Nonlinear dynamics in agricultural systems in Chad

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ABSTRACT
Changes to agricultural systems in Sub-Saharan Africa are subject to a wide range of drivers, often resulting in rapid and nonlinear dynamics. Such dynamics are however rarely recognized in studies of trends and drivers, which usually rely on assumptions of gradual progressions, and often using highly aggregated data. This paper addresses this lack of recognition and understanding of nonlinear processes in agricultural systems in Sub-Saharan Africa by statistically identifying breakpoints and trends in regional crop production data in Chad for 1983–2016, which also makes it the most extensive and detailed study of the agricultural sector in Chad to date. By summarizing and visualizing the identified breakpoints and trends of a large group of variables in a concise and informative way, the roles of both abrupt and gradual processes are made clear. Results show that the progressions in the data predominantly have been driven by abrupt changes with lasting effects rather than gradual changes, contrary to what analyses on higher levels of aggregation would conclude. The potency of the developed methodology lies in its capacity to identify and summarize nonlinear progressions in agricultural systems constituted by a large set of variables, by separating the influence of abrupt and gradual processes.

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1. Introduction

1.1. Nonlinear dynamics in agricultural systems in Sub-Saharan Africa

Agricultural systems in Sub-Saharan Africa are subject to drivers across a wide range of scales and intensities (Food and Agricultural Organization of the United Nations [FAO] & African Development Bank [AfDB], 2015; Hazell & Wood, 2008; Olson, 2013; Wood, Jina, Jain, Kristjanson, & DeFries, 2014), often under ongoing political and socioeconomic transformations, and with high dependencies on unstable environmental conditions. Processes of agricultural extensiﬁcation and intensiﬁcation are both common (Byerlee, Stevenson, & Villoria, 2014; Nin Pratt, 2015), but stagnations also occur (Ollenburger, Descheemaeker, Crane, Sanogo, & Giller, 2016), which all need to be monitored and managed under prevailing policy objectives of economic development, environmental protection, food security, and poverty alleviation. The determining factors of these processes on large spatiotemporal scales have been theorized extensively (Byerlee et al., 2014; Jayne, Chamberlin, & Headey, 2014; Nin Pratt, 2015), but under highly heterogeneous conditions, generally applicable research methods and policy strategies are lacking. The patterns and drivers of change must rather be analyzed and understood within more detailed analytical units. With added detail in the level of analysis, the patterns of change are likely to be dynamic and rapid, which can prove difficult to detect,
comprehend, and especially predict. Furthermore, they are likely to be marked by nonlinearities, as can be seen in several recent studies (Bachewe, Berhane, Minten, & Taffesse, 2015; Ebanyat et al., 2010; Hentze, Thonfeld, & Menz, 2017; Mutoko, Hein, & Bartholomaeus, 2014; Nilsson, Hochrainer-Stigler, Mochizuki, & Uvo, 2016; Sebeg, Athlapheng, Chanda, Mulale, & Mphinyane, 2017). Accurately identifying and analyzing patterns of change in such systems requires analytical methods that move beyond assumptions of linear and gradual progressions. A recent review of studies of food and climate systems concluded that both the non-stationarity in human–environment systems, as well as the combination of sudden and gradual effects, must be acknowledged (Nelson, Zak, Davine, & Pau, 2016). Other reviews of land-use and crop land changes across the Sahel have found conflicting evidence of the directions of change (Rasmussen et al., 2016) and have emphasized the need for improved knowledge of changes and their drivers in agricultural systems (Van Vliet, Reenberg, & Rasmussen, 2013). Despite such calls for improved analytical detail, combined with strong reasons to expect nonlinear progressions, linear analysis across extended time series seems to be the common practice in trend analyses of agricultural systems across Sub-Saharan Africa, either through linear regressions or interpolation between end values. Due to its simplicity, assumptions of gradual progression risk distorting both the established trends and the ensuing interpretations. The effect of neglected nonlinearities will depend on the application of the trend analysis, which for agricultural systems in Sub-Saharan Africa usually are comparing trends and growth rates between agricultural variables (e.g., Akinyoade, Dietz, Foeken, & Klaver, 2013; Al-Hamdan et al., 2017; Awamyo & Attua, 2016; Bachew et al., 2015; Dorosh, Rashid, & Asselt, 2016; FAO and AfDB 2015; John, Hambati, & Armah, 2014), identifying drivers behind the trends (e.g., Hierniaux et al., 2009; Kleemann, Baysal, Bulley, & Fürst, 2017; Mutoko et al., 2014; Van Vliet et al., 2013), or extrapolating established trends into future scenarios (e.g., Betru & Kawashima, 2010; Maikasuwa & Ala, 2013; Tahir, 2014). Identifying drivers and extrapolating trends are especially sensitive to potential nonlinear dynamics, while trend comparisons on broad spatiotemporal scales often are less affected. By reviewing peer-reviewed studies on drivers in agricultural systems in Sub-Saharan Africa over the past 15 years, resulting in a selection of 60 studies, the most common methodologies for identifying drivers were found to be household surveys, focus groups, or interviews in areas where changes and trends have been identified (Nin-Pratt & McBride, 2014; Ouedraogo, Mbow, Balinga, & Neufeldt, 2015; Ouédraogo et al., 2017; Valbuena, Groot, Mukalama, Gérard, & Tittonell, 2015; Wood et al., 2014); quantitative correlation to potential factors (Abro, Alemu, & Hanjra, 2014; Bachewe et al., 2015; Epule & Bryant, 2015; García De Jalón, Iglesias, & Barnes, 2016; Michler & Josephson, 2017; Nielsen & Reenberg, 2010; Ouédraogo et al., 2017; Wood et al., 2014); and attribution by qualitative analysis to political and socioeconomic factors (Berakhi, Oyana, & Adu-Prah, 2014; Kamwi, Kaetsch, Graz, Chirwa, & Manda, 2017; Li, Oyana, & Mukwaya, 2016; Mbow, Mertz, Diouf, Rasmussen, & Reenberg, 2008; Sandstrom & Juhola, 2017). For any of these methodologies, a specified understanding of the patterns of change would guide the driver identification not only spatiotemporally but could also provide information on the characteristics of the driver, as drivers with gradual or abrupt effects might be distinguishable in the given context. In cases of attribution by quantitative correlation, information about nonlinear patterns will alter the detrending of the dataset. Similar benefits can be seen in the application of trend analyses in extrapolation methodologies, where an increased accuracy can have a considerable effect on the projections.

Nonlinear progressions in agricultural systems can be captured by the use of breakpoint methodologies, where structural changes in the data series are identified and used to split the data into groups with more homogenous patterns. This allows for an identification of both periods of gradual changes and points of abrupt changes that in combination more accurately represent the progression in nonlinear data series. Of the previously mentioned 60 reviewed studies of drivers in agricultural systems in Sub-Saharan Africa, only three included breakpoint
methodologies in their trend analysis, enabling a detection of abrupt transitions between rainfed and irrigated agriculture in Tanzania (Hentze et al., 2017), an evaluation of the economic impacts of different political regimes in Uganda (Ebanyat et al., 2010), and a connection of fertilizer use and improved crop varieties to increased tea yields in Kenya (Mutoko et al., 2014). Despite its long running history in the statistical sciences (e.g., Chow, 1960; Watt, 1979) and with an extensive range of applications, breakpoints are usually neglected in recent studies of changes to agricultural systems in Sub-Saharan Africa. The lack of increased uptake of breakpoint methodologies in this field is probably due to a mix of data availability, statistical capacity, and research scope but also due to assumptions of gradual progressions in the studied systems.

This paper shows how the often neglected nonlinearities in changes to agricultural systems in Sub-Saharan Africa can be addressed through the use of breakpoint and trend analysis applied to a large set of high-varying crop statistics, by using regional crop statistics in Chad for 1983–2016 as an example. This also makes it the most detailed and extensive study of crop statistics in Chad to date and is advancing the knowledge of how its agricultural sector progresses. Compared to the common usage of linear regressions over the full sample on coarse levels of analysis, the increased level of detail in both the data and the statistical methodology results in an increased complexity in the results. This is addressed by applying a methodology that summarizes and visualizes nonlinear patterns of change in a concise and informative way.

