1 Is terrestrial water storage a useful indicator in assessing the impacts of 2 climate variability on crop yield in semi-arid ecosystems?

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6 Abstract

7 The productivity of global terrestrial ecosystems, especially in rain-fed agricultural systems and
8 water-limited semi-arid ecosystems is largely restricted owing to climate-induced freshwater
9 variability. In this study, Lake Chad basin (LCB) is selected as a tentative test bed to exam-
10 ine the utility of terrestrial water storage (TWS) inverted from Gravity Recovery and Climate
11 Experiment (GRACE) measurements as a useful indicator in assessing the impacts of climate
12 variability on annual crop yields (2003–2013) in a semi-arid ecosystem. Regression results show
13 that changes in the temporal series of GRACE-derived TWS in LCB explained significant and
14 higher proportion of variation ($R^2=55\%$, 39% , and 32% , $p < 0.05$) in cashew nut, potatoes, and
15 cowpea yields, respectively, compared to rainfall ($R^2=2\%$, 1% , and 7% , respectively). Rainfall
16 on the other hand, explained a higher ($R^2=32\%$) variability in soybeans than TWS ($R^2=2\%$).
17 Model soil moisture indicated significant relationship ($p < 0.05$) with cowpea ($R^2=48\%$), onions
18 ($R^2=44\%$), and cashew nuts ($R^2=30\%$) somewhat similar to TWS. TWS nonetheless, showed
19 relatively stronger and significant associations with four crops (i.e., cashew nut, potatoes, cow-
20 pea, and rice) than with soil moisture (except cowpea) and rainfall. By integrating TWS with
21 rainfall as input variables to model crop yield data in a neural network system, the input vari-
22 ables are related to crop yield and showed some predictive potentials ($r = 0.89$ for cashew nut
23 vs TWS/rainfall, $p < 0.05$), which can be improved considerably when longer times series of the
24 data (especially TWS) are available for robust network training, testing, and validation. Large
25 proportions of Africa and other non-industrialised regions of the world are heavily reliant on
26 rainfed agriculture. Hence, multi-model climate forecasting studies in these regions can leverage
27 on TWS not only as a soil moisture surrogate to assess the impacts of climate change on future
28 scenarios of food production patterns, but as critical and resourceful input to food security
29 analysis.

30 **Keywords:** Food security, Lake Chad basin, Rainfall, Agriculture, climate variability, Sahel

1. Introduction

Unfavourable hydro-climatic conditions in the Sahelian countries of West Africa, arguably have contributed to famine, decline of primary production, widespread desertification, and land degradation (see, e.g., 62, 41, 79, 87) and have resulted in several negative impacts on the socio-economic systems of the region. These impacts were the primary triggers of several ecosystem assessment based on Normalised Difference Vegetation Index (NDVI) and key hydrological indicators, e.g., rainfall and soil moisture (see, e.g., 4, 15, 38, 8, 37, 52, 37, 5, 35, 41). However, complex hydrological processes such as the well known ‘Sahelian paradox’, where despite the severe drought conditions of the 1970s and 1980s, an extensive network of well observations revealed that groundwater resources and water table in Niger increased tremendously due to changes in land use, amongst other factors (see, e.g., 16, 23, 78, 47, 48). This phenomenon, which has also been reported in several other Sahel regions of West Africa (e.g., 27, 54, 53) coupled with the restrictions of rainfall and soil moisture as hydrological indicators on surface vegetation dynamics in some parts of West Africa (e.g., 8, 37, 5, 35, 66), are notable challenges that warrants further understanding of the region’s eco-hydrological processes and the impacts of climate variability.

In West Africa, a plethora of region and basin-specific studies have employed the latest satellite geodetic programme, Gravity Recovery and Climate Experiment (GRACE, 84) as a vital tool in hydrological research. These studies focused on a wide range of applications, e.g., in droughts (e.g., 62, 59); terrestrial water budget closure (e.g., 26); hydrological characteristics, sub-surface water storage, aquifer system processes (see, e.g., 58, 60, 25, 28, 57, 33, 36); and evaluating the contributions of global climate teleconnections on regional dynamics of terrestrial water storage-TWS (an integrated sum of changes in catchment stores, e.g., groundwater and soil moisture; canopy; and surface waters) (e.g., 61). Given that the observed relationship between long term soil moisture changes and variations in some Sahelian vegetation was found to be inconsistent (37), more insightful studies using GRACE observations might be useful to further assess water-related impacts on the region’s terrestrial ecosystem.

Over mainland Australia, GRACE-observed TWS explained variations in surface vegetation greenness at both inter-annual and seasonal time scales (95) while its role in modulating vegetation response to temperature changes in Eurasia has also been reported (1). This suggests its utility as a hydrological indicator of ecosystem performance in water limited ecosystems and Arctic biomes. However, the potential of GRACE-derived TWS in assessing the response of annual crop yields to the impacts of climate variability in data deficient, semi-arid regions (e.g.,

the Sahel) has not been reported. As mentioned in Chen et al. (12), agricultural development and the productivity of the world’s terrestrial ecosystems depends largely on water availability. In societies where the agricultural production systems are considerably reliant on rainfall, and for semi-arid regions that are presumably water-limited ecosystems, water deficit and extreme hydrologic variability remains a major restriction not only to vegetation growth but crop production and economic output (see, e.g., 95, 32, 69). Hydrological variability has been identified as one of the key factors with adverse effects on the economic growth of non-industrialised regions (e.g., 32, 9), and represents a significant challenge to food security and infrastructure development. Lewis (50) recently pointed out that one major aspects of underlying systemic causes of acute food insecurity in Ethiopia is the high proportion of small scale farmers who are heavily reliant on rainfed agriculture. Similar to Ethiopia and other sub-regions in Africa, the sensitivity of West Africa’s agricultural production system and economy to climate variability is well known (see, e.g., 79, 11, 56, 70, 73, 88, 89). The strong variability of the West African Monsoon (WAM) on different time scales (e.g., inter-annual and multi-decadal), which brings about 70% of the annual rainfall (e.g., 80, 39) may impact adversely on agricultural systems, resulting in food insecurity and low national income. Because of this strong variability in the WAM system and large uncertainties and bias in regional climate projections (e.g., 86, 73, 76, 45), quantifying the impacts of climate variations on agriculture is challenging.

