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RESEARCH ARTICLE

VALIDATION OF A HERBACEOUS BIOMASS ASSESSMENT MODEL FOR SAHELIAN RANGELANDS (BIOMASAH) IN NIGER

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ABSTRACT

This study was carried out in the pastoral zone of Niger with the aim of validating outputs of the BIOMASAH model developed by the AGRHYMET Regional Centre (ARC) relative to real data collected over the 2001-2011 period by the Ministry Livestock and Animal Industries (MEIA) of Niger. We used parametric tests (t-tests) and nonparametric tests (Wilcoxon and sign tests) for mean comparisons. A correlation analysis was performed by calculating Pearson's r, Spearman's ρ, Kendall's T and Hoeffding's D correlation coefficients. The results showed that the BIOMASAH model generally overestimated biomass (983.17 vs. 591.17 kg/ha) with a highly significant difference relative to the field findings ($P < .0001$). Pearson's r (0.15), Spearman'sρ (0.22) Kendall's T (0.13) and Hoeffding's D (0.1) correlation coefficients were low but highly significant ($p < .0001$). Grazing pressure and spatiotemporal variability of rainfall helped explain the noted differences.

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INTRODUCTION

Rangeland productivity in sub-Saharan Africa has been investigated through several programmes, especially in the framework of early warning systems (Agrhymet, 1992). The developed approaches involve*in-situ* field measurement methods, sometimes combined with satellite imaging. These techniques have enabled a large-scale assessment of rangeland productivity (Justice *et al*., 1989). The increased availability of medium and low resolution Earth monitoring data from NOAA, SPOT VEGETATION, MODIS and METOP satellites, combined with the availability of *in situ* biomass production datashould facilitate the modelling of such assessments using simple models. The lack of field data and the difficulty of obtaining data on entire regions over periods of several years prompted the the AGRHYMET Regional Centre (CRA) to develop a herbaceous biomass assessment model tailored for Sahelian conditions. This model—which is based on approaches developed under the *Productivité des Pâturages Sahéliens au Mali* (PPS) programme—has never been validated because of the lack of field measurement data.

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However, products derived from this model have been used in crop assessments and in a study on risk areas (Andrea *et al.*, 2002). The integration of data generated by an existing geographical information system (GIS) model enhanced the feasibility of this approach. The original model is based on empirical relationships between the water balance, nitrogen balance and dry matter production in rangelands. The geographical inputs of the model include scanned digital maps from the *Atlas pastoral* of the *Institut d'Élevage et de Médecine Vétérinaire des pays Tropicaux* (Iemvt, 1987) and annual spatial rainfall data from the CRA database. Phytomass data have been collected by services of the Ministry of Livestock and Animal Industries of Niger (MEIA) since 1989. The availability of these historical field data enabled CRA to validate outputs of the BIOMASAH model. The aim of this study was to use these field observations to validate outputs of the biomass model over the 2001-2011 period through mean comparison tests and parametric and nonparametric correlation coefficient calculations.

Description of the area

The study area was essentially the pastoral zone of Niger, as outlined on maps from the *Atlas pastoral*(IEMVT, 1987). It extends from 13° to 16° latitude N and 2° to 12° longitude E (Figure 1). This Sahelian zone was selected for the biomass model validation because of the availability of *in situ* data. Like other Sahelian regions, this zone is characterized by high spatiotemporal variability in rainfall (Hiernaux and Le Houérou, 2006;Sivakumar *et al*., 1993). The climatic conditions are arid, with annual rainfall generally ranging from 150 to 300 mm(Touré *et al*., 2012).The length of the rainy season ranges from 60 to 120 days on average in central and western Sahel (Morel, 1992).

2. *The semi-detailed assessment method* based on field observations and on theoretical assessment of mean production per landscape unit and on the nitrogen content;
3. *The detailed assessment method*, similar to the semi-detailed method, but focused on a smaller area (*terroir*) with field data.