1.2. Crop production dynamics in Chad

An increased and stabilized crop production is currently one of the main objectives for the Chadian government (Ministry of Agriculture and Irrigation, 2013). Crop data on a national level are commonly used in country-wide assessments by development organizations and government agencies (e.g., FAO et al., 2011; World Food Programme [WFP], 2014; World Bank, 2015), but knowledge of crop production trends on subnational scales have so far been missing. With important subnational differences in livelihoods (World Bank, 2015), this is a limiting factor for development initiatives, and more specifically for seasonal and long-term food security planning. The Famine Early Warnings System Network’s (FEWS NET) livelihood profiles (2011a, 2005), some food security assessments for specific ecological zones (Government of Chad, 2009; WFP, 2010, 2013), and a recent study on crop production in the region around Lake Chad (Nilsson et al., 2016) are exceptions, but except for the latter, none of them include longitudinal analyses of the crop production patterns. Lack of further analysis on these levels can be explained by a limited access to subnational longitudinal crop data, joint with the complexity of crop production on aggregated levels. Furthermore, a substantial part of the reports and studies on agriculture in Chad comes from development organizations in the country, whose research scopes usually are limited to current events. Due to this, the current knowledge on the changes and drivers of crop production in Chad mostly encompass the national level and are in broad terms, with few subnational relationships established and quantified. For instance, both the rate of specialization in agriculture and the crop yields are often presented as among the lowest in Sub-Saharan Africa (FAO, 2017; FAO & AfDB, 2015). One core factor underlying this is the low population density and the agricultural systems’ vulnerability to the dry and high-varying climate, given the low usage of irrigation and general farm input (Nin Pratt, 2015; World Bank, 2015). Together with a lack of financing, insurance, transportation, and storing facilities, these vulnerabilities result in a situation where intensifying farming strategies have low expected returns and market reach, face high risks, and are difficult to finance (World Bank, 2015). This can explain the emergence of risk-reducing strategies through income diversification and extensive farming practices, instead of specialization through intensification as seen in other development contexts (World Bank, 2015). But given the limited amount of studies of these processes, they have generally not been specified and quantified further, which is now addressed in this paper.
2. Methods

2.1. Data

Through collaborations with the Chadian government agencies Direction de la Production et des Statistique Agricoles (DPSA) and the Institut National de la Statistique, des Études Économiques et Démographiques (INSEED), detailed and extensive datasets on cereal crop statistics have been acquired on the first administrative level under the national level (henceforth referred to as the regional level). The crop statistics from these agencies have not been available online so far, except in national aggregates through the FAOSTAT database (FAO, 2017). It consists of annual sums of the harvested area and production for all major cereal crops (maize, millet, wheat, rice, recession sorghum, and sorghum) for each of Chad’s 16 administrative regions for the time period 1983–2016. All data originate from the DPSA but were acquired from FAO’s Agro-MAPS database for 1983–1995 (FAO, 2006), the INSEED for 1993–1997 (INSEED, 1994, 1997), and the DPSA for 1998–2016 (DPSA, 2017). The yield was calculated as the quotient between the production and harvested area for each region and crop. All years in the covered time period (1983–2016) had full records except for 1996–1997, when only the production was reported (INSEED, 1997). The Pearson correlation coefficient between this dataset and the nationally aggregated FAOSTAT data is 0.998, which verifies that it is the same data, with the minor differences probably due to data entry errors.

A prominent data quality issue is that the reports and data collection efforts of the responsible agencies have had a high dependence on external and project specific funding and, as a consequence, publications have sometimes been irregular (INSEED, 2006). Furthermore, the turnover of specialized staff is high, and there are reoccurring issues with inconsistent data collection methodologies, which makes the quality of the data uncertain (DPSA, 1994; FAO, 2013; INSEED, 2006; Ministry of Agriculture, 2005). With no other sources of quantitative crop data to compare with, the data quality was verified based on the statistical patterns and its alignment with other descriptions of crop patterns in the country, as presented in the ‘Results’ section. As the analysis is focused on general trends and major changes in the data, it is less sensitive to year-to-year variations in the data collection procedures. Moreover, from at least 2000 onward, the crop data from the DPSA have continuously been used for operational food security work in the country by both local and international organizations, and combined with data on food insecurity and market prices, which strengthens its reliability (see, e.g., FEWS Net, 2000). Furthermore, crop variables whose total production over the full sample was <1% of the total production for each region were excluded, as were initial periods in variables with corresponding production levels of <1 t/crop/year (a noticeably low value for all of the included crops). A maximum filter was also necessary for the yield variables, since harvested area values near 0 could result in abnormally high yields. The maximum yield level was set to 5 t/ha, which was much higher than the normally reported yield of around 1 t/ha (FAO, 2017). Finally, an outlier filter set to three standard deviations (SDs) from the 5-year moving average was applied to exclude unrealistic values within each variable.

The ecological areas in Chad are often grouped into the Saharan, Sahelian, and Soudanian zones, with increasing humidity and vegetation when moving southwards (DPSA, 2017). Only crop variables from the Sahelian and the Soudanian zones were selected for the analysis, as the Saharan zone had much lower production levels and was less consistently reported on. The administrative divisions in Chad have undergone changes during the studied time period, and to enable comparisons over the full time period, the regional division with the lowest level of detail for the time period was used, which follows the division used by the DPSA during 1998–2009, and is presented in Figure 1 (DPSA, 2017). This resulted in 52 crops for the 13 administrative regions, with 29 in the Sahelian zone and 23 in the Soudanian zone, with 2 variables analyzed for each crop (harvested area and yield).
2.2. Statistical tests for breakpoints

The statistical analysis was developed in MatLab and aimed at finding breakpoints and trends in the data, as well as summarizing and visualizing them in concise and informative ways. Due to the small sample size (n = 34) and high variances, a methodology capable of detecting breakpoints in a wide range of patterns was required. Potential breakpoints were identified by using the Wald test, based on linear regressions (e.g., Andrews, 1993). To address the small sample size and high variances, a robust linear regression based on maximum likelihood type estimators (M-estimators) (e.g., Huber & Ronchetti, 2009; Stuart, 2011) was preferred. Following common usage and a couple of successful simulation studies, Huber’s M-estimator was selected (Kelly, 1992; Lambert-Lacroix & Zwald, 2011; Stuart, 2011), with Huber’s tuning constant set to its default value of 1.345 (Mathworks, 2016). Given the high variances and potential breakpoints in the data, the statistical significances of the breakpoints needed to be estimated without any assumptions of normally, identically, and independently distributed residuals. A bootstrap methodology was thus applied to determine the statistical significance of the breakpoints, by replicating the original residual structure from the regressions (Davidson & Mackinnon, 2006), which for robust regressions are the weighted residuals. Based on the original residual structure, 1000 simulated groups of data were generated, on which the same Wald test was run. The rate of exceedance of the original Wald test to the simulated ones was taken as the test’s significance level. The sieve bootstrap was used to replicate patterns of serial correlation in the residuals (Gonçalves & Kilian, 2007; Lee, 2011). It is based on approximating the serial correlation in the original residuals by fitting an autoregressive model, \( \theta \), to the data, and then using that model to generate the simulated data (Lee, 2011), defined as

\[
r(i) = \theta_1 r_{i-1} + \theta_2 r_{i-2} + \ldots + \theta_L r_{i-L} + \epsilon_{res}
\]

where \( L \) is the number of lags, and \( \epsilon_{res} \) is the estimated variance of the residuals. The number of lags was estimated by minimizing the Akaike Information Criterion under a maximum of three
lags. To address potential issues related to heteroscedasticity in the residuals, an addition of the commonly used wild fixed-regressor bootstrap was required (Flachaire, 2005; Hansen, 2000; Lee, 2011). Here, the pattern of variance in the residuals is replicated by multiplying each original residual with a random variable of expectation 0 and variance 1, from a 6-point distribution, as proposed by Webb (2014):

\[ v(r_i) = -\sqrt{\frac{3}{2}} - \sqrt{\frac{2}{2}} - \sqrt{\frac{1}{2}} - \sqrt{\frac{2}{2}} - \sqrt{\frac{3}{2}} \text{ all with probability } \frac{1}{6}; \]