While it is essential for government institutions to make informed and evidence-based decisions on appropriate indicators that will address specific policy issues relevant to food security governance (see, 68), understanding factors that impact on food availability is also critical. As mentioned in Brown and Lall (9), one of the challenges to food production and national income is rainfall variability. According to Vörösmarty et al. (90) who studied geospatial indicators of water stress in Africa, 25% of Africans are already experiencing water stress while an estimated 13% are direct recipients of drought-related stress once each generation. These indicators of water stress could have significant impact on a considerable proportion of Africa’s agricultural biomes, which are mostly found in arid regions. For those regions where agricultural systems are devoid of sophistication yet account for a significant proportion of the gross domestic product (GDP), water stress and increased rainfall variability could translate to food insecurity, social conflicts, and poverty.

Cenacchi (11), for example, noted that drought is a major constraint for crop and livestock production in Africa and across Asia. In a compendium of 16 related studies over West Africa (see, 73, and the references therein), there is evidence that climate change impact negatively on crop yield. Further, quasi-periodic phenomenon such as the El-Niño Southern Oscillation

(ENSO) episodes have shown statistically significant association with some crops in the Sahel region (e.g., 65). It is even anticipated that the impacts of global warming in the future will impact negatively on subsistence farming in several African countries (88). As most climate projections suggest, the result of drought intensity in some areas around the world may lead to risk of crop losses (11). In West Africa where an estimated 70% of the world's cocoa is produced, Schroth et al. (75) noted that drought years caused by El-Niño episodes affected cocoa yields. In addition to this, it has been shown that ENSO play significant roles in the characteristics of extreme climatic conditions in West Africa (e.g., 59, 67, 63), and largely contribute to the temporal and spatial distributions of TWS in the region (e.g., 61). The impacts of climate change on agro-ecosystems are mostly channelled through hydrological drivers such as precipitation, soil moisture, and available freshwater. Consequently, there is a further need to diagnose the suitability of GRACE-derived TWS in assessing the impacts of climate variations on crop yield, particularly when rainfall and soil moisture have shown some weakness in the semi-arid Sahel as indicators of water availability (e.g., 15, 37, 66).

In this study, the potential of GRACE-derived TWS as a useful terrestrial moisture surrogate in mapping the impact of hydrological conditions on annual crop yield in the Lake Chad basin (semi-arid Sahelian region-Fig. 1) is examined. The assessment of GRACE-derived TWS with crop yield data has become necessary given the (i) restrictions of rainfall as a hydrological indicator on terrestrial ecosystems and regional land surface phenology (e.g., 41, 77, 12, 95), (ii) uncertainties in water budget estimates (e.g., 1, 97), (iii) the morphological and physiological adaptations of Sahelian vegetation, which results in complex water use mechanisms during the dry season (e.g., 30, 77, 37), and (iv) lack of considerable investments in observational networks for ecological and hydrological applications.

2. Assessing the impacts of climate variability on food security in the Lake Chad basin

2.1. The region

The Lake Chad Basin (LCB) is the world's largest interior drainage basin covering an approximate area of 2,500,000 km², and supports an estimated 37 million people who depend on its water resources for economic and domestic purposes (e.g., 59, and references therein). Geographically, the basin is seated in the transition zone between the Sahara Desert and the tropical Sudano Sahel region of West Africa. Specifically, it is located between latitudes 6°N and 24°N and longitudes 7°W and 24°E and is occupied by Lake Chad at the centre (Fig. 1). The

Figure 1: Study area showing the riparian countries that constitute the Lake Chad basin and important river networks (blue line) within the basin. The contraction of the Lake Chad surface area owing to the impacts of climate variability for 1973, 1987, 2003, and 2013 are indicated. Map is adapted and modified from Figures 1 and 2 of Ndehedehe et al. (59).

130 impact of persistent and long drought episodes of the 1960s and 1980s in the basin resulted in
 131 a significant contraction of the Lake Chad surface area (see, e.g., 59, 92, 7, 14, 46, 49). Rainfall
 132 is annual, occurring mostly between July and September. The basin is one of the Sahel regions
 133 that is highly vulnerable to the impacts of climate variability and in most cases resulting in ex-
 134 treme drought and water deficit conditions. The various morphological transformations of the
 135 lake owing to several drought episodes in the region are indicated in Fig. 1. Whereas the north-
 136 ern catchment is predominantly arid, the southern catchment is hydrologically active because
 137 of the Chari/Logone River system, Komadougou-Yobe, and other minor rivers (Fig. 1). These
 138 rivers transport more than 95% of the river flows that nourish the Lake Chad (e.g., 59, 13).
 139 Although the desiccation of the Lake Chad was largely attributed to extreme droughts in the
 140 region, water withdrawals from the Lake for irrigation purposes during water deficit periods
 141 (see, e.g., 7, 14) compounded the effects of these drought episodes. Apparently, this underscores
 142 the role of human activities in not only exacerbating the impacts of climate variability but in

also reshaping the stability of Lake’s ecosystem.

