., 2015). The framework can be flexibly combined with cohort-based ecosystem models (Grote et al., 2011b) as well as crop growth models (Kraus et al., 2016b). The model framework and its predecessors have so far been used and applied to various natural and managed temperate and tropical ecosystems such as forests, grasslands, or rice paddies (Kraus et al., 2016b), including savanna grasslands (Grote et al., 2009b). However, so far it was never tested for its suitability to simulate C fluxes over a wide range of different managed and natural savanna ecosystems including different vegetation types.

For this analysis, a literature review has been carried out first to find suitable parameters for the physiological processes of typical grass and tree species in Sahelian and Sudanian savanna ecosystems. Also, thresholds of soil water availability to leaf development and senescence, which have been derived from twelve sites with ample data available for several years, were introduced. Finally, the model was evaluated against data from other sites representative for the region, including eddy flux measurements, satellite data, and in situ biomass measurements for both managed and natural ecosystems.

The objective of this paper is to test the ability of the LandscapeDNDC model in its current form to simulate C fluxes and stocks for various, representative savanna ecosystem types with varying human management activities within the Sahelian and Sudanian regions.

2 Material and methods

2.1 Study area

West African semi-arid drylands are located between 15°E-16°W and 07°N-19°N (between the Sahara and the Guinean zone), and spread over 11 countries (Benin, Burkina Faso, Côte d’Ivoire, Gambia, Ghana, Guinea, Mali, Niger, Nigeria, Senegal, and Togo; Fig. 1). Following a transect of decreasing precipitation from South to North there is a gradual transition from forest, woodland, savanna woodland, savanna grassland, to semi-desert grassland (Kaptue Tchuente et al., 2010). Along this gradient, the degree of ground coverage and the proportion of woody species (trees, shrubs, and bushes) decreases and the vegetation becomes shorter. This region is classified into two distinct ecological zones, “Sahelian” and “Sudanian”, which differ mainly in terms of precipitation amount and dry season length. In the Sahelian ecological zone which extends over 1.3 million km², the average annual temperatures vary between 25 and 31 °C and the annual precipitation is between 150 and 600 mm. The length of dry season lasts for seven to nine months annually and the monthly precipitation maximum is in August. The Sudanian zone of approximately 1.7 million km² extension is cooler (22–29 °C), wetter (600-1200 mm yr⁻¹) and
the dry season length is around four to seven months with monthly maximum precipitation also occurring around August (NASA Power climate dataset, https://power.larc.nasa.gov/).

Figure 1: Map of West Africa showing the Sudanian and Sahelian vegetation zones that were derived after (Buchhorn et al., 2020). Locations of measurements are indicated as towers (eddy covariance flux stations) or red dots (biomass production).

2.2 Datasets for simulation and evaluation

2.2.1 Initialization, climate, and deposition

As model input data, initial soil and vegetation properties as well as daily climate data are required. Land management need to be prescribed as boundary conditions. The soil parameters were bulk density (kg m\(^{-3}\)), pH, soil texture (i.e. clay, silt, and sand content), organic C and N content (kg kg\(^{-1}\)), and soil hydrological parameters (i.e. field capacity, wilting point (mm m\(^{-3}\))). These were gathered from available literature sources for each site and complemented by information from the Principal Investigators (PI) of these sites. In a few cases, soil
information was complemented with data from ISRIC-WISE (International Soil Reference and Information Centre-World Inventory of Soil Emission Potentials) soil dataset (Batjes, 2009). Similarly, vegetation was initialized with data of amount of grass biomass, tree sizes (average height and breast height diameter), and number of trees ha\(^{-1}\) as recorded at the sites.

Input climate data were maximum and minimum temperature (°C), precipitation (mm), relative humidity (%), solar radiation (W m\(^{-2}\)), and wind speed (m s\(^{-1}\)). These data were either obtained directly from measurements at the sites, or from the NASA-Power climate dataset. Except for Kelma, all sites were assumed to have no ground water access down to their maximum rooting depth of 1 m. For the Kelma site, a flooding period was prescribed for the years 2005 to 2007, according to published water content data (Timouk et al., 2009; de Rosnay et al., 2009). Management was also prescribed for both agricultural sites and savanna grasslands that were occasionally grazed with cattle. Fire impacts were not considered.

In addition to climate, daily input of dry and wet deposition of oxidized and reduced N compounds (nitrate, ammonia, nitric acid, and nitrogen oxide) were provided for the model runs. These were derived from the field measurements within the IDAF (IGAC (International Global Atmospheric Chemistry)/DEBITS (Deposition of Biogeochemically Important Trace Species)/AFRICA) project, in which also some of our investigation sites were included (Agofou, Banizoumbou, Djougou, and Katibougou). According to this dataset, the total wet deposition of N was estimated to be around 3.2 kg and dry deposition around 3.6 kg N ha\(^{-1}\) yr\(^{-1}\) with only little variation between Sahelian and Sudanian ecosystems (Galy-Lacaux et al., 2014).

### 2.2.2 Carbon flux and soil moisture measurements

We collected net ecosystem C exchange (NEE) measurements from 12 flux-tower sites, hereinafter called the core sites, in the Sudanian and Sahelian ecological zones. These data were used for calibrating the new phenological routine of the LandscapeDNDC model and to evaluate simulations for crop-dominated, tree-dominated grassland/woodland, and grass-dominated ecosystems. These eddy covariance measurements were carried out within the CarboAfrica (www.carboafrica.eu), AMMA-CATCH observatory (http://www.amma-catch.org), and AMMA (www.amma-international.org) projects or by the WASCAL research center (wascal.org).

The spatial distribution and characteristic of the core sites show that they are well distributed across the major natural and agricultural areas in the Sudanian and Sahelian ecological zones covering grassland savannas (from sparse grasslands to shrublands), woodlands (including seasonally flooded, open, and dense forests), and cultivated land types (major crops: maize (Zea mays), millet (Pennisetum glaucum), sorghum (Sorghum bicolor), peanut (Arachis hypogaea), and cassava (Manihot esculenta) (Fig. 1; Table 1). Five sites are located in the Sahelian...
ecological zone (Dahra-Senegal; Kelma-Mali; Agoufou-Mali; Wankama-1&2-Niger), and seven in the Sudanian ecological zone (Sumbrungu-Ghana; Bontioli-Burkina Faso; Kayoro-Ghana; Nalohou-Benin; Nazinga-Burkina Faso; Niakhar-Senegal; Bellefoungou-Benin). For more information, see Table 1 and the references therein.

In addition, soil moisture data measured close to the flux towers was used for evaluation of simulations. These measurements took place mostly within the first 30 cm (CS616 soil moisture probes by Campbell Scientific Inc., USA), although at the AMMA sites also deeper soil horizons were considered. In few cases, only moisture of the uppermost layers were recorded for comparison with estimates from satellite observations. In order to be consistent across sites, we thus use values recorded for the first 10cm, which are also those with the most complete records.

2.2.3 Above-ground biomass- and leaf area measurements

Above-ground herbaceous biomass and crop yield were available from sampled measurements for all core sites except for two of the Sudanian cultivated sites (Kayoro and Nalohou). For the Kayoro site, biomass was assumed to equal that at the Vea site in Ghana, and for the Nalohou site, maize data were taken from the Dassari site in Benin and the Wa site in Ghana, sorghum from the Samanko site in Mali, and cassava from the Ikenne site in Niger, because these sites have a similar climate.

In addition, 42 sites representing crop- (11), grassland savanna- (27), and grassland ecosystems with significant tree contributions (4) from which biomass data are available were used for validating the revised model (Fig. 1). These sites are located in Senegal, Benin, Mali, Ghana, Niger, and Burkina Faso covering overall 70 years of observations within the period 1984-2018 (not continuous for all sites). 24 sites in Senegal (20 grassland, four savanna woodlands) that were monitored between 1999 and 2017, were provided by the Centre de Suivi Ecologique (CSE) (Diouf et al., 2015). Data from four sites with contributions of trees as well as grasses (Egeruit, Hombori Hondo, Tara, and Timbadior) and one millet site (Bilantao) were obtained from the Gourma region in Mali representing a precipitation gradient from 300 to 450 mm yr\(^{-1}\). These field measurements cover the period between 2005-2016, and were gathered within the African Monsoon Multidisciplinary Analysis (AMMA) (Mougin et al., 2019; Mougin et al., 2009). Three more fallow and grassland sites are located in the Fakara region in Western Niger (Banizoumbou, Tigo Tégui, and Kodey). Measurements here began in 1994 taken by the International Livestock Research Institute (ILRI) (Hiernaux and Ayantunde, 2004) and continued until 1999 under the responsibility of the AMMA-CATCH observatory (Cappelaere et al., 2009). Furthermore, we gathered biomass production and yield data covering all major crops of the core sites from three sources. The first dataset containing data for maize, millet, and sorghum for 2004, 2005, 2010, 2015, and 2016 (with different fertilization treatments and different crop sowing windows) consists of 1 site in Benin (Dassari), 2 sites in Ghana (Vea and Wa), as well
as sites in Mali (Samanko) and Niger (Sadore) (Faye et al., 2018). The second dataset was obtained in Upper Ouémé Catchment in the Republic of Benin (for 2001, 2002, and 2003) providing information on total above-ground biomass in three sites (Dogue, Beterou, and Wewe) for peanut, maize, and sorghum production with different managements (e.g. different fertilization types/amounts) (Dagbenonbakin, 2005). The third dataset used for validating LandscapeDNDC was from cassava fields from the sites Ikenne and Oke-Oyi in Nigeria (Sobamowo, 2016).

Leaf Area Index (the half-sided leaf area per unit ground area, LAI) data for comparison with measurements were taken at 4-day temporal and 500 m spatial resolution from the MODe-rate resolution Imaging Spectroradiometer (MODIS) satellite data (MCD15A3H, https://doi.org/10.5067/modis/mcd15a3h.006, downloaded from the Land Processes Distributed Active Archive Center gateway LP DAAC, https://lpdaac.usgs.gov/). Only pixels were used where the core sites are located. MODIS data have been investigated before to be most suitable to represent the seasonality of the vegetation dynamics (Gessner et al., 2013; Mougin et al., 2019). We additionally checked with any data managers of the field site could provide and could generally support this view (Fig. 2). However, MODIS data are somewhat higher than site measurements when LAI is small while lower when LAI is large. Reasons for this include particularly large fractions of missing data during high-LAI episodes (Gessner et al., 2013), the size of the pixels that often include tree contribution at sites treated as agriculture or grasslands here (Kahiu and Hanan, 2018), as well as specific reasons that addressed in the discussion of the results at the specific sites.
Figure 2. Comparison between field LAI measurements and MODIS (MCD15A3H) LAI estimation at different EC sites
Table 1: Characteristics of eddy covariance sites used in this study (MAT: Mean annual temperature, MAP: Mean annual precipitation, Zones according to Fig. 1).