Combining these two methodologies gives the following bootstrap simulation model, as suggested by Lee (2011):

\[ r_{\text{sim}}(i) = \theta_1 r_{\text{sim} i-1} + \theta_2 r_{\text{sim} i-2} + \ldots + \theta_L r_{\text{sim} i-L} + r_i \cdot v(r_i) \]

As the first \( L \) residuals in each simulation with serial correlations will not have enough preceding values to complete this equation, they were estimated by using only the autoregressive model based on the original variance of the residuals. 100 + \( L \) points were simulated from these models, and the last \( L \) points were entered as the first \( L \) points in the bootstrap simulation. Wald tests based on all combinations of linear and constant regressions were calculated for each potential breakpoint, and the point with the highest Wald test score, with significance level \( \leq 0.05 \), was taken as the breakpoint for that sample. This procedure was repeated on the subsamples created by the breakpoints until no further breakpoints were found, or when the subsamples reached the minimum sample size of four. This limit was chosen based on the large fluctuations and reoccurring breakpoints in the data, and to be able to detect changes near the end of the samples. Linear regressions were then fitted to the subsamples created by the breakpoints, or on the full sample if no breakpoints were found. The significances of the slope coefficients in the linear regressions were estimated using the same bootstrap methodology as for the Wald test, but for the two-tailed t-test. Only slope coefficients with significance level \( \leq 0.05 \) were included in the regressions, otherwise slopes were set to 0.

The variance of the data, through its connections to the Chadian governments goal of stabilized crop production (Ministry of Agriculture and Irrigation, 2013), was another key component of the analysis. The identified breakpoints and trends were first used to detrend the data so that these would not influence the analysis of the variance. By taking the absolute first differences of the detrended data, thereby having each value represent the absolute change from the previous value, the same breakpoint and trend analysis based on linear regressions as used on the original data can be applied to identify breakpoints in the variance. After the positions of the breakpoints were identified accordingly, their corresponding variances were estimated by calculating the SD of a range of five values centered on the point of interest, within the identified subsample. If there were linear trends in the variance in a subsample, variances at the end sections of the subsample were used to interpolate the variance values over that subsample.

2.3. Supplementary rules

When using robust fitting, where residual weights will depend on their distance to the estimated regression values, supplementary rules are often needed to accurately identify the breakpoints. Two supplementary rules were applied to address this. First, breakpoints were evaluated and adjusted to ensure that the distance to its identified trend value was smaller than to the preceding trend value. The second rule concerned regressions that identified abrupt changes to the trend values at a breakpoint, but where there were a range of values all located in between the two distinct parts of the data, with no clear belonging to any of the two groups. If the number of such points in the middle 50% range between the distinct groups was not enough to result in a trend of their own, i.e., less than the set minimum sample size of four, so-called transitions trends were
applied. These consisted of a linear trend fitted to these points to connect them to the distinct groups surrounding them, thus creating a more continuous trend across the whole sample. When such transition trends were applied, new regressions were run on the remaining data in the respective subsamples. The range of 50% between the distinct groups as a selection criterion was based on evaluations of trend fitting results on random variables from the dataset, which together with the first supplementary rule showed satisfactory results.

2.4. Statistical summary and visualization

With a large number of variables analyzed separately, the results needed to be summarized and visualized in a concise and informative way. The use of breakpoint analysis and linear regressions enabled the distinction between abrupt and gradual changes to the trends in the data. An abrupt change was defined as a breakpoint where the trend difference to its expected value, as estimated by the trend in the preceding subsample, was larger than the slope coefficient in that subsample. All breakpoints with trend differences below or equal to that value were classified as gradual changes. To present overall trends in the data, all abrupt and gradual changes were then summarized in trend graphs for the Sahelian and Soudanian zones. For each zone, all gradual trends of the included variables were summed for each year, while the abrupt changes, being fewer and occurring at specific years, were kept separated. The previously mentioned transition trends did not readily fall in any of these two change categories, as they were linear approximations of abrupt changes over a few years. For such cases, transition periods of two years were classified as abrupt changes, while transition periods longer than 2 years were classified as gradual changes.

As the yield is the quotient of the production and the harvested area, the yield for each zone is expressed as an average yield for the included variables. Therefore, the effect of a crop-specific yield change, i.e., changes in one yield variable, does not translate into the same effect on the whole zone’s average yield. Instead, to estimate the effect of a crop specific yield change on the whole zone’s yield, such effects need to be weighted based on the rate of that yield variable’s harvested area to the whole zone’s harvested area, at the time of the occurring yield change. It should be noted that changes to the total yield of a group of variables can also be due to area-driven yield changes, i.e., changes in the harvested areas of the included variables, even if the yield of those variables remains constant. As the harvested area was analyzed separately, and the yield trend analysis concerned crop-specific yield changes, such area-driven yield changes were not analyzed further.

For each zone, the improvement by using breakpoint analysis and robust linear regression compared to a full sample OLS linear regression was estimated by comparing the total mean squared error (MSE) and sum of squared error (SSE). A drawback with this comparison is that the robust regression used, contrary to the OLS, does not minimize the SSE but instead minimizes a weighted SSE. This weighted SSE is however not appropriate for comparison between different regression methods, as the ascribed weights will differ depending on the identified breakpoints and regressions.

2.5. Trend attribution

The breakpoints and trends as identified and visualized in the trend graphs can be used to explore drivers behind them. Given the complexity of the potential drivers on regional scales in Chad, such an identification might be challenging and lead to broad conclusions at best. On a generic level, and with enough sample cases, this can be done by comparing to the total trend change over a set period with changes to key potential drivers, such as demographic and socioeconomic dynamics. To reach a higher precision in the trend attribution, abrupt changes and specific periods of gradual trends can be addressed by using the extensive set of food security reports which have been published tri-monthly since 2005 by the country office of FEWS NET (e.g., FEWS NET, 2010a), together with assessments and surveys from the FAO and the WFP. One
example of how this can be done is given in the ‘Results’ section, by analyzing potential drivers of two noteworthy abrupt changes in the harvested area for one of the Sahelian regions. As the focus of this paper was to develop a statistical methodology to identify and summarize nonlinearities in changes to agricultural systems in Chad and similar areas, the drivers behind the statistical patterns were not addressed further.

3. Results

Only a part of the results is presented here, while the data tables and additional figures in Appendix give a more extensive account of the patterns in each of the included crop variables. Following common trend analysis practice for agricultural systems in Sub-Saharan Africa, all data are first aggregated within the Sahelian and Soudanian zones (Figure 2), after which the breakpoints and trends in the constituting variables of the same zones are summarized in the trend graphs (Figures 3 and 4). In accordance with several others studies from the nearby countries, the aggregated harvested areas and yields show fairly linear increases for both zones, which can also be seen in the national level data (see, e.g., FAO, 2017; Ministry of Agriculture, 2005; World Bank, 2015). The linear progressions are more pronounced for the harvested areas than for the yields, and the harvested area for the Sahelian zone has a larger increase over this time period than the Soudanian zone. Seen for the whole country, this has resulted in an annual average growth rate of 6.5% of the cereal production, which can be compared with the population growth rate of 3.3% over the same period (World Bank, 2017), resulting in an overall increase in cereal per capita

![Figure 2](image-url). Aggregated harvested area and yield for cereal crops in the Sahelian and Soudanian zones.

![Figure 3](image-url). Trend graph for the harvested area in the Sahelian zone.
availability. Despite large area expansions over this period, land availability is still high, with the end values of the harvested areas representing 5% of the total land area in the Sahelian zone, and 8% in the Soudanian zone (FAO, 2009). The noteworthy increase in the harvested area for the Sahelian zone in 2010 is verified by reports of ‘unusually good water availability’ and ‘exceptionally good agricultural production’ for that year (FEWS NET, 2010b, 2011a). The gaps for 1996 and 1997 are due to missing data, which is seen in all of the result figures.