2.2. Climate change and food security

Ecosystems and global biodiversity are generally predisposed to adapting to the prevailing climatic conditions. As noted in a recent FAO report (22), when these conditions change, plants and animals will be impacted adversely, mostly in a profound way that diminish productivity and poses additional risk to agricultural production. The impacts of climate change on agro-ecosystems, be it direct or remote, could be enormous-impacting on crop yields and quality, market prices, ecosystem services, national income, and agricultural and other forms of livelihood. Both at region and global scales, not only is climate change expected to increase variability in crop yields in several regions of the world, there is evidence that it has adversely affected crop yields (e.g., 22, and the references therein). This, without doubt will have enormous impacts on food security and livelihood. As large segments of the West African Sahel are heavily reliant on rainfed agricultural systems, the impacts of climate variability on freshwater and ecosystem dynamics would be more devastating. The human-modified droughts of the Lake Chad basin, for example, is typical of the Anthropocene, where various forms of human activities and climate change impact on catchment storage, soil properties, and hydrological processes, thereby modifying or amplifying the severity of such droughts. The combined effects of human activities, climate variability and land surface conditions in the basin could restrict prominent hydrological controls (rainfall and soil moisture) as indicators of ecosystem performance. Apart from increasing water stress under a climate change scenario, significant constraints to estimating the impact of climate change on future freshwater availability have been identified and includes, bias and model uncertainties in rainfall prediction output of climate models even at finer spatial scales; and the fact that changes in rainfall do not show a linear response to water availability (e.g., 22, 86, 76, 45). Other reports (e.g., 1, 97) argued that uncertainties in regional precipitation estimates and water budget indicators are major challenges in understanding vegetation response to water constraints. Because of these issues, GRACE-derived TWS (Section 4.2) is introduced as a new hydrological state variable to help assess the impact of climate variability on annual crop yield in a semi-arid ecosystem. One important message in this assessment would be that it will enhance our understanding of the effects and role of climate on food security and nutrition in the region.

3. Data and methods

3.1. Data

Terrestrial water storage (TWS) product used in this study was derived from the GRACE (84) satellite mission. The mission provides an integrated sum of changes in surface waters, catchment stores (e.g., groundwater, soil moisture, etc.), and canopy based on the observations of the Earth's time variable gravity fields. GRACE observations have been extensively used to study the Earth's water storage changes at regional, continental, and global scales (e.g., 59, 83, 94, and the references therein). In this study, the GRACE Release-05 (RL05) spherical harmonic coefficients obtained from Center for Space Research (CSR, <http://icgem.gfz-potsdam.de/ICGEM/shms/monthly/csr-rl05/>) covering the period of 2002 – 2014, are used to estimate TWS over the region on a $1^\circ \times 1^\circ$ grid following the approach of Wahr et al. (91) as

$$\Delta TWS(\phi, \lambda, t) = \frac{R\rho_{ave}}{3\rho_w} \sum_{l=0}^{l_{max}} \frac{2l+1}{1+k_l} \sum_{m=-l}^l P_{lm}(\phi, \lambda) \Delta Y_{lm}(t), \quad (1)$$

where ΔTWS is the equivalent water height (hereafter TWS) for each month in time (t), and ϕ and λ are the geodetic latitudes and longitudes, respectively. R is the mean radius of the Earth (i.e., 6378.137 km), ρ_{ave} is the average density of the Earth (5515 kg/m^3), ρ_w is the average density of water (1000 kg/m^3), k_l is the load Love numbers of degree l , P_{lm} are the normalized spherical harmonic functions of degree l and order m with $l_{max}=60$ and ΔY_{lm} are the normalized complex spherical harmonic coefficients after subtracting the long term mean. Due to signal attenuation, which causes noise in the higher degree coefficients (e.g., 82), the regularization filter of Kusche et al. (43) was applied on the spherical harmonic coefficients in order to reduce the effect of the correlated noise. As this process of regularizing GRACE-observations usually result in leakage, the damping of the signal amplitude was compensated for using the Landerer and Swenson (44) approach. This approach, which has been widely employed in a plethora of GRACE-hydrological studies (see, e.g., 93, 81, 51, 24) derives a gain factor k by minimizing the misfit between the unfiltered and filtered storage time series based on simple least square regression (see, 44). This gain factor is applied to the gridded fields of GRACE data to recover the geophysical signals that were lost as (e.g., 58, 81)

$$TWS'(\phi, \lambda, t) = TWS * k(\phi, \lambda), \quad (2)$$

where TWS' is the GRACE-derived TWS corrected for leakage. This reduces the variance of the leakage error by more than 80% (e.g., 44). Further, averaged TWS (i.e., W) values over the

basin were computed using the area weighted average (see, e.g., 62):

$$\Delta W(\chi; t) = \sum_{l=1}^n \Delta W(\phi_i, \lambda_i, t) \frac{A_i}{A_\chi}, \quad (3)$$

where χ is the basin index, n is the number of pixels in the basin, A_i is the area of the grid cell i in χ and A_χ is the total area of χ . As opposed to GRACE applications in studies of droughts and floods (see, e.g., 59, 85, 71, 96), it is employed here as a tool for assessing the impacts of climate variability on crop yield. In the remainder of the manuscript GRACE-derived TWS is simply referred to as TWS. Since TWS are monthly anomalies, they were aggregated to yearly values in order to be consistent with annual crop data.

Further, selected national annual crop yield data for Nigeria (soybeans, cashew nut, cowpea, and potatoes) and Chad (beans, onions, potatoes, and rice) during the 2003 – 2013 period were downloaded from the Food and Agricultural Organisation’s (FAO) website (<http://faostat3.fao.org/download/Q/QC/E>). Also, precipitation from Tropical Rainfall Measuring Mission (TRMM) 3B43 (42), covering the period 2002–2013 is used in this study to examine the response of annual crop yield to rainfall variability. The data has a global coverage (50°S and 50°N) with a spatial resolution of 0.25° x 0.25° and is available at the National Aerospace and Space Administration (NASA) Goddard Space Flight Center (GSFC) website (<http://disc.gsfc.nasa.gov/datacollection/TRMM3B43-V7.shtml>). Further, monthly CPC model soil moisture data (21) with spatial resolution of 0.5° x 0.5° was used to investigate the response of crop yield data to soil moisture. Ideally, soil moisture is the most suitable indicator for studying the response of plants to climatic changes (e.g., 12). However, it has shown weak relationship with surface vegetation greenness in the Sahel region (e.g., 37). It would therefore be logical to compare its relationship with crop yield data to observed outcome of TWS-crop yield relationship. The CPC model soil moisture data is freely available at National Oceanic & Atmospheric Administration (NOAA) (<http://www.esrl.noaa.gov/psd/data/gridded/data.cpcsoil.html>) for download. In the remainder of the manuscript, the CPC model soil moisture is simply referred to as soil moisture for convenience. MODIS derived monthly evapotranspiration estimates with a spatial resolution of 0.5° x 0.5°, covering the period 2000 – 2014 are also used in the study to determine available freshwater over LCB expressed through net precipitation (e.g., 4). The ET data is available for download at the Earth Observing System of NASA’s website (<http://www.ntsg.umd.edu/project/mod16>).