| Site Name   | Country | Lat, Long     | Zone*            | Ecosystem                                      | Model category         | MAT (°C) | MAP (mm) | Soil Type | Overall water content at field capacity (mm m⁻³) | Overall water content at wilting point (mm m⁻³) | Period of flux tower measurements | Reference for description                     |
|------------|---------|---------------|------------------|------------------------------------------------|------------------------|----------|----------|-----------|------------------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
| Agoufou    | Mali    | 15.34°N, 01.48°W | Sahelian, grass dominated | Open grassland with sparse shrubs | grass, grazed           | 30.2     | 374      | Sand      | 178.9                                           | 42.8                                 | 2007-2008                          | Merbold et al. (2009), Mougin et al. (2009) |
| Dahra      | Senegal | 15.40°N, 15.43°W | Sahelian, grass dominated | Grassland/Shrubland | grass, grazed          | 28.0     | 404      | Sand      | 191.2                                           | 44.6                                 | 2015-2017                          | Tagesson et al. (2015) |
| Kelma      | Mali    | 15.22°N, 01.57°W | Sahelian, grass dominated | Seasonally flooded open woodland | trees and grass        | 29.6     | 380      | Clay-Loam | 295.4                                           | 98.7                                 | 2007-2008                          | Merbold et al. (2009), Mougin et al. (2009) |
| Wankama-1  | Niger   | 13.65°N, 02.63°E | Sahelian, grass dominated | Fallow land with bushes | grass                  | 29.5     | 510      | Sand      | 178.9                                           | 42.8                                 | 2005-2012                          | Velluet (2014)                     |
| Wankama-2  | Niger   | 13.64°N, 02.63°E | Sahelian, cultivated | Cultivated land | agriculture (millet)  | 29.5     | 510      | Sand      | 178.9                                           | 42.8                                 | 2005-2012                          | Velluet (2014)                     |
| Bellefoungou | Benin | 9.79°N, 01.72°E | Sudanian, tree/shrub dominated | Protected woodland | trees and grass        | 27.0     | 1624     | Loamy-Sand | 292.4                                           | 96.5                                 | 2008-2015                          | Ago (2016)                         |
| Bontioli   | Burkina Faso | 10.88°N, 03.07°W | Sudanian, tree/shrub dominated | Grassland/Shrubland | grass                  | 24.9     | 926      | Sandy-Loam | 367.4                                           | 178.8                                 | 2004-2006                          | Brümmer et al. (2008)               |
| Kayoro     | Ghana   | 10.92°N, 01.32°W | Sudanian, cultivated | Cultivated land | agriculture (sorghum, peanut, millet) | 28.0 | 994     | Loamy-Sand | 149.4                                           | 54.1                                 | 2013-2016                          | Quansah et al. (2015), Bliefernicht et al. (2018) |
| Nalouhou   | Benin   | 9.74°N, 01.61°E | Sudanian, cultivated | Cultivated savanna | agriculture (maize, sorghum, peanut, cassava) | 27.0 | 1190    | Loamy-Sand | 292.4                                           | 96.5                                 | 2007-2009                          | Ago et al. (2014)                  |
| Nazinga    | Burkina Faso | 11.15°N, 01.58°W | Sudanian, tree/shrub dominated | Pristine woody savanna | trees and grass        | 27.1     | 961      | Sandy-Loam | 221.8                                           | 90.0                                 | 2013-2016                          | Quansah et al. (2015), Bliefernicht et al. (2018) |
| Niakhar    | Senegal | 14.50°N, 16.45°W | Sudanian, cultivated | Cultivated land | agriculture (peanut, millet) | 26.9     | 578      | Sand      | 225.0                                           | 20.0                                 | 2018-2019                          | Roupsard et al. (2020)             |
| Sumbrungu  | Ghana   | 10.85°N, 00.92°W | Sudanian, grass dominated | Savanna grassland | grass, grazed          | 28.3     | 978      | Loamy-Sand | 157.7                                           | 66.5                                 | 2013-2016                          | Quansah et al. (2015), Bliefernicht et al. (2018) |
2.3 The LandscapeDNDC model

2.3.1 Description and parameterization

LandscapeDNDC is a framework for one-dimensional biogeochemical models, which mainly simulate C, water, and N cycling between the atmosphere, vegetation, and soil at daily to sub-daily temporal resolution for various ecosystems, i.e., arable, grassland, and forest (Haas et al., 2013). We used version 1.30.4 (ref. 9953) of this model (https://ldndc.imk-ifu.kit.edu/) including the sub-models MeTr4 for soil biogeochemistry and soil respiration (Kraus et al., 2015), ECM for microclimate (Grote et al., 2009a), and the original DNDC routines to describe the water cycle (Li et al., 1992; Kiese et al., 2011). For grasslands and grass/woodlands the physiological simulation module PSIM (Grote et al., 2011a; Werner et al., 2012) is used, which has been widely applied for forests including sites where ground vegetation needed to be considered (Lindauer et al., 2014; Dirnböck et al., 2020), and also on savanna grasslands (Grote et al., 2009b). However, the model doesn’t consider the production of fruits or similar. Therefore, we applied the PlaMox module (Kraus et al., 2016a; Liebermann et al., 2020) for the agricultural plants, which has been developed particularly to described crop growth based on the same physiological processes as PSIM.

While parameters for agricultural crops were mostly species-specifically defined in the model already, information about physiological properties of savanna grass- and tree- species were newly collected from literature. Some properties were assumed ubiquitous for savanna trees and grasses, but we also recognized some species-specific differences between the Sudanian and Sahelian ecosystems. Therefore, we selected Acacia (in particular A. tortilis also known as Vachellia tortilis) as dominant tree genus and Cenchrus biflorus as dominant grass species for the Sahelian zone. For the Sudanian ecoregion we chose Burkea africana as dominant tree species and Andropogoneae (in particular Andropogon gayanus) as dominant grass type (Bocksberger et al., 2016; Geerling, 1985; Sotelo Montes et al., 2014). The parameters describing the specific physiological properties of each species are given in Table 2 for natural and Table 3 for agricultural species.

Both vegetation models (PSIM and PlaMox) were using the Farquhar approach (with the extension for C4 photosynthesis by Collatz) (Farquhar et al., 1980; Collatz et al., 1992), which requires several parameters related to enzyme activities (also see Table 2 and 3). Respiration was differentiated into growth respiration and maintenance respiration. Growth respiration was estimated as a fixed fraction of net photosynthesis (25 %). Maintenance respiration was calculated using a linear relationship to N content, but modified by temperature and the relative depletion of C reserves as done by Thornley and Cannell (2000). Carbon was allocated into the different...
plant tissues according to Grote (1998), with leaf expansion determined by growing degree sum (see below) and C supplied from previous-year storages. Evapotranspiration was driven by potential evapotranspiration, calculated with a modified Thornthwaite approach (Camargo et al., 1999; Pereira and Pruitt, 2004; Thornthwaite, 1948) that depends on temperature and daylength and drives transpiration demand except in periods of wet surfaces. Actual transpiration, however, is constrained by soil water availability down to rooting depth (weighted by root mass density) as well as transpiration requirements for photosynthesis (calculated using a water use efficiency coefficient (WUEC, see Table 2 and 3)). WUEC is considered to increase with decreasing the relative available soil water content (RWC) for grasses and trees but is constant for crops. Without soil-water restrictions, photosynthesis and stomatal conductance were iteratively calculated based on the Ball-Berry approach (Ball et al., 1987) using a scaling parameter (GSA) and the species-specific maximum conductance as parameters (minimum conductance is generally set to 10 mmol H\textsubscript{2}O m\textsuperscript{-2} s\textsuperscript{-1}). If relative soil water availability is lower than a threshold value, either the stomatal conductance (PSIM) or the photosynthesis itself (PlaMo\textsuperscript{x}) was linearly reduced (Leuning, 1995; Knauer et al., 2015). The threshold is defined as the species-specific parameter H2OREF\textsubscript{GS} or H2OREF\textsubscript{A} respectively (Table 2 and 3). Interception was calculated from LAI, which is the product of specific leaf area and foliage biomass, and specific interception capacity following Gash et al. (1995). For soil water availability, we assumed a rooting soil depth of 1 m for all sites, with no difference between trees and grasses (according to the ISRIC soil data base available at https://www.isric.org/explore/wise-databases). Fine root abundance was exponentially decreasing with depth, with roots of grasses slightly more concentrated at the upper soil layers than tree roots (February and Higgins, 2010). Leaf flushing was assumed to begin when a threshold of cumulative daily temperature sum (growing degree days) had been reached and prolongs throughout a defined period of days. The newly grown foliage was assumed to be fully shed after a period defined by the leaf longevity, and also the shedding needed a defined period of days (Grote, 2007). In order to account for the close relationship between leaf flushing of savanna grasslands and rainfall events, we included a constraint that foliage starts to grow only if RWC was above a threshold value. Similarly, we also included a restriction so that drought-related senescence can only occur after foliage had been at least 90 \% developed. All phenological parameters have been defined as the best fit to all Sahelian and Sudanian core sites for natural as well as agricultural systems, respectively (Table 4 and 5).

2.3.2 Model setup and initialization

All simulations used a three-year spin-up to account for an uncertain initialization of carbon- and nitrogen pools that are adjusting to general environmental conditions during this time. At agricultural sites identical planting schemes are deployed with tilling always occurring before the planting date, meaning that all straw and grasses
that remained on the field were transferred to the soil and incorporated into the soil C and N pools. No additional irrigation or fertilization was reported at any site and thus are also not simulated. Grasslands are initialized with a total biomass of 1000 kg ha$^{-1}$ at the beginning of the simulations at all sites and adjusted during spin-up years to a value that accounts for the competition on light and water at the sites.

Agricultural sites:
For Kayoro, peanut was planted first each year (June-July), followed by pearl millet or sorghum that were harvested in October. At the Niakhar site, pearl millet was sown on May 15$^{th}$ 2018 (sowing density = 0.8 m$^{-2}$) and harvested on October 12$^{th}$. In 2019, peanut was planted July 05$^{th}$ (sowing density = 8.33 m$^{-2}$) and harvested at end of November. Wankama-2 had been under continuous millet cultivation generally being planted after the start of the wet season (around 10th of July) (sowing density of around 10,000 pockets per hectare) and harvested when precipitation had ceased (mid-October). At Nalohou, landscape was more heterogeneous and eddy flux measurements were influenced by both mixed crops and fallow bush. All crops at this site were planted/grown during the wet season (between April and September-Oct). The results were post-processed according to the footprint analysis (which indicates the contribution of each vegetation type to the measured flux for wet and dry season), percentage of area planted by each crop, and cropping pattern provided by Ago et al. (2014).