However, the linear progressions in the aggregated data in Figure 2 are constituted by more complex patterns which are only visible on more detailed levels, as seen in the trend graph for the harvested area of the crops in the Sahelian zone in Figure 3. It should be stressed that the results in this and the upcoming trend graphs show the changes to the trends in the data, identified for each included crop on the regional level, and that they indicate lasting changes occurring at specific years, as identified by the described methodology. Abrupt changes are separated by white lines, while all gradual changes for each year are joined together. By adding the identified breakpoints and trends from the harvested area of the 29 constituting crop variables of the 8 regions in the Sahelian zone, the diversity of the linear progression on higher levels of aggregation (harvested area for the Sahelian zone in Figure 2) is made clear. The significant contributions of positive abrupt changes to the trend changes in the data are noteworthy and constitute 73% of the total change over this period, compared to 21% for the positive gradual changes. This is in sharp contrast to the readings of Figure 2, which shows no obvious signs of abrupt changes. Some specific abrupt changes are of considerable size, such as the two occurring in 2010, which are for the millet and sorghum crops in the Ouaddai region, and are addressed further below. The total trend change over this time period is around 1750,000 ha. This can be compared with the change in mean values between the end sections of the aggregated data in Figure 2, which is around 1900,000 ha, a difference of 8%. Some differences are to be expected between the two estimates, as the trend estimates behind Figure 3 are based on specific statistical methodologies and definitions of trends, which might differ from the change in the aggregated mean values. In comparison with using the full sample OLS linear regression, this breakpoint and trend methodology reduced the SSE for the Sahelian zone by 52%, and the MSE by 48%.

The trend graph for the yield variables in the Sahelian zone is presented in Figure 4. Ongoing increases in the data are visible in this figure as well, with a similar relative contribution from positive abrupt changes (80%) as for the harvested area in Figure 3. The SSE reduction compared with a full sample OLS linear regression is 24%, and 22% for the MSE. The yield change over the whole period as estimated from this methodology is an increase of 0.16 t/ha, which only includes effects due to crop-specific yield changes. The area-driven yield changes in the Sahelian zone can be estimated by the difference between the total yield change in Figure 2 (0.43 t/ha) and the crop-specific yield changes, to

![Figure 4. Trend graph for the yield in the Sahelian zone.](image-url)
0.27 t/ha. For the Soudanian zone, these estimates are 0.20 t/ha for the crop-specific yield changes, and 0.09 t/ha for the area-driven yield changes. This indicates that increases to the total yield are due to both expansions of relatively high-yielding crops and yield improvements within specific areas and crops, with varying rates between the two zones. The corresponding trend graphs for the harvested area and the yield for the Soudanian zone are presented in Appendix.

### 3.1. Variance

Figure 2 gives an overview of the prominent interannual variations in Chadian crop dynamics. These patterns of variance can be illustrated more clearly on the same level of analysis by looking at the absolute first differences of the same data, as given in Figure 5. The variance of the harvested areas displays fluctuating patterns with some increases in the later parts of the time period for both zones, but with amplitudes around 10 times larger for the Sahelian zone. The two yield datasets show slight changes but in opposite directions, with increasing trends for the Sahelian zone and decreasing trends for the Soudanian zone. The trend graphs for the variances of the harvested area and the yield in the Soudanian zone are presented in Figures 6 and 7, where the bars represent the estimated trend changes to the zone’s SD for each year. Several changes to the variance trends of the harvested area can be seen in Figure 6. Similar to the trends in the Sahelian zone, the change in variance is foremost driven by positive abrupt changes (45%), followed by positive and negative gradual changes (27% and 26%). Seen over the whole time period, the harvested area is plotted on two y axes.
period, the SD increases by around 96,800 ha. The increasing changes can be noticed earlier in this figure than in Figure 5, which only displays increases after year 2000. The MSE and SSE reductions compared to the full sample OLS linear regression are 28% and 31%. In Figure 7, the variance of the yield is seen to decrease slightly, which can be concluded from Figure 5 as well. Again, the trend changes are mainly driven by abrupt rather than gradual changes, with variance decreasing abrupt events being mostly pronounced in the middle ranges of this time period, while several abrupt increases are occurring toward the end. The MSE and SSE reductions compared to the full sample OLS linear regressions are 35% and 36%.

3.2. Example of trend attribution

Attributing causes to the full range of identified abrupt and gradual changes in the different crop categories and regions is beyond the scope of this paper. Instead, two examples are given here on how these results can be used to identify drivers of Chad’s agricultural sector on a regional level. Starting at a generic level, the relationships between agricultural changes and key demographic or socioeconomic variables within the 13 regions can be evaluated through statistical correlations. Comprehensive and nationwide demographic censuses have only been conducted in 1993 and 2009 in Chad (INSEED, 1993, 2012), while rural occupations also were estimated in 2014 (INSEED & ICF International, 2016). The scarcity of the demographic data together with the small sample size of 13 cases is the main limitations for such analyses. In Figure 8, changes in the total population and the agricultural population over these time periods are compared with changes in the harvested area and the yield. It shows that growth in the total and agricultural population both have a strong positive correlation with increases in the harvested area. The total and agricultural population are however highly correlated, and a multivariate linear regression including both as predictors only improves the $R^2$ with 1% compared to only using the total population, which shows that the correlation to the harvested area stems from the total population. This indicates that an increasing total population, presumably through its effects on crop demand, is a main driver of the agricultural extensification processes. In terms of the yield, only the agricultural population has a reliable correlation, indicating that increased population pressure and labor availability in agricultural areas take part in driving the land intensification processes. Clear differences are also seen between the Sahelian and Soudanian zones, where the Sahelian zone has a larger spread in the agricultural variables, and primarily for the harvested areas. The Biltine region had extremely high increases in both total population (270%) and agricultural population (355%) over this period and was excluded from this comparison altogether and instead must be analyzed separately. Its deviating population increase is partly an effect of hosting
refugees from Sudan (FEWS Net, 2004; UNHCR, 2016). Figure 8 further shows that the agricultural population is decreasing in some regions, due to urbanization processes and growth of nonagricultural rural sectors.

To further understand what drives changes in the agricultural sector, the specific patterns of change within each region and crop need to be addressed. An analytical benefit with having identifying points of abrupt changes is that they are easier to link to specific causes, compared to gradual changes or the total rate of change over extended periods. The example chosen for this end is the abrupt and lasting increases of the harvested area in 2010 in the Sahelian zone, as identified in Figure 3. The two abrupt increases in that year are for millet and sorghum in Ouaddai, located in the eastern parts of the Sahelian zone, and are presented in Figure 9. Together they represent 22% of the total trend change for the Sahelian zone (see data tables in Appendix for additional data). A review of FEWS NET’s food security reports spanning over the 2010 crop season (Apr 2010–Jan 2011) found the following factors related to increases in crop production in the areas covering the Ouaddai region. Overall, favorable rain conditions were given as a strong positive factor, which was supported by that large expanses of the surrounding areas experienced above normal harvests (FEWS NET, 2010b). In the period preceding that crop season, the Chadian government and the FAO both provided free and subsidized seeds, as well as farming training (FEWS NET, 2010a). Furthermore, reports of unusually high market prices in the area around Ouaddai in the months leading up to the crop planting period, due to two consecutive poor harvest seasons before that year, could have increased the incentives for increased production (FEWS NET, 2010a). And finally, a 7-year long trade embargo with Sudan, which shares a border with Ouaddai, was lifted that year, which opened up a new market for the farmers in Ouaddai (FEWS NET, 2010b). Out of these factors, the ones with the most apparent pattern of abrupt and lasting change are the lifted trade embargo with Sudan and the farming training. Specifying the respective contribution from each of these factors further will require more detailed analysis, e.g., by coupling it with other sources, and preferably by collaborating with organizations.
and farmers in the concerned areas. Still, combining the proposed statistical methodology with a brief review of food security reports is able to narrow down the identification and quantification of the drivers of change in Chad’s agricultural sector.