3.2. Method

The association of TWS anomalies and TRMM-based precipitation to these crop yield data is evaluated using a simple linear regression model (note that only normalised units of the data

are used). Regression analysis is a popular statistical technique for investigating and modelling the relationship between variables. To establish the relationship between n paired data series (x_i, y_i) , the expression is given as

$$y' = \beta_0 + \beta_1 \cdot x + \varepsilon, \quad (4)$$

where y' is the target data (response or dependent variable) and x is the independent variable (predictor), β_0 and β_1 are constants and ε is the error term, which can be minimized in the least square sense by defining an error function, ξ as

$$\xi = \frac{1}{n} \sum_{i=1}^n \varepsilon_i^2 = \frac{1}{n} \sum_{i=1}^n (y' - y_i)^2, \quad (5)$$

such that the error function becomes the sum of the squared differences between the data series and the linear equation. Coefficient of determination (R^2) is employed to measure the proportion of variance in the dependent variable (y') that is explained by the independent variables (x) in the linear regression model. The null hypothesis of no relationship between two variables is tested using the Student-t distribution test ($\rho < 0.05$). Further, TWS was integrated with rainfall in an Artificial Neural Network (ANN) framework to model their relationship with crop yield. ANN models are widely used machine learning applications for forecasting purposes. Our motivation for the ANN model is because they are flexible computing frameworks and universal approximators that can be used in several forecasting problems with relatively high accuracy (e.g., 40). The relationship between the output (y_t) and the inputs ($y_{t-1}, \dots, y_{t-p}$) can be represented mathematically as (e.g., 40)

$$y_t = w_0 + \sum_{j=1}^q w_j \cdot g(w_{0,j} + \sum_{i=1}^p w_{i,j} \cdot y_{t-i}) + \epsilon_t, \quad (6)$$

where w_j ($j = 0, 1, 2, 3, \dots, q$) and $w_{i,j}$ ($i = 0, 1, 2, 3, \dots, p, j = 1, 2, 3, \dots, q$) are the model parameters referred to as the connection weights; p and q are number of input nodes and hidden nodes, respectively. The network performs a nonlinear functional mapping from the observations (rainfall and TWS) to the predicted value (crop data) similar to a nonlinear auto-regressive model. The model's performance is assessed by dividing the input data into training and test samples. There is no systematic rule in choosing q as it is largely data-dependent. Other implementation protocols include choosing the number of hidden nodes appropriately and the selection of the number of lagged observations, p , and the dimension of the input vector (e.g., 40). The predictive performance of the model is improved based on the data presented to the network (e.g., 34). Details about the types of activation functions and implementation guidelines for developing ANN model can be found in Maier and Dandy (55).

Figure 2: Hydrological drivers of the Lake Chad basin. The observed relationships of monthly anomalies after removing the mean for the common period (2002/04-2013/12) is indicated for (a) precipitation vs TWS, (b) TWS vs CPC model soil moisture, and (c) TWS vs available freshwater flux expressed as net-precipitation (difference between precipitation and evapotranspiration over the basin). Cross correlation was used to examine the time lag (months) in which maximum correlation is observed for the rainfall-TWS and TWS-net-precipitation relationships in (a) and (c), respectively.

4. Results

4.1. Hydrological drivers in the Lake Chad basin

Understanding hydrologic drivers of the LCB is crucial to assessing the influence of variations in regional climates on agricultural systems. As shown in Fig. 2a, rainfall is poorly associated with TWS ($r = 0.37$) but shows maximum correlation ($r = 0.89$) at approximately two months lag. Although rainfall leads TWS by two months in much of West Africa (58), observed phase shift between rainfall and TWS could go up to 90 days in other regions (e.g., 81). TWS is strongly associated with soil moisture ($r = 0.95$) with the former indicating a rather similar peak-to-peak amplitude during the period as soil moisture (Fig. 2b). The CPC model soil moisture, which is derived from gauge rainfall and reanalysis-derived temperature data could be

Figure 3: Comparing the response of TWS and rainfall to crops in northern Nigeria. (a) Relationship between annual crop yield in Nigeria and average annual TRMM based precipitation anomalies over Lake Chad basin and (b) relationship between annual crop yield in Nigeria and TWS anomalies in the Lake Chad basin. The crop yield data and TWS are in normalised units. Other regression outputs such as the slope values (r) and root mean square errors (RMSE) are also indicated. Asterisks (*) show that the observed relationship is not statistically significant ($\rho < 0.05$).

a very useful complementary data in hydrological studies of the region. Essentially, the strong TWS-soil moisture relationship represents variations of soil moisture components in the GRACE water column. Similar to Fig. 2a, monthly net-precipitation in Fig. 2c shows a considerable lower association with TWS ($r = 0.26$) but indicates a maximum correlation ($r = 0.85$) at two months lag. Net-precipitation can be used as a hydrological indicator to depict the state of available freshwater flux (e.g., 4). It can be combined with TWS to evaluate water budget