An intermediary application was developed for the BIOMASAH model. It uses elements from both methods (global and semi-detailed). A herbaceous biomass calculation

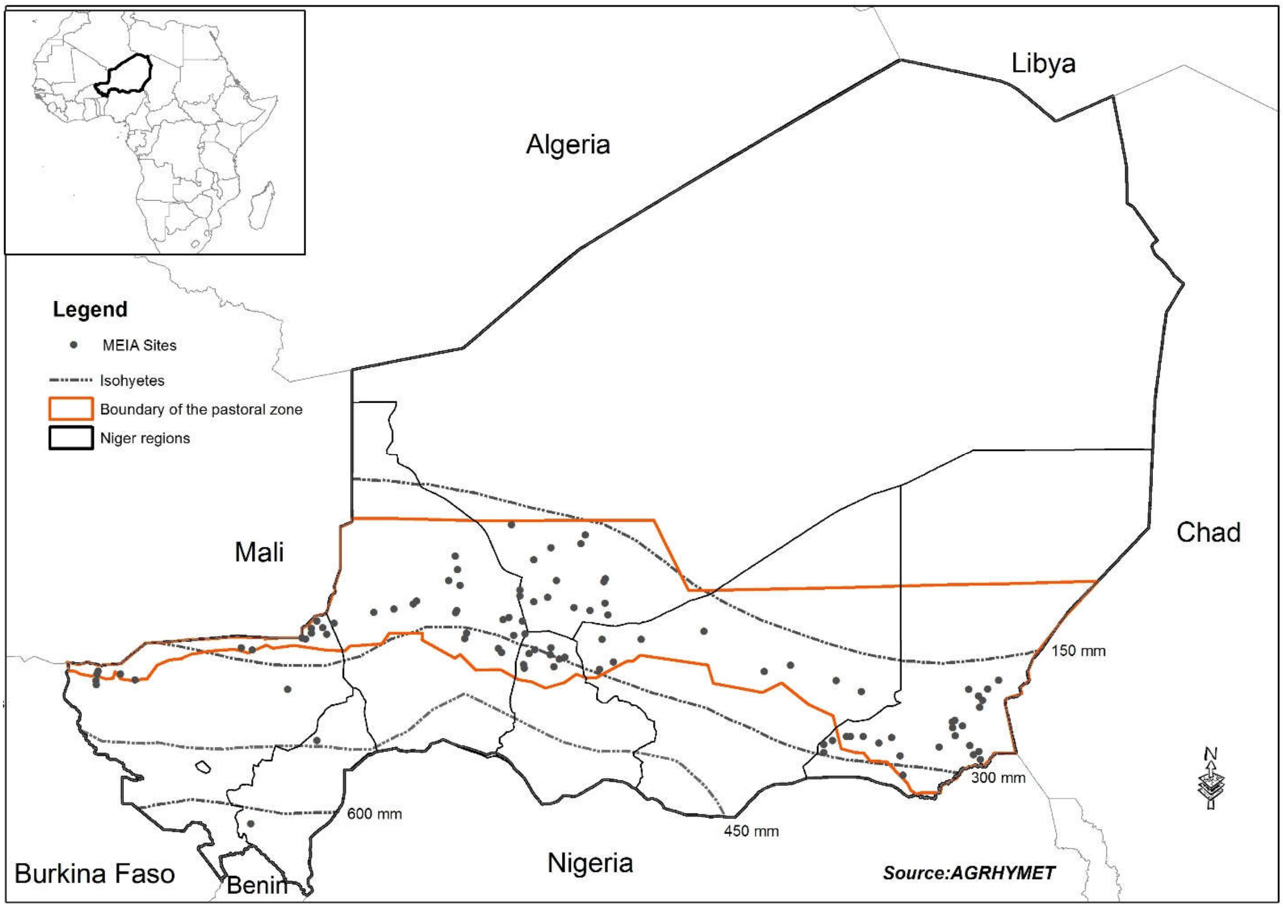

Figure 1. Map of the study area

MATERIALS AND METHODS

The study was conducted using satellite rainfall data estimations (Rainfall Estimation Algorithm, version 2 [RFE2]), a soil texture table to produce herbaceous biomass maps using the BIOMASAH model and *in-situ* field data collected by MEIA. We then used parametric and nonparametric tests to compare the mean biomass levels simulated by the model with the mean field data.

Biomasah

The adopted approach is based on the *Productivité des Pâturages Sahéliens* project (Penning and Djitèye, 1982).The authors of this study proposed three plant production assessment methods:

1. *The global assessment method* for forage production based on a limited quantity of information and without prior fieldwork;

unit was defined by cross-tabulating pastoral potential features from the pastoral potential map of the Tropical Livestock and Veterinary Medicine Institute (IEMVT) and estimated annual rainfall image pixels. The water balance was calculated in each pastoral unit previously classified in geomorphological units corresponding to relatively homogeneous groups: detrital, sandy, fluvial and lacustrine (Breman and De Ridder, 1991), coded according to their texture determined in a soil study carried out in CILSS countries (AGRHYMET, 2001). A runoff coefficient was then attributed to each unit consisting of pastoral units and geomorphological units. Infiltration in each unit was calculated using the following formula: $I = P(1 - R)$ where I is the quantity of infiltrated water (mm/year), P is the annual rainfall (mm/year), and R is the runoff coefficient. The runoff coefficients used are annual means per soil type. In the method, water is the factor limiting plant growth when infiltration is less than 250 mm (Penning *et al*., 1982). However, nitrogen and phosphorus are determining factors when infiltration is above the 250 mm threshold. The application, which is perfectly integrated in a GIS, calculates the herbaceous biomass per unit on the basis of the following relationships shown as-is or graphically in the tropical rangeland manual:

For areas where water is the limiting factor, equations 1 and 2 are used, and then a second relationship is deduced.