Savanna sites:
Grasslands were supposed to be fully covered with either the Sudanian or Sahelian grass type while mixed grass/woodlands were simulated by considering grass and tree species as different cohorts within the same simulation run (Grote et al., 2011b). Therefore, competition effects between the plant groups depended on the abundance of trees which was characterized by a ground coverage of 80 % in Bellefoungou, 72 % in Nazinga (Sudanian), and 25 % in Kelma (Sahel). This has been initialized by first defining the dimension (height and diameter at 1.3m) of the average tree at the specific site, and calculating the ground coverage according to allometric relations described in Grote et al. (2020) and parametrized with data from literature (Buba, 2013). These calculations do not assume a difference between species allometry. The total number of trees at the site was adjusted in order to reach the measured total coverage.
Table 2: Plant parameters affecting the C and water exchange in the PSIM vegetation model used for simulating biomass growth of natural savanna ecosystem types.

| Variable name | Description | Savanna trees | Savanna grasses (C4) |
|---------------|-------------|---------------|---------------------|
|               |             | Sahelian (A.tortilis) | Sudanian (B.africana) |
|               |             | Sahelian (C.biflorus) | Sudanian (A.gayanus) |
| Parameters related to C gas exchange | | | |
| AEJM          | activation energy for electron transport rate (J mol⁻¹) | 79500¹ | 77900² |
| AEKC          | activation energy for Michaelis-Menten constant for CO₂ (J mol⁻¹) | 79430¹ | 64200³ |
| AEKO          | activation energy for Michaelis-Menten constant for O₂ (J mol⁻¹) | 36380¹ | 10500³ |
| AERD          | activation energy for dark respiration (J mol⁻¹) | 46390¹ | 50967⁴ |
| AEVC          | activation energy for Rubisco carboxylation (J mol⁻¹) | 65330¹ | 78000⁵ |
| AEVO          | activation energy for Rubisco oxygenation (J mol⁻¹) | 37530⁵ | 55300³ |
| HDJ           | deactivation energy (J mol⁻¹) | 201950¹ | 210000⁵³ |
| SDJ           | entropy term (kJ K⁻¹ mol⁻¹) | 650¹ | 645³ |
| KC25          | Michaelis-Menten constant for CO₂ at 25 °C (µmol mol⁻¹) | 275¹ | 650⁶ |
| KO25          | Michaelis-Menten constant for O₂ at 25 °C (µmol mol⁻¹) | 420¹ | 450⁶ |
| THETA         | convexity term for electron transport (-) | 0.9⁷ | 0.7⁶ |
| QJVC          | ratio between electron transport rate and carboxylation capacity (-) | 3.65⁸ | 2.27⁹ | 9.80⁸ | 6.60¹⁰ |
| QRD25         | ratio between dark respiration and carboxylation capacity (-) | 0.03¹¹ | 0.03¹¹ | 0.026¹² | 0.038¹³ |
| VCMAX25       | max. Rubisco activity at 25 °C | 49.6⁸ | 32.2⁹ | 40.7⁸ | 23.9¹³ |
| Parameters related to water balance | | | |
| GS MAX        | max. stomatal conductivity (mmolH₂O m⁻² s⁻¹) | 125¹⁴/¹⁶ | 230¹⁵ |
| GSA           | change rate of stomatal conductance with assimilation (mmolH₂O µmolCO₂⁻¹) | 9.5¹⁹ | 4.0¹⁹ |
| H2 OREF GS    | RWC below which stomatal conductance is decreased (-) | 0.3¹⁶ | 0.4¹⁶ |
| MWFM          | specific interception capacity of foliage (mm m⁻² LAI) | 0.05¹⁷ | 0.5¹⁸ | 0.35¹⁷ |
| SLA           | specific leaf area (m² kg⁻¹) | 10.8⁸ | 8.1²⁰ | 13.1²¹ | 10.6²² |
| WUEC          | min. and max. water use efficiency (mgCO₂ gH₂O⁻¹), linearly related to RWC | 1.6-5.3²³ | 1.0-5.0²⁴ |

¹Chen et al. (2008), ²Massad et al. (2007), ³Boyd et al. (2015), ⁴Collatz et al. (1992), ⁵Martin et al. (2000), ⁶Von Caemmerer (2000), ⁷Thornley (2002), ⁸Sibret (2018), ⁹Kgope and Musil (2004), ¹⁰Kim and Verma (1991), ¹¹Fürstenau Togashi et al. (2018), ¹²Sonawane et al. (2017), ¹³Feng and Dietze (2013), ¹⁴Ullmann (1989), ¹⁵Simioni et al. (2000), ¹⁶Baldocchi et al. (2004), ¹⁷de Jong and Jetten (2007), ¹⁸Running and Coughlan (1988), ¹⁹Baldocchi and Meyers (1998), ²⁰Guenther et al. (1996), ²¹Chandra and Dubey (2008), ²²Setterfield et al. (2018), ²³Kebbas et al. (2015), ²⁴Snyman (2005)
Table 3: Plant parameters affecting the C and water exchange in the PlaMo vegetation model used for simulating biomass growth and yield at the agricultural sites.

| Variable name | Description | C4 crops | C3 crops |
|---------------|-------------|----------|----------|
|               |             | Maize (Z. mays) | Sorghum (S. bicolor) | Millet (P. glaucum) | Peanut (A. hypogaea) | Cassava (M. Esculenta) |
| AEJM          | See table 2 | 77900  | 45000  |          |          |          |
| AEKC          | See table 2 | 59430  | 59356  |          |          |          |
| AEKO          | See table 2 | 36000  | 35948  |          |          |          |
| AERD          | See table 2 | 50967  | 66405  |          |          |          |
| AEVC          | See table 2 | 52000  | 36000  | 47000  | 58520  |          |
| AEVO          | See table 2 | 55300  |        | 37530  |          |          |
| HDJ           | See table 2 |        |        | 200000 |          |          |
| SDJ           | See table 2 | 630  |        | 646  |          |          |
| KC25          | See table 2 | 650  |        | 270  |          |          |
| KO25          | See table 2 | 450  |        | 165  |          |          |
| THETA         | See table 2 | 0.7  |        | 0.9  |          |          |
| QJVC          | See table 2 | 6.7  |        | 2.0  | 1.7  |          |
| QRD25         | See table 2 | 0.02  |        | 0.01  |          |          |
| VCMAX25       | See table 2 | 100  | 50  | 50  | 150  | 100  |
| Parameters related to C gas exchange |
| GMAX          | See table 2 | 350  | 340  | 210  | 650  | 200  |
| GSA           | See table 2 | 4  |        | 10.4  |        |        |
| H2OREF_A      | RWC below which photosynthesis is decreased (-) | 0.45  | 0.5  |        |        |        |
| MWFM          | See table 2 |        |        | 0.05  |        |        |
| WUEC          | water use efficiency (mgCO2 gH2O-1) | 7.2  | 5.0  | 6.0  | 3.0  | 9.0 |

Parameters related to water balance

1 Massad et al. (2007), 2 Groenendijk et al. (2011), 3 Yu et al. (2001), 4 Farquhar et al. (1980), 5 Collatz et al. (1992), 6 10.1093/treephys/tpab044, 7 Von Caemmerer (2000), 8 Bernacchi et al. (2002), 9 Boyd et al. (2015), 10 Martin et al. (2000), 11 Kattge and Knoor (2007), 12 Ainsworth and Rogers (2007), 13 Caldararu et al. (2017), 14 Vico and Porporato (2008), 15 Kothavala et al. (2005), 16 Pallas and Samish (1974), 17 de Souza Nóia Júnior et al. (2020), 18 Gleason et al. (2017), 19 Körner et al. (1979), 20 Da Matta et al. (2001), 21 Vu (2005), 22 Sellers et al. (1996), 23 Baldocchi and Xu (2005), 24 from FAO database (http://www.fao.org/3/x0490e/x0490e0e.htm#total%20available%20water%20(taw)), 25 Running and Coughlan (1988), 26 Holá et al. (2010), 27 Ünlü and Steduto (2000), 28 Vitkauskaitė and Venskaitytė (2011), 29 Kalariya et al. (2015), 30 Yao and Goué (1992)

*Since there is a certain variability for this parameter (H2OREF_A) with respect to species and sites, we conducted an additional analysis to assess how sensitive biomass production of each crop species responds to this parameter. To do this, we varied H2OREF_A between 0.30 to 0.70 at each site and for each species. Results indicated that when applying the upper limit of 0.7, productivity are lower than the standard value for C3 (0.5) and C4 (0.45) crops by 6.4% for peanut, 3.9% for millet, 1.9% for cassava, 0.78% for sorghum, and 0.11% for maize. On the other hand, applying the lower limit of 0.3 increased productivity relative to the standard value by 3.8% for peanut, 1.5% for millet, 1.1% for cassava, 0.07% for sorghum, and 0.05% for maize. Thus, the overall sensitivity of biomass production to the RWC threshold value of photosynthesis decline was judged to be low.
Table 4: Plant parameters related to new phenological processes used in the PSIM model for describing dynamics in natural savanna ecosystem types, derived from measurements at the core-sites of the investigation.

| Variable   | Description                                                                 | Savanna trees | Savanna grasses |
|------------|------------------------------------------------------------------------------|---------------|-----------------|
| DLEAFSHED  | leaf longevity (period from leaf flush to total leaf loss) (days)            | 380           | 380             |
| GDD<sub>emerg</sub> | threshold of cumulative temperature sum (°C)                               | 2000          | 1000            |
| H2OREF_FLUSH | min. RWC required to start flushing                                         | 0             | 0               |
| H2OREF_SENES | RWC at which senescence is induced                                           | 0             | 0               |
| MFOLOPT    | Optimum amount of foliage biomass from reserves or seeds (kg m<sup>-2</sup>) | 1.5           | 1.2             |
| NDFlush    | period of leaf expansion (days)                                             | 150           | 150             |
| NDMORTA    | period of leaf senescence (days)                                            | 160           | 180             |

1(Mougin et al., 2019; Timouk et al., 2009; Sjöström et al., 2013), 2(Quansah et al., 2015; Ago et al., 2016), 3(Delon et al., 2015; Hiernaux et al., 2009; Timouk et al., 2009; Baup et al., 2007; Tagesson et al., 2016; Boke-Olén et al., 2016; Velluet, 2014), 4(Quansah et al., 2015; Berger et al., 2019)

Table 5: Plant parameters that describe phenology and ontology/yield in the PlaMo<sup>x</sup> vegetation model for agricultural simulations (taken from the WOFOST model v.6.1 http://github.com/ajwdewit/WOFOST_crop_parameters).

| Variable name | Description                                                                 | C4 crops       | C3 crops       |
|---------------|------------------------------------------------------------------------------|----------------|----------------|
|               |                                                                               | Maize (Z. mays) | Sorghum (S. bicolor) | Millet (P. glaucum) | Peanut (A. hypogaea) | Cassava (M. Esculenta) |
| SLA           | See table 2                                                                  | 9              | 35             | 20              | 25              | 25               |
| GDD<sub>emerg</sub> | See table 3                                                                  | 110            | 70             | 60              | 120             | 10               |
| GDD<sub>flow</sub> | GDD for flowering                                                           | 860            | 670            | 1000            | 720             | 60               |
| GDD<sub>grain</sub> | GDD for grain filling                                                        | 780            | 820            | 1100            | 836             | 70               |
| GDD<sub>matur</sub> | GDD for maturity                                                             | 1560           | 1400           | 1800            | 1672            | 360              |
| GDD<sub>base</sub> | Base temperature for GDD calculation                                         | 10             | 11             | 10              | 10              | 0                |

2.4 Statistical analysis

To identify the relationship between the simulated and measured NEE and LAI, Pearson's correlation coefficient (r) analysis was performed. The correlation coefficient measures the strength of the linear relationship between
two variables (here between the simulated and measured NEE and LAI during the crop growing period for the agricultural sites and the entire year for savanna grasslands and savanna mixed tree-grassland sites).

3 Results and discussion

3.1 Agricultural sites

Fig. 3. shows measurements and simulation results for NEE and LAI of the four core sites that are used for agriculture (Kayoro, Niakhar, Nalohou, and Wankama-2). It should be noted that LAI simulations are only shown during the crop-growing period and are otherwise assumed as zero.

For Kayoro in northern Ghana, the predominant cropping pattern between 2013 and 2016 is peanut in rotation with pearl millet (2013, 2015) or peanut in rotation with sorghum (2014, 2016). Simulated seasonal dynamics and magnitudes of NEE and LAI are well in accordance with measurements (r = 0.79 and 0.76, respectively, Fig. 3). However, in 2013 the model overestimated LAI and therefore also C uptake during the crop-growing period (-55.5 kg C ha\(^{-1}\) d\(^{-1}\) as estimated from measurements whereas -72.1 kg C ha\(^{-1}\) d\(^{-1}\) was simulated). A possible reason is the occurrence of weeds that may have prevented peanut and millet to grow to their full potential, or that the fetch of the eddy covariance tower extended beyond the investigation area were less productive plants or bare land result in a reduction of the average data from measurements (Quansah et al., 2015).