4. Discussion

Although using the same data, the differences in conclusions stemming from the trend graphs (Figures 3, 4, 6, and 7) and the aggregated original data (Figures 2 and 5) are substantial. These trend graphs are able to show that cereal crop dynamics in Chad have predominantly been driven by abrupt, rather than gradual, changes, contrary to what analyses on higher levels of aggregation would conclude (e.g., FAO, 2017; Ministère de l’Agriculture, 2005; World Bank, 2015). By emphasizing the importance of such specific events, and identifying their contribution, potential drivers can be looked for with more precise scopes than what would be possible if just relying on the data in Figures 2 and 5. This methodology also enables an increased specification of the role of gradual processes. It further illustrates the diverse and nonlinear patterns of the constituting variables, which give rise to gradual progressions on coarser level of analyses. By showing the prevalence of nonlinearity in the case of Chad, an emphasis is put on the need to further recognize and understand the role of nonlinear processes in agricultural systems in regions with similar development profiles. The literature review conducted for this study indicates that this methodology could improve current analytical practices of trend and driver analyses in agricultural systems across Sub-Saharan Africa. At the same time, the relevance of this kind of analysis does not depend on the presence of abrupt over gradual changes, as it can be adapted to any set of statistical patterns present in the data, such as differences in gradual trends between time periods and the included variables.

Applying the proposed statistical methodology requires a certain level of data access, together with training in statistical analysis and computer programming. An additional concern is the reliability of the results when using more precise data and analysis. The data quality is preferably verified by assessing the data collection procedure but can also be explored based on the patterns in the data, and in comparison with other sources, such as food security reports from FAO, FEWS NET, and WFP. In the case of the Chadian crop statistics, where the extent of the data collection might vary with budget constraints and the capacity of the responsible institutions, it can be assumed that the potential variations in data collection procedures would affect the data on the production and the harvested area more than that of the yield, as the latter is the quotient between the first two, assuming a certain stability of the yield across adjacent areas. And irrespectively of the concerns about the quality of the data analyzed here, the presented methodology has proved to be useful in identifying and visualizing changes to large group of variables with diverse patterns. The reliability of the statistical results is best verified by using rigorous statistical methodologies, such as the outlined bootstrap methodology for statistical inference, as well as inspections of the
results on random variables. The sensitivity of the breakpoint and trend identification can be
tweaked based on such inspections through the significance levels and the application of supple-
mentary rules, similar to the ones applied here. The MSE and SSE can further provide broad
metrics for groups of variables of how the applied methodology is performing compared to other
methodologies, such as a full sample linear regressions. In a dataset known to have varying
patterns and breakpoints, the MSE and SSE should be considerably lower than for a full sample
OLS linear regression, with reductions in this example ranging from 22% to 48% for the MSE and
24% to 52% for the SSE.

The results show that processes of agricultural extensiﬁcation and intensiﬁcation are prevalent in
both the Sahelian and Soudanian zones of Chad, but with higher rates of change in the Sahelian zone.
The extensiﬁcation is progressing faster than the intensiﬁcation in both zones, which ﬁts general
descriptions of the dynamics in the agricultural sector by earlier work, and presumably is a response to
increasing demand and high land availability under conditions of high risk and low return on
investments (Nin Pratt, 2015; World Bank, 2015). The analysis also shows that the extensiﬁcation of
relatively high-yielding crops are the main drivers of yield increases in the Sahelian zone, contrary to
the Sudanian zone where a higher rate of yield improvements within crop variables are seen. The
variances have less clear developments, where the variance of the harvested area is increasing in both
zones, but at levels almost 10 times higher in the Sahelian zone. The variance of the yield is decreasing
in the Soudanian zone and increasing slightly in the Sahelian zone. A decreasing yield variance in the
Soudanian zone points to more controlled agricultural management, which ﬁts descriptions of its
agricultural systems being more specialized and irrigated than in the Sahelian zone (FEWS Net,
2011b). The otherwise increasing variances pose direct issues for food security and are complicating
risk management and investment prospects in the agricultural sector. This can partly be addressed by
reducing the risks farmers face in their livelihoods, by identifying the key factors behind the varying
agricultural output, and possibly by reducing the effect from the varying output by insurance schemes
tailored against such factors. Successfully implementing insurance schemes however requires strong
insurance regulative framework and ﬁnancial facilities, precise and reliable data, high literacy rates,
and ﬁnancial capacity on the farmers’ side (Ntukamazina et al., 2017), which are generally not found in
Chad’s rural sector.

One promising area of future research is to build on this analysis to establish precise knowledge
of the changes and drivers in agricultural systems in Chad, to be able to address and steer the
ongoing processes of extensiﬁcation, intensiﬁcation, and increasing variance in the output. Such
knowledge would also improve the accuracy of seasonal outlooks and future scenarios, which
could guide food security planning and development trajectories. Research to make these links
between the patterns of change and their drivers will require coupling the agricultural data with
environmental, socioeconomic, and political processes in the respective regions. Despite generally
assumed to be a data scarce country for these matters, both Chadian institutions and development
organizations based in country are continuously releasing reports and studies related to rural
development and food security. These data sources have barely been addressed in the academic
literature, and coupling them with environmental data and the agricultural analysis provided here
will open up a broad span of fruitful research avenues. Furthermore, with ongoing institutional
development in Chad, the extent and detail of such data is constantly increasing, but generally
without any concurrent development of research programs to address the increasing analytical
potential and complexity. Due to the extensive and explorative nature of such research, govern-
ment institutions and development organizations are unlikely to conduct it on their own, while
academic actors might have a stronger interest to do so. Results from such research are set to
provide much needed knowledge on the processes of rural change across the country, in both the
short and long run. The methodologies developed would also be relevant to other regions in
similar development contexts as Chad’s, where patterns of change and drivers in agricultural
systems under unstable environmental conditions and rapid socioeconomic changes generally are
poorly understood.
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**Appendix**

**Data tables**

Table 1. Trend results for the harvested area in the Sahelian zone.

| Region       | Crop              | Total change* | % abrupt | % gradual | Breakpoints | % positive change in group | % negative change in group | % change in group |
|--------------|-------------------|---------------|----------|-----------|-------------|-----------------------------|---------------------------|-------------------|
| Batha        | Millet            | 100.873       | 52       | 48        | 1           | 5                          | 0                         | 5                 |
| Batha        | Sorghum           | 54.526        | 68       | 32        | 3           | 3                          | 0                         | 3                 |
| Batha        | Rec. Sorghum      | 89.066        | 100      | 0         | 1           | 5                          | 0                         | 5                 |
| Biltine      | Millet            | 84.693        | 100      | 0         | 2           | 5                          | 0                         | 4                 |
| Biltine      | Sorghum           | 20.033        | 62       | 38        | 3           | 2                          | 18                        | 3                 |
| Ch. Baguirmi | Millet            | 177.091       | 84       | 16        | 3           | 10                         | 0                         | 9                 |
| Ch. Baguirmi | Sorghum           | 230.911       | 51       | 49        | 3           | 13                         | 0                         | 12                |
| Ch. Baguirmi | Maize             | 74.168        | 58       | 42        | 2           | 4                          | 0                         | 4                 |
| Ch. Baguirmi | Rice              | 21.348        | 15       | 85        | 1           | 1                          | 0                         | 1                 |
| Ch. Baguirmi | Rec. Sorghum      | 14.476        | 0        | 100       | 2           | 1                          | 0                         | 0                 |
| Guéra        | Millet            | 22.15         | 100      | 0         | 3           | 2                          | 9                         | 2                 |
| Guéra        | Sorghum           | 44.547        | 100      | 0         | 1           | 2                          | 0                         | 2                 |
| Guéra        | Rec. Sorghum      | 14.768        | 65       | 35        | 2           | 2                          | 17                        | 3                 |
| Kanem        | Millet            | 0             | -        | -         | -           | -                          | -                         | -                 |
| Kanem        | Sorghum           | 0             | -        | -         | -           | -                          | -                         | -                 |
| Kanem        | Maize             | -7.445        | 100      | 0         | 1           | 0                          | 7                         | 0                 |
| Lac          | Millet            | 0             | -        | -         | -           | -                          | -                         | -                 |
| Lac          | Sorghum           | 0             | -        | -         | -           | -                          | -                         | -                 |
| Lac          | Maize             | 19.001        | 100      | 0         | 1           | 1                          | 0                         | 1                 |
| Lac          | Wheat             | 0             | -        | -         | -           | -                          | -                         | -                 |
| Ouaddai      | Millet            | 275.782       | 100      | 0         | 2           | 15                         | 0                         | 14                |
| Ouaddai      | Sorghum           | 259.584       | 85       | 15        | 3           | 13                         | 0                         | 13                |
| Ouaddai      | Maize             | 54.833        | 0        | 100       | 2           | 3                          | 0                         | 3                 |
| Ouaddai      | Rec. Sorghum      | 4.844         | 54       | 46        | 1           | 2                          | 29                        | 3                 |
| Salamat      | Millet            | 2.364         | 71       | 29        | 2           | 0                          | 2                         | 0                 |
| Salamat      | Sorghum           | 11.041        | 87       | 13        | 3           | 2                          | 18                        | 2                 |
| Salamat      | Maize             | 24.266        | 3        | 97        | 2           | 1                          | 0                         | 1                 |
| Salamat      | Rice              | 5.015         | 100      | 0         | 1           | 0                          | 0                         | 0                 |
| Salamat      | Rec. Sorghum      | 162.811       | 92       | 8         | 2           | 9                          | 0                         | 8                 |