more comprehensively. For example, years when TWS indicated higher pronounced peaks than net-precipitation (e.g., 2006 – 2012, Fig. 2c) were characterised by excess water evident in strong positive values of standardised precipitation index and increased Lake Chad water levels (e.g., 59). On the other hand, years when TWS and net-precipitation have similar peak amplitudes (e.g., 2002 – 2004, Fig. 2c) are either marked by excessive ET or characterised by drought conditions. The years between 2002 and 2004 actually coincided with extreme low water levels of Lake Chad and location-specific water deficit condition in the LCB (59). As noted in FAO (22), increased demand for water during ET process by vegetation and crops, caused by a rise in temperature will result in rapid soil moisture loss. If increasing temperature is considered an indication of high evaporative demand (the rate of water loss from a wet surface), in dry tropics where atmospheric conditions regulate the development, population and the life span of canopy phenology (18), TWS would better account for plant water availability. Hence, as soil moisture is strongly associated with TWS (Fig. 2b), the latter apparently would be the most critical hydrological unit for assessing the impacts of climate variability on annual crop yield in the riparian countries of the LCB, given its water column and depth. Soil moisture may also be useful in such assessment but the lack of moisture observational networks coupled with the uncertainties and restrictions in satellite and model estimates of soil moisture (e.g., 95, 17, 64) however, are challenging issues for the region. TWS therefore becomes an ideal and available hydrological unit to support the knowledge of climatic influence on the region’s agricultural systems, especially given the structural formation of vegetation in the semi-arid Sahel region, which may be subject to complex water use during the dry season (e.g., 30, 77, 37).

4.2. The influence of TWS on annual crop yields

Two riparian countries of the LCB (i.e., north-east Nigeria and southern Chad) have been used here as tentative test beds to examine the potential of GRACE-derived TWS as a soil moisture surrogate to monitor the influence of climate on crop yield. The regression of annual crops in Nigeria with TWS and rainfall indicate that soybeans are more influenced by rainfall anomalies ($R^2=32\%$) while cowpeas, cashew nuts, and potatoes are more associated with TWS anomalies ($R^2=32\%$, 55% , and 39% , respectively). Their R^2 and linear correlation (r) values suggest that rainfall and TWS explain fairly significant proportion of the variability in the aforementioned crops (Figs. 3a-b). In Chad, contrary to rainfall, which shows no significant association with any of the crops ($p > 0.05$), TWS anomalies explain more variabilities in potatoes and rice. Specifically, TWS anomalies explain a higher variability in potatoes and rice (34% and 32% , respectively) in Chad compared to rainfall, which indicates a rather little

Figure 4: Comparing the response of TWS and rainfall to crops in southern Chad. (a) Relationship between annual crop yield in Chad and average annual TRMM based precipitation anomalies over Lake Chad basin and (b) relationship between annual crop yield in Chad and TWS anomalies in the Lake Chad basin. Other regression outputs such as the slope values (r) and root mean square errors (RMSE) are also indicated. Asterisks (*) show that the observed relationship is not statistically significant ($p < 0.05$).

association with the same crops (Fig. 4). Unlike in Nigeria where rainfall was found to explain slightly higher proportion in the variability of soybeans than TWS anomalies (Fig. 3a), in Chad, beans has no relationship with either rainfall or TWS (Figs. 4a-b). Overall, rainfall shows a significant association with only soybeans (Fig. 3a) while TWS is associated with cashew nut, cowpea, potatoes, and rice (Figs. 3b and 4b).

The regression results of soil moisture with cashew nuts ($R^2=30\%$) and cowpea ($R^2=48\%$) in Nigeria (Fig. 5a) are somewhat similar to those of TWS in Fig. 3b as they are generally

Figure 5: Comparing the response of crops to soil moisture conditions. (a) Relationship between annual crop yield in Nigeria and average annual CPC based soil moisture anomalies over Lake Chad basin and (b) relationship between annual crop yield in Chad and average annual CPC based soil moisture anomalies over the Lake Chad basin. The crop yield data and soil moisture units have been normalised. Other regression outputs such as the slope values (r) and root mean square errors (RMSE) are also indicated. Asterisks (*) show that the observed relationship is not statistically significant ($p < 0.05$).

statistically significant ($p < 0.05$). Whereas TWS comparatively indicates a better association with cashew nuts ($R^2=55\%$; $r = 0.74$) compared to soil moisture, on the other hand, soil moisture is more associated with cowpea ($R^2=48\%$; $r = 0.69$) compared to TWS ($R^2=32\%$; $r = 0.56$). Again, TWS actually indicated significant relationships with more crops (Figs. 3b and 4b) unlike soil moisture (Figs. 5a and b). Be it Nigeria or Chad, potatoes showed significant relationship with TWS ($R^2=39\%$ and $r = 0.62$; $R^2=34\%$ and $r = 0.59$, respectively, Figs. 3b and 4b) unlike soil moisture, which indicated no significant relationship with potatoes despite a near-moderate correlation value of 0.46 (Fig. 5a). In Chad, the relationship of TWS to potatoes and rice are significant ($R^2=34\%$ and $r = 0.59$; $R^2=32\%$ and $r = 0.57$; respectively, $p < 0.05$) unlike soil moisture that indicates no significant association with these crops (Fig. 5b), though a significant relationship exist between soil moisture and onions ($R^2=44\%$). Figure 6 shows the neural network results of combining TWS and rainfall as input variables to model the

Figure 6: Integrating TWS and rainfall in an ANN framework to assess relationship with crops. The annual crop yield and TWS/rainfall data were standardised before input into the ANN framework. The regression plots and system validation performance are indicated for (a) cashewnut vs TWS/rainfall, (b) potatoes vs TWS/rainfall, (c) cowpea vs TWS/rainfall, and (d) soybeans vs TWS/rainfall.

crop yield data. The model output, which also shows the nature of the best-fitted network (validation performance) in terms of their mean squared error indicates cashew nut can be predicted better with some degree of accuracy by integrating TWS with rainfall ($r = 0.89$, Fig. 6a) as opposed to other crops (Figs. 6b-d). Although the forecast experiment is limited by samples of training and testing data used, generally, there are some indications that combining TWS and rainfall in a neural network can be helpful in forecasting crop yield. The various correlation values of 0.79 (potatoes vs TWS/rainfall), 0.75 (cowpea vs TWS/rainfall), and 0.80 (soybeans vs TWS/rainfall), as shown in Figs. 6b-d suggest these crops are somewhat related to the composites of TWS/rainfall. However, the response of these crops to state variables and fluxes can be significantly improved if longer times series are available for robust network training and testing. Hence, we interpret the modelling of TWS/rainfall-crop relationship with caution owing to the limited temporal series of data used in the neural network training and validation.