At Niakhar, a representative site for the so-called “groundnut basin” of Senegal, either pearl millet (2018) or peanut (2019) was grown in an annual rotation. LAI for millet and peanut was underestimated by the model, both by approximately 30%. This is likely due to trees in the region (Roupsard et al., 2020) that are considered in the observations but not simulated. Nevertheless, the deviations between measured and modelled NEE were relatively small (r = 0.80). A possible uncertainty at this site is the presence of *Faidherbia albida* trees (6.8 trees ha\(^{-1}\)) that typically show a different phenology which explains a negative NEE (C uptake) during the dry season which was not considered by the simulations.

At Nalohou, located in the Ara watershed in the northern part of Benin, four crops were planted sequentially and periodically and several crops even grew simultaneously, explaining a rather irregular shape of NEE and LAI (including a continuous coverage throughout the dry season in 2009). Nevertheless, simulations of both terms generally agree with measurements showing average correlation coefficients of 0.74 and 0.86, respectively. Uncertainties are related to the vegetation distribution. For example, a footprint analysis presented by Ago et al. (2014) showed that crops contribute only about 77% of the C exchange fluxes while the rest is attributed to natural savanna. Variation between years also occur due to different climate conditions such as the precipitation that was
about 25% higher in 2009 than in 2008. The relatively high precipitation, which was above long-term average in both years, may partly explain the insensitivity of NEE to the underestimation of water storage in the simulations. This underestimation mainly originates from a field capacity that has been initialized with a relatively small value based on site measurements and thus doesn’t allow for the high moisture values that have actually been observed. It is obvious that the mismatch is caused by the small-scale heterogeneity of upper soil conditions at this site. Overall, the long vegetation period of Nalohou caused it to become a substantial C sink of 2814 kg C ha\(^{-1}\) yr\(^{-1}\).

For Wankama-2, located in the Southwest of the Republic of Niger, annual rotations with pearl millet remained unchanged throughout the 7-year study period (2005-2012). Simulations correlated highly with NEE and LAI with coefficients of 0.84 and 0.82, respectively. Also, simulated patterns of biomass development were matching observations closely. The simulated C sink was on average 810 kg C ha\(^{-1}\) yr\(^{-1}\), whereas estimates based on measurements were 720 kg C ha\(^{-1}\) yr\(^{-1}\). However, the simulations indicate a larger variability of yields than indicated by measurements, leading for example to smaller than average yields during 2009-10 (0.12 kg m\(^{-2}\) compared to the average of 0.21 kg m\(^{-2}\)). These years were somewhat dryer than average (320 mm of annual precipitation in 2009-10 while the normal amount is around 410 mm yr\(^{-1}\)), indicating that the model seems to be too sensitive to changes in soil water availability. Other uncertainties are potentially varying planting densities and the occurrence of weeds.

The results of the agricultural core sites were obtained by calibrating the parameters that determine the maximum biomass and yield values separately for all five crops using observations. Accordingly, the deviation between measured and simulated biomass/yield values across all sites has been minimized resulting in an overall correlation coefficient of 0.93 (Fig. 4A). Simulating biomass production for six further sites (17 years) across West Africa with the derived parameters and no further adjustment yielded an overall correlation coefficient of 0.82 (Fig. 4B), indicating that the model was well suitable to represent the development of the major crops throughout the investigated area.
Figure 3: (A-D): Time series of the observed and modelled NEE (kg ha\(^{-1}\), negative values represent a flux into the biosphere, positive values a flux towards the atmosphere), LAI (m\(^2\) m\(^{-2}\)), and soil water content (in 10 cm depth). In addition, precipitation and temperature at four different crop-dominated sites in Sahelian (D) and Sudanian (A-C) ecological zones are presented.
Figure 4: A) Observed and simulated annual biomass/yield production for crop-dominated sites involved in the calibration process over all 18 investigated years, and B) the same for 17 years at 6 additional validation sites.

3.2 Savanna grasslands

Fig. 5. shows the comparison of measured and simulated NEE and LAI for the five grass-dominant core sites used for calibration. They are differentiated according to their location in Sahelian (A-C: Agoufou, Dahra, and Wankama-1) and Sudanian regions (D-E: Sumbrungu, Bontioli).

The Agoufou site is located in the southern part of the Gourma region in Mali, which is a typical Sahelian grassland with 2-3 % tree cover (that was neglected in the simulation), at which occasional livestock grazing occurs. Correlation coefficients between the measured and modelled NEE and LAI over the period of 2007-2008 were 0.80 and 0.88, respectively. Nevertheless, the impact of drought on NEE in autumn 2007 was overestimated, probably because the simulated water content is lower than indicated by the measurements (Fig. 5A, third panel). We attribute this underestimation to a mismatch between the plot where initialization data were taken and the location of the measurements similar to what we observed at Nalohou, although in this case not only the field capacity but also the wilting point is underestimated. Some small deviations after a sudden LAI decrease in the middle of the first vegetation period can be seen (Fig. 5A, second panel). This was most likely caused by a dry spell in September that triggered wilting of herbaceous vegetation but not of the grasses taken as representative vegetation here. This indicates that on the one hand, care has to be taken by selecting representative vegetation for a larger region, and on the other hand that satellite data are only of limited use to compare with estimates for
specific sites. Below-ground respiration also seems to be overestimated after the end of this vegetation period, which might be caused by the model assuming litter decomposition of grass material that was fully or partly removed by management activities. Overall, measurements indicate that the Agoufou site acted as a C sink of 890 kg C ha\(^{-1}\) yr\(^{-1}\) while the net C sequestration according to simulations is 761 kg C ha\(^{-1}\) yr\(^{-1}\).

At the Dahra site, which is in the northern part of Senegal, the footprint of the eddy-covariance tower is also largely dominated by grass vegetation with occasional trees leading to a negligible tree coverage of 3% (Tagesson et al., 2015). There was a general good agreement with NEE data \((r = 0.67)\), even though the simulations did not capture the peak net C uptake rates during the wet periods. Phenology also started too late, particularly in 2016 (Fig. 5B). The underestimation could be related to this site being more productive than in general of this region because it is relatively high nutrient availability (Tagesson et al., 2016). Nevertheless, both measurements and simulations indicate that Dahra was a substantial C sink for all years (2015-2017).

The Wankama-1 site in the Southwest of the Republic of Niger is known as a fallow savanna (herbs and shrubs) where the land-use remained unchanged from 2005 to 2012. The relatively high abundance of shrubs (Boulain et al., 2009) that are evergreen but have shading impacts on the surrounding grass cover is not represented in the model and leads to an overestimation of grass LAI during the vegetation period and an underestimation during the rest of the year. Correlation coefficients between measured and simulated NEE and LAI were 0.77 and 0.78, respectively. However, in some years such as 2006 and 2012, the model assumed longer vegetation periods and thus higher NEE which might be caused by a mismatch between physiological properties of assumed and actual species or an unusually intensive grazing that has not been adequately considered in the simulations (Fig. 5C). The average simulated NEE for Wankama-1 was an uptake of 1894 kg C ha\(^{-1}\) yr\(^{-1}\) (the measured value indicates 1505 kg C ha\(^{-1}\) yr\(^{-1}\) but major data gaps prevent the calculation of a meaningful annual average).

Regarding the Sudanian ecozone, the first core site is Sumbrungu, located in Ghana’s Upper East Province. The overall correlation between NEE measurement and model simulations was high \((r = 0.89)\), even though simulations seemed to slightly overestimate the fluxes. According to the simulations, the maximum C uptake was in August and September at a rate of 29.3 kg C ha\(^{-1}\) d\(^{-1}\). The average C loss over the dry period varies considerably from 4320 kg C ha\(^{-1}\) (in 2013) to 1487 kg C ha\(^{-1}\) (in 2015), correlating strongly with the annual precipitation (679 mm of annual precipitation in 2013 while the normal precipitation amount is around 978 mm yr\(^{-1}\)).

The second Sudanian site is Bontioli in the Southwest of Burkina Faso. Here, NEE was in absolute values again overestimated by the model during the wet season. Nevertheless, simulations do capture the transition phase from dry and wet period (Fig. 5D) although the simulated vegetation period was about 2-3 weeks longer than indicated by the eddy-covariance measurements. However, there was a good correlation between measured and simulated LAI \((R = 0.95)\), possibly indicating that the efficiency of the plants in capturing C was underestimated. It might
be caused by higher N availability than indicated by the deposition regime, for example due to deposition of fertile ash from nearby fires (Bauters et al., 2018).
Figure 5 (A-C): Time series of the observed and modelled NEE (kg ha$^{-1}$, negative values represent a flux to the biosphere, positive values a flux to atmosphere), LAI (m$^2$ m$^{-2}$), and soil water content (in 10 cm depth). In addition, precipitation and temperature at different grass-dominated sites in Sahelian zone are presented.

Similar to the core crop sites, we used the parameters obtained for the core sites for the validation of the model’s ability to represent grassland savanna sites. In Fig. 6A the above-ground biomass production simulated by the LandscapeDNDC model is compared with field observations of 23 samples from the 5 core sites. It demonstrates that the simulated above-ground biomass production generally agreed with the observations for all studied sites in Sahelian as well as Sudanian ecological zones (correlation coefficient of 85 %). The validation exercise with additional 27 grass-dominated sites across Sahelian and Sudanian ecological is shown in Fig. 6B. It should be noted that some biomass yields in the validation sites are considerably larger than those found in any of the core sites.
Figure 6: Correlations between the observed and modeled biomass production at different grass-dominated sites in Sahelian and Sudanian ecological zone for the calibration (A) and validation data (B).

3.3 Savanna mixed tree-grassland sites

We furthermore investigated the NEE and LAI of three grassland sites with considerable but different tree contribution. Two of which are located in the Sudanian zone (Nazinga and Bellefoungou) and one in the Sahelian zone (Kelma). For the Nazinga site in southern Burkina Faso the model was able to simulate the fluctuations in NEE and LAI over time series well (correlation coefficient of 0.79 and 0.85, respectively). However, the model underestimates ecosystem respiration during the dry period (especially in 2013), while LAI values (for both trees and grasses) were well simulated (Fig. 7A). The high variability of measured fluxes showed C releases during wet periods, indicating that some uncertainty exists with respect to species properties and the measured footprint, possibly involving other species during specific periods (Bliefernicht et al., 2018).

The Kelma site, a facility located in the southern part of the Gourma region in Mali, is specific with respect to its water supply because it is a seasonally flooded open woodland. Patterns and magnitudes of NEE and LAI were generally well simulated by the model, although the onset of the vegetation period was estimated somewhat too early by the model (Fig. 7B). Furthermore, measurements indicated high levels of ecosystem respiration occurring at the end of the dry period in 2007, which could not be fully represented by the model. Such rewetting events are assumed to be related to increased decomposition and have been observed before (Epron et al., 2004; Grote et al., 2009b) but remain challenging for soil C models to capture (see Fraser et al. (2016)).
Figure 7 (A-C): Time series of the observed and modelled NEE (kg ha\(^{-1}\), negative values represent a flux to the biosphere, positive values a flux to atmosphere), LAI (m\(^2\) m\(^{-2}\)), and soil water content (in 10 cm depth). In addition, precipitation and temperature at different tree-dominated grassland/woodland sites in Sahelian (Kelma) and Sudanian (Nazinga, Bellefougou) ecological zones are presented.
In contrast, LAI at Bellefoungou in the Djougou district located in the northern part of Benin was overestimated during the peak of the wet season and underestimated during transition phases (Fig. 7C), resulting in a relatively small correlation coefficient between the simulated and measured NEE and LAI (0.63 and 0.52, respectively). Again, this may be related to a relatively high density of (tree) species or to a mismatch between the selected tree and grass species and the actual species composition (Ago, 2016; Mamadou, 2014). On-site observations show that the different species renew or keep their leaves along the dry season, indicating that trees have access to deep ground water reservoirs, which is not considered in our simulations. Therefore, simulations cannot represent the continuous abundance of LAI and carbon sequestration throughout the dry season (Fig. 7C). It should also be noted that MODIS estimates are not very reliable at this site during the wet seasons because of fog formation which impacts infrared and visible remote sensing measurements. Nevertheless, the simulated NEE indicated a similar cumulative annual NEE budget of about -5660 kg C ha\(^{-1}\) yr\(^{-1}\) as compared to measurements.