Equation1 (R=0): B_1= 5.11 * Rainfall – 48.28 (B_1)
Equation 2 (R=0.5): B_2= 2.37 * Rainfall – 216(B_2)

Where B1 is the biomass in (R= 0) runoff conditions and B2 is the biomass in (R= 0.5) runoff conditions.

Biomass production (B) (kg.dm.ha^{-1}) is deduced by interpolation $B = B_1 \frac{R*(B_1-B_2)}{0.5}$

For areas where nitrogen in the limiting factor, annual losses from the system are assessed according to the mean rainfall (Penning *et al.*, 1982). Similarly, the mean nitrogen content in above-ground biomass (Nb in kg) is assessed according to standard methods. It is assumed that 1 mm of rainfall supplies 8.3 g.ha^{-1}of nitrogen in rangelands in the Sahel. Biological nitrogen fixation is 0.02 kg.ha^{-1}by percent of legumes present. Bacteria associated with grasses and free bacteria respectively provide 0.013 kg and 0.025 kg N/kg.dm biomass. With all of these contributions, and based on the assumption that legumes contribute at least 5%, the equation for Nb: Nb = 0 .0083 *I/ (f-0.13), where f is the annual loss and I is infiltration. The nitrogen content is determined by interpolation of steady-state conditions and runoff is determined by the following equations, where P represents the annual rainfall considered:

$$A_1(R=0) = 4.119 + \frac{15.48}{1-0.01546*P} \quad ; \quad A_2(R=0.5) = 9.913 + \frac{217}{1-0.00473*P}$$

The nitrogen content A

$A = A_1 + \frac{R*(A_2-A_1)}{0.5}$ WhereA_1 is the biomass under R = 0 runoff conditions; andA_2 is the biomass under R = 0.5 runoff conditions. Based on knowledge of the mean nitrogen content in above-ground biomass and the nitrogen content in the herbaceous layer at the end of the growing season, biomass production can be estimated in kg.dm^{-1}.ha^{-1}according to the equation: B=1000 Nb/A.

Validation method

Data from the model

The biomass calculation application was developed under the Avenue program with Arc View GIS 3.2 software. A script is also available under the VisualCarte software package[1]. This program, written in extension form, was designed so that estimated rainfall data would be the only factor that changes yearly, while other input parameters are fixed (soils and pastoral units). We used rainfall data estimated by the Rainfall Estimation Algorithm, version 2(RFE2) package developed by the Climate Prediction Center (NOAA-CPC)(Novella and Thiaw, 2012). These data have the advantage of being generated with the same algorithm over the validation period (2000-2011) and may be downloaded free of charge on the FEWS NET website[2].A study comparing RFE2 data with soil measurements obtained by CRA gave an R^2 determination coefficient of 0.61. Ten-day RFE2 images were viewed at 3 x 3 km spatial resolution. Preprocessing was carried out with the QGIS freeware package, in an operation involving annual cumulative 10-day images corresponding to the rainy season. Then there was a rollback to the pixel size (5 km) compatible with the program and the file was saved in gis format (ERDAS Imagine). Estimated cumulative rainfall images were used to apply the model for all of the years (2000-2011) (Figures 2-13).

MEIA data

The tabular database of georeferenced sites containing ground observations for the years 2000to 2011 was developed by MEIA. There was a total of 68 sites mainly distributed in the pastoral area of Niger because we eliminated the site found in Lake Chad. These data were collected by departmental teams and centralized by the MEIA Pastoral Service. The observation data had the advantage of being collected by agents with experience on the double sampling technique. They have been used for years to determine the national forage balance.

GIS processing

A 9 km² buffer zone (two pixels corresponding to the area of each site) was used to extract data from the biomass model for validationpurposes. The zonal statistics of these buffers were obtained using the zonal statistics plugin of the QGIS software package to extract mean values corresponding to each year. This generated a tabular database containing geographical references, site identifiers (to enable linkage of the database data and ground observations) and biomass values simulated by the model for the 2000-2011 period (Figure 14).