5. Discussion

5.1. Water availability as the driver of annual crop yield

The observed significant associations of crop yield with TWS in Figs. 3b and 4b do not negate the influence of rainfall on crop yield and vegetation dynamics in the Sahel zone as Guan et al. (29) had reported the influence of rainfall on sorghum yields in West Africa. They argued that crop yield is fundamentally dictated by the total rainfall amount during the wet season. Consistent with previous studies (e.g., 41, 8, 5, 66, 35) however, eccentric environmental situations exists in the Sahel, where the development of vegetation and crops are not explained by rainfall alone, instead by multiple strings of anthropogenic factors. These factors, for example, include; population displacement, change in land use pattern, improved land management, use of fertilizers, and irrigation amongst others. Since agriculture in these two riparian countries (northern Nigeria and Chad) of the basin are somewhat irrigated as rainfall is relatively low, that could explain in part the slightly higher proportion of variability explained by TWS anomalies compared to rainfall. It is known that TWS changes integrates precipitation over time and for the Lake Chad basin it is largely driven by changes in soil wetness. Given the low annual rainfall and the influence of hydraulic characteristics of the soil and increased evapotranspiration in the basin during drought periods (59), TWS may be considered a suitable and readily available hydrological control for crops and vegetation. TWS is increasingly becoming useful in drought characterisation and monitoring of terrestrial moisture changes. Apart from its capability in the characterisation of the 2002/2003 Canadian Praire droughts, Yirdaw et al. (96) stressed the resourcefulness of TWS as a soil moisture surrogates for drought studies in data-deficient regions around the globe, and those that show similar hydro-geological characteristics of the Canadian Prairie. Recently, TWS was also included in a suite of other multi-resolution data to characterize agricultural drought in East Africa (2).

In spite of the foregoing results (Section 4.2), we acknowledge the fact that other human and environmental factors may introduce some uncertainties in our results, which have not been accounted for, hence the need to interpret the results with caution. For example, soil type, the use of fertilizers, root system, disease, weeds, differences in growing season, temperature, and the use of drought tolerant species (crops) amongst others may also affect the response of crop yield to TWS anomalies, rainfall and soil moisture. However, if these factors and improved farming techniques and adaptation strategies are constant, one significant factor that will determine the trajectory of agricultural yield for most rainfed agricultural systems is freshwater availability. Since a shift in climate trends impact on water water availability, crop yield arguably will be

374 affected. Further, as indicated in Fig. 3a, rainfall explained higher proportion of the variability
 375 in soybeans ($R^2=32\%$; $r=0.57\%$, $p < 0.05$) in Nigeria compared to TWS while the latter showed
 376 a stronger association with cowpea, cashew nuts and potatoes as opposed to rainfall (Fig. 3b).
 377 This distinction in crop response to rainfall and TWS in the region, apart from irrigation, also
 378 emanates from local (e.g., temperature), and numerous human, and environmental conditions in
 379 the sub-regions. Cashew nut, for example, shows relatively the strongest association with TWS
 380 ($R^2=55\%$; $r=0.74\%$ and apparently the lowest RMSE, $p < 0.05$) compared to other sampled
 381 crops in Nigeria (Fig. 3b). Cashew nut is a tree crop with deep tap root system that can thrive
 382 in arid environments and survives several months without water (irrigation or rainfall). As ET
 383 is a major source of water loss in the LCB (e.g., 59), increased ET could result in longer periods
 384 of soil moisture deficits. It is worthy of note that the water use mechanics of such crops could be
 385 somewhat complex owing to their ability to draw moisture from the water table region. Given
 386 the multi-layer components of TWS, which includes soil moisture and sub-surface quantities,
 387 it could be more useful in assessing the direct impacts of climate variability on the production
 388 systems of tree crops such as cashew nuts in semi-arid regions. Overall, the considerably strong
 389 association between TWS and soil moisture (Fig. 2b) supports the argument that it can serve
 390 as a soil moisture surrogate in semi-arid regions for studying water driven variability in surface
 391 vegetation and the effects of climate change on agricultural activities. The observed association
 392 between soil moisture and TWS ($r=0.95\%$) merely suggest that changes within the multi-layer
 393 water column of GRACE-TWS are primarily within the unsaturated moisture zone. This zone
 394 responds faster to strong meteorological shifts resulting from regional climate change. The
 395 significant response of cashew nuts and cowpeas to soil moisture conditions in Fig. 4a, similar to
 396 TWS (Fig. 3b) supports this assumption. In high risk groundwater-dependent arid ecosystems
 397 where agriculture is profoundly irrigation based, increased ET owing to a rise in land surface
 398 temperature may lead to an imbalance in the water budget as rainfall is very limited and highly
 399 variable. Considering that TWS provides an overview of the water budget, in this circumstance,
 400 its potential as a suitable hydrological indicator to monitor the impact of climate variations on
 401 agricultural water use cannot be stressed enough.

402 It is noticed, though not absolutely general, that crops grown during the dry season (Novem-
 403 ber to March) are more likely to be associated with TWS anomalies and soil moisture (e.g.,
 404 cashew nuts, onions, etc.) as water supply is mostly through irrigation while those planted in
 405 the rainy season (either onset or the peak) tend to be more associated with rainfall (soybeans).
 406 Because of strong variability in annual rainfall over the region, yearly cumulations from 3 and
 407 6-monthly rainfall did not improve the associations between rainfall and crop yields (not shown).