Since measured foliage or above-ground biomass data of trees are unavailable, we compare measured and simulated herbaceous biomass, as harvested at the peak of the vegetation period only (Fig. 8). For the five sites and across the two climate zones, simulations and measurements were highly correlated (correlation coefficients are 0.95 and 0.64 for the Sahelian and 0.98 and 0.90 for the Sudanian region, for calibration and validation, respectively).

![Figure 8: Correlations between the observed and modelled biomass production at different tree-dominated grassland/woodland sites in Sahelian and Sudanian ecological zone through calibration and validation process.](image)
4 Conclusions

Biogeochemical models can be used to determine terrestrial carbon pool developments and fluxes at temporal resolutions and regional scales that cannot be covered by field measurements. However, calibration and evaluation are needed for a range of representative sites in order to be reliable for assessing effects of environmental and anthropogenic (management) changes. Therefore, this study presented the - to date - most extensive calibration and evaluation exercise of a biogeochemical model for natural and agricultural ecosystems in the Sahelian and Sudanian ecological zones of West Africa. More specifically, the LandscapeDNDC model framework was applied to 54 (12 core sites plus 42 validation sites) intensive investigation sites where eddy-covariance and/or biomass measurements were available for more than one year. These sites covered the major natural vegetation types as well as the most important agricultural vegetation classes.

The results showed that the parameterized and complemented LandscapeDNDC model was able to represent C fluxes and pools for croplands, grasslands as well as tree/grass mixtures in various combinations independent of nutrient availability and climatic conditions. Deviations from measurements could mostly be explained by simplifications in species initialization, still having only a minor effect on overall carbon exchange and yield. Also, satellite observation (MODIS) had too coarse spatial resolution to fully capture various parallel dynamics within one observation pixel. While C-fluxes were mostly well represented by the model, soil C emission following re-wetting of dry soils was occasionally underrepresented, which is a common problem in biogeochemical models. Since the respective periods were relatively short and didn’t occur at all sites, the overall effect on the annual C balance was rather minor.

Since the model only considers one representative plant species per natural ecosystem type, it is not able to account for species-specific combinations or a shift in species abundance that might change ecosystem sensitivity over longer periods. It is, however, feasible to run scenarios of land cover and land-use changes that can happen rather quickly and investigate the impact on the regional carbon cycle considering an altered abundance of different ecosystems. Also, scenarios of environmental changes (e.g. changes in rainfall patterns, temperature, length of drought/rainy periods) that can develop in relatively short periods of time and thus are faster than ecological adaptation responses, can well be investigated. With the evaluation presented here, the model is rendered particular suitable as decision-support tool to explore climate-smart agricultural practices, as well as various management practices in natural and agricultural land-use systems in West Africa on biosphere-atmosphere exchange. Furthermore, since the model is particularly designed to simulate trace gas exchanges (i.e. because of its detailed consideration of soil processes), also greenhouse gas emissions from soils other than carbon releases can be simulated (e.g. N₂O and CH₄). Thus, it can be applied to assess further management effects such as different
fertilization practices on West African semi-arid ecosystems, and to estimate impacts on greenhouse gas emissions as well as on plant growth. However, it would be good if further evaluation with respect to such trace gas exchanges could be provided, particularly covering rewetting events.

570 **Code Availability**: The LandscapeDNDC model source code of released versions is permanently available online upon request at the KIT institutional webpage of the model https://ldndc.imk-ifu.kit.edu/download/download.php. The release version of this study is “win64 ldndc-1.30.4”.

575 **Data Availability.** EC data are available from the AMMA-CATCH database (bd.amma-catch.org), Fluxnet (http://fluxnet.ornl.gov), WASCAL Data Discovery Portal (Portalwascal-dataportal.org) and CarboAfrica (http://www.carboafrica.net/indexen.asp). The NASA POWER climate and the MCD15A3H version 6 MODIS Level 4 data are available from NASA’s Surface Meteorology and Solar Energy Web Portal (https://power.larc.nasa.gov/) and the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/), respectively. The model code of LandscapeDNDC has been published in the Radar4KIT database and is freely available under DOI: [10.35097/438](https://doi.org/10.35097/438), together with all setup and model initialization information (DOI: [10.35097/437](https://doi.org/10.35097/437)).

580 **Author contribution.** J.R., R.G, E.H, and K.B.B conceived and designed the study. J.R., R.G and D.K. pre-proceed the data, parameterized, and validated the model. E.E.A., A.A., S.B., J.B., B.C., A.A.D., U.F., P.H., H.T.T., O.R., A.K.S. provided all the flux and biomass measurement data for the analysis. J.R. and R.G wrote the first draft with all authors contributing to further revisions.

585 **Competing interests.** The authors declare that they have no conflict of interest.

590 **Acknowledgement.** The authors are thankful to the UPSCALERS project (AURG II-1-074-2016) which is part of the African Union Research Grants financed through the Agreement between the European Commission and the African Union Commission (DCI-PANAF/2015/307-078), to the EU-Aid funded project CASSECS, and to the AMMA-CATCH observatory (http://www.amma-catch.org/?lang=en) that all supplied basic data. Special funding was supplied by the Swedish National Space Agency (SNSA). Furthermore, part of the climate data was obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program. Finance support for open access publishing was granted from the Library of the Karlsruhe Institute of Technology.
Ago, E. E., Agbossou, E. K., Galle, S., Cohard, J.-M., Heinesch, B., and Aubinet, M.: Long term observations of carbon dioxide exchange over cultivated savanna under a Sudanian climate in Benin (West Africa), Agric. Forest Meteorol., 197, 13-25, 10.1016/j.agrformet.2014.06.005, 2014.

Ago, E. E.: Dynamique des flux de carbone entre l'atmosphère et des écosystèmes ouest-africains: cas des forêts et savanes sous climat soudanien au Bénin, Doctorat en Sciences Agronomiques et Ingénierie Biologique, Université de Liège, Gembloux, Belgique, 184 pp., 2016.

Ago, E. E., Agbossou, E. K., Cohard, J.-M., Galle, S., and Aubinet, M.: Response of CO$_2$ fluxes and productivity to water availability in two contrasting ecosystems in northern Benin (West Africa), Ann. For. Sci., 73, 483-500, 10.1007/s13595-016-0542-9, 2016.

Ahlström, A., Raupach, M. R., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J. G., Friedlingstein, P., Jain, A. K., Kato, E., Poulter, B., Sitch, S., Stocker, B. D., Viovy, N., Wang, Y. P., Wiltshire, A., Zaehle, S., and Zeng, N.: The dominant role of semi-arid ecosystems in the trend and variability of the land CO$_2$ sink, Science, 348, 895-899, 10.1126/science.aaa1668, 2015.

Ainsworth, E. A., and Rogers, A.: The response of photosynthesis and stomatal conductance to rising [CO$_2$]: mechanisms and environmental interactions, Plant Cell Environ., 30, 258-270, 10.1111/j.1365-3040.2007.01641.x, 2007.

Akponikpè, P. B. I., Gérard, B., Michels, K., and Bielders, C.: Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel, European Journal of Agronomy, 32, 144-154, 10.1016/j.eja.2009.09.005, 2010.

Baldocchi, D., and Meyers, T.: On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: a perspective, Agric. Forest Meteorol., 90, 1-25, 10.1016/S0168-1923(97)00072-5, 1998.

Baldocchi, D., and Xu, L.: Carbon exchange of deciduous broadleaved forests in temperate and Mediterranean regions, in: The Carbon Balance of Forest Biomes, edited by: Griffiths, H., and Jarvis, P. J., Garland Science/BIOS Scientific Publishers, 187-213, 2005.

Baldocchi, D. D., Xu, L., and Kiang, N.: How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland, Agric. Forest Meteorol., 123, 13-39, 10.1016/j.agrformet.2003.11.006, 2004.

Ball, J. T., Woodrow, I. E., and Berry, J. A.: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, in: Prog. Photosyn. Res., edited by: Biggins, J., Martinus-Nijhoff Publishers, Dordrecht, The Netherlands, 221-224, 1987.

Batjes, N. H.: Harmonized soil profile data for applications at global and continental scales: updates to the WISE database, Soil Use and Management, 25, 124-127, 10.1111/j.1475-2743.2009.00202.x, 2009.

Baup, F., Mougin, E., de Rosnay, P., Timouk, F., and Chênerie, I.: Surface soil moisture estimation over the AMMA Sahelian site in Mali using ENVISAT/ASAR data, Remote. Sens. Environ., 109, 473-481, 10.1016/j.rse.2007.01.015, 2007.

Bauters, M., Drake, T. W., Verbeeck, H., Bodé, S., Hervé-Fernández, P., Zito, P., Podgorski, D. C., Boyemba, F., Makelele, I., Cizungu Ntaboba, L., Spencer, R. G. M., and Boeckx, P.: High fire-derived nitrogen deposition on central African forests, PNAS, 115, 549-554, 10.1073/pnas.1714597115, 2018.

Berger, S., Bliefernicht, J., Linstädter, A., Canak, K., Guug, S., Heinzeller, D., Hingerl, L., Maurer, M., Neidl, F., Quansah, E., Salack, S., Steinbrecher, R., and Kunstmann, H.: The impact of rain events on CO$_2$ emissions from contrasting land use systems in semi-arid West African savannas, Sci. Total Environ., 647, 1478-1489, 10.1016/j.scitotenv.2018.07.397, 2019.
Bernacchi, C. J., Portis, A. R., Nakano, H., von Caemmerer, S., and Long, S. P.: Temperature Response of Mesophyll Conductance. Implications for the Determination of Rubisco Enzyme Kinetics and for Limitations to Photosynthesis in Vivo, Plant Physiol., 130, 1992-1998, 10.1104/pp.008250, 2002.

Bliefernicht, J., Berger, S., Salack, S., Guug, S., Hingerl, L., Heinzzeller, D., Mauder, M., Steinbrecher, R., Steup, G., Bossa, A. Y., Waongo, M., Quansah, E., Balogun, A. A., Yira, Y., Arnault, J., Wagner, S., Klein, C., Gessner, U., Knauer, K., Straub, A., Schönrock, R., Kunkel, R., Okogbue, E. C., Rogmann, A., Neidl, F., Jahn, C., Diekkrüger, B., Aduna, A., Barry, B., and Kunstmann, H.: The WASCAL Hydrometeorological Observatory in the Sudan Savanna of Burkina Faso and Ghana, Vadose Zone J., 17, 180065, 10.2136/vzj2018.03.0065, 2018.

Bocksberger, G., Schnitzler, J., Chatelain, C., Daget, P., Janssen, T., Schmidt, M., Thiombiano, A., and Zizka, G.: Climate and the distribution of grasses in West Africa, J. Veg. Sci., 27, 306-317, 10.1111/jvs.12360, 2016.