Statistical analysis

The two datasets were compared using parametric and nonparametric tests. This included the paired t-test, which requires conditions suitable for validation (paired observations, data independence, random sampling, normal difference distribution and variance homogeneity); the Wilcoxonand sign tests, which do not require any preliminary hypothesison the forms of distribution (Dagnelie, 2013, Johnson and Bhattacharyya, 2010).

t-test

The t-test was implemented because the two plant biomass datasets to compare were from the sites. For each site, one variable was derived from the model and one was from the *in-situ* field surveys. The t statistic in the case of paired data was calculated using the following equation:$= \frac{M_d}{SE_d}$, where M_d is the difference between the two means, SE_d is the standard error of the difference between the two means. The variable distributions were studied prior to these analyses, along with the variance equality, which is a prerequisite for applying mean comparison tests.

Sign test

This test is used with paired samples. The sign test involves replacing observations greater than *Mo* with a + sign and those

1 A.A.V.V. — Pj AP3A (2001) — VisualCarte — *Système de Gestion de la Cartographie Thématique Version Beta* (CD_ROM. ISBN : 88-900502-8-4.

2http://earlywarning.usgs.gov/fews/africa/

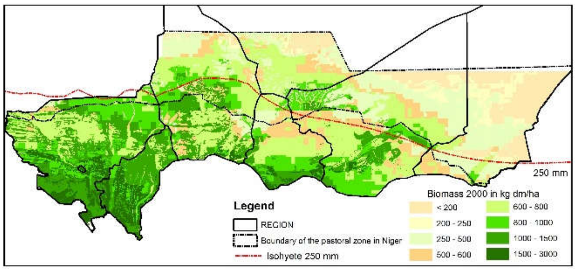

Figure 2. Herbaceous biomass 2000

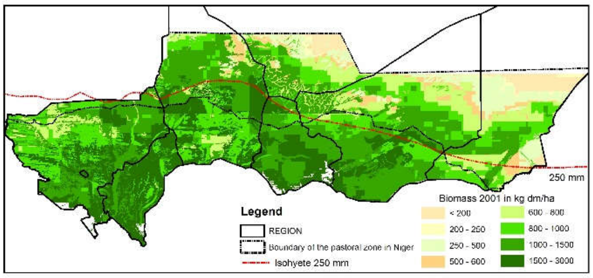

Figure 3. Herbaceous biomass 2001

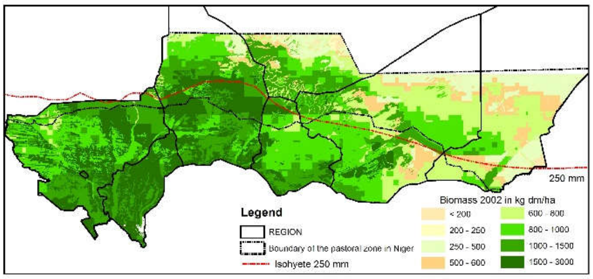

Figure 4. Herbaceous biomass 2002

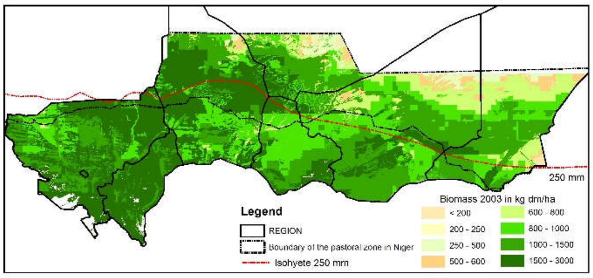

Figure 5. Herbaceous biomass 2003

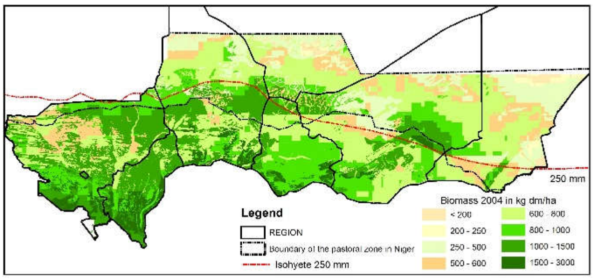

Figure 6. Herbaceous biomass 2004

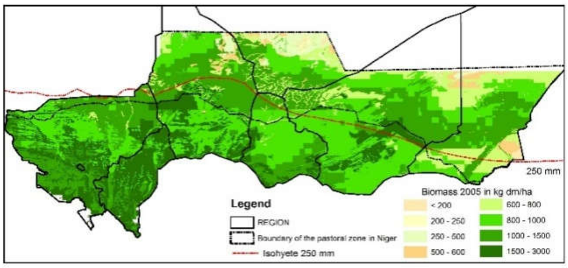

Figure 7. Herbaceous biomass 2005

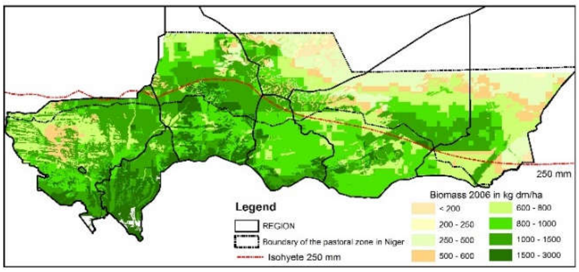

Figure 8. Herbaceous biomass 2006

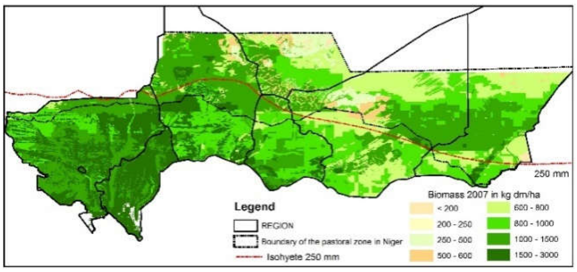

Figure 9. Herbaceous biomass 2007

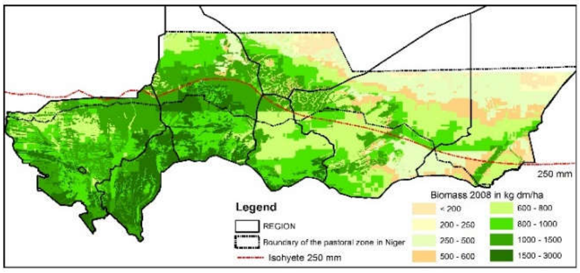

Figure.10. Herbaceous biomass 2008

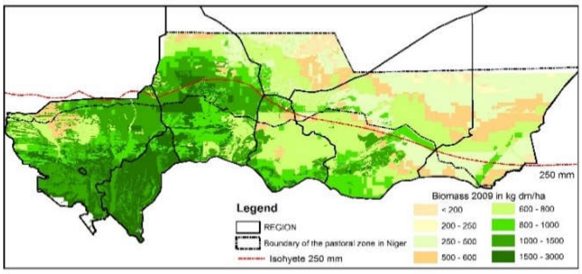

Figure 11. Herbaceous biomass 2009

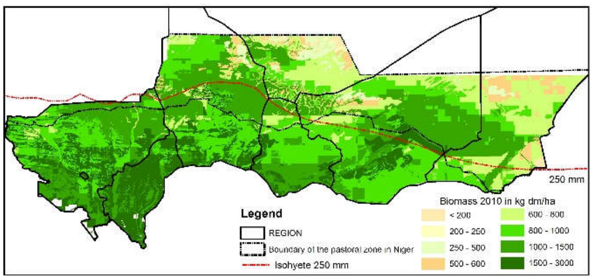

Figure 12. Herbaceous biomass 2010

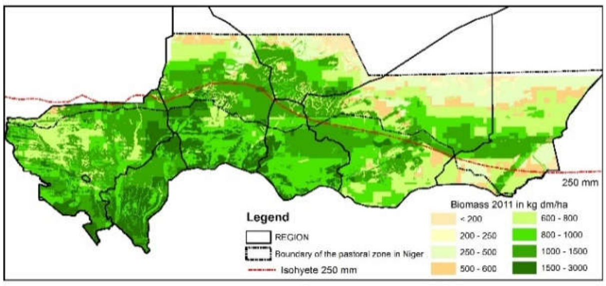

Figure 13. Herbaceous biomass 2011

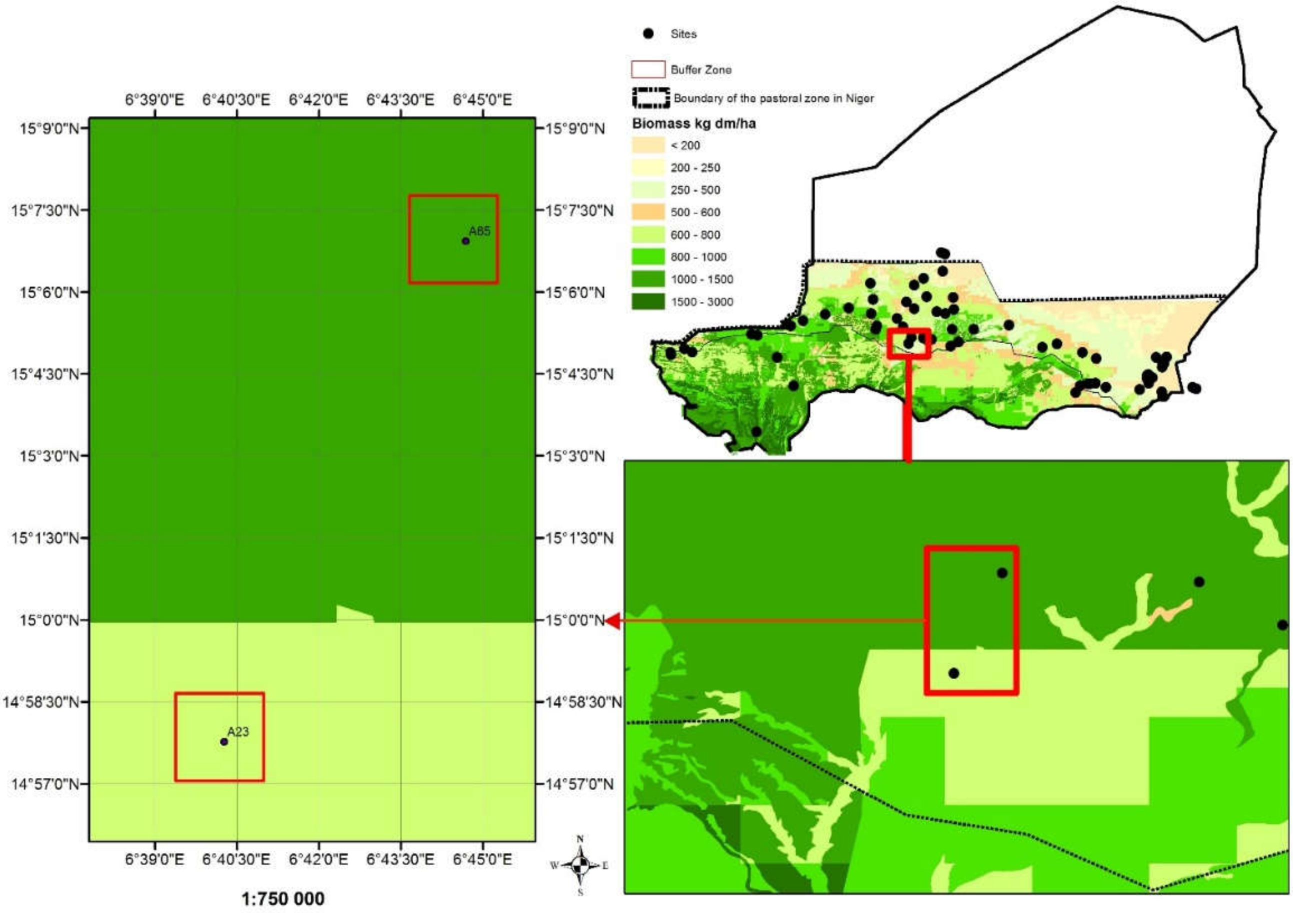

Figure 14. Extraction of herbaceous biomassper site

less than *Mo* with a - sign. If the null hypothesis (H0) holds, then the number of + signs (*n*+), should be close to the number of – signs (*n*). Regardless of the *x* distribution, the number of + signs (which will constitute the statistical test)will have a binomial distribution of parameters n and ½ (this also holds for *n* -, i.e. the number of - signs). If the alternative is unidirectional of the form H1, then the median is greater than*M0* (Gilbert, 2004)

$$H_0\colon \Pr(x \geq 0) = \tfrac{1}{2} \text{versus} H_1\colon \Pr(x \geq 0) \neq \tfrac{1}{2}$$

Wilcoxon test

According to this method, observations are classified in pairs, which enabled us to obtain a count of the difference in signs in pairs (as in the sign test) and the ranks of these differences. Y (+) denotes the sum of the ranks of positive differences, while Y (-) denotes the sum of ranks of negative differences. The principle is: Y (+) + Y (-) = n (n+1)/2, where n is the number of pairs. On average, if the two samples are from the same population, Y (+) and Y (-) both represent half of this value, or: n (n+1)/4 (Rousson, 2013, Good *et al*., 2012, Weiers and Heinz, 2011, Lejeune, 2010).