408 Given that only soybeans showed a fairly significant association with rainfall ($r = 0.57$), it is
 409 not clear if planting season and or crop type (long cycle and short cycle) impact on observed
 410 relationship. However, in Ethiopia the narrative is different as rainfall deficits have negatively
 411 affected crop yields and have significantly contributed to food insecurity, amongst other factors
 412 (e.g., 50, 88, and the references therein). Furthermore, the response of crops to rainfall and
 413 TWS differ across ecological landscapes. For dry and arid Sahelian environments, where an-
 414 nual rainfall is relatively low and may be poorly associated with vegetation conditions due to
 415 aridity, rainfall is largely limited as a hydrological indicator for crops since agriculture is mostly
 416 irrigation based and cultivated crops are most likely drought tolerant species. Consequently,
 417 TWS could perform better than rainfall in monitoring crop yield, especially for crops grown
 418 during dry season and also those that require longer periods for optimum yield. Region-specific
 419 detailed studies in West Africa will be required to further examine such possibilities and the
 420 potential of TWS in this capacity. Nonetheless, if TWS can be considered as a low pass filter to
 421 rainfall (i.e., it's an integration of changes in rainfall over time), integrating rainfall with TWS
 422 in a predictive framework could be useful in forecasting crop yield, especially when the length of
 423 input variables are sufficiently large to support robust training and validation. Using the ANN
 424 model, such potentials have been demonstrated in Fig. 6 and confirms water availability as a
 425 key driver of crop yield in arid ecosystems. The response of crops to TWS, or to the combi-
 426 nation of rainfall/TWS in an ANN framework as highlighted in this study nevertheless, should
 427 be interpreted with caution as longer records of GRACE-derived TWS would be required for
 428 further assessment and validation.

429 Further, Guan et al. (29) believes that total rainfall during the rainy season coupled with
 430 a delayed rainy season in the arid regions of West Africa largely determines crop yield. Some
 431 local scale studies in Nigeria (e.g., 3, 19), however, have argued that planting dates for soybeans
 432 and cowpea, also largely contributes to crop yield. For example, they argue that late planting
 433 may expose crops to late season pests and insufficient soil wetness condition, owing to the early
 434 cessation of rain, thereby reducing annual crop yield. Rainfall is no doubt a major catalyst
 435 and driver of hydrological conditions. But owing to aridity which is a feature of most Sahelian
 436 countries, and the other factors mentioned earlier (e.g., irrigation), it cannot by itself explain
 437 significant proportions of variability in annual crop yields. In this study, the intricacies associ-
 438 ated with rainfall and crop yield in arid ecosystems and other environmental conditions are well
 439 noted and future studies maybe warranted in this regard in order to provide further clarification.
 440 Apart from the suitability of GRACE-derived TWS as an indicator of water availability over
 441 much of the Sahelian countries, this contribution also provides a schema for future studies, to

442 explore extended GRACE observations as a tool to enhance our understanding of the impacts of
443 climate variability on crop yield and agricultural production systems. Such studies will provide
444 new perspectives on African ecology, especially in the arid ecosystems where strong positive
445 association of TWS changes with soil moisture was found.

446 *5.2. Implications on food security*

447 The anticipated increase in the population of Africa would likely be met by inadequate
448 food supply if pressing issues such as climate change adaptation, increased food production,
449 investment in the development of water infrastructures for agricultural purposes, increased
450 economic integration, amongst others are not included in scientific discourse. Malnutrition,
451 hunger, and limited food supply are apparently critical indicators of food insecurity. Apart
452 from the leading cause of food insecurity being linked to insufficient food production, sad
453 enough, it is still a major global concern, given the estimated 1 billion people who are un-
454 dergoing suffering, starvation, and malnutrition (e.g., 74). In an assessment of the efforts made
455 by Economic Community of West African States (ECOWAS) towards agriculture and food
456 security in West Africa, poverty, instability, social agitations, overpopulation, poor develop-
457 ment of water resources, environmental degradation were identified as the hallmarks of the re-
458 gion (http://www.osiwa.org/ecowas_at_40/agriculture-food-security-west-africa/). The impacts
459 of long term climatic trends in the past, which attracted the interventions of the international
460 community and other relevant donor organizations are few indications of the long history of
461 the region's vulnerability to extreme climatic conditions. These impacts as detailed by Ben-
462 son and Clay (6) combined with structural adjustment problems affected the economies of the
463 region, for example, on national income through foreign-exchange availability and government
464 expenditures.

465 Several challenges and constraints, e.g., lack of sophistication and modernisation of agri-
466 cultural systems, combine with climatic factors to restrict agricultural development and food
467 production system. In most sub-regions of West Africa, agriculture is heavily reliant on rain-
468 fall and largely characterised by insufficient water management, limited fertilizer use, low soil
469 fertility, amongst other factors. Because of these, droughts and other forms of extreme changes
470 in climate do have devastating effects on food security and national incomes due to failure in
471 agricultural production. For example, Haggblade et al. (31) noted that whereas staple food
472 production is more stable in the coastal West African region due to favourable climate, drought
473 in the Sahelian West Africa reduces domestic rainfed cereal production by 20%. Similarly,
474 during the 2008 – 2009 period in Southern Africa, more than 22 million people were classified

475 as food insecure owing to severe drought ([http://theconversation.com/sub-saharan-africa-has-](http://theconversation.com/sub-saharan-africa-has-a-long-way-to-go-before-it-cracks-food-insecurity-56100)
476 [a-long-way-to-go-before-it-cracks-food-insecurity-56100](http://theconversation.com/sub-saharan-africa-has-a-long-way-to-go-before-it-cracks-food-insecurity-56100)). Whereas drought in Sub-Sahara-SSA
477 (includes large parts of West Africa) is the most significant climate influence on GDP (10),
478 the need to understand the contributions of climate and the food system of the region to food
479 insecurity has recently been emphasized (50). Apart from West Africa, several other African
480 sub-regions have experienced multiple drought events and rainfall deficits, which had consider-
481 able and significant impacts on the region’s resources, contributing to famine and malnutrition
482 (e.g., 2, 72, 79, 6). Generally, agriculture in West Africa is sensitive to climatic conditions and
483 for the low income Sahelian house holds, multiple climate shocks and variability are signifi-
484 cant challenges to ensuring food security, amongst other factors. Hence, understanding the link
485 between hydrological variability and agricultural yield supports the development of an early
486 warning system that could mitigate food insecurity in the region.