Boke-Oléń, N., Lehsten, V., Ardö, J., Beringer, J., Eklundh, L., Holst, T., Veenendaal, E., and Tagesson, T.: Estimating and Analyzing Savannah Phenology with a Lagged Time Series Model, PLoS ONE, 11, e0154615-e0154615, 10.1371/journal.pone.0154615, 2016.

Boone, R. B., Galvin, K. A., Coughenour, M. B., Hudson, J. W., Weisberg, P. J., Vogel, C. H., and Ellis, J. E.: Ecosystem modeling adds value to a south african climate forecast, Clim. Change, 64, 317-340, 10.1023/B:CLIM.0000025750.09629.48, 2004.

Boulain, N., Cappelaere, B., Ramier, D., Issoufou, H. B. A., Halilou, O., Seghieri, J., Guillemain, F., Oï, M., Gignoux, J., and Timouk, F.: Towards an understanding of coupled physical and biological processes in the cultivated Sahel – 2. Vegetation and carbon dynamics, J. Hydrol., 375, 190-203, 10.1016/j.jhydrol.2008.11.045, 2009.

Boyd, R. A., Gandin, A., and Cousins, A. B.: Temperature Responses of C4 Photosynthesis: Biochemical Analysis of Rubisco, Phosphoenolpyruvate Carboxylase, and Carbonic Anhydrase in Setaria viridis, Plant Physiol., 169, 1850-1861, 10.1104/pp.15.00586, 2015.

Brümmer, C., Falk, U., Papen, H., Szarzynski, J., Wassmann, R., and Brüggemann, N.: Diurnal, seasonal, and interannual variation in carbon dioxide and energy exchange in shrub savanna in Burkina Faso (West Africa), J. Geophys. Res., 113, G02030, doi:10.1029/2007JG000583, 10.1029/2007JG000583, 2008.

Buba, T.: Prediction equations for estimating tree height, crown diameter, crown height and crown ratio of Parkia biglobosa in the Nigerian guinea savanna, African Journal of Agricultural Research, 7, 6541-6543, 10.5897/AJAR12.276, 2013.

Buchhorn, M., Smets, B., Bertels, L., De Roo, B., Lesiv, M., Tsendbazar, N. E., Herold, M., and Fritz, S.: Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe 2020. 2020. 2020.

Camargo, A. P., Marin, F. R., Sentelhas, P. C., and Picini, A. G.: Adjust of the Thornthwaite's method to estimate the potential evapotranspiration for arid and superhumid climates, based on daily temperature amplitude, Bras. Agrometeorol., 7, 251-257, 10.1007/s00704-019-02873-1, 1999.

Cappelaere, B., Descroix, L., Lebel, T., Boulain, N., Ramier, D., Laurent, J. P., Favreau, G., Boubkraoui, S., Boucher, M., Bouzou Moussa, I., Chaffard, V., Hiernaux, P., Issoufou, H. B. A., Le Breton, E., Mamadou, I., Nazoumou, Y., Oi, M., Ottlé, C., and Quantin, G.: The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger – Investigating water cycle response to a fluctuating climate and changing environment, J. Hydrol., 375, 34-51, 10.1016/j.jhydrol.2009.06.021, 2009.

Chandra, A., and Dubey, A.: Evaluation of genus Cenchrus based on malondialdehyde, proline content, specific leaf area and carbon isotope discrimination for drought tolerance and divergence of species at DNA level, Acta Physiol. Plant., 30, 53-61, 10.1007/s11738-007-0090-x, 2008.
Chen, Q., Baldocchi, D., Gong, P., and Dawson, T.: Modeling radiation and photosynthesis of a heterogeneous savanna woodland landscape with a hierarchy of model complexities, Agric. Forest Meteorol., 148, 1005-1020, 10.1016/j.agrformet.2008.01.020, 2008.

Collatz, G. J., Ribas-Carbo, M., and Berry, J. A.: Coupled photosynthesis-stomatal conductance model for leaves of C4 plants, Aust. J. Plant Physiol., 19, 519-538, 10.1071/PP9920519 1992.

Da Matta, F. M., Loos, R. A., Rodrigues, R., and Barros, R.: Actual and potential photosynthetic rates of tropical crop species, Revista Brasileira de Fisiologia Vegetal, 13, 24-32, 10.1590/S0103-31312001000100003., 2001.

Dagbenonbakin, G. D.: Productivity and water use efficiency of important crops in the upper Oueme Catchment: influence of nutrient limitations, nutrient balances and soil fertility, PhD, Hohe Landwirtschaftliche Fakultät – Wilhelms – Universität Bonn, Bonn, 212 pp., 2005.

Dayamba, S. D., Djoudi, H., Zida, M., Sawadogo, L., and Verchot, L.: Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa, Agr. Ecosyst. Environ., 216, 61-72, 10.1016/j.agee.2015.09.023, 2016.

de Jong, S. M., and Jetten, V. G.: Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis, International Journal of Geographical Information Science, 21, 529-545, 10.1080/13658810601064884, 2007.

de Rosnay, P., Gruhier, C., Timouk, F., Baup, F., Mougin, E., Hiernaux, P., Kergoat, L., and LeDantec, V.: Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali, J. Hydrol., 375, 241-252, 10.1016/j.jhydrol.2009.01.015, 2009.

de Souza Nóia Júnior, R., Amaral, G. C., Pezzopane, J. E. M., Fonseca, M. D. S., Câmarã da Silva, A. P., and Xavier, T. M. T.: Ecophysiological acclimatization to cyclic water stress in Eucalyptus, J. Forestry Res., 31, 797-806, 10.1007/s11676-019-00926-9, 2020.

Delon, C., Mougin, E., Serça, D., Grippa, M., Hiernaux, P., Diawara, M., Galy-Lacaux, C., and Kergoat, L.: Modelling the effect of soil moisture and organic matter degradation on biogenic NO emissions from soils in Sahel rangeland (Mali), Biogeosciences, 12, 3253-3272, 10.5194/bg-12-3253-2015, 2015.

Delon, C., Galy-Lacaux, C., Serça, D., Personne, E., Mougin, E., Adon, M., Le Dantec, V., Loubet, B., Fensholt, R., and Tagesson, T.: Modelling land-atmosphere daily exchanges of NO, NH3, and CO2 in a semi-arid grazed ecosystem in Senegal, Biogeosciences, 16, 2049-2077, 10.5194/bg-16-2049-2019, 2019.

Dimobe, K., Kouakou, J. L. N. d., Tondoh, J. E., Zoungrana, B. J.-B., Forkuor, G., and Ouédraogo, K.: Predicting the Potential Impact of Climate Change on Carbon Stock in Semi-Arid West African Savannas, Land, 7, 124, 10.3390/land7040124, 2018.

Diouf, A. A., Brandt, M., Verger, A., Jarroudi, M. E., Djaby, B., Fensholt, R., Ndione, J. A., and Tychon, B.: Fodder Biomass Monitoring in Sahelian Rangelands Using Phenological Metrics from FAPAR Time Series, Remote Sens., 7, 9122-9148, 10.3390/rs70709122, 2015.

Dirnböck, T., Kraus, D., Grote, R., Klatt, S., Kobler, J., Schindlbacher, A., Seidl, R., Thom, D., and Kiese, R.: Substantial understory contribution to the C sink of a European temperate mountain forest landscape, Landscape Ecol., 35, 483-499, 10.1007/s10980-019-00960-2 2020.

Do, F. C., Goudiaby, V. A., Gimenez, O., Diagne, A. L., Diouf, M., Rocheteu, A., and Akpo, L. E.: Environmental influence on canopy phenology in the dry tropics, Forest Ecol. Manage., 215, 319-328, 10.1016/j.foreco.2005.05.022, 2005.

Elberling, B., Fensholt, R., Larsen, L., Petersen, A.-I. S., and Sandholt, I.: Water content and land use history controlling soil CO2 respiration and carbon stock in savanna soil and groundnut fields in semi-arid Senegal, Danish Journal of Geography, 103, 47-56, 10.1080/00167223.2003.10649491, 2003.

Epron, D., Nouvellon, Y., Roupstrand, O., Mouvondo, W., Mabiala, A., Saint-Andre, L., Joffre, R., Jourdan, C., Bonnemfond, J. M., Berbigier, P., and Hamel, O.: Spatial and temporal variations of soil respiration in a Eucalyptus plantation in Congo, Forest Ecol. Manage., 202, 149-160, 10.1016/j.foreco.2004.07.019, 2004.
Farquhar, G. D., Von Caemmerer, S., and Berry, J. A.: A biochemical model of photosynthetic CO$_2$ assimilation in leaves of C$_3$ species, Planta, 149, 78-90, 10.1007/BF00386231, 1980.

Faye, B., Webber, H., Naab, J. B., MacCarthy, D. S., Adam, M., Ewert, F., Lamers, J. P. A., Schleussner, C.-F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., and Gaiser, T.: Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna, Environ. Res. Lett., 13, 034014, 10.1088/1748-9326/aaab40, 2018.

February, E., and Higgins, S.: The distribution of tree and grass roots in savannas in relation to soil nitrogen and water, S. Afr. J. Bot., 76, 517-523, 10.1016/j.sajb.2010.04.001, 2010.

Feng, X., and Dietze, M.: Scale dependence in the effects of leaf ecophysiological traits on photosynthesis: Bayesian parameterization of photosynthesis models, New Phytol., 200, 1132-1144, 10.1111/nph.12454, 2013.

Fraser, F. C., Corstanje, R., Deeks, L. K., Harris, J. A., Pawlett, M., Todman, L. C., Whitmore, A. P., and Ritz, K.: On the origin of carbon dioxide released from rewetted soils, Soil Biology and Biochemistry, 101, 1-5, 10.1016/j.soilbio.2016.06.032, 2016.

Fürstenau Togashi, H., Prentice, I. C., Atkin, O. K., Macfarlane, C., Prober, S. M., Bloomfield, K. J., and Evans, B. J.: Thermal acclimation of leaf photosynthetic traits in an evergreen woodland, consistent with the coordination hypothesis, Biogeosciences, 15, 3461-3474, 10.5194/bg-15-3461-2018, 2018.

Galy-Lacaux, C., Delon, C., Solmon, F., Adon, M., Yoboué, V., Mphepya, J., Pienaar, J. J., Sigha, L., Dungall, L., Akpo, A., Mougin, E., Gardrat, E., and Castera, P.: Dry and Wet Atmospheric Nitrogen Deposition in West Central Africa, in: Nitrogen Deposition, Critical Loads and Biodiversity, edited by: Sutton, M., Mason, K., Sheppard, L., Sverdrup, H., Haeuber, R., and Hicks, W., Springer, Dordrecht, 2014.

Gash, J. H. C., Lloyd, C. R., and Lachaud, G.: Estimating sparse forest rainfall interception with an analytical model, J. Hydrol., 170, 79-86, 10.1016/0022-1694(95)02697-N, 1995.

Geerling, C.: The status of the woody species of the Sudan and Sahel zones of West Africa, Forest Ecol. Manage., 13, 247-255, 10.1016/0378-1127(85)90038-6, 1985.

Gessner, U., Niklaus, M., Kuenzer, C., and Dech, S.: Intercomparison of Leaf Area Index Products for a Gradient of Sub-Humid to Arid Environments in West Africa, Remote Sens., 5, 1235-1257, 10.3390/rs5031235, 2013.

Gleason, S. M., Wiggins, D. R., Bliss, C. A., Comas, L. H., Cooper, M., DeJonge, K. C., Young, J. S., and Zhang, H.: Coordinated decline in photosynthesis and hydraulic conductance during drought stress in Zea mays, Flora, 227, 1-9, 10.1016/j.flora.2016.11.017, 2017.