Correlation

Relationships between the model simulation data and the *in-situ* field data were analysed with different types of correlation coefficient: Pearson'sr, Spearman'sρ, Kendal'sτ and Hoeffding'sD (Brase and Brase, 2012, Weiers *et al*., 2011, Rakotomalala, 2010). Interannual variations in the correlation coefficients were studied. Pearson's correlation is obtained via Pearson's r correlation coefficient, which summarizes the relationship between two numerical variables, and the linkage between the variables$r_p = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$, where$\sigma_{xy}$ denotes the covariance between variables x and yand their standard deviations$\sigma_x \sigma_y$. Spearman's correlation calculates a correlation coefficient between ranks of values of the two variables. This correlation is used when the variable distributions are skewed. The interpretation is identical to that conducted for Pearson's correlation coefficient. Spearman's correlation coefficient is defined by:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)}$$

where *di* = *RXi*− *RYi R* is the rank.

Regarding Kendall's correlation, Kendall's rank correlation coefficient (Kendall τ) is a nonparametric correlation measurement. It is used to determine the relationship between two datasets, as calculated by the equation:$\tau = 1 - \frac{4Q}{n(n^2 - 1)}$ where *Q* is the number of inversions required amongst *Y* values to obtain the same order (increasing) as that of *X* values, while n is the number of paired observations.

Hoeffding's D correlation represents the extent of the dependency relationship between two variables using a rank-based equation (Wilding and Mudholkar, 2008).

$$D = \frac{(n-2)(n-3)D_1 + D_2 - 2(n-2)D_3}{n(n-1)(n-2)(n-3)(n-4)}$$

where $D_1 = \sum_i (Qi-1)(Qi-2)$; $D_2 = \sum_i (Qi-1)(Qi-2)$; $D_3 = \sum_i (Ri-2)(Si-2)(Qi-1)$

RESULTS

The mean comparison results revealed—generally and according to the upper and lower classes of the rainfall threshold (250 mm)—a very significant difference at the 1:10000 level (p<.0001) between the actual *in-situ* productivity (expressed in kgdm.ha^{-1}) and the potential productivity derived from the biomass model simulations (Tables 1, 2 and 3). The year-by-year comparisons also highlighted very significant differences for 2002, 2003, 2004, 2009 and 2011, moderately significant for 2001, 2005, 2006 and 2008, while the null hypothesis could be rejected for 2007 and 2010 at the 5% probability level (Table 4). This confirmed that the model simulations generally overestimated biomass production. The parametric and nonparametric correlations of the entire datas*et al*so revealed highly significant relationships (Table 5). The results were interesting because, even when the correlation coefficients r barely exceeded 0.19, the relationships were still highly significant (p< .0001), depending on the years. The null hypothesis that there is no relationship between the measured data and the model simulation data was thus rejected (Table 5). The annual correlations showed that the relationships varied between the methods implemented depending on the years (Figure 15).

Table 1. Comparison of overall means using the t, Wilcoxon and sign tests

	Number of observations	Mean	SD	t-test	Wilcoxon test	Sign test
Modeled biomass	306	983.17	348.36	t=12.38	s=16394.5	M=96
Actual biomass	306	591.17	521.19	NDOF=305		
				p < .0001	p < .0001	p< .0001

Table 2. Comparison of overall means per rainfall threshold (> 250 mm) using three tests

	Number of observations	Mean	SD	t-test	Wilcoxon test	Sign test
Modeled biomass	261	1042.93	332.53	t=10.93	s=11435.5	M=76.5
Actual biomass	261	641.81	541.46	NDOF=260		
				p < .0001	p < .0001	p< .0001

Table 3. Comparison of overall means per rainfall threshold (> 250 mm) using three tests

	Number of observations	Mean	SD	t-test	Wilcoxon test	Sign test
Modeled biomass	45	666.63	227.16	t=9.66	s=510.5	M=19.5
Actual biomass	45	297.48	216.95	NDOF=44		
				p < .0001	p < .0001	p< .0001

NDOF: number of degrees of freedom

Table 4. Comparison of annual means using three types of test

Year	Nb obs	Modeled biomass		Actual biomass		P		
		Mean	SD	Mean	SD	t-test	Wilcoxon test	Sign test
2001	24	1136.38	63.00	576.50	578.55	0.0003	0.0001	0.0001
2002	24	1097.08	448.15	446.89	298.29	< .0001	< .0001	< .0001
2003	10	1327.65	383.09	833.89	443.53	< .0433	< .0273	0.10
2004	21	808.48	258.82	304.61	211.08	< .0003	< .0003	< .0029
2005	34	1051.31	279.29	643.58	490.98	0.0003	0.0003	0.0029
2006	28	932.17	289.62	684.92	598.89	0.0355	0.0243	0.0037
2007	28	1035.86	319.15	664.22	526.92	0.0708	0.1417	0.3449
2008	40	867.66	302.25	412.97	429.03	0.0001	0.0001	0.0001
2009	20	792.18	366.31	382.09	274.70	< .0001	< .0001	< .0001
2010	35	1013.76	297.52	921.136	779.56	0.80	0.58	0.17
2011	40	963.62	293.97	481.44	578.55	< .0001	< .0001	< .0001