*Ha x 10³.
Table 2. Trend results for the variance of the harvested area in the Sahelian zone.

| Region          | Crop         | Total change* | % abrupt | % gradual | Breakpoints | % positive change in group | % negative change in group | % change in group |
|-----------------|--------------|---------------|----------|-----------|-------------|-----------------------------|----------------------------|-------------------|
| Batha           | Millet       | 21.788        | 63       | 37        | 2           | 14                          | 24                         | 16                |
| Batha           | Sorghum      | 10.102        | 0        | 100       | 2           | 3                          | 0                          | 2                 |
| Batha           | Rec. Sorghum | 28.717        | 100      | 2         | 8           | 24                         | 0                          | 6                 |
| Biltine         | Millet       | 23.501        | 0        | 100       | 2           | 9                          | 7                          | 8                 |
| Biltine         | Sorghum      | 2.588         | 100      | 0         | 1           | 1                          | 0                          | 0                 |
| Ch. Baguirmi    | Millet       | 17.534        | 100      | 0         | 1           | 5                          | 0                          | 3                 |
| Ch. Baguirmi    | Sorghum      | 0             | -        | -         | -           | -                          | -                          | -                 |
| Ch. Baguirmi    | Maize        | 4.814         | 100      | 1         | 1           | 1                          | 0                          | 1                 |
| Ch. Baguirmi    | Rice         | 0             | -        | -         | -           | -                          | -                          | -                 |
| Ch. Baguirmi    | Rec. Sorghum | 13.065        | 0        | 100       | 3           | 3                          | 0                          | 3                 |
| Guéra           | Millet       | -9.789        | 100      | 0         | 1           | 0                          | 8                          | 2                 |
| Guéra           | Rec. Sorghum | 19.36         | 0        | 100       | 1           | 5                          | 0                          | 4                 |
| Guéra           | Sorghum      | 6.328         | 100      | 0         | 3           | 4                          | 6                          | 4                 |
| Kanem           | Millet       | 0             | -        | -         | -           | -                          | -                          | -                 |
| Kanem           | Sorghum      | 0             | -        | -         | -           | -                          | -                          | -                 |
| Kanem           | Maize        | -5.481        | 100      | 0         | 2           | 0                          | 4                          | 1                 |
| Lac             | Millet       | 0             | -        | -         | -           | -                          | -                          | -                 |
| Lac             | Sorghum      | -8.674        | 87       | 13        | 1           | 0                          | 7                          | 2                 |
| Lac             | Maize        | 6.688         | 100      | 0         | 1           | 2                          | 0                          | 1                 |
| Lac             | Wheat        | 0             | -        | -         | -           | -                          | -                          | -                 |
| Ouaddai         | Millet       | 30.428        | 0        | 100       | 2           | 8                          | 0                          | 6                 |
| Ouaddai         | Sorghum      | 91.126        | 88       | 12        | 1           | 24                         | 0                          | 18                |
| Ouaddai         | Maize        | 0             | -        | -         | -           | -                          | -                          | -                 |
| Ouaddai         | Rec. Sorghum | 0             | -        | -         | -           | -                          | -                          | -                 |
| Salamat         | Millet       | 0             | -        | -         | -           | -                          | -                          | -                 |
| Salamat         | Sorghum      | 0             | -        | -         | -           | -                          | -                          | -                 |
| Salamat         | Maize        | 6.974         | 100      | 0         | 1           | 2                          | 0                          | 1                 |
| Salamat         | Rice         | 0             | -        | -         | -           | -                          | -                          | -                 |
| Salamat         | Rec. Sorghum | -1.925        | 100      | 0         | 2           | 14                         | 42                         | 21                |

*Ha x 10³, Standard deviations.
## Table 3. Trend results for the yield in the Sahelian zone.

| Region          | Crop        | Total change* | % abrupt | % gradual | Breakpoints | % positive change in group | % negative change in group | % change in group |
|-----------------|-------------|---------------|----------|-----------|-------------|---------------------------|---------------------------|------------------|
| Batha           | Millet      | 0             | -        | -         | -           | -                         | -                         | -                |
| Batha           | Sorghum     | 0             | -        | -         | -           | -                         | -                         | -                |
| Batha           | Rec. Sorghum| 0             | -        | -         | -           | -                         | -                         | -                |
| Biltine         | Millet      | 0.285         | 100      | 0         | 1           | 5                         | 0                         | 5                |
| Biltine         | Sorghum     | 0             | -        | -         | -           | -                         | -                         | -                |
| Ch. Baguirmi    | Millet      | 0             | -        | -         | -           | -                         | -                         | -                |
| Ch. Baguirmi    | Sorghum     | 0.285         | 100      | 0         | 1           | 1                         | 0                         | 1                |
| Ch. Baguirmi    | Maize       | 0.057         | 100      | 0         | 2           | 0                         | 14                        | 2                |
| Ch. Baguirmi    | Rec. Sorghum| 0             | -        | -         | -           | -                         | -                         | -                |
| Guéra           | Millet      | 0             | -        | -         | -           | -                         | -                         | -                |
| Guéra           | Sorghum     | 0.08          | 59       | 41        | 1           | 17                        | 79                        | 24               |
| Guéra           | Rec. Sorghum| 0             | -        | -         | -           | -                         | -                         | -                |
| Kanem           | Millet      | 0.2           | 38       | 62        | 1           | 4                         | 0                         | 4                |
| Kanem           | Sorghum     | -0.753        | 100      | 0         | 1           | 0                         | 6                         | 1                |
| Lac             | Millet      | 0             | -        | -         | -           | -                         | -                         | -                |
| Lac             | Sorghum     | 0             | -        | -         | -           | -                         | -                         | -                |
| Lac             | Maize       | 1.159         | 100      | 0         | 2           | 12                        | 0                         | 2                |
| Lac             | Wheat       | 0.851         | 100      | 0         | 1           | 1                         | 0                         | 1                |
| Ouaddai         | Millet      | 0.23          | 100      | 0         | 1           | 12                        | 0                         | 11               |
| Ouaddai         | Sorghum     | 0.227         | 100      | 0         | 1           | 6                         | 0                         | 6                |
| Ouaddai         | Maize       | 0.843         | 63       | 37        | 1           | 8                         | 0                         | 7                |
| Ouaddai         | Rec. Sorghum| 0.437         | 100      | 0         | 2           | 3                         | 0                         | 2                |
| Salamat         | Millet      | 0.294         | 100      | 0         | 2           | 1                         | 0                         | 1                |
| Salamat         | Sorghum     | 0.535         | 0        | 100       | 2           | 6                         | 0                         | 5                |
| Salamat         | Maize       | 0.881         | 100      | 0         | 1           | 2                         | 0                         | 2                |
| Salamat         | Rice        | 2.321         | 100      | 0         | 2           | 3                         | 0                         | 2                |
| Salamat         | Rec. Sorghum| 0.379         | 100      | 0         | 1           | 18                        | 0                         | 16               |