Groenendijk, M., Dolman, A. J., van der Molen, M. K., Leuning, R., Arneth, A., Delpierre, N., Gash, J. H. C., Lindroth, A., Richardson, A. D., Verbeeck, H., and Wohlfarth, G.: Assessing parameter variability in a photosynthesis model within and between plant functional types using global Fluxnet eddy covariance data, Agric. Forest Meteorol., 151, 22-38, 10.1016/j.agrformet.2010.08.013, 2011.

Grossiord, C., Sevanto, S., Adams, H. D., Collins, A. D., Dickman, L. T., McBranch, N., Michaletz, S. T., Stockton, E. A., Vigil, M., and McDowell, N. G.: Precipitation, not air temperature, drives functional responses of trees in semi-arid ecosystems, J. Ecol., 105, 163-175, 10.1111/1365-2745.12662, 2017.

Grote, R.: Integrating dynamic morphological properties into forest growth modeling. II. Allocation and mortality, Forest Ecol. Manage., 111, 193-210, 10.1016/S0378-1127(98)00328-4, 1998.

Grote, R.: Sensitivity of volatile monoterpene emission to changes in canopy structure — A model based exercise with a process-based emission model, New Phytol., 173, 550-561, 10.1111/j.1469-8137.2006.01946.x, 2007.

Grote, R., Lavoir, A. V., Rambal, S., Staudt, M., Zimmer, I., and Schnitzler, J.-P.: Modelling the drought impact on monoterpene fluxes from an evergreen Mediterranean forest canopy, Oecologia, 160, 213-223, 10.1007/s00442-009-1298-9, 2009a.

Grote, R., Lehmann, E., Brümmer, C., Brüggemann, N., Szarzynski, J., and Kunstmann, H.: Modelling and observation of biosphere-atmosphere interactions in natural savanna in Burkina Faso, West Africa, Phys. Chem. Earth, 34, 251-260, 10.1016/j.pce.2008.05.003, 2009b.
of biosphere

Kiese, R., Heinzeller, C., Werner, C., Wochele, S., Grote, R., and Butterbach

Kgope, B. S., and Musil, C. F.: Differential photosynthetic responses of broad

Kebbas, S., Lutts, S., and Aid, F.: Effect of drought stress on the photosynthesis of Acacia tortilis subsp. raddiana at the young seedling stage, Photosynthetic, 53, 288-298, 10.1007/s11099-015-0113-6, 2015.

Kgope, B. S., and Musil, C. F.: Differential photosynthetic responses of broad- and fine-leaved savanna trees to elevated temperatures, S. Afr. J. Bot., 70, 760-766, 10.1016/S0254-6299(15)30177-0, 2004.

Kiese, R., Heinzeller, C., Werner, C., Wochele, S., Grote, R., and Butterbach-Bahl, K.: Quantification of nitrate leaching from German forest ecosystems by use of a process oriented biogeochemical model, Environ. Pollut., 159, 3204-3214, 10.1016/j.envpol.2011.05.004, 2011.
Kim, J., and Verma, S. B.: Modeling canopy photosynthesis: scaling up from a leaf to canopy in a temperate grassland ecosystem, Agric. Forest Meteorol., 57, 187-208, 10.1016/0168-1923(91)90086-6, 1991.

Knauer, J., Werner, C., and Zaehle, S.: Evaluating stomatal models and their atmospheric drought response in a land surface scheme: A multi biome analysis, J. Geophys. Res. - Biogeosci., 120, 1894–1911, 10.1002/2015JG003114, 2015.

Körner, C., Scheel, J., and Bauer, H.: Maximum leaf diffusive conductance in vascular plants, Photosynthetica, 13, 45-82, 1979.

Kothavala, Z., Arain, M. A., Black, T. A., and Verseghy, D.: The simulation of energy, water vapor and carbon dioxide fluxes over common crops by the Canadian Land Surface Scheme (CLASS), Agric. Forest Meteorol., 133, 89-108, 10.1016/j.agrformet.2005.08.007, 2005.

Kraus, C., Zang, C., and Menzel, A.: Elevational response in leaf and xylem phenology reveals different prolongation of growing period of common beech and Norway spruce under warming conditions in the Bavarian Alps, Eur. J. Forest Res., 135, 1011-1023, 10.1007/s10342-016-0990-7, 2016a.

Kraus, D., Weller, S., Klatt, S., Haas, E., Wassmann, R., Kiese, R., and Butterbach-Bahl, K.: A new LandscapeDNDC biogeochemical module to predict CH₄ and N₂O emissions from lowland rice and upland cropping systems, Plant Soil, 386, 125-149, 10.1007/s11104-014-2255-x, 2015.

Kraus, D., Weller, S., Klatt, S., Santabárbara, I., Haas, E., Wassmann, R., Werner, C., Kiese, R., and Butterbach-Bahl, K.: How well can we assess impacts of agricultural land management changes on the total greenhouse gas balance (CO₂, CH₄ and N₂O) of tropical rice-cropping systems with a biogeochemical model?, Agr. Ecosystems Environ., 224, 104-115, 10.1016/j.agee.2016.03.037, 2016b.

Kucharik, C. J., Barford, C. C., El Maayar, M., Wofsy, S. C., Monson, R. K., and Baldocchi, D. D.: A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO₂ and H₂O vapor exchange, Ecol. Modelling, 196, 1-31, 10.1016/j.ecolmodel.2005.11.031, 2006.

Leuning, R.: A critical appraisal of a combined stomatal-photosynthesis model for C3 plants, Plant Cell Environ., 18, 339-355, 10.1111/j.1365-3040.1995.tb00370.x, 1995.

Li, C., Frolking, S., and Frolking, T. A.: A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and Sensitivity, J. Geophys. Res., 97, 9759-9776, 10.1029/92JD00509, 1992.

Liebmann, R., Breuer, L., Houska, T., Kraus, D., Moser, G., and Kraft, P.: Simulating Long-Term Development of Greenhouse Gas Emissions, Plant Biomass, and Soil Moisture of a Temperate Grassland Ecosystem under Elevated Atmospheric CO₂, Agronomy, 10, 50, 10.3390/agronomy10010050, 2020.

Lindauer, M., Schmid, H. P., Grote, R., Mauder, M., Steinbrecher, R., and Wolpert, B.: Net ecosystem exchange over a non-cleared wind-throw-disturbed upland spruce forest – measurements and simulations Agric. Forest Meteorol., 197, 219-234, 10.1016/j.agrformet.2014.07.005, 2014.

Livesley, S. J., Grover, S., Hutley, L. B., Jamali, H., Butterbach-Bahl, K., Fest, B., Beringer, J., and Arndt, S. K.: Seasonal variation and fire effects on CH₄, N₂O and CO₂ exchange in savanna soils of northern Australia, Agric. Forest Meteorol., 151, 1440-1452, 10.1016/j.agrformet.2011.02.001, 2011.

Loustau, D., Berbigier, P., Granier, A., and Moussa, F. E. H.: Interception loss, throughfall and stemflow in a maritime pine stand. I. Variability of throughfall and stemflow beneath the pine canopy, J. Hydrol., 138, 449-467, 10.1016/0022-1694(92)90130-N, 1992.

Mamadou, O.: Etude des flux d'Evapotranspiration en climat soudanien: comportement comparé de deux couverts végétaux au Bénin, Université de Grenoble (France) et Université d'Abomey-Calavi (Bénin), Abomey-Calavi, 2014.

Martin, M. J., Stirling, C. M., Humphries, S. W., and Long, S. P.: A process-based model to predict the effects of climatic change on leaf isoprene emission rates, Ecol. Modelling, 131, 161-174, 10.1016/S0304-3800(00)00258-1, 2000.
Massad, R.-S., Tuzet, A., and Bethenod, O.: The effect of temperature on C4-type leaf photosynthesis parameters, Plant Cell Environ., 30, 1191-1204, 10.1111/j.1365-3040.2007.01691.x, 2007.

Massad, R. S., Lathière, J., Strada, S., Perrin, M., Personne, E., Stéfanon, M., Stella, P., Szopa, S., and de Noblet-Ducoudré, N.: Reviews and syntheses: influences of landscape structure and land uses on local to regional climate and air quality, Biogeosciences, 16, 2369-2408, 10.5194/bg-16-2369-2019, 2019.

Merbold, L., Ardo, J., Arneth, A., Scholes, R. J., Nouvelon, Y., De Grandcourt, A., Archibald, S., Bonnefond, J. M., Boulain, N., Brüggemann, N., Brümmer, C., Cappelaere, B., Ceschia, E., El-Khidir, H. A. M., El-Tahir, B. A., Falk, U., Lloyd, J., Kergoat, L., Le Dantec, V., Mougin, E., Muchinda, M., Mukelabai, M. M., Ramier, D., Roupsard, O., Timouk, F., Veenendaal, E. M., and Kutsch, W. L.: Precipitation as driver of carbon fluxes in 11 African ecosystems, Biogeosciences, 6, 1027-1041, 10.5194/bg-6-1027-2009, 2009.

Mougin, E., Lo Seena, D., Rambal, S., Gaston, A., and Hiernaux, P.: A regional Sahelian grassland model to be coupled with multispectral satellite data. I: Model description and validation, Remote. Sens. Environ., 52, 181-193, 10.1016/0034-4257(94)00126-8, 1995.

Mougin, E., Hiernaux, P., Kergoat, L., Grippa, M., de Rosnay, P., Timouk, F., Le Dantec, V., Demarez, V., Lavenu, F., Arjounin, M., Lebel, T., Soumaguel, N., Ceschia, E., Mougenot, B., Baup, F., Frappart, F., Frison, P. L., Gardelle, J., Gruhier, C., Jarlan, L., Mangiarotti, S., Sanou, B., Tracol, Y., Guichard, F., Trichon, V., Diarra, L., Soumaré, A., Koité, M., Dembélé, F., Lloyd, C., Hanan, N. P., Damesin, C., Delon, C., Serca, D., Galy-Laucke, C., Seghieri, J., Becerra, S., Dia, H., Gangneron, F., and Mazzeega, P.: The AMMA-CATCH Gourma observatory site in Mali: Relating climatic variations to changes in vegetation, surface hydrology, fluxes and natural resources, J. Hydrol., 375, 14-33, 10.1016/j.jhydrol.2009.06.045, 2009.

Mougin, E., Diawara, M. O., Soumaguel, N., Maïga, A. A., Demarez, V., Hiernaux, P., Grippa, M., Chaffard, V., and Ba, A.: A leaf area index data set acquired in Sahelian rangelands of Gourma in Mali over the 2005–2017 period, Earth System Science Data, 11, 675-686, 10.5194/essd-11-675-2019, 2019.

Odekunle, T. O., Andrew, O., and Aremu, S. O.: Towards a wetter Sudano-Sahelian ecological zone in twenty-first century Nigeria, Weather, 63, 66-70, 10.1002/wea.172, 2008.

Pallas, J. E., and Samish, Y. B.: Photosynthetic response of peanut, Crop Sci., 14, 478-482, 10.2135/cropsci1974.0011183X001400030042x, 1974.

Pereira, A. R., and Pruitt, W. O.: Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration, Agricultural Water Management, 66, 251-257, 10.1016/j.agwat.2003.11.003, 2004.

Pielke, R. A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K. K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P., and de Noblet, N.: Land use/land cover changes and climate: modeling analysis and observational evidence, Wiley Interdisciplinary Reviews: Climate Change, 2, 828-850, 10.1002/wcc.144, 2011.

Pitman, A. J.: The evolution of, and revolution in, land surface schemes designed for climate models, Int. J. Climatol., 23, 479-510, 10.1002/joc.893, 2003.