Nb: number; obs: observation; SD: standard deviation

Table 5. Parametric and nonparametric correlations for the whole dataset

Correlation	coefficient	probability
Pearson's r	0.19	< .0001*
Spearman's ρ	0.22	< .0001*
Kendal's τ	0.13	< .0001*
Hoeffding's D	0.01	< .0001*

*significant at the 1:10000 level

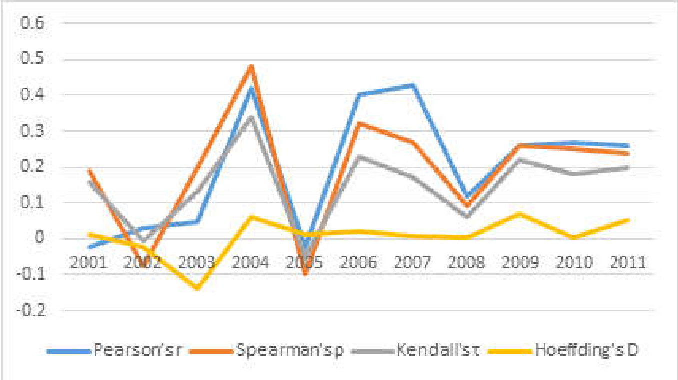

Figure 15. Annual variations in correlation coefficients according to the different tests

DISCUSSION

The differences noted between the BIOMASAH model simulations and the field observations could partly be explained by the livestock grazing pressure. Niger has an overall herd of more than 35 million head of cattle, located mainly in the pastoral area (Zakaria, 2010). According to the Intergovernmental Panel on Climate Change (IPCC), on the global scale, over 20% of rangelands are degraded through overgrazing, compaction and erosion induced by herds. This percentage is even higher in dry land regions where poorly tailored policies and livestock management strategies prevail (Nori and Davies, 2007). This pressure could be partially responsible for substantially lowering the actual productivity because the extent of herd grazed forage intake at these sites (open all year) is unfortunately not accounted for in the model. The seasonal distribution of dry sequences could also partly explain this difference. In recent years, there has actually been increasingly high temporal variability in rainfall, especially with a high frequency of extreme phenomena such as drought and flooding, which can have impacts on productivity (Steinfeld *et al*., 2006). For instance, high cumulated rainfall could be recorded within a very small number of rainy days, but this rainfall is not very favourable for good plant growth because of the high concomitant runoff (resulting in enormous quantitative and qualitative soil loss). Drought slows down plant growth and may even be fatal to them, thus reducing the capacity of rangelands to fully express their grazing potential. When a dry spell occurs during a critical stage of plant growth, it may have catastrophic effects on yields, even when rainfall levels are abundant overall (Aguiar, 2009). Note that the model was not designed to manage dry spells and rainfall deficits are not taken into consideration. High cumulated rainfalltends to overestimate the production potential. The satellite rainfall estimation data were generated by a model, but the coefficient of determination obtained via the CRA validation process was interesting (0.61). The similarities in the overall interannual correlation coefficient variation trends were noteworthy. Moreover, the similarity in the interannual *in-situ* biomass data and the model simulations enhance the prospects of using the biomass model in studies on the impacts of climate change on forage production under spatiotemporal variability conditions. The BIOMASAH model outputs are very interesting because they enable users to monitor and analyse major trends in the annual biomass productivity potential. For instance, the model could be used for qualitative monitoring of the pastoral season and for early warning systems, thus serving as a decision-making tool.

Conclusion

The comparison of means concerning the *in situ* biomass data and the model simulations over the 2001 to 2011 period highlighted a significant difference between these two approaches. The BIOMASAH model overestimated the biomass production, as shown by the parametric test (t-test) and nonparametric test (Wilcoxon and sign tests) findings. The Pearson correlation coefficient was highly significant even though it barely exceeded 0.15, thus supporting the Spearman'sρ, Kendal'sτ and Hoeffding's D correlation results. Further studies are nevertheless required to improve the model, particularly by taking dry spells and grazing pressure into account. The availability of relatively long vegetation index image series and other agro meteorological datasets broadens the prospects for taking 10-day changes in vegetation and phenological aspects of rangelands into consideration.

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