*Ton/ha.
Table 4. Trend results for the variance of the yield in the Sahelian zone.

| Region     | Crop       | Total change* | % abrupt | % gradual | Break-points | % positive change in group | % negative change in group | % change in group |
|------------|------------|---------------|----------|-----------|--------------|----------------------------|----------------------------|------------------|
| Batha      | Millet     | 0             | -        | -         | -            | -                          | -                          | -                |
| Batha      | Sorghum    | 0.16          | 74       | 26        | 1            | 5                          | 2                          | 3                |
| Batha      | Rec. Sorghum | 0.04         | 63       | 37        | 1            | 1                          | 4                          | 2                |
| Biltine    | Millet     | 0             | -        | -         | -            | -                          | -                          | -                |
| Biltine    | Sorghum    | 0             | -        | -         | -            | -                          | -                          | -                |
| Ch. Baguirmi | Millet   | -0.081        | 100      | 0         | 1            | 0                          | 3                          | 2                |
| Ch. Baguirmi | Sorghum | 0             | -        | -         | -            | -                          | -                          | -                |
| Ch. Baguirmi | Maize     | -0.542        | 100      | 0         | 1            | 0                          | 13                         | 6                |
| Ch. Baguirmi | Rice      | 0             | -        | -         | -            | -                          | -                          | -                |
| Ch. Baguirmi | Rec. Sorghum | 0.19         | 95       | 5         | 2            | 9                          | 5                          | 7                |
| Guéra      | Millet     | 0             | -        | -         | -            | -                          | -                          | -                |
| Guéra      | Sorghum    | 0.099         | 100      | 0         | 1            | 3                          | 0                          | 2                |
| Guéra      | Rec. Sorghum | 0            | -        | -         | -            | -                          | -                          | -                |
| Kanem      | Millet     | 0             | -        | -         | -            | -                          | -                          | -                |
| Kanem      | Sorghum    | -1.388        | 100      | 0         | 1            | 0                          | 4                          | 2                |
| Kanem      | Maize      | -0.658        | 100      | 0         | 1            | 0                          | 4                          | 2                |
| Lac        | Millet     | -0.106        | 100      | 0         | 1            | 0                          | 7                          | 3                |
| Lac        | Sorghum    | 0.121         | 58       | 42        | 1            | 0                          | 4                          | 2                |
| Lac        | Maize      | -0.095        | 58       | 42        | 1            | 3                          | 8                          | 5                |
| Lac        | Wheat      | 0             | -        | -         | -            | -                          | -                          | -                |
| Ouaddai    | Millet     | 0.061         | 74       | 26        | 2            | 12                         | 7                          | 10               |
| Ouaddai    | Sorghum    | -0.02         | 100      | 0         | 2            | 1                          | 3                          | 2                |
| Ouaddai    | Maize      | 0.105         | 92       | 8         | 2            | 9                          | 13                         | 11               |
| Ouaddai    | Rec. Sorghum | 0            | -        | -         | -            | -                          | -                          | -                |
| Salamat    | Millet     | -0.052        | 100      | 0         | 2            | 0                          | 0                          | 0                |
| Salamat    | Sorghum    | 0.259         | 100      | 0         | 1            | 6                          | 0                          | 3                |
| Salamat    | Maize      | -0.308        | 43       | 57        | 1            | 4                          | 8                          | 6                |
| Salamat    | Rice       | -0.052        | 51       | 49        | 1            | 3                          | 8                          | 6                |
| Salamat    | Rec. Sorghum | 0.018        | 100      | 0         | 2            | 42                         | 7                          | 26               |

*Ton/ha, standard deviations.
Table 5. Trend results for the harvested area in the Soudanian zone.

| Region          | Crop          | Total change* | % abrupt | % gradual | Break-points | % positive change in group | % negative change in group | % change in group |
|-----------------|---------------|---------------|----------|-----------|--------------|---------------------------|---------------------------|------------------|
| Mayo-Kebbi      | Millet        | -11.933       | 59       | 41        | 2            | 5                         | 18                        | 9                |
| Mayo-Kebbi      | Sorghum       | 23.778        | 55       | 45        | 4            | 21                        | 44                        | 27               |
| Mayo-Kebbi      | Maize         | 43.125        | 92       | 8         | 2            | 7                         | 2                         | 6                |
| Mayo-Kebbi      | Rice          | 39.264        | 100      | 0         | 3            | 6                         | 0                         | 4                |
| Mayo-Kebbi      | Rec. Sorghum  | 56.099        | 100      | 0         | 2            | 9                         | 0                         | 6                |
| Tandjilé        | Millet        | -4.319        | 100      | 0         | 3            | 1                         | 5                         | 2                |
| Tandjilé        | Sorghum       | -20.549       | 19       | 81        | 1            | 0                         | 9                         | 2                |
| Tandjilé        | Maize         | 7.1           | 70       | 30        | 3            | 2                         | 3                         | 2                |
| Tandjilé        | Rice          | 40.218        | 100      | 0         | 3            | 6                         | 0                         | 5                |
| Tandjilé        | Rec. Sorghum  | 0             | -        | -         | -            | -                         | -                         | -                |
| Log. Occidental | Millet        | 0             | -        | -         | -            | -                         | -                         | -                |
| Log. Occidental | Sorghum       | 21.081        | 100      | 0         | 2            | 3                         | 0                         | 2                |
| Log. Occidental | Maize         | 13.015        | 55       | 45        | 2            | 2                         | 0                         | 1                |
| Log. Occidental | Rice          | 10.251        | 100      | 0         | 2            | 2                         | 0                         | 1                |
| Log. Oriental   | Millet        | 5.316         | 42       | 58        | 2            | 3                         | 6                         | 4                |
| Log. Oriental   | Sorghum       | 0             | -        | -         | -            | -                         | -                         | -                |
| Log. Oriental   | Maize         | 15.426        | 84       | 16        | 2            | 3                         | 2                         | 3                |
| Log. Oriental   | Rice          | 20.449        | 81       | 19        | 3            | 3                         | 0                         | 2                |
| Moyen-Chari     | Millet        | 13.425        | 100      | 0         | 2            | 4                         | 4                         | 4                |
| Moyen-Chari     | Sorghum       | 75.139        | 100      | 0         | 3            | 15                        | 8                         | 13               |
| Moyen-Chari     | Maize         | 20.474        | 35       | 65        | 2            | 3                         | 0                         | 2                |
| Moyen-Chari     | Rice          | 23.548        | 100      | 0         | 3            | 4                         | 0                         | 3                |
| Moyen-Chari     | Rec. Sorghum  | 0             | -        | -         | -            | -                         | -                         | -                |

*Ha x 10³.
Table 6. Trend results for the variance of the harvested area in the Soudanian zone.