Quansah, E., Mauder, M., Balogun, A. A., Amekudzi, L. K., Hingerl, L., Bliefmicht, J., and Kunsmann, H.: Carbon dioxide fluxes from contrasting ecosystems in the Sudanian Savanna in West Africa, Carbon Balance Manag., 10, 1-17, 10.1186/s13021-014-0011-4, 2015.

Quenum, G. M. L. D., Klutse, N. A. B., Dieng, D., Laux, P., Arnault, J., Kodja, J. D., and Oguntunde, P. G.: Identification of Potential Drought Areas in West Africa Under Climate Change and Variability, Earth Systems and Environment, 3, 429-444, 10.1007/s41748-019-00133-w, 2019.

Roupsard, O., Audebert, A., Ndour, A. P., Clermont-Dauphin, C., Agbohessou, Y., Sanou, J., Koala, J., Faye, E., Sambakhe, D., Jourdan, C., le Maire, G., Tall, L., Sanogo, D., Seghieri, J., Cournac, L., and Leroux, L.: How far does the tree affect the crop in agroforestry? New spatial analysis methods in a Faidherbia parkland, Agr. Ecosyst. Environ., 296, 106928, 10.1016/j.agee.2020.106928, 2020.
Running, S. W., and Coughlan, J. C.: A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes, Ecol. Modelling, 42, 125-154, 10.1016/0304-3800(88)90112-3, 1988.

Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R., de Camargo, P. B., Crill, P., Daube, B. C., de Freitas, H. C., Hutyr, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J. W., Pyle, E. H., Rice, A. H., and Silva, H.: Carbon in amazon forests: Unexpected seasonal fluxes and disturbance-induced losses, Science, 302, 1554-1557, 10.1126/science.1091165, 2003.

Scheiter, S., and Higgins, S. I.: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach, Glob. Change Biol., 15, 2224-2246, 10.1111/j.1365-2486.2008.01838.x, 2009.

Scholes, R. J., and Hall, D. O.: The carbon budget of tropical savannas, woodlands and grasslands, in: Global change: effects on coniferous forests and grasslands, edited by: Breymeyer, A. I., Hall, D. O., Melillo, J. M., and Ågren, G. I., Scope, John Wiley and Sons, Chichester, 69-100, 1996.

Sellers, P. J., Randall, D. A., Collatz, G. J., Berry, J. A., Field, C. B., Dazlich, D. A., Zhang, C., Collelo, G. D., and Bounoua, L.: A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: model formulation, J. Clim., 9, 676-705, 10.1175/1520-0442(1996)009<0676:ARLSPF>2.0.CO;2, 1996.

Setterfield, S. A., Clifton, P. J., Hutley, L. B., Rossiter-Rachor, N. A., and Douglas, M. M.: Exotic grass invasion alters microsite conditions limiting woody recruitment potential in an Australian savanna, Sci. Rep., 8, 6628-6628, 10.1038/s41598-018-24704-5, 2018.

Sibret, T.: The Sahelian Drylands under Pressure: Studying the Impact of Environmental Factors on Vegetation in Dahra, Senegal, Master of Science in Bioscience Engineering, Ghent University, 113 pp., 2018.

Simioni, G., Le Roux, X., Gignoux, J., and Sinoquet, H.: Treegrass: a 3D, process-based model for simulating plant interactions in tree-grass ecosystems, Ecol. Modelling, 131, 47-63, 10.1016/S0304-3800(00)00243-X, 2000.

Sjöström, M., Ardö, J., Arneth, A., Boulain, N., Cappelaere, B., Eklundh, L., de Grandcourt, A., Kutsch, W. L., Merbold, L., Nouvellon, Y., Scholes, R. J., Schubert, P., Seaquist, J., and Veenendaal, E. M.: Exploring the potential of MODIS EVI for modeling gross primary production across African ecosystems, Remote. Sens. Environ., 115, 1081-1089, 10.1016/j.rse.2010.12.013, 2011.

Sjöström, M., Zhao, M., Archibald, S., Arneth, A., Cappelaere, B., Falk, U., de Grandcourt, A., Hanan, N., Kergoat, L., Kutsch, W., Merbold, L., Moug, E., Nickless, A., Nouvellon, Y., Scholes, R. J., Veenendaal, E. M., and Ardö, J.: Evaluation of MODIS gross primary productivity for Africa using eddy covariance data, Remote. Sens. Environ., 131, 275-286, 10.1016/j.rse.2012.12.023, 2013.

Snyman, H. A.: Rangeland degradation in a semi-arid South Africa—I: influence on seasonal root distribution, root/shoot ratios and water-use efficiency, Journal of Arid Environments, 60, 457-481, 10.1016/j.jaridenv.2004.06.006, 2005.

Sobamowo, J. O.: Effect of harvesting dates and fertilizer application on cassava productivity in rainforest and guinea savanna agroecological zones of Nigeria, PhD, University of Cape Coast, Ghana, 2016.

Sonawane, B. V., Sharwood, R. E., von Caemmerer, S., Whitney, S. M., and Ghannoum, O.: Short-term thermal photosynthetic responses of C4 grasses are independent of the biochemical subtype, J. Exp. Bot., 68, 5583-5597, 10.1093/jxb/erx350, 2017.

Sotelo Montes, C., Weber, J. C., Silva, D. A., Andrade, C., Muñiz, G. B., Garcia, R. A., and Kalinganire, A.: Growth and fuelwood properties of five tree and shrub species in the Sahelian and Sudanian ecozones of Mali: relationships with mean annual rainfall and geographical coordinates, New Forests, 45, 179-197, 10.1007/s11056-013-9401-9, 2014.

Tagesson, T., Fensholt, R., Guiro, I., Rasmussen, M. O., Huber, S., Mbow, C., Garcia, M., Horion, S., Sandholt, I., Holm-Rasmussen, B., Götsche, F. M., Ridler, M.-E., Olén, N., Lundegard Olsen, J., Ehammer, A., Madsen, M., Olesen, F. S., and Ardö, J.: Ecosystem properties of semiarid savanna grassland in West Africa and its relationship with environmental variability, Glob. Change Biol., 21, 250-264, 10.1111/gcb.12734, 2015.
Tagesson, T., Ardö, J., Guiro, I., Cropley, F., Mbow, C., Horion, S., Ehammer, A., Mougin, E., Delon, C., Corinne, G.-L., and Fensholt, R.: Very high CO\textsubscript{2} exchange fluxes at the peak of the rainy season in a West African grazed semi-arid savanna ecosystem, Geografisk Tidsskrift-Danish Journal of Geography, 116, 1-17, 10.1080/00167223.2016.1178072, 2016.

Tews, J., and Jeltsch, F.: Modelling the impact of climate change on woody plant population dynamics in South African savanna, BMC Ecology, 4, 10.1186/1472-6785-4-17, 2004.

Tews, J., Esther, A., Milton, S. J., and Jeltsch, F.: Linking a population model with an ecosystem model: Assessing the impact of land use and climate change on savanna shrub cover dynamics, Ecol. Modelling, 195, 219-228, 10.1016/j.ecolmodel.2005.11.025, 2006.

Thornley, J. H. M., and Cannell, M. G. R.: Modelling the components of plant respiration: Representation and realism, Ann. Bot., 85, 55-67, 10.1006/anbo.1999.0997, 2000.

Thornley, J. H. M.: Instantaneous canopy photosynthesis: Analytical expressions for sun and shade leaves based on exponential light decay down the canopy and an acclimated non-rectangular hyperbola for leaf photosynthesis, Ann. Bot., 89, 451-458, 10.1093/aob/mcf071, 2002.

Thornthwaite, C. W.: An approach toward a rational classification of climate, Geogr. Rev., 38, 55, 10.2307/210739, 1948.

Timouk, F., Kergoat, L., Mougin, E., Lloyd, C. R., Ceschia, E., Cohard, J. M., Rosnay, P. d., Hiernaux, P., Demarez, V., and Taylor, C. M.: Response of surface energy balance to water regime and vegetation development in a Sahelian landscape, J. Hydrol., 375, 178-189, 10.1016/j.jhydrol.2009.04.022, 2009.

Ullmann, I.: Stomatal conductance and transpiration of Acacia under field conditions: similarities and differences between leaves and phyllodes, Trees-Struct. Funct., 3, 45-56, 10.1007/BF00202400, 1989.

Velluet, C.: Building a field-and model-based climatology of local water and energy cycles in the cultivated Sahel – annual budgets and seasonality, Hydrol. Earth Syst. Sci., 18, 5001-5024, 10.5194/hess-18-5001-2014, 2014.

Vico, G., and Porporato, A.: Modelling C3 and C4 photosynthesis under water-stressed conditions, Plant Soil, 313, 187-203, 10.1007/s11104-008-9691-4, 2008.

Vitasse, Y., Francois, C., Delpierre, N., Dufrene, E., Kremer, A., Chuine, I., and Delzon, S.: Assessing the effects of climate change on the phenology of European temperate trees, Agric. Forest Meteorol., 151, 969-980, 2011.

Vitkauskaitė, G., and Venskaitytė, L.: Differences between C3 (Hordeum vulgare L.) and C4 (Panicum miliaceum L.) plants with respect to their resistance to water deficit, Žemdirbystė (Agriculture), 98, 349-356, 2011.

Von Caemmerer, S.: Biochemical models of leaf photosynthesis, Technique in Plant Sciences, CSIRO, Collingwood VIC 3066, Australia, 2000.

Vu, J. C. V.: Acclimation of peanut (Arachis hypogaea L.) leaf photosynthesis to elevated growth CO\textsubscript{2} and temperature, Environmental and Experimental Botany, 53, 85-95, 10.1016/j.envexpbot.2004.03.006, 2005.

Werner, C., Haas, E., Grote, R., Gauder, M., Graeff-Hönninger, S., Clauein, W., and Butterbach-Bahl, K.: Biomass production potential from Populus short rotation systems in Romania, GCB Bioenergy, 4, 642-653, 10.1111/j.1757-1707.2012.01180.x, 2012.

Wesolowski, T., and Rowinski, P.: Timing of bud burst and tree-leaf development in a multispecies temperate forest, Forest Ecol. Manage., 237, 387-393, 2006.

Whitley, R., Beringer, J., Hutyra, L. B., Abramowitz, G., De Kauwe, M. G., Duursma, R., Evans, B., Haverd, V., Li, L., Ryu, Y., Smith, B., Wang, Y. P., Williams, M., and Yu, Q.: A model inter-comparison study to examine limiting factors in modelling Australian tropical savannas, Biogeosciences, 13, 3245-3265, 10.5194/bg-13-3245-2016, 2016.
opportunities in land surface modelling of savanna ecosystems, Biogeosciences, 14, 4711-4732, 10.5194/bg-14-4711-2017, 2017.

Yao, N. g. R., and Goué, B.: Water use efficiency of a cassava crop as affected by soil water balance, Agric. Forest Meteorol., 61, 187-203, 10.1016/0168-1923(92)90049-A, 1992.

Yu, G.-R., Zhuang, J., and Yu, Z.-L.: An attempt to establish a synthetic model of photosynthesis-transpiration based on stomatal behavior for maize and soybean plants grown in field, Journal of Plant Physiology, 158, 861-874, 0.1078/0176-1617-00177, 2001.

Yuan, W., Zhou, G., Wang, Y., Han, X., and Wang, Y.: Simulating phenological characteristics of two dominant grass species in a semi-arid steppe ecosystem, Ecological Research, 22, 784-791, 10.1007/s11284-006-0318-z, 2007.