487 West Africa being one of the world’s poorest regions with increasing population and con-
488 siderable intensity in climate extremes, under a climate change scenario, the region perhaps,
489 could be the most vulnerable to severe water stress and human-modified drought in the nearest
490 future. As most agricultural goods are produced in regions that are vulnerable to water-related
491 impacts, this could have massive implications not just on food security in West Africa but other
492 regions of the world that directly consume the agricultural goods produced in West Africa (e.g.,
493 cocoa). Water availability can therefore be thought of as a critical food security indicator that
494 is useful for policy makers and can support risk management and monitoring efforts of relevant
495 government agencies. The relationship of TWS with some crop yield data in northern Nigeria
496 as observed in the regression result (Fig. 3b), for example, could be useful in a number of ways.
497 Firstly, it can be used as a resourceful input to predict future yields in the region where there
498 is considerable reliance on climate sensitive activities. Secondly, it demonstrates the utility of
499 TWS as a soil moisture surrogate to assess the impacts of climate change on future scenarios of
500 food production patterns. Given the contemporary global status on the water, energy, and food
501 nexus (20), a renewed focus on the relationship between water availability and food security
502 systems in the semi-arid regions of Africa and its impact on agricultural systems is critical,
503 especially to support the formulation of policies that mitigate losses due to climate change
504 and promote the sustainability of freshwater and food production. Further, the formulation of
505 structural adjustment programmes and modelling of drought impacts that incorporates hydro-
506 logical state variables such as TWS could enhance the region’s management of available water
507 resources to support agricultural production system. The use of satellite rainfall estimates to
508 study the links between climate and crops in data deficient regions of West Africa are good

alternatives (70). Nonetheless, as mentioned earlier in this study, they are largely restricted because of uncertainties and only provides an indirect observation of water availability (e.g., 1, 12, 95). As recently showed in West Africa, satellite rainfall estimates can lead to large biases in crop modelling (70). Hence, as water availability is a major factor that limits crop growth, multi-ensemble climate modelling studies can employ TWS as a critical input to crop water balance model. This model as described in Verdin et al. (88) evaluates moisture availability to a crop relative to its needs during the growing season. This could be useful in food production projections and improve future scenarios of crop yield production patterns.

6. Conclusions

When the prevailing climatic conditions of a typical rain-fed agricultural system changes (e.g., change to water deficits or drought conditions), plants and ecosystem services are likely to be impacted adversely in ways that could diminish agricultural productivity and increase variability in crop yields, leading to food insecurity, poverty, and other social problems. This study provides an overview of the utility of GRACE-derived TWS in assessing the impacts of climate variability on annual crop yields in a semi-arid ecosystem (the Lake Chad basin). Because of the uncertainties in water budget estimates, restrictions of rainfall as a hydrological indicator on terrestrial ecosystems, and the limited observational infrastructure for terrestrial moisture monitoring, amongst other factors, the potential of TWS to support food security assessment in a rainfed agricultural system was investigated. The use of global climate models to study the impact of climate change on West Africa's agro-ecological system is challenging owing to significant uncertainties and bias in regional climate change projections. Consequently, GRACE-derived TWS is here introduced as a new hydrological state variable to help assess the impact of climate variability on annual crop yield in a semi-arid ecosystem. The use of GRACE-derived TWS in this study to assess the impacts of climate variability on annual crop yields demonstrate the novel potential of TWS as a prominent driver of ecosystem performance that complements rainfall and soil moisture in the data deficient region. GRACE-derived TWS explained significant variability in the annual yields of some major crops in the Sahel region. This observed relationship can be used to improve crop models that will support future evaluation of the impacts of climate variability on crops.

Climate variability represents a significant challenge to water availability, which in turn influences global food production patterns. As already highlighted in this study, hydrological variability and food insecurity are prominent key features of regions in monsoonal and tropical climates. To help address some of the challenges of unmitigated impacts of climate change in

542 these regions, especially for those tropical semi-arid ecosystems where significant proportion
543 of annual rainfall and annual river flows are concentrated in only few months of the year,
544 integrating TWS and rainfall in climate monitoring and forecasting will be a useful logical step
545 in creating a dichotomy between the impacts of climate change and other socio-economic and
546 environmental variables on national food security systems. The results from the study on the
547 one hand, show the resourcefulness of TWS as a terrestrial moisture surrogate in studying the
548 impacts of climate variability on the annual yield of some crops in semi-arid ecosystems. On
549 the other hand, by integrating TWS with rainfall as input variables to model crop yield data,
550 this study demonstrated the potential of these hydrological indicators as possible and critical
551 inputs, amongst other parameters that could transform and benefit food security analysis.

552 Further, although not completely general, it is noticed that crops grown during dry season
553 are more related to TWS as water supply is mostly through irrigation and also those that require
554 longer periods for optimum yield. Conversely, crops planted during the rainy season tend to
555 be more associated with rainfall. The impact of planting season and crop type (long cycle
556 and short cycle) on the observed rainfall-crop relationship however, requires further assessment.
557 But it is noted that other non-climatic factors could influence crop yields depending on land
558 surface conditions, presence of weeds, and biophysical factors, amongst others. The results
559 nonetheless, should be interpreted with caution, given the fact that longer records of GRACE-
560 derived TWS would be required for further validation. In addition, this study sets the pace for
561 the use of GRACE-derived TWS in monitoring the impact of climate variability on crop yield
562 in arid ecosystems and future studies maybe warranted to provide further clarification. This
563 study further confirms GRACE observations as a reliable tool in the data deficient semi-arid
564 region for studies of eco-hydrological processes and advances our understanding of the impacts
565 of climate variability on annual crop yield. As water availability is a major factor that limits
566 crop growth, the climate modelling community in a multi-ensemble approach can employ TWS
567 as a resourceful tool and soil moisture surrogate to provide early warning systems and improve
568 future scenarios of food production and crop yield projections.

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