| Region          | Crop          | Total change* | % abrupt | % gradual | Breakpoints | % positive change in group | % negative change in group | % change in group |
|-----------------|---------------|---------------|----------|-----------|-------------|---------------------------|---------------------------|------------------|
| Mayo-Kebbi      | Millet        | 5.635         | 81       | 19        | 1           | 5                         | 3                         | 4                 |
| Mayo-Kebbi      | Sorghum       | -0.172        | 97       | 3         | 3           | 19                        | 50                        | 28                |
| Mayo-Kebbi      | Maize         | 5.324         | 100      | 0         | 1           | 3                         | 0                         | 2                 |
| Mayo-Kebbi      | Rice          | 10.676        | 27       | 73        | 3           | 7                         | 0                         | 5                 |
| Mayo-Kebbi      | Rec. Sorghum  | 0             | -        | -         | -           | -                         | -                         | -                 |
| Tandjilé        | Millet        | 4.283         | 100      | 0         | 1           | 3                         | 0                         | 2                 |
| Tandjilé        | Sorghum       | -3.787        | 100      | 0         | 2           | 10                        | 32                        | 16                |
| Tandjilé        | Maize         | -1.134        | 100      | 0         | 1           | 0                         | 2                         | 1                 |
| Tandjilé        | Rice          | 9.116         | 0        | 100       | 0           | 6                         | 0                         | 4                 |
| Tandjilé        | Rec. Sorghum  | 0             | -        | -         | -           | -                         | -                         | -                 |
| Log. Occidental | Millet        | 4.129         | 100      | 0         | 2           | 3                         | 0                         | 2                 |
| Log. Occidental | Sorghum       | 5.806         | 100      | 0         | 2           | 7                         | 7                         | 7                 |
| Log. Occidental | Maize         | 0             | -        | -         | -           | -                         | -                         | -                 |
| Log. Occidental | Rice          | -0.443        | 100      | 0         | 2           | 2                         | 5                         | 3                 |
| Log. Oriental   | Millet        | 0             | -        | -         | -           | -                         | -                         | -                 |
| Log. Oriental   | Sorghum       | 16.089        | 100      | 0         | 1           | 10                        | 0                         | 7                 |
| Log. Oriental   | Maize         | 0             | -        | -         | -           | -                         | -                         | -                 |
| Log. Oriental   | Rice          | 3.685         | 0        | 100       | 2           | 2                         | 0                         | 2                 |
| Moyen-Chari     | Millet        | 18.454        | 0        | 100       | 0           | 12                        | 0                         | 8                 |
| Moyen-Chari     | Sorghum       | 16.078        | 0        | 100       | 0           | 10                        | 0                         | 7                 |
| Moyen-Chari     | Maize         | 0             | -        | -         | -           | -                         | -                         | -                 |
| Moyen-Chari     | Rice          | 3.673         | 0        | 100       | 2           | 2                         | 0                         | 2                 |
| Moyen-Chari     | Rec. Sorghum  | -0.589        | 100      | 0         | 1           | 0                         | 1                         | 0                 |

*Ha x 10³, standard deviations.
Table 7. Trend results for the yield in the Soudanian zone.

| Region          | Crop          | Total change* | % abrupt | % gradual | Breakpoints | % positive change in group | % negative change in group | % change in group |
|-----------------|---------------|---------------|----------|-----------|-------------|---------------------------|---------------------------|------------------|
| Mayo-Kebbi      | Millet        | -0.025        | 100      | 0         | 2           | 3                         | 14                        | 6                |
| Mayo-Kebbi      | Sorghum       | 0.236         | 100      | 0         | 2           | 13                        | 0                         | 10               |
| Mayo-Kebbi      | Maize         | 0.355         | 74       | 26        | 2           | 9                         | 7                         | 8                |
| Mayo-Kebbi      | Rice          | 1.379         | 77       | 23        | 3           | 20                        | 49                        | 27               |
| Mayo-Kebbi      | Rec. Sorghum  | 0.206         | 100      | 0         | 3           | 10                        | 19                        | 12               |
| Tandjilé        | Millet        | 0.156         | 100      | 0         | 1           | 2                         | 0                         | 2                |
| Tandjilé        | Sorghum       | 0.232         | 100      | 0         | 2           | 6                         | 0                         | 5                |
| Tandjilé        | Maize         | 0.161         | 100      | 0         | 1           | 1                         | 0                         | 0                |
| Tandjilé        | Rice          | 0             | -        | -         | -           | -                         | -                         | -                |
| Tandjilé        | Rec. Sorghum  | 0.487         | 100      | 0         | 2           | 2                         | 0                         | 1                |
| Log. Occidental | Millet        | 0             | -        | -         | -           | -                         | -                         | -                |
| Log. Occidental | Sorghum       | 0.355         | 100      | 0         | 2           | 9                         | 0                         | 7                |
| Log. Occidental | Maize         | 0.192         | 100      | 0         | 1           | 1                         | 0                         | 1                |
| Log. Occidental | Rice          | 0.852         | 100      | 0         | 1           | 3                         | 0                         | 3                |
| Log. Oriental   | Millet        | 0             | -        | -         | -           | -                         | -                         | -                |
| Log. Oriental   | Sorghum       | 0.327         | 100      | 0         | 2           | 10                        | 0                         | 8                |
| Log. Oriental   | Maize         | 0.318         | 67       | 33        | 2           | 5                         | 8                         | 6                |
| Log. Oriental   | Rice          | 0.918         | 71       | 29        | 2           | 5                         | 4                         | 5                |
| Moyen-Chari     | Millet        | 0             | -        | -         | -           | -                         | -                         | -                |
| Moyen-Chari     | Sorghum       | 0             | -        | -         | -           | -                         | -                         | -                |
| Moyen-Chari     | Maize         | 0.135         | 100      | 0         | 1           | 1                         | 0                         | 1                |
| Moyen-Chari     | Rice          | 0.626         | 82       | 18        | 2           | 1                         | 1                         | 1                |
| Moyen-Chari     | Rec. Sorghum  | 0.261         | 100      | 0         | 1           | 0                         | 0                         | 0                |

*Ton/ha.
Table 8. Trend results for the variance of the yield in the Soudanian zone.

| Region          | Crop      | Total change* | % abrupt | % gradual | Break-points | % positive change in group | % negative change in group | % change in group |
|-----------------|-----------|---------------|----------|-----------|--------------|-----------------------------|---------------------------|------------------|
| Mayo-Kebbi      | Millet    | -0.096        | 74       | 26        | 2            | 4                          | 5                         | 5                |
| Mayo-Kebbi      | Sorghum   | 0.005         | 93       | 7          | 2            | 5                          | 4                         | 4                |
| Mayo-Kebbi      | Maize     | -0.004        | 49       | 51         | 1            | 8                          | 5                         | 7                |
| Mayo-Kebbi      | Rice      | -0.377        | 100      | 0          | 1            | 0                          | 11                        | 7                |
| Mayo-Kebbi      | Rec. Sorghum | 0          | -        | -          | -            | -                          | -                         | -                |
| Tandjilé        | Millet    | 0             | -        | -          | -            | -                          | -                         | -                |
| Tandjilé        | Sorghum   | -0.062        | 100      | 0          | 3            | 13                         | 10                        | 11               |
| Tandjilé        | Maize     | -0.101        | 100      | 0          | 1            | 0                          | 1                         | 1                |
| Tandjilé        | Rice      | -0.612        | 74       | 26         | 1            | 0                          | 30                        | 19               |
| Tandjilé        | Rec. Sorghum | -0.04       | 57       | 43         | 1            | 3                          | 3                         | 3                |
| Log. Occidental | Millet    | -0.043        | 100      | 0          | 1            | 0                          | 1                         | 1                |
| Log. Occidental | Sorghum   | 0.088         | 100      | 0          | 1            | 2                          | 0                         | 1                |
| Log. Occidental | Maize     | 0.063         | 100      | 0          | 1            | 2                          | 0                         | 1                |
| Log. Occidental | Rice      | 0.08          | 63       | 37         | 3            | 24                         | 8                         | 13               |
| Log. Oriental   | Millet    | 0.091         | 100      | 0          | 1            | 3                          | 0                         | 1                |
| Log. Oriental   | Sorghum   | 0.093         | 71       | 29         | 2            | 24                         | 3                         | 11               |
| Log. Oriental   | Maize     | 0.008         | 100      | 0          | 2            | 3                          | 2                         | 2                |
| Log. Oriental   | Rice      | 0             | -        | -          | -            | -                          | -                         | -                |
| Moyen-Chari     | Millet    | -0.018        | 100      | 0          | 2            | 3                          | 3                         | 3                |
| Moyen-Chari     | Sorghum   | -0.112        | 100      | 0          | 1            | 0                          | 12                        | 7                |
| Moyen-Chari     | Maize     | 0             | -        | -          | -            | -                          | -                         | -                |
| Moyen-Chari     | Rice      | -0.101        | 55       | 45         | 1            | 5                          | 2                         | 3                |
| Moyen-Chari     | Rec. Sorghum | 0           | -        | -          | -            | -                          | -                         | -                |

*Ton/ha, standard deviations.

Figure. A1. Trend graph for the variance of the harvested area in the Sahelian zone (SD: standard deviations).
Figure. A2. Trend graph for the variance of the yield in the Sahelian zone (SD: standard deviations).

Figure. A3. Trend graph for the harvested area in the Soudanian zone.

Figure. A4. Trend graph for the yield in the Soudanian zone.